Renewing power

Including global asymmetries within the system boundaries of solar photovoltaic technology

Roos, Andreas

2021

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Roos, A. (2021). *Renewing power: Including global asymmetries within the system boundaries of solar photovoltaic technology*. Lund University.

Total number of authors:
1

LUND UNIVERSITY

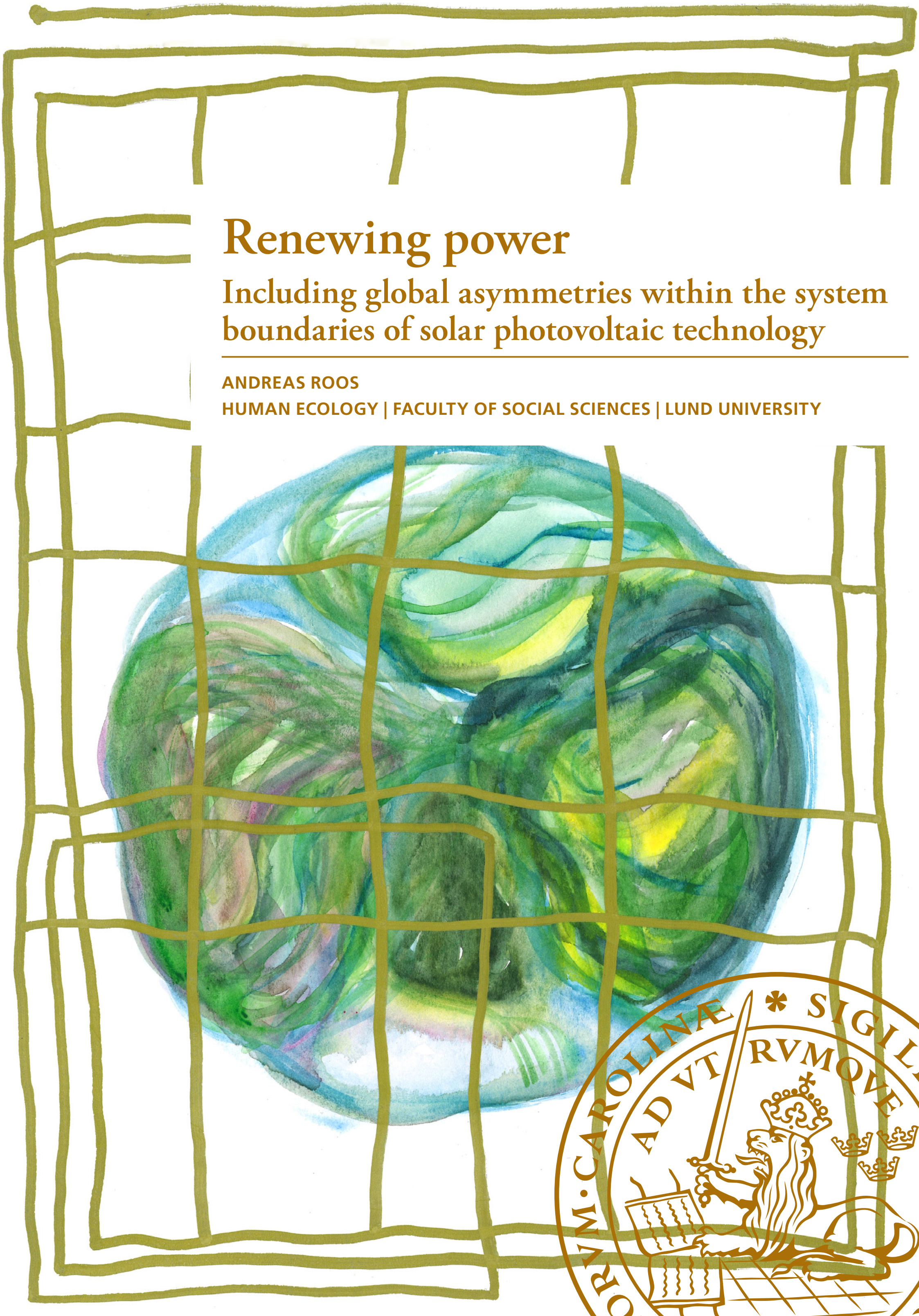
PO Box 117
221 00 Lund
+46 46-222 00 00

Renewing power

Including global asymmetries within the system boundaries of solar photovoltaic technology

ANDREAS ROOS

HUMAN ECOLOGY | FACULTY OF SOCIAL SCIENCES | LUND UNIVERSITY



SOLAR PHOTOVOLTAIC (PV) TECHNOLOGY is rapidly emerging as a cost-effective option in the world economy. Governments, corporations, and grassroots actors are promoting solar PV power in the hope of transforming the fossil-based energy regime and mitigating climate change. However, reports about miserable working conditions, environmentally deleterious mineral extraction, and toxic waste dumps corrode the image of a problem-free future based on solar power.

The research is contradictory and the environmental movement is divided. Meanwhile, few are asking fundamental questions about what solar PV technology *is* from the perspective of global inequalities and asymmetric resource flows. This thesis investigates the extent to which the detrimental global consequences of solar PV technology are contingent or inherent conditions for the technology itself.

Printed by Media-Tryck, Lund 2021 NORDIC SWAN ECOLABEL 3041 0903

LUND
UNIVERSITY

Faculty of Social Sciences
Human Ecology Division

ISBN 978-91-7895-799-6

9 789178 957996

Renewing power

Renewing power

Including global asymmetries within the system boundaries of solar photovoltaic technology

Andreas Roos

LUND
UNIVERSITY

DOCTORAL DISSERTATION

by due permission of the Faculty Social Sciences, Lund University, Sweden.
To be defended online on the 28th of April, 15.00 CET, 2021.

Faculty opponent
Langdon Winner

Organization LUND UNIVERSITY	**Document name** Doctoral dissertation
	Date of issue 30.03.2021
Author Andreas Roos	**Sponsoring organization** N/A

Title and subtitle Renewing power: Including global asymmetries within the system boundaries of solar photovoltaic technology

Abstract

Solar photovoltaic (PV) technology is one of the most favored means of mitigating climate change. At the same time, there is a growing concern over how this technology is both environmentally harmful and unevenly distributed in the world economy. Researchers and environmentalists differ on whether a global relation of power is inherent in solar technology. This thesis investigates to what extent the global, social and material conditions of solar PV technology contrast with conventional conceptions of it. Building on insights from ecological economics and the philosophy of technology, it offers an interdisciplinary approach to solar PV technology. Its central question is whether 'ecologically unequal exchange' is a necessary condition for large-scale solar PV development. The theory of ecologically unequal exchange explains how wealthier nations rely on net imports of resources to sustain their levels of consumption and technological development, while displacing much of their work and environmental loads to poorer nations. This theory is tested in an LCA-based account of ecologically unequal exchange between Germany and China during the emergence of the global solar PV market (2002-2018). It is also tested through an application of the concept of 'power density' to four leading solar nation's PV ambitions (China, Germany, India, Italy). The findings demonstrate how large-scale development of solar PV technology may require global asymmetries as much as polysilicon, electrical components, engineers, or direct sunshine. To the extent that decision-makers disregard this, it may be a symptom of 'machine fetishism,' which masks the global asymmetries of the emerging energy regime while also preventing us from grasping what modern technology ultimately *is*.

Key words solar energy; photovoltaic technology; ecologically unequal exchange; philosophical materialism; social metabolism; political artifacts; authoritarian technics; machine fetishism; environmental justice; environmental sustainability

Classification system and/or index terms (if any)

Supplementary bibliographical information		**Language** English
ISSN and key title N/A		**ISBN** (Print): 978-91-7895-799-6 **ISBN** (PDF): 978-91-7895-800-9
Recipient's notes	**Number of pages** 230	**Price**
	Security classification	

I, the undersigned, being the copyright owner of the abstract of the above-mentioned dissertation, hereby grant to all reference sources permission to publish and disseminate the abstract of the above-mentioned dissertation.

Signature **Date** 16.03.2021

Renewing power

Including global asymmetries within the system boundaries of solar photovoltaic technology

Andreas Roos

Lund
University

Coverphoto by Sonja Regårdh

Faculty of Social Sciences
Human Ecology Division

ISBN (Print) 978-91-7895-799-6
ISBN (PDF) 978-91-7895-800-9

Printed in Sweden by Media-Tryck, Lund University, Lund 2021

Printed matter
3041 0903

Media-Tryck is a Nordic Swan Ecolabel
certified provider of printed material.
Read more about our environmental
work at www.mediatryck.lu.se

MADE IN SWEDEN

This dread, this shadow of the mind must, thus be swept away
Not by rays of the sun nor by the brilliant beams of day
But by observing nature and her laws. And this will lay
The warp out for us – her first principle: that nothing’s brought
Forth by any supernatural power out of naught.

Lucretius

Table of contents

Acknowledgements

I wrote this thesis with the conviction that human societies cannot survive without healthy relations to their environments. By the same line of reasoning, there can be no inside without an outside; no us without a them; and no me without a you. I believe that our thoughts are rarely our own, or, to be more humble, that *my* thoughts are rarely my own. It is abundantly clear to me that I could not have written this thesis without the support of family, friends, and colleagues who shaped my thinking and who stood firm when the harsh winds blew.

I first want to thank my family for always supporting me. Your love and your tireless encouragement has made me who I am today. It seems that you have always trusted me to find my own way, and thereby taught me the subtle art of following the heart. Your support throughout my PhD studies has been nothing short of fantastic. To my parents Karin Roos and Ingvar Roos, my sister Cecilia Roos, my sister Åsa Roos, my sister Ylva Svedenmark (with family), my brother-in-law Sherif Ibrahim, and my mother-in-law Sziliva Roos, thank you!

It is said that we are standing on the shoulders of giants. This is certainly true for my work, which was carried high on the shoulders of my supervisors. To Alf Hornborg I am deeply grateful for the academic support, stimulating discussions, and intellectual challenges that you have so enthusiastically provided throughout the years. Among many things, you have taught me that subversive academic work must strike a balance between disciplinary disobedience and analytic rigor. Thank you also for meticulously reading and commenting on my entire manuscript no less than two times. To Vasna Ramasar I owe a similar gratitude for the unwavering support, stimulating discussions, and continual inspiration to be a positive force in the world. Among many things, you have taught me that subversive academic work must be based on a trust and a belief in one's own ability to make a difference.

I also want to thank the colleagues who have been part of my long learning journey. This includes teachers who became colleagues at the Human Ecology Division, including Anders Burman, Andreas Malm, Pernille Gooch, Thomas Malm, Rikard Warlenius, and Ragnheiður Bogadóttir. Your knowledge of the

world has no doubt influenced my work and me. The same goes for my fellow PhD students in human ecology. Thank you Sarah Kollnig, Sanna Händén-Svensson, Amr Khairy, and Mariko Takedomi-Karlsson for the incredibly stimulating and good-humored workdays at the office.

Thank you to all of my fellow PhD students and colleagues at the Department of Human Geography, not the least to Ilia Farahani for the invigorating evening jams. For critical feedback on manuscript drafts, thanks to Pasi Heikkurinen, Wim Carton, and Henner Busch. I wish you all the best of luck in your current and future aspirations.

I wish to extend a special thanks to Vasilis Kostakis and the fellows at the P2P Lab in Ioannina, Greece. I am ever grateful for the critical discussions and the academic collaborations that prepared me for my PhD studies.

My gratitude also goes to Marlis Wullenkord for the loving support, to Bergitte Lowzow, and to all of my inspiring friends who are fighting for a habitable planet.

1. Solar power at the brink: On the need to relate solar visions to reality

> "*The majority of problems in the world are the result of the difference between how nature works and the way people think.*"
>
> Gregory Bateson

Solar photovoltaic (PV) technology is today one of the most favored responses to the ecological crisis. Simultaneously, researchers and environmentalists are concerned that the social and ecological consequences of solar power may be both harmful and unequally distributed (e.g., Zehner, 2012; Andersen, 2013 Trainer, 2014; Hornborg, 2014; Yenneti et al., 2016; Dale, 2019; Sonter et al., 2020; Jensen et al., 2021). This concern has been met by polarized responses ranging from a rejection of solar PV technology (e.g. Zehner, 2012) to prompt solutions (e.g., Mulvaney, 2019) to outright denial (e.g., Phillips, 2020). The question whether the harmful and unequally distributed consequences are inherent or transitory to solar PV technology lies at the very heart of the polarization. Meanwhile, few are asking the most fundamental question of what solar PV technology *is*. In this thesis, I combine perspectives from philosophy of technology and ecological economics in the hope to provide an answer to this question.

The aim is a) to understand whether an uneven distribution of resources in the world economy is inherent to large-scale solar PV development, b) what this condition means for the definition of solar PV technology, and c) what this in turn implies for the premise that solar PV technology is a feasible option for a socially just and ecologically sustainable world.[1] The purpose is to present propositions about ecologically unequal exchange and the ontology of technology that will clarify and deepen current discussions on solar power in

---

[1] The aim is not to compare whether the ecological effects of fossil fuels presents a better or worse ecological situation than the effects of solar power. It is abundantly clear that fossil fuels are finite and non-sustainable stocks of energy that the world's actors must immediately stop burning in order to halt the detrimental effects of climate change (IPCC, 2014A, 2018).

a way that I hope will be useful for the manifold efforts to create a socially just and ecologically sustainable world.

The thesis builds on the conviction that the conventional understanding of technology as "applied science" is fragmentary and misleading (e.g., Heidegger, 1977[1954]; Ellul, 1964; Winner, 1978, 2020[1986]; Feenberg, 1991; Hornborg, 2001, 2013; Marx, 2010). Following this, the typical problem with technological solutions is that the full social, political, and ecological conditions of their deployment become apparent only after significant changes have already occurred (Winner, 2020[1986]; Johnston, 2020). "[A]s technologies are built and put into use," Winner suggests, "significant alterations in patterns of human activity and human institutions are already taking place. New worlds are being made" (Winner, 2020[1986]: 11). However, we seldom stop to consider what kind of world is actually being made. This applies to solar PV technology as a contestant to fossil fuels. This time, however, the stakes are so consequential to the fate of the biosphere that we cannot afford to ignore what social-ecological conditions they may require.

Considering that "solar power is no longer alternative technology," it is both possible and incumbent upon us to consider how visions of a solar powered future compare to the social-ecological reality of its existence (Mulvaney, 2019: 1). Importantly, there is a substantial amount of literature showing that the technologies that are applied to solve the ecological crisis seldom live up to their promises (e.g., Pimentel, 2003; Huesemann and Huesemann, 2011; Kabasakal and Albayrak, 2012; Bonds and Downey, 2012; Hornborg, 2014; Giampietro and Mayumi, 2015; Carton, 2019; Adua et al. 2021). In many of these examples, including biofuels, electric cars, nuclear power, and carbon capture storage, "green" technological solutions are pursued because they are granted a symbolic meaning that overshadow the reality of their application.[2] Following these studies, the hypothesis of this thesis is that the conception of solar PV technology contradicts the actual conditions of its existence.

Human ecology, grounded in both the social and natural sciences, is uniquely equipped to understand how the symbolic meaning of solar PV technology relates to the physical conditions of its existence. As Paul Shepard (1967) contended long ago, "the central problem of human ecology may be characterized as the relationship of the mind to nature." In particular, I draw

---

[2] So-called "greenwashing" – whereby corporations falsely brand commodities as environmentally sustainable to increase the rate of profit – is a well-known phenomenon by which misleading symbolism obscures the real world impacts of commodities (see e.g. Lyon and Montgomery, 2015; Takedomi Karlsson and Ramasar, 2020).

upon the theory of "ecologically unequal exchange," which explains the mechanism by which industrial societies enjoy high levels of material wealth and technological development, while exporting the environmental loads of their lifestyles to the world's impoverished (see chapter two). Importantly, it has been argued that the rise of fossil-powered machinery and industrial manufacturing was contingent upon an ecologically unequal exchange whereby the British Empire appropriated large amounts of embodied land and embodied labor from North America (Hornborg, 2006).[3] So far, however, only two studies have empirically examined the relation between "green" technology and ecologically unequal exchange (Bonds and Downey, 2012; Hornborg et al., 2019).

The possibility that solar PV technology is contingent on ecologically unequal exchange means that an uneven distribution of resources and environmental impacts in the world economy may be an inherent condition of solar PV technology. If this is so, then solar PV technology is more than an "applied science" to harness the forces of nature, since it then involves global social-ecological relations without which it would not exist. In turn, this raises important questions concerning the premise that solar PV technology can be employed to solve global environmental problems. To get to the bottom of this, I ask the following set of research questions (RQs):

- RQ1: *Is solar PV technology based on ecologically unequal exchange? Can large-scale solar PV technological development occur without global asymmetric flows of resources?*
- RQ2: *In turn, what does this say about solar aspirations that are based on the premise that solar PV technology is a feasible option for a socially just and ecologically sustainable world?*
- RQ3: *What can this tell us about what solar PV technology is? More generally, what can this tell us about what technology is?*

In drawing on insights and discussions from philosophy of technology, I situate the core questions of this thesis as part of a long tradition attempting to understand the inconsistencies and contradictions of technological solutions in industrial societies. Among philosophers such as Karl Marx, Lewis Mumford, Martin Heidegger, Jacques Ellul, Herbert Marcuse, Ivan Illich, Langdon Winner, Ernst Schumacher, and others, there is a common ambition to examine the wider historical implication of advanced technology in industrial societies

---

[3] For a description of the term "embodied," see Appendix A.

and its emancipatory promises. Importantly, these examinations were often raised from observations on how new machinery and new technologies were repeatedly inconsistent with their liberating and cornucopian promises. I draw upon these thinkers today, because it is now possible to identify contradictions in the visions of a future society based on solar PV technology.

In this chapter, I first examine the social-ecological arguments for solar power and how the visit to a solar park in Sweden compelled me to ask questions about these arguments. I then show how solar power is a celebrated technological solution across the political spectrum, all while there is a growing group of contenders pointing out its drawbacks and contradictions. This is followed by a brief overview of the contents and structure of the thesis. Finally, I provide a note on the thesis's interdisciplinary approach.

The promising arguments for solar power: A contradictory vision

Around ten to twenty years ago, every other book on the state of the planet seemed to end with a hopeful note on some of the most promising technological solutions. The "good news," one well-known student textbook claimed, "is that we know a number of ways to slow the rate and degree of global warming and the resulting climate change caused by our activities" (Miller and Spoolman, 2009: 514). The solutions came down to three strategies: "[a] improve energy efficiency to reduce fossil fuel use; [b] shift from nonrenewable carbon-based fossil fuels to a mix of carbon-free renewable energy resources; and [c] stop cutting down tropical forests" (ibid.). The chapter proceeded to discuss seventeen different solutions, out of which over a half implied either a novel application or significant development of an advanced technology. Among these solutions was the suggestion to "[i]ncrease solar power 700-fold to displace coal-fired plants," a figure that was much higher than the suggested installation of other renewable energy technologies (ibid.). At the time, countless books ended with similar visions proclaiming devotion to technological solutions and in particular solar power. Since then, much has changed, and it is now possible to assess the practical implications of these visions.

It must be understood that the predisposition towards technological solutions such as solar power is based on important *ecological* reasons. There is no doubt that fossil-based energy systems need to be replaced as swiftly as possible for world society to have any chance of mitigating anthropogenic emissions of greenhouse gases and stay below 2°C warming compared to pre-industrial levels (Hansen et al., 2013; IPCC, 2014a, 2018a). Many are convinced that solar power will largely replace fossil energy. Unlike fossil energy, solar power does not directly emit greenhouse gases in the process of generating electricity, which means that it does not directly cause air pollution that adversely affects plants, humans, and non-human animals in local ecosystems. By all practical accounts, direct sunshine is also a near-infinite energy resource that does not disappear from the world[4] once it is "used," as is the case with the combustion of coal or oil.

There are also important *social* reasons for turning to solar power. Solar advocates have long pointed out how generating electricity from locally sourced direct sunshine is much more aligned with democratic values and just social relations (Mander, 1991; Scheer, 2007; Klein, 2014). Even technology critic Jerry Mander (1991), who accused the environmental movement in the 1990s for "failing to effectively criticize technical evolution despite its obvious, growing, and inherent bias against nature," saw solar power as "intrinsically biased toward democratic use" (Mander, 1991: 3, 36). This, he argued, was because solar technology "is buildable and operable by small groups, even families" and "does not require centralized control … a reason why big power companies oppose it" (ibid. 36).

Together, the combined social and ecological reasons for advocating solar power form a powerful foundation for contemporary visions of a more democratic and ecologically sustainable future. Among the best syntheses to date can be found in Naomi Klein's (2014) acclaimed book *This Changes Everything,* in which she tells the story of Henry Red Cloud, a Lakota entrepreneur who is working with the local community in the Pine Ridge Reservation in South Dakota to install solar power. For Red Cloud "'solar power was always part of Native's way of life'" because it embodies a worldview in which people are adapting to the rhythms of natural ecosystems, as opposed to dominating and controlling them (ibid. 393). The relinquishing of control, Klein continues, is inherent to solar power because in contrast to the power of coal, the sun does not shine all the time and cannot therefore generate energy on demand. This means that solar power also embodies fundamentally different "power *relations* between humanity and the natural

---

[4] I use the term "the world" in the philosophical sense to denote the whole of the physical universe (for a full list of concepts and terms see Appendix A).

world" and that humans have to work "with the earth" instead of simply consuming it, as if it was a resource (ibid. 239, emphasis in original).

Klein argues that solar power should be understood as a tangible alternative for local communities to convert fossil infrastructure in their own backyard into locally owned and democratically operated solar parks. With examples from Navajo- and Hopi-led initiatives to convert a local coal mine into a solar park, she argues that these parks could provide training skills, jobs, and steady revenues for members in the community, all while generating "power not just for their reservation but also large urban centers" (ibid. 296). They would make a "fundamentally new [social-ecological] relationship" possible, in which communities themselves can set the framework and agenda for their own development while rejecting the extractive logic of fossil technology that destroys the land and the Earth (ibid. 297). In the case of the Navajo and Hopi, however, this vision could never be fully realized because of one major barrier: lack of capital.

Despite the absence of practical examples, the core thrust of Klein's vision remains strong: solar technology can inaugurate new social-ecological relations that are inherently aligned with ecological sustainability and democracy. For several reasons, rivalling energy options such as nuclear power cannot serve the same democratic, nature-bound basis for future societies. Nuclear power plants require expert knowledge on how to stabilize the fission process in the reactor core as well as expertise on how to build and maintain the necessary infrastructure and how to (not) take care of the radioactive waste materials. This immediately places a disproportionate amount of power – political and physical – in the hands of a few people. Contrary to capturing sunshine, the process of splitting atoms (fission) also implies that one intentionally encourages and exploits a natural weakness (molecular instability) to destroy the very fabric of life. This is often done under the misleading narrative that it will be possible to contain the fission process within the reactor cores and avoid releasing it upon the world through accidental meltdowns, or purposeful military operations (Sovacool, 2011; Diaz-Maurin and Kovacic, 2015; Wealer et al., 2019). Despite the ecomodernist conviction that "nuclear fission, and nuclear fusion represent the most plausible pathways towards the joint goals of climate stabilization and radical decoupling human from nature" (Asafu-Adjaye et al., 2015: 23-24), nuclear power is associated with higher demand on the natural world than fossil fuels (Diaz-Maurin and Giampietro, 2013). As such, solar power will likely remain a far more democratic and environmentally favorable option than nuclear power.

Armed with these arguments for solar power, I was curious to visit a local solar park that was founded upon values of ecological sustainability and grassroots democracy. In Sweden, the most famous solar park resembling what Klein described, is being developed and operated by a company called ETC just outside the town of Katrineholm. ETC is primarily a media company running an online media platform and publishing a monthly magazine consisting of left-leaning news that also caters to environmental concerns. Over the years, the company has gained some attention and is now making a name for itself among progressives and environmentalists. In contrast to the Navajo- and Hopi- led organization for solar power, ETC has been able to invest capital in a self-operated solar park funded by its readers, who either contribute financially through the subscription fee or invest directly in the solar park with an interest rate of two percent. ETC's solar park displays both similarities with and differences from the proposed solar park of the Navajo and Hopi. Most importantly, ETC seem to have solved the problem of capital.

I decided to contact the head of the park and was happy to receive the reply that I was more than welcome for a guided tour and a chat. A few months later, I was on my way to the park located roughly two kilometers north of Katrineholm. I arrived by train and decided to walk to the solar park. To my surprise, arriving at the park by foot was rather difficult. My immediate thought was that the park must have been newly built and that they simply had not had time to construct a proper entrance. It was only later that I realized that the park entrance was located on the other side of the compound and that visitors were expected to access the solar park by car. After orienting myself from the backdoor, I could see that the park was located just next to a large road and that some of the constructions in the park (e.g., a large solar tower with the ETC logo) were meant as advertisements for cars passing by on the highway. The idea, I figured, was that the visitors coming by car were exposed to an association between solar power and electric vehicles as a viable transportation alternative for the future. I later learned that the park offers free electric charging for those who pass by with electric vehicles. In this sense, the solar park was not a solar park at all, but a gas station, or, rather, a solar station. This came as a surprise to me, who had taken to heart Ivan Illich's conviction that "[p]articipatory democracy demands low energy technology, and free people must travel the road to productive social relations at the speed of a bicycle" (1974: 12).

At the park, the head of operations, David Eskilsson[5], greeted me. He was just finishing an education session with a group of schoolchildren. David had been

---

[5] This name is a pseudonym.

a project manager at the ETC solar park for over seven years and now thought of himself primarily as an inspirer for solar cells and climate transformation. It became apparent through our talk that the solar park was founded on the idea of demonstrating that solar PV cells and other solar power solutions are effective to combat climate change, regardless of what critics say. But technological solutions, David told me, were by no means the most important aspect of what they were doing. Instead, their primary objective was to demonstrate that alternative ways of harnessing energy are a feasible option for the future. The purpose was to make people feel empowered to install solar cells or solar modules of their own after a visit to the park.

To say that solar power is easy, David explained, is not to say that the development of solar projects is without setbacks. Technically, solar PV modules are easy to install, but the social-political context is not exactly generous to organizations (such as ETC) who are seeking to transform the nation's energy regime. He proceeded to give a brief account of the power dynamics between the electric grid operators, the role of the state, and how the park could be part of a grassroots movement that could influence political decisions, if it grew big enough. He pointed out that this had in fact already occurred in Germany, where small-scale energy producers together formed a political force of consequence. In 2010, I later learned, up to 40% of Germany's installed renewable energy capacity was owned by citizen energy cooperatives, so-called *Energiegenossenschaften* (Buchan, 2012: 9-11). Recently, David continued, this had become a tangible option for Sweden, because the price of solar energy had fallen considerably over the last years. This meant that energy cooperatives could soon wield considerable political power and influence many important decisions in Sweden, but only if people felt encouraged to install solar modules on their rooftops and organize into cooperatives.

When I asked why the prices had fallen, David told me that it was because of lower production costs in solar PV cell manufacturing. In turn, I asked why he thought that production costs of solar cell had dropped in prices over the recent years. "It is because of the Chinese," he replied without hesitation, "and that there is now a mass production [of solar PV modules]" (interview 02-10-2019). We briefly discussed the issue of being dependent on the international market for solar PV modules. David thought that it would be difficult if Sweden sought to become completely self-sufficient in solar PV module production. A certain level of international trade would remain necessary, he asserted. With the analogy of textile production in India and Pakistan, he explained how clothes would be far too expensive for Swedish consumers if they were all produced in Sweden where labor is more expensive and where there are strong environmental regulations in place. “We need to find a good form for it [production of solar PV modules],” he argued, because we cannot completely get rid of this situation (ibid.). Both David and I saw the problem.

The problem was that the vision for an environmentally sustainable and democratically aligned solar-powered energy regime orchestrated by grassroots actors was founded upon what seemed to be a socially and environmentally dubious division of labor in the world economy. To keep prices on solar panels low enough to be politically subversive appeared to *require* that they be produced on the other side of the world at low wages, with low environmental regulations, and often in fossil-powered industries. This confirmed my suspicion that solar power, however decentralized it appears when installed on rooftops and balconies, is not a local affair at all. To the extent that solar PV modules are made within an economic system largely organized in terms of price differences, even the smallest local initiatives to put solar modules on rooftops is contingent on a wider global economy. While the powerful solar visions of Naomi Klein and ETC are ecologically and democratically aligned, neither of them fully account for the processes occurring outside the boundaries of the solar parks, where these price differences are exploited (even if David was certainly aware of the issue).

This means that the political visions for a solar powered future may not be consistent with the reality of their practical implementation. With reference to the introductory quote by Gregory Bateson, this inconsistency exemplifies a “difference between how nature works and the way people think” when it comes to solar PV technology as a feasible option for a socially just and ecologically sustainable future.[6] To democratize the global production chains by increasing salaries and enforcing environmental regulations in China would not necessarily dissolve the inconsistency, because the solar parks and democratic solar cooperatives would then likely become unaffordable to Swedish citizens. The democratic possibility and sustainability potential of solar power available to the globally affluent may therefore be inextricably bound to the uneven and environmentally degrading conditions among the globally impoverished. This would mean that the massive push for solar PV technology is not only generating solar power in the sense of renewable energy, but also *renewing the global social relations of power* that has characterized

---

[6] Perhaps it would be more accurate to say that the situation exemplifies a difference between how the economy works and the way people think. This, however, would overlook the biophysical, nature-given aspects harnessed by economies to produce technological artifacts, including solar modules (see chapter two).

the world economy at least since the 16th century. By extension, if solar power is being posited as one of the most promising technological solutions to environmental problems, while simultaneously embodying notable environmental disadvantages and global asymmetries, have we really understood the nature of technological solutions to environmental problems, and, by extension, technology itself?

With the world at stake:
Renewables, ecomodernism, and ecorealism

Despite disagreement among researchers and environmentalists, solar power is widely celebrated across the political spectrum. Over the last two decades, corporations from a diverse range of industries (oil to cosmetics) have transformed the production of solar technology into a profitable commercial industry driven by capital accumulation (Nemet, 2019).[7] This is a still ongoing process occurring with considerable support from both socialist and neoliberal governments (see e.g., Dong et al., 2015a; Yu et al., 2016; Spivey, 2020). Simultaneously, the idea of a global "solar communism," according to which solar technology can be installed to overthrow capitalist relations of production, is promoted by some eco-socialists (Schwartzman, 1996; Klein, 2014). In this camp, solar technology is understood as antithetical to corporate energy generation and the fossil-based transportation system that is at the heart of global capitalism (Malm, 2016). Some advocates of degrowth – a controlled downscaling of modern industrial societies to ecologically sustainable levels of matter-energy throughput under socially favorable conditions – also consider solar power as a promising solution, given the right circumstances (for an overview, see Dale, 2019; Adler et al., 2019). On the opposite side of the political spectrum, parties on the far right, particularly in some European countries such as France, have articulated ambitions to develop their countries' renewable energy capacity (Jeffries, 2017). This demonstrates how ambitions for solar power is now favored across the political spectrum.

The many different proposals for a Green New Deal (GND) also reflect a common convergence around renewable energy technologies. The GND is an "ecology-centered economic stimulus program" with focus on renewable energy technology, economic growth, efficiency improvements, and creation

---

[7] I analyze this recent historical development in chapter four.

of “green” jobs (Chohan, 2019). In the United States, the GND has primarily been driven by social democrats occupying a moderate position between proponents of capitalist growth and advocates of degrowth (Dale, 2019). Currently, however, it is favored both in neoliberal proposals for “green growth” and in eco-socialist visions of an “ecological politics for the working class” (Schwartzman and Schwartzman, 2013; Kim and Thurbon, 2015; Huber, 2019). From this, we can conclude either that the respective ideologies share a common philosophy, or that there is a confusion regarding the politics and feasibility to transform the modern human-environmental condition through “green” technologies. While the former conclusion appears farfetched, there does indeed seem to be a confusion regarding the transformative potential of technology both in mainstream and Marxist theory (Hornborg and Roos, 2021).

Despite this confusion, the contradictions of renewable energy technologies have not gone unnoticed. A significant body of literature has emerged that critically examines the social and ecological conditions of different renewable energy technologies, including solar power, hydroelectric power, wind power, and biofuels. Here I attempt to summarize some of the most relevant findings of this rapidly growing literature:

- *Renewable energy technologies require comparatively large amounts of land per energy unit harnessed* (Scheidel and Sorman, 2012; de Castro et al., 2013; Smil, 2015; Huber and McCarthy, 2017; Capellán-Pérez et al., 2020). There is strong evidence that solar power, wind power, hydroelectric power, and biofuels require large amounts of horizontal surface area compared to fossil fuels (Smil, 2015). Renewable energy sources such as sunshine, wind, and water are dispersed flows of energy that are not highly concentrated in subterranean deposits like coal, oil, or fossil gas. Since flows of energy are less concentrated, technologies capturing them must be dispersed across large surface areas.

- *Renewable energy technologies require comparatively large amounts of energy per energy unit harnessed* (Hall and Klitgaard, 2012; Hall et al. 2014; Ferroni and Hopkirk, 2016; de Castro and Capellán-Pérez, 2020). All renewable energy technologies – with the exception of hydropower– require a large energy investment per unit of energy return. By extension, these studies show that it will be problematic to maintain advanced industrial societies solely with the help of renewable energy technologies.

- Large-scale manufacturing, transportation, and installation of renewable energy technologies *require significant amounts of fossil energy and imply greenhouse gas emissions* (Fu et al., 2015; Stamford and Azapagic, 2018). The new energy regime can only emerge from the energetic and material basis of the old one, i.e., by burning fossil fuels. This fact gives rise to the dilemma known as the "energy-emissions trap" that states that economies seeking to transition away from high net energy fossil fuels to lower net energy renewables for the sake of reducing greenhouse gas emissions must significantly increase the emissions of greenhouse gases temporarily (Sers and Victor, 2018).

- There are some studies suggesting that *there are limits to the quantity and quality of material*s needed for massively scaling up the installation of renewable energy technologies (Feltrin and Freundlich, 2008; de Castro et al., 2013; McLellan et al. 2016; Tokimatsu et al. 2017; Rhodes, 2019). For solar power, this includes potential limits to recoverable reserves of silver, tellurium, indium, and selenium. Given the geographical dispersal of high-quality materials and the fact that "low-hanging fruits" are picked first, the finite nature of mineral deposits will likely drive increasing levels of geopolitical conflicts across the globe as renewable energy technologies are commercialized (Vakulchuk et al., 2020).

- *The installation of renewable energy technologies is not strictly speaking replacing fossil technologies* (York, 2012; York and Bell, 2019; Gellert and Ciccantell, 2020). Since the consumption of fossil energy carriers is increasing, installing more renewable energy technologies amounts to an energy addition, rather than an energy transition. As we will see later in this thesis, most of the ambitious plans to increase the relative level of solar power in the energy mix simultaneously imply a total increase in fossil fuel use. Considering that modern iron and steel production necessitate coke (pyrolysed coal), fossil fuels cannot be completely replaced with renewable energy (Smil, 2009, 2016a).

- In the global commodity chains, there are *negative and unequally distributed health effects and environmental consequences of renewable energy technologies* (Dubey et al., 2013; Yue et al., 2014; Mulvaney, 2013, 2019; Nain and Kumar, 2020). These effects include toxicity and environmental pollution in the manufacturing, transportation, and end-of-life processes. The effects disproportionally affect people who do not immediately benefit from the energy harnessed by the technologies. Similar injustices have been observed in state-backed enclosure of common land and dispossession of vulnerable communities to make way for utility-scale renewable energy parks producing energy for urban populations (e.g., Huber et al., 2016; Yenneti et al., 2016; Franquesa, 2018; Stock and Birkenholtz, 2019a, 2019b; Temper et al., 2020).

- In the process of mining and producing more metals for renewable energy technologies there are *significant risks to biodiversity*. These "new threats to biodiversity," one study concluded, "may surpass those averted by climate change mitigation" (Sonter et al., 2020). Rehbein et al. (2020) found that solar power, in comparison to other renewable energy technologies, is more likely to be installed in protected areas even if solar irradiation is widely available in low-biodiversity lands.

This critical literature shows that it is not at all clear that renewable energy technologies can contribute to the environmentally sustainable and socially just energy regime that so many desire. Thus, the benefits of solar power appear contradictory: On the one hand, solar power might embody the transformative potential to inaugurate new social-ecological relations by mitigating climate change, providing clean renewable energy, and encouraging democratic forms of ownership and decision-making. On the other hand, solar technologies may imply notable amounts of greenhouse gas emissions and other forms of pollution, depletion of non-renewable resources, global wage gaps, and non-democratic conditions along the entire commodity chain. This multifaceted contradiction is significant because it forces us to question the conventional understanding of technology as "applied science" and what it means to choose renewable energy technologies in the hope of creating a better world.

Despite all this, there is an unswervingly optimistic view characterized by faith in technological progress that tends to deny, downplay, or even ridicule the empirically observed downsides to solar power (e.g., Bastani, 2019; Phillips, 2020). In this view – commonly labelled *ecological modernism* – new technologies, efficiency improvements, material/resource substitutes, and engineering design are frequently invoked as means to counter socially articulated concerns over technological problems or contradictions (see e.g., Spaargaren and Mol, 2013; Asafu-Adjaye, 2015). For ecomodernists, environmental degradation and socially eroding consequences of a particular technology are regarded as a "transient yet necessary phase" (Levidow et al., 2012: 159). The Environmental Kuznets Curve is frequently invoked by ecological modernists to explain how the environmental impacts in a country get worse before it gets better with further technological development and increasing income per capita (Stern, 2004). Technologies, in this view, are never inherently problematic, because they are continually improved, redesigned, or replaced by other technologies with different material components and social implications. In the discussions on the energy return of solar power, for example, the notion of technological progress is invoked to explain how solar PV cells can be made more energy efficient in the future and thereby fulfill one of the key criteria for feasibly sustaining advanced industrial societies (see chapter five). In this view, to choose a particular technology (e.g., solar power) does not mean to choose a particular world (e.g., a world without advanced industrialism). Ecological modernism offers a comfortable narrative suggesting that no significant social change is necessary for solving the ecological crisis. Any concerns regarding negative repercussions of "green" technology are brushed aside on the basis that human ingenuity represents an infinite creative and productive force. The alleged evidence for this infinite force is the rapid development that industrial nations have enjoyed since the Industrial Revolution (cf. Barca, 2011). This position is coupled with a teleological notion of history as a progressive journey of human mastery over nature, where an infinitely malleable nature exists to serve human ends (Pellizzoni, 2011).

For those who are unwilling to trust this notion of technological progress, the contradictions associated with solar power represent significant risks to the world. In contrast to the defensive response of ecomodernists, these *ecological realists* (as we may call them) acknowledge contradictions and question the validity and desirability of technological – as opposed to social-political or cultural – solutions to environmental problems (e.g., Huesemann and Huesemann, 2011; Johnston, 2020; Ruuska et al., 2020). Matter-energy throughput and environmental impacts have massively increased in the world economy despite two centuries of technological progress (Wackernagel et al., 2002; Wiedmann et al., 2015; Steffen et al., 2015a; WWF, 2020). Considering this historical evidence, ecological realists do not assume that technologies that have not yet been formally implemented in the world will necessarily solve environmental problems. Emphasis is placed on caution, risk prevention, and understanding rather than risk taking and a rush to deploy new technologies for the sake of technological progress itself (e.g. Gowdy, 1994). In this view, which Earl Cook (1976) once labelled the "prudence option," problems are unlikely to be solved with technological solutions that are dependent upon the forces that generated them, but they may be solved through social-cultural change. Many ecological realists argue that there needs to be a societal-wide convergence around the ambition to create a way of living in which less is produced, less is consumed, and in which life is simpler, slower, more caring and more communal (Trainer, 2007; Trainer and Alexander, 2019; Norberg-Hodge, 2019). In relation to solar power, this position is exemplified in a study by Capellán-Pérez et al. (2020), which shows that the low energy return of solar PV technology means that solar power cannot support advanced industrial societies. Even if this is so, the authors argue, advanced industrial societies could in fact exist in the future, but only if solar PV modules are complemented with fossil fuels (see also Georgescu-Roegen, 1978). Thus, the contradictions of solar power serve to question the trajectory of advanced industrial societies based on the social condition to endlessly exploit the human and natural world.

The structure and contents of this study

This thesis consists of six chapters. In the next chapter, I clarify the methodological point of departure and the theoretical framework of the thesis. I first give a brief overview of philosophical materialism and the key relevance it has for understanding the biosphere and the current state of the planet. I then present my unanticipated discovery that the most prominent philosophies of technology have not been concerned with understanding technology as something contingent on matter-energy in the physical sense (ontological materialism). It follows that the interpretation of nature that is today employed to understand the dire state of the planet is broadly absent in the conception of solar PV technology as one of the most favored solutions. I propose that there is much to gain by allowing philosophical materialism to inform the understanding of technology. I attempt to show this by suggesting an interdisciplinary framework for understanding technology that is commensurable with the philosophical assumptions guiding research on the biosphere. The resultant “critical ecological philosophy of technology,” derived from the philosophies of Karl Marx, Lewis Mumford, and Alf Hornborg, invites us to consider modern technology as intertwined with the socially organized exchange of matter-energy that began with the Industrial Revolution. This notion is captured in a conceptual model that I call “the technological continuum,” which I will frequently refer to throughout the thesis.

In the third chapter, I contextualize visions of transforming society by means of solar power by looking at the social-ecological prerequisites and consequences of the Industrial Revolution. As argued by environmental historians, large-scale development of solar PV technology and other renewable energy technologies is conventionally envisioned to form the technological basis of an entirely new social-ecological regime. Such a transformation is analogous to historical events such as bipedalism, the adoption of fire, the Neolithic Revolution, and the Industrial Revolution. To understand what it means to transition away from the industrial regime based on fossil fuels, I place particular emphasis on accounting for the socio-ecological conditions of the Industrial Revolution from which modern technologies first arose. I highlight how it is difficult to separate modern technology from some of the defining features of the industrial regime (other than analytically). This, as I show, is only one of at least three interpretations in the discussion of the potential of solar PV technology to inaugurate a new energy regime. At stake is whether large-scale development of solar PV technology can be said to continue, transcend, or reverse the social-ecological conditions of the Industrial Revolution.

The fourth chapter deals with the recent and rapid developments in the global solar PV industry. Between the years 2000-2018, solar PV technology developed from being an “alternative technology” to becoming a fully-fledged “commercial commodity” on the world market. I show that the most common explanations for why and how this boom occurred have largely omitted any meaningful consideration of material flows in world trade. Through an LCA-based assessment of ecologically unequal exchange, I examine the biophysical link between the two crucial actors Germany and China during the booming years. The results demonstrate that an ecologically unequal exchange – whereby demands on labor, land, energy, and greenhouse gas emissions could be displaced to China – was necessary for Germany to fulfill its solar visions at the time. This demonstrates that the recent low prices of solar PV modules are intimately connected to the contemporary world division of labor. From a broad perspective, this means that the notion of solar technology, as an “alternative technology” with promising democratic and sustainability potential must be reconsidered based on its potentially inherent global asymmetries.

In chapter five, I discuss the question of whether and in what sense global asymmetric transfers of resources are inherent to large-scale solar PV technology projects. I discuss this in relation to Langdon Winner’s (1980) idea of the politics of technological artifacts. Drawing on methodological discussions on how to measure “energy return on energy investment” and “power density,” I raise the question of how drawing boundaries around what constitutes solar power can affect whether we perceive large-scale solar PV development as inherently political or not. By calculating the “power density extended” of four leading nations’ solar aspirations (China, Germany, India, and Italy), I demonstrate that a technological boundary that extends further back in the global commodity chain shows that substantial amounts of indirect land requirements are necessary for fulfilling modern solar PV aspirations. In this way, the large-scale solar PV projects of China, Germany, India, and Italy all necessitate a highly politicized world division of labor as much as they necessitate polysilicon, engineers, electrical components, and direct sunshine. In this view, the world division of labor is an integral part of a new metabolism based on large-scale construction of solar PV parks. In contrast, a narrow technological boundary that perceives solar PV modules merely as artifacts independent from society cannot see this political condition as inherent in solar PV technology. I argue that the low “energy return on energy investment” and “power density” of solar PV technologies should not be understood as something that renders a large-scale transition to solar PV technology impossible, but that it may require (not merely encourage) unequal distribution of social and environmental burdens and benefits in the global economy that are problematic for the ongoing transition away from fossil fuels. Importantly, these problems will not be visible to us as long as we retain a narrow understanding of what solar PV technology, and indeed technology, is.

In the final chapter, I reflect on the questions raised in this introductory chapter and discuss the results in relation to the theoretical point of departure. The results of the thesis suggests that ecologically unequal exchange is likely a prerequisite for practically realizing conventional solar visions and how this condition is repeatedly overlooked or denied by researchers, policy makers, corporations, and governments who are working towards a low-carbon transition. Thus, solar PV technology is being embraced without fully considering its global prerequisites. I suggest that this is a symptom of fetishization, whereby the biophysical history of solar PV modules is rendered immaterial and “forgotten”, and how it is likely that alienation, power, ideology, and denial are the determinants for this forgetting. I raise the question whether the strategic omission of the global distributive dimension of solar PV technology could one day be compared to ExxonMobil’s strategic denial of climate change. Finally, through an organic analogy, I discuss the ontology of technology and provide a definition of technology that can be employed to avoid this problem.

A note on interdisciplinarity

In the process of writing, presenting, and discussing this thesis, I have realized that the reader deserves a clarification of the thesis's interdisciplinary approach. This realization came in part from colleagues and friends who told me so quite explicitly and in part from self-reflection on how to communicate the thesis effectively to readers who do not have an interdisciplinary background.

The first step in this clarification is to repeat that this thesis is a work within the interdisciplinary field of Human Ecology. Human ecology is a field of study that integrates insights from disciplines such as Biology, Physics, Sociology, Anthropology, Economics, History, Psychology, and Philosophy in order to reach a holistic understanding of human-environmental relations (Steiner and Nauser, 1993: 2-6). This means that the reader should be prepared that concepts from any of these disciplines could be presented, employed, and critically discussed in the thesis. Among these disciplines, many have "environmental" or "ecological" offshoots of their own with relevance for understanding solar PV technology. In particular, I draw upon concepts and insights from Ecological Economics, Philosophy of Technology, Environmental Sociology, Environmental History, Geography, Environmental Anthropology, and to a lesser extent Environmental Psychology.

The second step is to clarify what an interdisciplinary approach is and what purpose it serves. One definition of interdisciplinarity is that it involves "bringing together distinctive components of two or more disciplines" (Nissani, 1997: 203).[8] A discipline is "any comparatively self-contained and isolated domain of humane experience which possesses its own community of experts" (ibid. 203). Interdisciplinarity is a process that includes the cognitive task of "integration," which involves "critically evaluating disciplinary insights and creating common ground among them" (Repko and Szostak, 2017: 669). Whereas the disciplinary approach studies a range of cases, events, or things in order to develop a particular concept describing the world, the interdisciplinary approach integrates concepts from a variety of disciplines to understand one particular case, event, or thing in the world (figure 1). Emphasis is placed on general knowledge as opposed to specialized knowledge; integration as opposed to separation; and concept synthesis as opposed to concept analysis.

---

[8] Transdisciplinarity, contrary to interdisciplinarity, includes social groups outside academia as part of the research process (Jahn et al., 2012). By including social groups with knowledge that cannot be reduced to disciplinary categorization, transdisciplinarity transcends the very systematization upon which scientific disciplines are based.

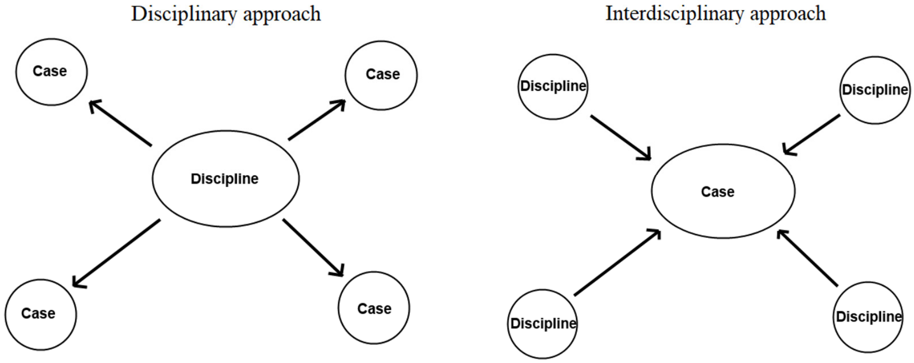


Figure 1. A basic illustration of the disciplinary and interdisciplinary approaches.
The arrows represent knowledge and/or concept application.

The purpose of the interdisciplinary approach is to generate a more comprehensive knowledge of the phenomena studied. As such, the interdisciplinary approach encourages an epistemological transformation in the researcher during which numerous perspectives are eventually taken as a multitude of languages for expressing the same single phenomenon. Interdisciplinarity has the potential to generate a "hitherto non-existent connection" that cannot be generated from the perspectives of each of the disciplines it draws upon (Jahn et al., 2012: 9). In short, the disciplinary parts are integrated into a whole that is qualitatively distinct from the separate parts taken together. This thesis seeks to expose precisely such "hitherto non-existent connections" of solar PV technology.

The third step is to clarify the strengths and weaknesses of the interdisciplinary approach. The perhaps most persuasive strength of interdisciplinarity is that reality – contrary to modern scientific attempts to understand it – is not compartmentalized into disciplines. "These [disciplinary] boxes," as Wallerstein (2004: x) called them, are in fact "constructs more of our imagination than of reality." Moreover, a compartmentalized view of reality encourages professionals who, as Nassani put it (1997: 209), know "everything about the chemistry of CFCs yet nothing about the ozone layer," or "everything about internal combustion engines and nothing about global warming." Rigid disciplinarity may thereby create a situation in which scientific experts become alienated from the wider effects of their expertize (Jahn et al., 2012). One strength of interdisciplinarity is that it counters this situation.

The perhaps most important weakness of interdisciplinarity is that it aspires to translate “the chaos of babel,” as Steiner and Nauser (1993: 17) put it. This weakness, to be more concrete, is that each discipline comes with an often-unique terminology, which prevents clear and effective communication across disciplines (ibid. 17). Pellmar and Eisenberg (2000: 43) articulates this challenge by pointing out how “extensive effort must be made to learn the language [terminology] of another field and to teach others the language of one’s own” before “successful collaboration can occur.” If the writer-reader relation is anything like a collaboration, then this means that interdisciplinarity may demand both increased efforts to communicate (on the part of the writer) and to understand what is written (on the part of the reader). For this reason, I have included a list with explanations of the most frequently recurring concepts in the thesis (Appendix A).

2. Earthing philosophy of technology: A methodological point of departure[9]

> "*There is a widespread philosophical tendency towards the view which tells us that Man is the measure of all things, that truth is man-made, that space and time and the world of universal are properties of the mind, and that, if there be anything not created by the mind, it is unknowable and of no account for us. This view, if our previous discussions were correct, is untrue; but in addition to being untrue, it has the effect of robbing philosophic contemplation of all that gives it value, since it fetters contemplation to Self. What it calls knowledge is not a union with the not-Self, but a set of prejudices, habits, and desires, making an impenetrable veil between us and the world beyond.*"
>
> Bertrand Russell

How do we study whether solar PV technologies are conventionally perceived in ways that are incongruent with reality? In this chapter, I argue that answering this question requires that we have a notion of what constitutes reality and how this reality is filtered by modern cultural categories. This requires that we take a view of technology that is rooted in a recognition of nature as a physical phenomenon. In particular, as I will show, the assertions of philosophical materialism have been pivotal in modern history for recognizing the existence of a self-orchestrating nature, which the ancient Greeks called *physis* and the Chinese word *Ziran*. To this day, however, the same assertions have not been accepted or emphasized in the understanding of technology. This is a situation wherein the understanding of nature and the understanding of technology are based on fundamentally different assumptions about the world. To remedy this

---

[9] This is a reworked draft of a chapter that has been published by Oxford University Press in the book *Sustainability beyond technology: Philosophy, critique, and implications for human organization*, edited by Pasi Heikkurinen and Toni Ruuska (Roos, 2021).

situation, I side with the philosophical assertions that now guide research on the biosphere. I thereby situate the phenomenon of solar PV technology within a biophysical reality that is constituted by self-orchestrated processes of matter-energy. Ultimately, this methodological point of departure makes it possible to study how conceptions of solar PV technology contrast with the real-world conditions of solar PV development.

The argument of this chapter is developed in three parts. I will first give a brief overview of philosophical materialism and the key relevance it has for understanding the biosphere and the current state of the planet. I then show that the most prominent philosophies of technology over the last two centuries have not primarily been concerned with understanding technology as something contingent upon matter-energy in the physical sense (ontological materialism). It follows that the interpretation of nature that is employed to understand the state of the biosphere is broadly absent in the articulation of the most favored solutions, such as solar PV technology. Third, I will propose that philosophy of technology, and indeed humanity, has much to gain by allowing philosophical materialism to inform the conception of technology. I attempt to show this by suggesting an interdisciplinary philosophical framework for understanding technology that is commensurable with the philosophical assumptions underscoring research on the biosphere. The subsequent "critical ecological philosophy of technology," derived primarily from the works of Lewis Mumford, Alf Hornborg and John Bellamy Foster, invites us to consider modern technology as intertwined with the human-environmental exchange of matter-energy that started with the Industrial Revolution and greatly accelerated with the access to oil. From this methodological and philosophical framework, I develop a pre-analytic model of technology that I call "the technological continuum" that will follow the reader throughout the thesis.

Does nature matter? Materialism as recognition of nature

A general commitment to philosophical materialism implies an acknowledgement that all processes and things arise within nature itself. All that is, in short, is of this world as it emerges from the physical. In this view, even human thought is a physical expression of nature's internal processes. As poetically pointed out by Loren Eiseley (1969: 52), even "the human mind burns by the power of a leaf." Materialism in the philosophical sense must therefore be distinguished from the more common understanding of materialism as a collection of values for accumulating desirable artefacts (“to be materialistic"). Following critical realist Roy Bhaskar (1991: 369), philosophical materialism consists of three foundational statements:

a) *Ontological materialism*, asserting the unilateral dependence of social upon biological (and more generally physical) being and the emergence of the former from the latter;

b) *Epistemological materialism*, asserting the independent existence and transfactual activity of at least some of the objects of scientific thought;

c) *Practical materialism*, asserting the constitutive role of human transformative agency in the reproduction and transformation of social forms.

Materialism in the philosophical sense has been lively debated for at least two thousand years and is typically contrasted with “idealism,” asserting that what exists are ideas. An important aspect of the material position is its formal opposition to religious explanations of nature and society that ascribe tangible powers to entities without substance in the world. While the rise of the material-mechanistic understanding of nature in Renaissance Europe has been identified as a central historical event underscoring modern ecological problems (Merchant, 1980), paradoxically, it is in the rejection of God that materialism bears a positive significance for an ecological understanding of the world. As John Bellamy Foster (2000) has demonstrated, philosophical materialism catalyzed ecological ways of thinking about the world. The tenets that today are central for ecology, Foster shows, can be directly related to the teachings of the ancient Greek materialist Epicurus. These include that i) everything is connected to everything else, ii) everything must go somewhere, iii) nature (or evolution) knows best, and iv) nothing comes from nothing (ibid. 14). The full historical ebb and flow of these material-ecological tenets will not be reviewed here. Suffice to say, the historical prominence of materialism has fluctuated (for an overview see Lange, 1925).

One important breakthrough for philosophical materialism came during the 19th century. This breakthrough is today mostly associated with the work of Charles Darwin (2011[1859]), who in his theory of evolution by natural selection contributed to an understanding of the variation of species as a result of natural-historical processes. The philosophical pathway for this theory had been cleared by earlier materialist thinkers both the organic and mechanical kind, such as De La Mettrie, Diderot, Holbach, and the Comte de Buffon. Even so, Darwin's materialism was highly controversial in a culture that for a long time had been dominated by theological explanations of the world (Clark et al. 2007). Even early materialists such as Isaac Newton, Francis Bacon, and Thomas Hobbes combined materialism with an acknowledgement of God (natural theology) that retained the understanding of nature as a static, non-changeable, phenomenon. In modern history, according to Engels (1964[1925]), it was first with Immanuel Kant's notion of nature as something that is "coming into being" and "passing away" that the mechanistic outlook on nature could be fundamentally challenged.[10] This discovery, Engels lauded, "contained the point of departure for all further progress" for an understanding of the world as historical-material (ibid. 27).

Even if the work of Charles Darwin might be the most famous example today, the insight that nature was undergoing internal processes of change was actually first taken up in the field of geology. Already in the early 1800s, Abraham Gottlob Werner had revolutionized the field of geology by demonstrating how differences in rocks existed due to differences in the time and mode of formation (for a discussion, see Foster, 2000: 117-122). In short, Werner's argument implied that different rock features did not simply exist statically in the world as orchestrated by a divine will. Rather, they had been formed by the Earth itself through geological processes over long periods of time. One of the principal contributions of Werner was that it allowed for an understanding of the Earth as a historical entity characterized by self-organized changes not ordained by God. Reference to nature's internal processes, quite independent of any God, thus started to make sense as a basis for understanding an increasing range of phenomena in the world.[11]

At this time, a physicist by the name of John Tyndall took an interest in the peculiar geological evidence indicating that there had been a prehistoric Ice Age. Armed with a material epistemology, he suggested that the cause of the disappearance of this Ice Age might have been climatic changes. Tyndall supported his claim by demonstrating that water vapor had the capacity to prevent infrared radiation from dissipating into space and thereby creating a heating effect in the atmosphere. Consequently, he proposed that fluctuating

---

[10] However, Kant's notion was preceded by the ancient Greek philosopher Epicurus's understanding of nature as *mors immortalis* (see below). Notably, the Greek word Physis meant nature, such as it "creates itself" and "emerges from out of itself" (Feenberg, 2009: 160). The Chinese word Ziran similarly means, "it is so by virtue of its own" (Chan, 2005: 542, emphasis in original).

[11] Notably, Marx's and Engels's programme, historical materialism, was an attempt to understand the evolution of human organization in this sense.

levels of H2O in the atmosphere could have been the cause for the observed climatic changes. Svante Arrhenius, a Swedish scientist, later showed that concentration of CO_2 in the Earth's atmosphere, fluctuating in self-reinforcing feedback mechanisms, was a better explanation for climatic changes. As the physicist Spencer Weart (2003: 6) explained in *The Discovery of Global Warming,* even if Arrhenius was "far from proving how the climate would change if CO_2 varied, he did in truth get a rough idea of how it *could* change."

Today, the notion that nature is a material-historical process may seem obvious, even trivial. However, it is important to appreciate how the 19th century materialist turn constituted a fundamental shift away from the earlier European understanding of nature as a static phenomenon created and organized by God. A new epistemology took hold that acknowledged nature itself as God-independent processes of great complexity. The very notion of the biosphere as a complex living system of biogeochemical cycles was later to be founded upon such a material understanding of the world (Suess, 1875; Vernadsky, 1998[1929]; Clark et al. 2007; Steffen et al., 2011). As the Soviet scientist Vladimir Vernadsky explained in *The Biosphere*:

> Creatures on Earth are the fruit of extended, complex processes, and are an essential part of a harmonious cosmic mechanism, in which it is known that fixed laws apply and chance does not exist. We arrive at this conclusion via our understanding of the matter of the biosphere (1998[1929]: 44).

Vernadsky's seminal work and understanding of the biosphere as a cosmic process with complex internal interactions between living and non-living matter later influenced the development of Western ecology through G.E. Hutchinson, Eugene Odum, and Arthur Tansley in the 20th century (Oldfield and Shaw, 2013). What is more, Vernadsky contended, "all organisms are connected [to the biosphere] indissolubly and uninterruptedly, first of all through nutrition and respiration, with the circumambient material and energetic medium" (Vernadsky, 1945: 4). Importantly, humans too were regarded as organisms that were "indissolubly and uninterruptedly" part of the biosphere. In conversations with French scientists, Vernadsky proceeded to hypothesize that the biosphere was undergoing significant changes due to human influences. In the words of Steffen et al. (2011: 843), these "prophetic observers," therefore laid the foundation not only for the understanding of the biosphere, but even anticipated today's critical historical impasse. Contemporary deliberations on the "Anthropocene," "Technocene," or "Capitalocene" can all be interpreted as late variations to Vernadsky's observation that humans, “through [their] labor and [their] consciousness,” are shifting the Earth into a new geological state (Vernadsky, 2001[1938]: 22).

This historical discussion simply scratches the surface of materialism and its significance for a recognition of nature.[12] I nevertheless hope to have demonstrated that the understanding that is today driving an increasing concern for the natural world is underlined by philosophical materialism. In sum, materialism is an acknowledgement that nature matters in at least two basic ways:

1. Nature matters in the physical sense of constituting biogeochemical processes that exchange and transform matter and energy.
2. Nature matters in the sense of being necessary for the continuation of humans and other forms of life.

While it is important to reflect upon nature as a mental concept, it is essential that we acknowledge and recognize nature in the biophysical sense if we wish to study the contrast between conventional social aspirations and ecological reality (Soper, 1995; Ruuska et al., 2020). In relation to the second point, human populations, like any other animal population, are part of the natural world, which they are dependent upon for their continuation (Daly, 1996; Heikkurinen et al., 2016). No organism can exist without an environment from which to draw matter-energy.

Today, the 19th century materialist turn is important not simply because it reminds us that a fundamental shift in European epistemology occurred, but because the shift was never fully completed. For the purpose of this thesis, it is of particular relevance that this material turn was never fully applied to the understanding of technology. Even Vernadsky (1945: 4), who insisted that humans are “indissolubly” part of the biosphere, thought that technological progress was “the result of ‘cephalization,’ the growth of man’s brain and the work directed by his brain.” Karl Marx, who drew on the work of Charles Darwin, came closest to a materialist understanding of technology by speculating how it might be the human equivalent to “the formation of the organs of plants and animals, which serve as the instruments of production for sustaining their life” (Marx, 1990[1867]: 493, footnote 4). In the same footnote he wrote:

---

[12] For example, I have purposefully left out the question of whether consciousness (mind) is dependent or independent from nature. I address this issue in more detail below.

> Technology reveals the active relation of man to nature, the direct process of the production of his life, and thereby it also lays bare the process of the production of the social relations of his life, and of the mental conceptions that flow from those relations (Marx, 1990[1867]: 493-494).

However, even in the extensive corpus of Marx, this historical materialism of technology was relegated to only one footnote. To the extent that we can draw a distinction between technology and machines,[13] Marx was much more interested in machines than in technology. For Marx, as for many of his contemporaries, the theme of the machine as a labor-saving device was of utmost interest. When reading Marx most famous passages on the machine, however, it is evident that Marx had an inclination to consider the productive potential of machines as originating from within the machines themselves (see e.g., Marx 1990[1867]: 494, 502; Marx 1993[1939]: 818-819). In particular, machines regularly appear in Marx as if they have been simply conjured into existence with a ready-made productive potential. This is an understanding of technology that resembles the pre-materialist geology, where rock formations are conceived of as independent from their geological history.

Still today, I argue, the non-materialist view haunts contemporary analyses of technology. In effect, as I show further on in this chapter, modern conceptions of technology systematically miscalculate the feasibility to employ technology in the hope of solving environmental problems. The rejection of materialist ontologies of technology is most obvious in philosophical frameworks where technology is explicitly understood as “cognitive activity” or as a “consciousness.” However, ontological materialism appears to be absent even in supposed materialist philosophies of technology. The following section is meant to demonstrate this surprising situation.

What is technology? A review of contemporary philosophy of technology as immaterial

Let us now turn to contemporary philosophy of technology and ask what technology is. Among philosophers of technology, there have been countless

---

[13] In this thesis, I distinguish between technological artifacts (or objects) and technology as a continuum wherein technological artifacts are temporal manifestations (see below under sub-headline “The technological continuum: An illustrative model”). In this view, a machine is a type of technological artifact.

ways of approaching this question (see Scharff and Dusek, 2014). Here, I will follow Andrew Feenberg's (1991; 2008) categorization, which distinguishes between three overarching theoretical approaches to technology. These are "instrumentalism," "substantivism," and "critical theory." To this list, I will add "actor-network theory." While this is not an exhaustive account of all existing philosophies of technology, it does provide a point of departure from which it is possible to engage with the 20th-21st century discussions of technology.

Instrumentalism: A gift from the other

Instrumental theory is commonly pointed to as the dominant understanding of technology today (Feenberg, 1991: 5-7, 2008; Dusek, 2006: 53-69). This theoretical lens is employed for the most parts by governments and policy makers but is also common within the social sciences. At the core of *scientific* instrumentalism lie an anti-realist argument asserting that no theoretical explanation or concept can be claimed as explaining reality (Stanford, 2006). From this perspective, it is better to understand "theories as tools for pursuing practical ends" rather than as true descriptions of reality (ibid. 403). In instrumental takes on technology, this practical imperative extends from theories to technologies, which must only be judged by the degree of efficiency with which they can be employed to solve problems. Concerns regarding the conditions and effects of technologies are typically brushed to the side as an external concern. As Dewey (2008: 354-55) put it:

> There is no problem of why and how the plow fits, or applies to, the garden, or the watch-spring to time-keeping. They were made for those respective purposes; the question is how well they do their work, and how they can be reshaped to do it better.

This position gives rise to the common, yet widely criticized notion that technologies are value-neutral (Winner, 1980; Huesemann and Huesemann, 2011: 235-41). Technological neutrality, or value-neutrality, is recognized as a concept that can be captured in the cliché "guns don't kill people, people kill people." Technologies, in this reductivist view, are independent from the contexts in which they arise and which they reproduce. Such a value-neutrality underscores Marx's famous critique of John Stuart Mill in the opening of chapter 15 in *Capital vol. 1* where Marx argues that the role of machinery under capitalism is not to save labor, but that machinery can take on this social role in other social modes.

The anti-realism that underscores instrumental theories of technology is key to understanding in what way technology is value neutral. In Dewey's work, summed up by Larry Hickman (2014: 408, 410), technology is considered a "cognitive activity" that is "brought to bear on raw materials and intermediate stock parts, with a view to the resolution of perceived problems." This implies that technology is essentially an immaterial (cognitive) phenomenon, yet with tangible consequences in the material world.[14] This process is made possible through the technical operation of engineers, or "engineering design" (Mitcham, 1994: 225-228). Technology in the engineering sense is a result of the human ability to come up with different designs. "Designing," Mitcham (1994: 220) writes, can be identified as a process of extracting thoughts from the head of the engineers and delivering them into the real physical world via drawings, modelings and blueprints (see also Layton 1974: 38). Technology is consequently thought to originate from scientific knowledge and therefore understood as a form of applied science (Kline, 1995).

The notion that technology *is* design is similar to the European pre-materialist view of nature, in which nature's geological features were explained with reference to God's design. At times, the similarity is striking. For example, Frederich Dessauer, one of the founders of modern philosophy of technology, claimed that the mind of the engineer or inventor may be in contact with a transcendental realm (the Kantian thing-in-itself) when engaged in ingenious thought processes and when developing novel design patterns (see Mitcham 1994: 29-33). Engineers are, in this Dessauerian sense, uniquely trained to maintain the relation between human cognition and the transcendental thing-in-itself in order to conjure more efficient objects into the world. A similar notion is found in physicist Freeman Dyson's widely cited statement that "Technology is a gift from God" and that "After the gift of life it is perhaps the greatest of God's gifts." It is not surprising that we should discover these quoted by ecomodernists such as Aaron Bastani (2019: 31) who builds his claims on the notion that technological progress is "amounting to nothing more than an upgraded [more efficient] re-arrangement of previous information" (ibid. 63).

Underscoring the instrumentalist preoccupation with efficiency is the very common but seriously underexamined assumption that engineering design and technological progress is "an effort (at first sight, of a mental sort) to save effort (of a physical sort)" (Mitcham, 1994: 221). The engineer, it is believed, solves

---

[14] Vernadsky's (1945) notion of the human brain as the determinant of technological progress is an example of this view.

"problems of fabrication that will save work (as materials or energy) in either the artifact to be produced, the process of production, or both" (ibid.). Design for efficiency, in other words, reduces physical expenditure through the application of knowledge. This is in fact no small assumption since a closer examination shows that it contradicts both the laws of thermodynamics and Epicurus's observation that "nothing comes from nothing" (for the former, see Georgescu-Roegen, 1975). It is worth mentioning that instrumentalist physicist Ernst Mach (1911: 49) explicitly criticized the principle of conservation of energy and argued that:

> What we represent to ourselves behind the appearances exists only in our understanding, and has for us only the value of a memoria technica or formula, whose form, because it is arbitrary and irrelevant, varies very easily with the standpoint of our culture.

That is to say, atoms, molecules and physical events, are semiotic representations, not true explanations, of the world (*epistemological idealism*). It follows that technology, as applied knowledge, must be considered as something immaterial.

From the standpoint of philosophical materialism, this implies that engineering invention and design can circumvent natural laws and cheat nature for the benefit of humans and other technology-wielding organisms. It follows that technologies do not require, so much as "save," matter-energy. This, I would like to argue, is the philosophical terminus of instrumental theory that is now at heart of the notion of "decoupling" that serves as a lodestar for ecomodernists. Moreover, it is likely that it also underscores the neoliberal commitment to take nature as purely instrumental and plastic for human benefit (cf. Pellizzoni 2011). It follows, as Feenberg (1991: 6) argued, that there is little left but unreserved commitment to technology if we accept this essentially Promethean framework, which encourages the notion of technology as historical destiny.

Substantivism: A call for the sleeper to awake

If instrumental theory is the dominant theory of technology then "substantivism"[15] can be understood as its antagonistic rival. In contrast to instrumentalism, substantivist theories of technology point out that it is a dangerous fallacy to consider technologies merely as instruments without tangible consequences in the world. For substantivists, technologies are often

---

[15] Substantivism is sometimes called "the cultural approach" (Drengson, 1995: 39-50).

catalyzers for wider social-political change. Since it is not widely recognized that technologies often encourage social change, the uncritical acceptance of a new technologies is understood as something like a Trojan horse, which imposes often-unwelcomed changes to social relations and values.

This perspective is primarily associated with Martin Heidegger and the French philosopher Jacques Ellul. In *The Question Concerning Technology*, Heidegger examines the instrumental notion of technology in order to understand its essence – "Enframing" (*Gestell*) – as a way of revealing nature as a "standing-reserve" of resources. The essence of technology, Heidegger contends, is nothing technological. Rather, we must understand technology as a historically specific method of revealing, or interpreting, what nature and history (or Being) is all about. Heidegger uses the case of the river Rhine and argues that the river is through the technological mode of revealing understood as a standing-reserve that subsequently appears to exist for the purpose of being exploited. The dam as technology, in other words, denotes not the dam itself with its turbines or valves, but the underscoring idea that the river exists primarily as an inert flow of exploitable matter (resource) available for human exploitation. In short, technology is more a phenomenological lens through which the natural world is understood and approached rather than itself a tangible material phenomenon in the world.

In a similar vein, Jacques Ellul (1964: xxv) defines technology as "the totality of method rationally arrived at and having absolute efficiency." The defining feature of the technological society as understood by Ellul is that every action and domain of social life are transformed by technology into rationalized processes with improved efficiency. However, technological values of rationality and efficiency occur at the expense of human values (connection, equality, sustainability, democracy, etc.). In the words of Langdon Winner (2020[1986]: 6), "technologies are not merely aids to human activity, but also powerful forces acting to reshape that activity and its meaning." Technologies thereby engender new lifeworlds.

But why is this technological change occurring according to substantivists? For Heidegger, the essence of Enframing was inherited by technology from the modern physical theory of nature. An answer as to why Being is revealed through enframing can therefore only be found by questioning "the essential origin of modern science" (Heidegger, 1977[1954]: 23; cf. Merchant, 1980). According to Ellul, in contrast, technology has come to execute societal transformations autonomously. Whereas the technical operation is that of efficiency, the technical phenomenon is an autonomous consciousness[16] in the presence of which humans are merely the “cellular tissue” in its total biology (Ellul, 1964: 142). All societal contact with nature or history is mediated by technology that thereby functions as a barrier for authentic communication with nature. “Enclosed within this artificial creation” Ellul writes, “man finds that there is “no exit”; that he cannot pierce the shell of technology to find again the ancient milieu to which he was adapted for hundreds of thousands of years” (ibid. 428).

To break with the technological condition, if possible, humans must awake from “technological somnambulism,” a condition in which the symptom is to sleepwalk past the technological choices that produce the existence of the afflicted (Winner, 2020[1986]: 5-10). This implies that humans must become aware of what world they are making through their everyday technological choices and practices. Only once the end purpose of technology is made an explicit object of reflection can the appropriate means be discussed, developed, and implemented in possibly humane and democratic ways (cf. Illich, 1973). More importantly, since technologies may be inherently political, technological fixes are seldom the answer to social or ecological problems (Winner, 2020[1986]). Alternatives to technologies are therefore favored over alternative technologies (Winner, 1979; Heikkurinen, 2018).

Critical theory: A political struggle over the technical code

The critical theory of technology is primarily associated with the philosopher of technology Andrew Feenberg (1991, 2008) who draws on perspectives from the Frankfurt School, Georg Lukács and the early writings of Karl Marx. A key feature of the critical theory of technology is that it opposes the “take-it-or-leave-it attitude” towards technology that Feenberg believes characterizes the ying-yang of instrumentalism and substantivism. Critical theory moves beyond considering technology as something either emancipatory or repressive by drawing on constructivist technology studies that open for considerations of the role of social power in the design of technologies (Feenberg, 1991; Bijker et al., 1989).

More specifically, critical theory considers technological values (efficiency, productivity) as originating from the interests of the social group that has the most influence over the design process. Given the social character of the design process, technology is socially designed with a specific end in mind, rather

---

[16] In more recent work, this consciousness is not so much autonomous as something of ‘our own subconscious intelligence’ (Drengson, 1995, quoted in Heikkurinen, 2018: 1659).

than itself being an autonomous mind or cultural lens (as for substantivists). Feenberg (1991: 14) writes, “technology is not a thing in the ordinary sense of the term, but an ‘ambivalent’ process of development suspended between different possibilities.” What technology is, in other words, depends upon what social class, or interest, is in control of the design. Technology is in this sense a plastic, malleable, phenomenon that is considered ontologically plural (i.e., it can be many different things). Following this reasoning, Feenberg considers technology a medium within which societal values and developmental pathways are politically negotiated and contested. What is contested, more specifically, is the “technical code,” understood as “the realization of an interest or ideology in a technically coherent solution to a problem” (Feenberg, 2008: 52). Technology, in the most general sense, is therefore a mediator of social-political action and influence.

Critical theorists visualizes alternative technologies designed democratically, which can overcome the problems associated with capitalism, patriarchy, and modern industrialism. This requires active resistance to the current hegemony over the technical code through protests, grassroots movements, and reforms (see e.g., Kostakis et al., 2016; Likavčan and Scholz-Wäckerle, 2018). However, before this can occur, the illusion of technological transcendence must be exposed as an instance of reification that operate to maintain social inequalities. Here, Feenberg (2008) draws on both Martin Heidegger and Herbert Marcuse and argues that the transcendence via technology is a cultural illusion at the heart of the modern experience that legitimizes divisions of labor.[17] Since no one is able to act without repercussions in a finite world, “technical action” represents not a full but “*a partial escape from the human condition*” (Feenberg, 2008: 48, emphasis added). While technology provide humans with net benefits, it has adverse and unequally distributed impacts in the world for different social groups.

To understand how Feenberg’s critical theory arrives at the plastic ontology of technology, we need to explore the underscoring “philosophy of praxis” situated within the Western Marxist philosophical tradition (Feenberg, 2014). In particular, since Feenberg draws heavily on Georg Lukács, we need to understand how Lukács approached the society-nature distinction and in what

---

[17] Importantly, Feenberg’s critical theory shares some philosophical assumptions with both instrumentalism and substantivism. Feenberg agrees with instrumentalism that the ontology of technology is decided in the process of its design but rejects the notion of its mysterious origin or purpose. Feenberg also agrees with substantivism that technological values must be opposed and questioned but rejects the notion of technology as in any way *inherently* political or problematic.

way this has colored the take on materialism in Feenberg's critical theory of technology. Lukács's seminal work *History and Class Consciousness* is perhaps one of the most influential texts for Western Marxists. In a famous footnote, Lukács limits the Marxist method to society and history while simultaneously levying a critique against Engels' dialectic method for claiming to know nature (Lukács, 1968[1923]: 24, footnote 6). To know anything about nature and matter, according to Feenberg's reading of Lukács, we would have to resort to investigating the *social production of nature* in which formulations of laws and ecological limits are cases of reifications in service of the capitalist class. Marxists such as John Bellamy Foster, Alfred Schmidt, and others have rejected this approach as granting too much primacy to the realm of consciousness. They have consequently charged the early Lukácsian view with misinterpreting objectification (the coming to being, or evolution, of the natural world) as alienation, like Hegel (Feenberg, 2014:124-128; Schmidt, 2014[1971]: 69-70; Foster, 2000: 244-49). Even Lukács himself, in what Feenberg calls a "unique example of philosophical self-misunderstanding," rejected his approach as a flawed attempt to "out-Hegel Hegel" (Lukács, 1968[1923]: xxiii; Feenberg, 2014: 126).

Despite this, Feenberg continues to develop Lukács's earlier statements on the society-nature distinction. According to Feenberg, Lukács's solution was to argue for two separate ontological realms in which the dialectic method was to be applied differently. That is to say, we cannot understand nature the way that we understand society (see also Burkett, 2013). This clarification is central because it shows that Feenberg's critical theory of technology is not seeking to understand technology from an interdisciplinary social-ecological perspective in which it is possible to study the common denominators of society and nature. While some (natural scientific) objects of thought exist independently of society, technology is not understood as such a natural object. To clarify, we can say that technology is more like the category "money" (semiotic) than the category "metal" (material) or "coin" (material-semiotic). This becomes clear if we remember that Feenberg's work concentrates on the process of design, thereby conceiving technology as a primarily semiotic category. It follows that technology is ontologically plastic and can be transformed through human praxis if only people were conscious that they themselves produced it (much like the category "money"). Technology, then, similarly to money, is a social medium through which relations are decided and orchestrated.

The notion that the natural (or physical) gives rise to the social (*ontological materialism*) is absent in this philosophy of technology. By following Lukács's earlier separation of society and nature only to exile technology to the social, Feenberg excludes the possibility that technology can be *both* a reification and an object in the world in the ontological-material sense (much like what is implied by the word ”coin”). Notably, for Marx, even if human labor is taken away, “a material substratum is always left. This substratum is furnished by Nature without human intervention” (Marx, 1990[1867]: 133). “The physical bodies of commodities,” Marx continues, “are combinations of two elements, the material provided by nature, and labour” (ibid. 133). Crucially, in Feenberg’s critical theory of technology, the physical element of matter is missing, or at least appears to be underrepresented. This implies in turn that society and technology can be transformed from the inside (through design), without reference to an outside (or a human-environmental relation), much like a caterpillar metamorphoses into a butterfly in isolation.

Actor-Network Theory: Machines as social actors

The final theory reviewed in this chapter, Actor-Network Theory (ANT), has gained widespread popularity within the social sciences and sparked many controversies in recent decades. The main thinkers associated with ANT are Bruno Latour, Michel Callon and John Law, two of whom have argued that ANT should not be understood as a theory at all (Latour, 1996: 377; Law, 2009). It is nevertheless true that ANT is made up of a set of principles and assumptions that together form a coherent “metatheory” (Bhaskar and Danermark, 2006; cf. Latour, 1996: 377-378).[18]

As a metatheory, then, ANT consists of a set of principles that are all constitutive of the central assertion of ANT; *that the world is exclusively made up of networks*. At heart, “ANT is a change of metaphors to describe essences: instead of surfaces one gets filaments [threads],” writes Latour (1996: 370). By substituting the metaphor of surfaces for the metaphor of network, ANT is seeking to get rid of the conceptual dichotomies (such as society-nature) that are believed to be at the root of the problems of the modern age (Latour 1993, 2004). Nature and society are therefore shattered into millions of analytical pieces called “actants” that relate in complex “networks.”

ANT invites us to think of the world in terms of actants and networks, but is technology an actant or a network? The question itself does not make sense within ANT because the actants are ontologically defined by reference to their relations in the network (Latour 1988; MacGregor 1991). This underscores the relation between humans and technological artefacts who are seen as mutually

---

[18] These include (i) a radical rejection of conceptual dichotomies, (ii) the principle of symmetry, (iii) a definition of agency as “having an effect,” and (iv) the principle of decentralized power.

giving rise to one another: On the one hand, humans are in control of technologies as far as humans create and delegate tasks to technologies. On the other hand, technologies, such as a door-closer, "prescribe back what sort of people should pass through the door" and is therefore interpreted as a "highly moral, highly social actor" (Latour, 1988). As in substantivism and critical theory, technologies challenge human values. However, instead of thinking of technology as a consciousness or a politically contested medium for social transformation, Actor-Network theorists think of technologies themselves as social actors (Latour, 1988, 1996). As social actors, technologies are constituted through technology-human relations and are therefore not purely autonomous – but then again, neither are humans. This philosophy resembles postmodernist feminist Donna Haraway's categorization of the "cyborg," which blurs the boundary between the organic and the inorganic, much like the blurred boundary between the female and the male (1991).

ANT is frequently described as "material-semiotic" (Law, 1999, 2009; Law and Mol, 1995). This can be understood as a perspective that simultaneously takes into consideration the fact that materials (frequently referred to as "stuff") effect and gives shape to what is typically categorized as social. "The social," writes Law and Mol (1995:276) "isn't purely social" but also material because all social relations involve relations with stuff. In turn, the same goes for technologies; "the electric vehicle is a set of relations between electrons, accumulators, fuels cells … *and consumers*" (ibid. 276-277, emphasis added). In short, stuff is vital for the existence of people and people are vital for the existence of stuff. However, while networks involve and gives rise to material stuff, "a network is [itself] not a thing" writes Latour (1996: 378). Rather, networks are essentially semiotic. Networks, as opposed to actants, are invisible connections that are "immersed in nothing," writes Latour (1993: 128).

From the position of philosophical materialism, some of the premises in ANT are based on fallacies. The first fallacy arises from the tendency to fetishize artefacts (Hornborg, 2017). Fetishization, in the Marxist sense, refers to the fallacy of assigning agency to commodities (Marx, 1990[1867]: 163-77). We will return to this point later. A second fallacy that ANT makes is to think of agency and relations (albeit not "stuff") as something essentially non-physical. Exponents of ANT (and new materialism) claim that inanimate things "have effects," "do things," "produce effects," or "have powers," and that these agential powers come from *within things*. For example, Bennett (2010: 18) writes "so-called inanimate things have a life, that deep within is an inexplicable vitality or energy … a kind of thing-power." This energy, or "thing-power," does not follow the regular habits of energy explained by physics.[19] The notion that things can animate themselves from within, without reference to an environment from which to draw the necessary matter-energy to exert their power, reduces relations in ANT to the study of signs (semiotics). Actants may be material "stuff" but relations are purely semiotic. This is so because the "effects" and "powers" that actants exert over one another are not understood as physical. Thus, Latour (1993: 378) writes, "what circulates [in networks] has to be defined like the circulating object in the semiotics of texts" and "a network is not a thing, but the recorded movement of a thing." Networks of signs are thereby thought to give rise to material "stuff" (*ontological idealism*). A third fallacy that indicates the ontological idealism underscoring ANT is the very notion that dichotomies can be transcended by efforts of thought alone. To simply un-think the dichotomies of the world is mistaken from a materialist point of view, since dualities are tangible, material, differences in the real world that arise historically. As shown by Adrian Wilding (2010), ANT thus cannot explain how the dichotomy that they criticize has come to bear significance in the world in the first place.

So what is technology? On lightbulbs as bright ideas and technology as a historical novelty

So, what have we learned from inquiring into these philosophies of technology? First, it is possible to see that there are both important differences and similarities across the four theories in the conception of technology. However, what is arguably most striking is the general commitment to understanding technology as ontologically non-material. The reference to human cognition, consciousness, design, and semiotic networks as core aspects of technology demonstrates the absence of ontological materialism. This is quite remarkable, but it should perhaps not come as a surprise in a culture that visualizes bright ideas as lightbulbs.

If these interpretations are correct, then we have every reason to question why ontological materialism is absent from contemporary philosophies of technology. The embryo of an answer can be found in Leo Marx's (2010) fascinating study on technology as a concept. While the concept of technology originates from a combination of the ancient Greek words *technē* and *logos*, it was not used in the now familiar sense of the word until well into the 20th century. Technology as a concept emerged as late as 1880 to fill the "semantic void" appearing due to considerable material changes in industrializing regions

---

[19] MacDuffie, in his study on the fictionalization of energy, shows that energy as a metaphor in this sense arose from the erroneous 19th century British experience of the city as a closed system capable of feeding on itself (MacDuffie 2014).

at that time. While the word technology first emerged to describe the complex material development of railway networks, the very “lack of specificity” made it “susceptible to reification” and eventually only the most obvious parts of the system stood in as “tacit referents” of the whole (Marx, 2010: 574). This suggests that the modern-day conception of technology has much more to do with the world-historical changes in the 19th century than with the ancient Greek notions of *technē* and *logos*.

Through a search on Google Book’s Ngram Viewer we can confirm Leo Marx’s assessment that the word technology is a historical novelty (figure 2). This data shows how the word technology emerged in the beginning of the 1900s only to gain momentum by the 1960s and peaking in popularity just prior to the 2000s. Technique seems also to have entered the English language sometime in the beginning of the 1900s only to reach a modest peak in the late 1980s. In contrast, the word “machine” was used already from the 1700s onward and peaked just before the 1920s.[20] This confirms that the idea of technology is a very recent historical phenomenon. As we shall now see, reuniting the concept of technology with the specific socio-metabolic system emerging at this time in Europe and North America has major consequences for our understanding of what technology is.

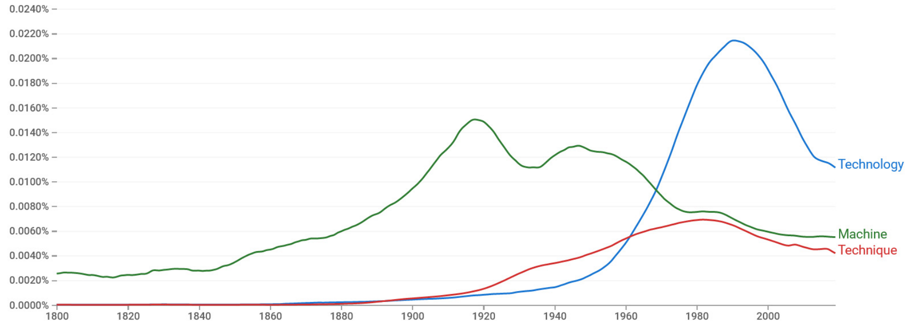


Figure 2. The occurrence of the words “technology,” “machine,” and “technique” in books published in the English language, 1800-2019. Source: Ngram Viewer (2020a).

---

[20] In other European languages, the results are similar. In French, the word “technique” shows a similar curve as the word “technology” in the English language (Ngram Viewer, 2020b). In German, the word “technologie” follows a curve very similar to English (Ngram Viewer, 2020c).

En route to a critical ecological philosophy of technology

I will now attempt to bring together Foster's devotion to Epicurus's and Marx's philosophical materialism and Hornborg's interdisciplinary understanding of technological systems. The aim is to point out how the abovementioned philosophies of technology can be understood to represent different interpretations and analytical foci of the single social-ecological phenomenon of technology. The purpose is to offer a hypothesis of technology that is based upon the same philosophical assumptions of the world as research on the biosphere. The social-ecological philosophy that I propose is indebted to all the philosophies of technology reviewed above. However, based on its commitment to materialism it is also distinct from them. It relates to the abovementioned philosophies as follows:

1. It agrees with instrumentalism that the truth-value of conceptions is determined through successful and sustained praxis, but adds that this truth-value should primarily be considered in terms of how such conceptions relate to social-ecological sustainability (i.e., the long-term survival of society in nature). For example, if the mental category of "technology" is part of a conceptual arsenal to exploit the natural world in an unsustainable fashion, then it can rightfully be considered to have a low truth-value and ought to be reconsidered.
2. It agrees with substantivism that modern technologies may be indistinguishable from the social or political relations that they encourage or demand, but adds that such relations might also originate from the matter-energy required to produce them. For example, if solar PV projects require more matter-energy than can reasonably be supplied by a social group itself, then, in order for it to exist, it might encourage or demand specific social relations of exchange through which resources are appropriated.
3. It agrees with critical theory that technological transcendence is an illusion of the capitalist mode of production but adds that technology is likely not transcendent under other modes of production either. For example, even if solar PV technology is installed to harness energy at low monetary costs, such harnessing is impossible without material demands on the natural world and cannot therefore transcend the fundamental metabolic condition of human societies.

4. It agrees with ANT that modern technology can be defined by reference to a network but asserts that this network is foremost an international trade network orchestrating a global exchange of matter-energy. For example, even if solar PV technology design and manufacturing is orchestrated by actors in networks of knowledge exchange, the production process of solar PV modules necessarily involves an exchange of matter-energy in international trade to take physical form.

To understand this philosophical position, we will first have to look to the notion of materialism and metabolism in Karl Marx and understand how it suggests an understanding of dialectics as metabolic.

Ontological materialism, metabolism, and dialectics

The nature of Marx's materialism has long been a matter of dispute (Lukács, 1968[1923]; Schmidt, 2014[1971]; Vogel, 1996; Foster, 2000; Cassegård, 2017). Despite wide-ranging disagreements, there is nevertheless a consensus that Marx's materialism was heavily influenced by ancient Greek and Roman philosophers such as Epicurus, Democritus, and Lucretius. Remarkably, modern understandings of space, time, evolution, and human origins were to a large degree anticipated by these philosophers. It is clear that Epicurus's philosophical materialism influenced not only Marx but played an extraordinary role for the founders of modern science and the English and French Enlightenment in general (Foster, 2000: 39-51). This hinged in large part on the fact that Epicurus's philosophy of nature was non-teleological. For Lucretius, the concept of nature was *mors immortalis* (immortal death), which refers to the inescapable and transitory mortality of nature itself. It was in the false notion that this condition could be escaped (e.g., the promise of an afterlife) that institutionalized religions could gain extraordinary powers. In opposition to this, Epicurus contended, true freedom was only ever achieved by embracing death as senseless (Foster, 2000: 6, 36).

In this material philosophy, dynamic and open-ended change in nature take precedence over God or final causes. By extension, humans are not created in the image of God or Spirit but are temporal and sensuous beings through whom nature actively engages with itself. Thus, Marx (2000[1841]: in Ch. 4) quoted Epicurus: "In hearing nature hears itself, in smelling it smells itself, in seeing it sees itself." Contrary to Lukács's charge against Engels that humans cannot know nature dialectically, Epicurus's and Marx's position implies that nature can be known, because knowing nature is synonymous with knowing oneself. This does not mean that human knowing is always true or complete. Rather, as a biological species, *what is true is whatever mental representation of the world sustaining a given human organization (society) over time in any given environment (nature)*.[21] In this, signs are as much supportive of material relations as they are "plays," "struggles," "quests for mastery," or whatever signs or meaning the social metabolism invites or demands (cf. Rappaport, 1968; Harris, 1980).

If critics argue that such epistemological materialism is Baconian, it is because they fail to acknowledge the relationism in Marx's notion of metabolism (Foster 2000: 10-11). Schmidt (2014: 78) illuminates this contested topic by noting that Marx abandoned his early Baconian view once he replaced the linear notion of human appropriation of nature with the dialectical notion of "metabolism" [*Stoffwechsel*]. Stoffwechsel, or metabolism from the Greek metabolē (exchange), was a term that came to be used by German biologists in the 1800s to explain how cells in the human body could maintain their material form over time. The understanding that there was a similar metabolic exchange between human bodies and their environment was later pointed out by Justus von Liebig. Influenced by Liebig, Marx wrote, "man lives on nature … nature is his body, with which he must remain in continuous exchange if he is not to die" (Marx, 2000[1844]: 31). Crucially, since human organisms are social, the metabolic exchange also applies to different social formations. Hence, some interdisciplinary scholars use the term "social metabolism" to denote the socially organized relation to the environment (Sorman, 2012). A cell, a human or a human society, is then, primarily, a materially integrated component of nature sustaining itself through metabolic relations with its surrounding. The essential difference between the Baconian view and the metabolic view is whether nature (the biogeochemical processes in the biosphere) is understood as an external resource existing for human exploitation or as the necessary counterpart of society without which society would not exist.

The notion that human societies can escape this metabolic relation to nature, bound within *mors immortalis*, is a central theme in religion and political ideologies throughout history. Today, in both instrumentalism and ANT, we see attempts at breaking with this fundamental metabolic condition in two

---

[21] For example, as Foster (2000:55) noted, "in Epicurus is found even the view that our consciousness of the world (for example, our language) develops in relation to the evolution of the material conditions governing subsistence." God, in this sense, can be true (but not real) if the specific practical actions derived from the worshipper positively affects the reproduction of the social metabolism. In contrast to the instrumental conception of objective truth as socially constructed, human knowledge of the world is here understood to operate in feedback with a real material world (Rappaport, 1968; Bateson, 2000[1972]).

opposite ways. While instrumentalism and ecomodernists champion a radical separation of society and nature, ANT champions a radical unity of society and nature. Neither approach is correct from the metabolic view because metabolic exchange forms a relation that is characterized by both connection and separation. While society and nature are the same at one level, they cannot exist in unity without a separation that facilitates a metabolic exchange between the two. We might say that relations necessitate separation; otherwise, there would be nothing to connect. This is true if we consider human-to-human relations in our everyday life and it is true physically, as becomes evident by the "useful fact" that the "universe is not one solid mass, all tightly packed," as Lucretius (2007: 18) wittingly observed. This means that we have good reasons to question whether escaping from the social metabolic condition through technology or any other method is possible. The material perspective of Epicurus and Marx implies that this is indeed an impossibility. This is something that we learn also from thermodynamics.

Thermodynamics, evolution, and exosomatic organs

The modern science of thermodynamics has its antecedents in 19th century Britain and France. At that time, the rise of the political power of the bourgeoisie was increasingly connected with the steam engine, employed to pump water out of coalmines and perform mechanical work in industries (Malm, 2016). Still, the early steam engines managed to convert only a paltry two percent of the potential energy in coal into useful work. Increasing the efficiency of steam engines was therefore a key concern for early industrialists. At this time, one important question was how efficient steam engines could become. Was it possible that steam engines could be developed to feed on their own boilers in perpetuity without further human effort? These questions were intimately bound to relations of power. As Rabinbach (1992: 58) argued, the quest for perpetual motion was "the phantasmagoria of a society dedicated to making work superfluous." In effect, there was a "pervasive moral criticism of those who resisted work" because they were defectors in the "search for an alchemy of work without struggle" (ibid. 58).

It was in the search for a *perpetual motion machine* that Sadi Carnot discovered the irreversibility of heat passing from hot to cold, now known as the second law of thermodynamics (the entropy law). The implications of Carnot's engine were later formalized by Rudolf Clausius (1867), who stated that the transfer of energy from a warmer to a colder body always implies a total loss of useful energy. The nature of energy, which Hermann von Helmholtz (2001[1862]) praised for being a universal indestructible "Kraft", was that it universally tended towards less useful states. It slowly dawned; the world was characterized by *entropy*, an inescapable tendency towards disintegration and thermal equilibrium. The cornucopian potential in the first law of thermodynamics – that energy cannot be created or destroyed – was effectively shattered with the understanding of the entropy law. It implied that the omnipresent "Kraft" could not be reused infinitely. The implications were game-changing because they struck at the core of the 19th century European cosmology.

As Stokes (1994: 67) points out, "the effect of the thermodynamic laws on the thinking about evolution in the universe was profound." How could organisms live, grow, and evolve in a universe characterized by entropy? It did not take long until the biologist Herbert Spencer (1904) provided an answer: The human body counter-maneuvered the law of entropy by drawing energy from its environment. Schrödinger (1945: 75) later defined life in general as that which "feeds upon negative entropy":

> Thus, the device by which an organism maintains itself stationary at a fairly high level of orderliness … really consists in continually sucking orderliness from its environment. This conclusion is less paradoxical than it appears at first sight. Rather could it be blamed for triviality.

However, it is through this "triviality" that the anti-mechanism of the law of entropy becomes evident, since it implies that nothing can be said to exist simply by reference to its internal parts. For example, take a human body, a tree, or a clockwork mechanism. A human cannot continue without food; a tree cannot continue without sunshine; a clockwork mechanism cannot continue without a human winding up its spring. The entropy law was and still is proof of the inescapably relational character of artefacts, life, and societies (Georgescu-Roegen, 1971; Bateson, 2000[1972]; Foster et al., 2010).

In terms of evolution, humans have been highly successful in maintaining metabolizing collectives in a wide range of environments without any drastic variation in their physiology (Bates, 2001). This can partly be explained by the fact that human organs are not all part of the physiology of the individual human body, as becomes evident through thermodynamics and as Karl Marx, his contemporary Ernst Kapp, and later Alfred Lotka pointed out (Marx, 1990[1867]: 493; Kapp, 2018[1877]; Lotka, 1956). Apart from the "endosomatic organs" that are part of the body, human depend extensively on "exosomatic organs" outside their bodies that provide access to a range of different environments (Lotka, 1956). One universal example is fire, an exosomatic organ for digestion and an aid to making environments more accessible to the human body through cooking and more effective hunting. Another example is the plow, an exosomatic organ intensifying the amount of humanly available biomass that can be extracted from a given environment. Yet another example is the British Imperial coal network and the colonial triangular trade that facilitated an appropriation of labor time and natural resources from ever more remote environments and peoples (Hornborg, 2006; Pomeranz, 2000). As will be elaborated below, all such organs provide matter-energy, but only through prior and continual use of matter-energy.

Even if exosomatic organs all in varying degrees facilitate an appropriation of resources from the environment, different organs may imply different relations within a society. Lewis Mumford (1964) sheds light on this issue by separating what he calls "democratic technics" from "authoritarian technics." Examples of democratic technics are fire, baskets, nets, bows and simple water pumps, all defined as democratic with reference to the fact that they can be learned, produced, and controlled by any adult member of the species. Democratic technics, he writes, are "relatively weak, but resourceful and durable" and work best in contexts where aspirations for accumulation are low (Mumford, 1964: 2). However, as is evident both historically and in our own time, social aspirations may imply material pressures on environments that exceed their regenerative biocapacity (Pomeranz, 2000; Wackernagel et al., 2002; WWF, 2020). For such aspirations to be saturated, energy and material resources have to be extracted from non-local environments and peoples (Hornborg et al., 2007; Rice, 2007). The "authoritarian technics" required for such aspirations included an orchestration of both nature and people in systems of material and ideological power (Mumford, 1954; Hornborg, 2001). In short, these organs cannot be democratically produced or maintained since they necessitate (and in a sense are) undemocratic relations of production whereby some people work for the benefit of others.[22] Mumford (1964) pointed out that contrary to the humble democratic technics, authoritarian technics excel simultaneously in both mass construction and mass destruction. Whether these technics, or organs, are understood as emancipatory or destructive is therefore contingent upon how particular social groups are positively or negatively affected by

---

[22] Engels (1972[1874]) position on authority and industrialism recognized that industrial machinery is inherently authoritarian regardless of ownership. In effect, "wanting to abolish authority in large-scale industry is tantamount to wanting to abolish industry itself" (ibid. 731). Moreover, since authority was seen by Engels as inseparable from large-scale industry and since industrialism was interpreted as inevitable, Engel's regarded large-scale industry as being exempt from moral questioning or radical critique.

them, something that today often corresponds to particular geographical locations (see Hornborg, 2014; Isenhour, 2016).

Ecologically unequal exchange and machine fetishism

Like Mumford's "authoritarian technics," Alf Hornborg's interdisciplinary work on ecologically unequal exchange has suggested that modern technology is inseparable from the global social-ecological arrangement orchestrated by European colonial powers at least since the 18th century (Hornborg, 1992, 2001, 2013, 2016). Drawing on world-systems analysis (Wallerstein, 2011a-d), dependency theory (Frank, 1966; Amin, 1972; Emmanuel, 1972; Bunker, 1985), and ecological economics (Georgescu-Roegen, 1971; Martinez-Alier, 1987), the theory of ecologically unequal exchange proposes that capitalist world trade orchestrates an exchange whereby richer (core) regions of the world appropriate resources from impoverished (peripheral) regions of the world (Giljum and Eisenmenger, 2004; Hornborg, 2006; Jorgenson et al., 2009; Lawrence, 2009; Dorninger and Hornborg, 2015; Hao, 2020; Dorninger et al., 2020). It explains these differences by empirically demonstrating how economic exchange – conventionally measured in money – facilitates an unequal exchange in terms of labor time, embodied land, and/or natural resources. This is possible because any *symbolically equal* exchange, for example in terms of money ($100 for $100), may simultaneously imply a *physically uneven* exchange in terms of resources or resource investments (say, 100 kg for 10 kg).

In our own time, Hornborg (1998: 131-132) argues, "*market prices* are the specific mechanism by which world system centres extract exergy from, and export entropy to, their peripheries."[23] According to Wallerstein (2004), core regions in the world economy are those in which the production process is largely controlled by state-backed corporations. Through tariffs, subsidies, tax benefits, and other measures, states in core regions facilitate a wide margin between production costs and sales prices for corporations. Thus, wages and prices remain high in core regions because market competition is effectively annulled. In contrast, corporations in peripheral regions of the world economy do not enjoy the same state benefits. They are therefore "truly competitive" in a manner that pushes down wages and prices on their products (Wallerstein 2004: 28). Semi-peripheries exhibit both core-like and peripheral-like conditions of production. If we look at China as an example, wages and prices remain low in China by international standards even if there is a growing

---

[23] For a description of "exergy," see Appendix A.

middle class enjoying a higher income. When the country opened for international capital in 1978, the inflow of foreign direct investments (FDIs) forced state-operated firms to compete with private firms from overseas. This led the Chinese state to purge the state-operated firms from low productivity workers in the 1990s (Yang et al., 2010). These included less educated workers, old workers, and women in precarious positions. As production was made more efficient, wage levels increased. Thus, state regulations generated higher wages. Even as wages increased, however, the unskilled population was left without a steady income, effectively becoming (in Marxist terms) a "reserve army of labor," desperately offering unskilled labor at very low wages (Yang et al., 2010). While wages and worker benefits are increasing in China, these effects are also unevenly distributed. In countries with weaker states, wages are even more exposed to market competition driving down wages. When commodities are exchanged on the international market under regional price differences, a net transfer of embodied resources tends to flow from periphery to core, periphery to semi-periphery, and semi-periphery to core. By extension, much of the environmental load of the high-consumption lifestyles in the core is displaced to the world peripheries (Hornborg, 2009; Dorninger et al., 2021).

According to the theory of ecologically unequal exchange, technologies have been intertwined with socially determined rates of exchange (prices) whereby some nations have been able to appropriate resources from other nations to build and maintain modern infrastructure at least since the mid-19th century. Hornborg (2005, 2013) shows, for instance, that in exchanging British cotton manufactures for North American raw cotton at equal monetary prices, Britain in 1850 established a net flow of embodied labor and embodied land to Britain. Technology can be understood from two vantage points in the orchestration of such material exchange:

1. Machine technology such as water mills and steam engines *necessitated* a concentration of resources to be constructed and operated. For example, the development of early industrial machinery in Britain was based upon the import of large amounts of Scandinavian iron, and later, after the repeal of the Corn Laws, Russian and Prussian wheat for feeding the labor force (Pomeranz, 2000; Debeir et al., 1991: 108-11; Hornborg, 2006).

2. Machine technology such as water mills and steam engines *facilitated* asymmetric metabolic relations by lowering production costs in the cotton industries. This in turn leads to more favorable exchange rates and further rounds of resource appropriation. In such a way, not only

state power, but also productive infrastructure contribute to low production costs relative to commodity prices (Warlenius, 2016). To this rationale, we add the use of military technologies to subdue and exploit peoples around the world to secure labor and resource-abundant or geopolitically favorable locations (Headrick, 2010).

Asymmetric metabolic relations, in theory, are what modern technology at once necessitates and facilitates. As such, modern technology can be understood as emerging due to the ecologically unequal exchange that allowed the elites of the British Empire to eventually accumulate more resources than the biocapacity of the British Isles could provide (Pomeranz, 2000; Hornborg, 2006). The same asymmetric relations, Hornborg contends, can be observed in the distribution of light in night-time satellite images of the Earth today (see NASA, 2017). If the "inventors of nuclear bombs, space rockets, and computers are the pyramid builders of our own age" (Mumford, 1964: 5), then Hornborg argues that ecologically unequal exchange is the indispensable mechanism through which the necessary labor and natural resources for these inventions can be accessed.

The notion that modern technologies necessitate ecologically unequal exchange has profound implications for a philosophical consideration of technology. This is so because the work that technological artifacts appear to perform in a local environment necessitate resource expenditures (materials, land, labor, etc.) elsewhere in the world economy. This means that "the rationale of machine technology" is not necessarily to do work, but rather to "(locally) save or liberate time and space, but (crucially) at the expense of time and space consumed elsewhere in the social system" (Hornborg, 2006: 80). Smartphones, for instance, provide obvious benefits (time, energy "saved") for those who can afford them, but they simultaneously imply obvious burdens (time, energy "spent") across the global production process. From this, we may ask, do the physical costs shouldered by nature and workers outweigh the physical benefits gained by the technology user? With reference to the second law of thermodynamics, the transformation of matter-energy is always accompanied by an increase in disorder. This alone excludes the possibility that technology is something that delivers net benefits in a physical sense. In addition, as pointed out by Lucretius (2007: 11), "nothing can be made from nothing." *Technologies, then, do not add anything physical to the world.*

From a critical ecological perspective, to believe that technologies provide physical net benefits in the world is an illusion maintained by the fact that the adverse costs of any given technological artefact or efficiency improvement are displaced to nature or to other parts of the world. The question, then, is for *whom* a given technology is biophysically worthwhile. In the world economy, the burdens, or costs, associated with technology are taking place far from the everyday sensuous experience of the user. This is the root of "machine fetishism" wherein technologies appear to have innate productive qualities (or, agency) since they are understood as isolated from the global social-ecological arrangement that generated them (Hornborg 1992, 2016). Rather than having innate productive qualities, however, technologies are better understood as having productive qualities due to resource expenditures elsewhere in society or nature. The "agency" or "thing-power" spoken of by new materialist and ANT theorists is therefore not innate to the technological artefacts themselves but granted to them by virtue of being the embodiments of resources dissipated elsewhere. To put it simply, we can say that the smartphone is working because it has implied a loss of resources (low entropy) earlier in its life cycle. The degree to which a given technology works to the maximal benefit of the user depends upon to what degree the loss of low entropy can be displaced to other systems (social or natural) or not. The question concerning technology is therefore ultimately a matter of matter-energy distribution (not addition) between natural processes (e.g., nutrient cycles) and social groups.

In sum, the critical ecological framework in this thesis is underscored by at least six basic assumptions. These assumptions are all related to the overarching assumption explored in this chapter, i.e., that philosophical materialism provides invaluable insights into the processes of nature and history. This includes:

- *First*, an agreement with ontological materialism asserting that human populations emerge from nature's independent processes, to which they therefore are metabolically bound. From this assumption emerges an understanding of the fundamental paradox that all human-environmental relations imply human-environmental separation.
- *Second* is an agreement with epistemological materialism when assuming that human semiotic representations of nature are true to the extent that they support a particular metabolic interaction with – and so survival in – nature. Given today's ecological problems, this assumption motivates a questioning of the modern outlook of science, economics, and technology and their relation to the metabolic reliance upon fossil fuels and the Industrial Revolution (for science and economics, see Georgescu-Roegen, 1971; Daggett, 2019). The notion that technology constitutes a problematic concept in modern culture is reflected in the lack of ontological materialism in contemporary philosophies of technology that have effectively omitted biophysical nature.

- *Third,* any given technology is part of a socially organized metabolism.
- *Fourth*, since “nothing comes from nothing” and “everything must go somewhere,” technologies do not add – merely redistribute and dissipate – matter-energy in the world. By virtue of being made of large amounts of initially dispersed material compounds, modern technologies require global social relations that concentrate resources. The neglect of this fact leads to the pervasive modern cultural misrepresentation of technologies referred to as “machine fetishism.”
- *Fifth*, the question concerning technology is foremost a question of matter-energy distribution across social groups and natural processes in contrast to the conception of it. This is the theme of this thesis, as applied to solar power.
- *Sixth*, in line with practical materialism (see definition above), human-environmental relations can change in a more sustainable direction through deliberate human technological practices adjusted to carrying capacities and nature’s processes (see below).

The technological continuum: An illustrative model

To explain my critical ecological approach to technology, I propose a continuum of technology (figure 3) that analytically divides the complete phenomenon of technology into:

i) Technology as **past** social conditions and consequences (prior to being assembled as artefacts).

ii) Technology as an artifact in the **present**.

iii) Technology as **future** social relations and consequences.

With reference to this continuum, Hornborg’s concept of “machine fetishism” explains a collective difficulty in thinking of past social-ecological relations and consequences – and so the full material continuum – as essential to what technology is. If the full continuum is taken into consideration, we understand that we are dealing with a relation between the systems on the left side of the continuum (among which the loss of low entropy occurs and the technological artifact’s capacity to do work is generated) and the systems on the right side of the continuum (in which technological artifacts are applied for their capacity to do work). In this view, technological artifacts in the present embody low entropy (or resources) “spent” that can be put to work by the user to facilitate further rounds of appropriation in the future. In other words, technologies are means for continuous ecologically unequal exchange (Hornborg, 2003).

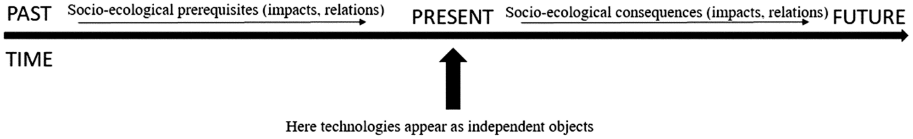


Figure 3. The technological continuum.
Representing an exchange of embodied matter-energy from the left end to the right end.

Let us briefly take a closer look at the biophysical past of a specific technological artifact to see what is omitted in the fetishized perspective. To this end, I would like to refer to the German company Nager IT, which produces the “Faire Maus.” The aim of the company is to produce a computer mouse that is a hundred percent fair. It meticulously documents the working conditions under which all the mouse’s material components are manufactured. Figure 4 is a summary illustration of the company’s effort to trace and assess the mouse’s commodity chain. This represents the biophysical past of a particular technological artifact – in this case a computer mouse – as an illustration of the technological continuum. The mouse itself, of course, represents the technological artifact, such as it appears to consumers in the present. In this illustration, we can see how the biophysical past of a modern technological artifact is immensely complex. To produce something as seemingly simple as a computer mouse requires more than twenty material components extracted from around the world, which are then transported, processed, packaged, and assembled in a range of different stages. If the boxes in the illustration represent particular material components or manufacturing processes, the lines in between the boxes represent instances of matter exchange and transportation.

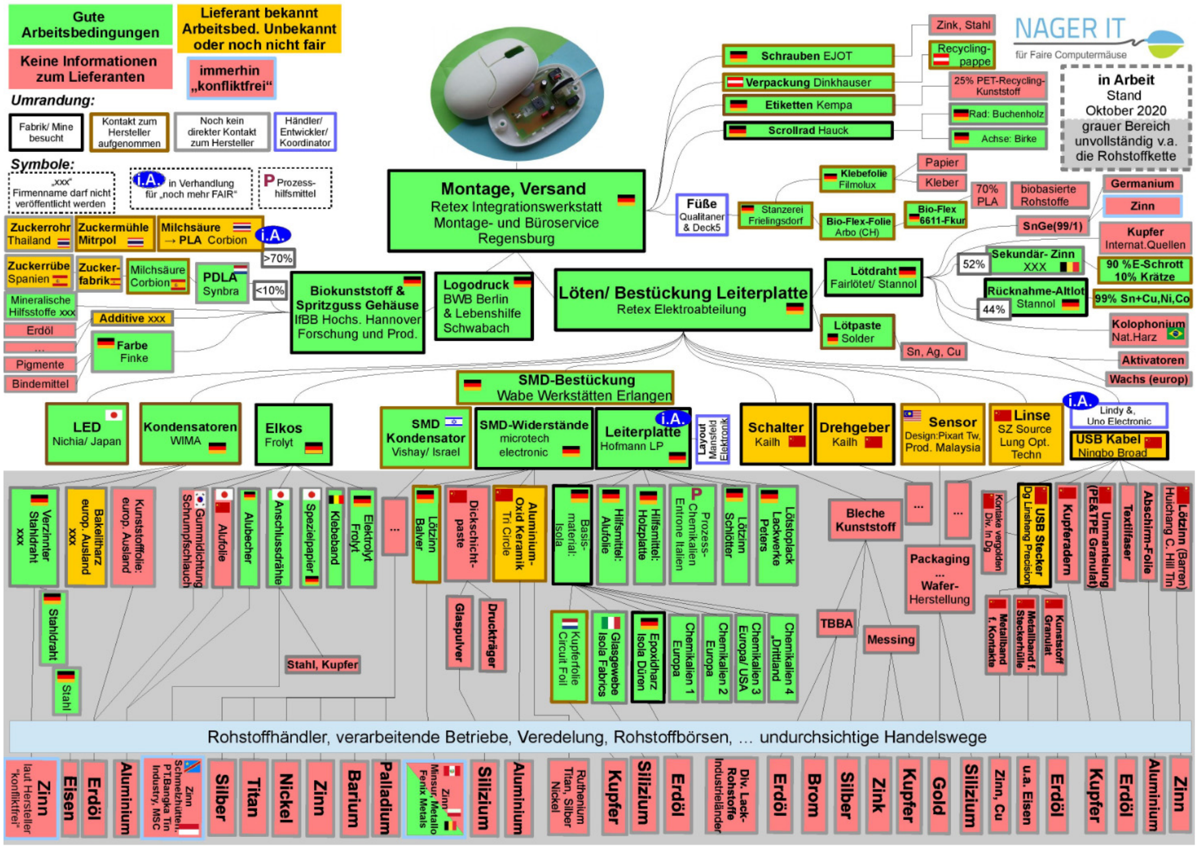


Figure 4. The commodity chain of the computer mouse "Faire Maus." Produced by the German company Nager IT. Source: Nager IT (with permission).

A recurrent problem for ecological economists who are interested in the exchange of matter-energy is the fact that commodity chains are conventionally accounted for in terms of money. Money, however, is simply the symbolic representation of what is actually being exchanged (matter-energy) and spent (low entropy). In this physical sense, technological artifacts do not come from money, but from matter-energy that has been appropriated from nature and transformed by labor. In industrial capitalism, this process occurs with the aid of highly energy-dense fossil fuels (see chapter three). So far, it seems, this fundamental biophysical condition of technological artifacts has been sidestepped in the philosophies of technology reviewed above.

The review of the assumptions in contemporary philosophies of technology suggests that it is common to consider technology as something ontologically non-material, yet often with tangible consequences in nature. This is most obvious in instrumentalism, in which technology, like a *deus ex machina*, is lowered down onto the theatre of the present to solve material problems for the future (Smith and Marx, 1994; Foster et al., 2010: 116). This is the view that powerful organizations such as OECD and UNEP are now operating with, using defunct notions of "green and sustainable growth" (OECD, 2011; UNEP, 2011, 2014; cf. Hickel and Kallis, 2019; Parrique et al., 2019). This omission can also be deduced from the assumptions in ANT, which thinks of technologies as emerging from semiotic networks (as if that which the boxes and lines of the Faire Maus commodity chain illustration represent are simply ideas). The reference to technology as design or consciousness is similarly problematic since it downplays and sometimes obfuscates the social-ecological origin of technological artifacts. This is not to say that design and consciousness are not necessary aspects of technology. However, it does mean that design and consciousness are not sufficient to describe the complete material phenomenon of technology. To acknowledge the complete technological continuum implies a consideration of what a given technological artifact at once *necessitates* (the left side of the continuum) and *facilitates* (the right side of the continuum). By understanding technologies this way, it becomes possible to evaluate how a given technology alters nature's processes and/or contributes to a transformation of human-environmental relations within the confines of the biosphere.

Perhaps the most important point offered here is that technologies should not be assumed to alleviate environmental pressures in one area without implying such pressures elsewhere in the world.[24] With that said, the notion that modern technology is a means to orchestrate unequal exchange of matter-energy does not mean that technology can or should be rejected. As we have seen, all organisms, or collective of organisms, require strategies of appropriation for their very survival, i.e., strategies to suck orderliness from their environment, or, to metabolize. Without such strategies, they would cease to exist. This is an inescapable condition of being an organism, or a collective of socially organized organisms, in nature. While this appropriation is by definition unequal, human organizations can, in theory, choose to what degree they expend other people's resources by exploiting their land and labor. As current global ecological footprints greatly exceed the carrying capacity of the Earth (WWF, 2020), this will be a major challenge for 21st century societies seeking to transition away from fossil fuels in a just and humane way.

This chapter has highlighted the discrepancies between the philosophical assumptions of natural science and the philosophical assumptions dominant within the philosophy of technology. In particular, it has shown that ontological materialism has remained marginal in the major strands of 20th century philosophy of technology. While research on the biosphere has emerged from an understanding of the world as a complex interplay of geological forces and biogeochemical cycles of matter-energy commensurable with philosophical materialism, technology has come to be interpreted as ontologically immaterial, springing forth from human cognition, consciousness, design, or semiotic networks. The remedy to this discrepancy – by acknowledging ontological materialism in the philosophy of technology – suggests that technology may be understood as a means to orchestrate ecologically unequal exchange. Technology, in this view, is not merely an artifact but a processual continuum, which requires and reproduces specific social-ecological conditions.

---

[24] Similar forms of displacement may also apply to the working conditions and gender relations altered when new technologies are commercialized in the world core.

3. The industrial regime as a historical parenthesis: The social-ecological context of solar PV technology and the question of the new metabolism

> "*People make their own history, but not exactly as they please. Rather, they must struggle under conditions established by the complex coevolution of nature and human production, and the relations of power and ideology, inherited from the past.*"
>
> – Foster, Clark, and York

If solar power is to play a significant role in replacing fossil fuels, as is conventionally expected, we need to consider what such a replacement implies. To this end, it is essential to understand how the current energy regime emerged historically and how it still affects us today. The purpose of this chapter is to sketch out an interdisciplinary understanding of the most recent major energy transformation – the Industrial Revolution – to understand the ramifications of altering the metabolic basis of industrial societies by means of solar PV technology. We will see how the Industrial Revolution both *necessitated* and *facilitated* specific ecological conditions, social relations of power, and cultural imaginaries, which are not easily separated from the development of solar PV technology today. This will be followed by an analysis of three different interpretations of the Industrial Revolution, which all understand the prospects and implications of leaving the industrial regime differently. I show that the answer to whether solar PV technology is based on ecologically unequal exchange (RQ1) tells us whether solar PV technology is a means to continue the metabolic basis of industrial societies, or a means to alter it.

Numerous approaches have been developed by social scientists to understand how energy technologies at once arise from and generate particular social relations (Fouquet and Pearson, 2012; Markard et al., 2012; Geels, 2012, 2014; Last, 2015; Sovacool, 2016). However, as we saw in the previous chapter, the most relevant approaches to energy technology are those that acknowledge how energy transformations are biophysical events. Energy transformations are bound to alterations in the natural environment and of nature's processes. As recently suggested by environmental historians Ian Jared Miller and Paul Warde "energy transitions are always at some level also environmental events" (2019: 466). This means that the unit of analysis must include not only the socio-technical formation associated with a particular energy regime, but the socio-technical formation *within its environment*. Many of the interdisciplinary studies that have been conducted in this vein have concluded that to leave the fossil regime implies a transformation that is comparable to the Neolithic and Industrial Revolutions (Debeir et al. 1991; Fischer-Kowalski and Haberl, 2007; Podobnik, 2005; Haberl et al., 2011; Lenton et al., 2016).

The history of human-environmental relations is not the history of humans or the history of environments, but a history of the relation between the two. Weisz et al. (2001: 122) summon Maurice Godelier to argue that humans "transform their relation *with* nature by transforming *nature itself*."[25] In turn, these transformations, which affect the dynamic biogeochemical processes of nature itself, provoke the historical opportunity or necessity for social-technical changes. This social-ecological dialectic is the underlying methodological departure for the study of a range of phenomena, such as "energy systems" (Debeir et al., 1991), "dialectical materialism" (Foster, 2000; Foster et al. 2010), "raw materialism" (Gellert and Ciccantell, 2020), "ecological-economic history" (Martinez-Alier and Schandl, 2002) and "ecologically unequal exchange" (Hornborg, 1998; Bunker and Ciccantell, 2005a; Hornborg, 2009). We can say that these approaches all in one way or another deal with the process of "coevolution" wherein societies are "structurally coupled to parts of their environment, leading to a process where both mutually constrain each other's future evolutionary options" (Weisz et al., 2001: 123; see also Kallis and Norgaard, 2010).

The concept of "social-ecological regimes" (Fischer-Kowalski and Haberl, 2007; Krausmann et al., 2016) provides a helpful systematization of human-

---

[25] As we saw in chapter two, humans cannot choose to end this transformative interaction if they wish to survive in nature, since the reproduction of society necessitates a matter-energy exchange, a Stoffwechsel, which always implies a transformation of nature.

environmental coevolution in history. Essentially, a social-ecological regime denotes “a specific fundamental [metabolic] pattern of interaction between (human) society and natural systems” (Fischer-Kowalski and Haberl, 2007:8). These fundamental patterns may contain different forms of social relations and are therefore broader historical categories than Marxist “modes of production,” which are defined foremost by historically developed social relations (Debeir et al., 1991: 12).[26] The essential difference between different social-ecological regimes is how human populations harness matter-energy from their surrounding environment. Crucially, however, such metabolic interactions cannot fully be understood without considering how internal social relations facilitate and reproduce them. Social interaction, its preconditions and form, alters continually in relation to the dynamic changes of natural environments. In the study of social-ecological regimes, culture, understood as the “the total socially acquired life-style of a group of people including patterned, repetitive ways of thinking, feeling and acting,” is similarly understood as facilitating the reproduction of a given social metabolism (Harris, 1997: 88; Weisz et al., 2011). Alongside environmental changes, transitions from one socio-ecological regime to another are therefore associated with major historical alterations in both social relations and cultural imaginaries.[27]

In this chapter, I describe the Industrial Revolution as the emergence of a historically novel social-ecological regime, with far-reaching consequences for the global environment, for the cementation of a world division of labor, and for modern imaginaries. To this end, I first deal with its prerequisites and how it necessitated particular historical conditions. In particular, I consider how colonialism, capitalism, and fossil fuels were crucial for the formation of this

---

[26] For example, what in historical materialism are called the ‘ancient mode of production’ and the ‘feudal mode of production’ can be understood both to be encompassed within the ‘agrarian socio-ecological regime’ because they are both metabolically based on energy captured through cultivation of plants. Modes of production have at times changed simultaneously as transitions in social-ecological regimes. Hypothetically, therefore, new social-ecological regimes might imply new modes of production in the Marxist sense, but not necessarily the other way around (see Fischer-Kowalski et al. 2019). As such, it seems likely that changes in social relations alone do not determine changes in socio-ecological regimes. However, the opposite might hold some truth historically. As argued by York and Mancus (2009) this difference in periodization between “critical human ecology” and classical historical materialism is rooted in the former’s acceptance of an ahistorical understanding of nature, such as exemplified by natural laws.

[27] In this thesis, I distinguish “social metabolism” from “social-ecological regime.” Whereas “social metabolism” denotes a socially organized exchange of matter-energy with the environment, a “social-ecological regime” denotes the social metabolism and the cultural imaginaries to support it.

social-ecological regime. This reading stands apart from the conventional interpretation of the Industrial Revolution as a progressive and liberating transformation emerging primarily from enlightened rationality and engineering ingenuity. I then deal with its consequences and how it *facilitates* particular historical conditions. Similar to the previous part, I provide a reading of the consequences of the Industrial Revolution that contrasts with the conventional view, which commonly ignores how it required and generated social inequalities and unprecedented environmental destruction (Barca, 2011). I show that these consequences must be considered as much a part of industrial societies as the widely celebrated boons of technological progress. Given the numerous interpretations of the social and ecological consequences of the Industrial Revolution, the last part of this chapter deals with three distinct understandings of what it means to attempt to leave the industrial regime by means of renewable energy technologies, such as solar PVs. This part shows that it is still up for debate whether today's solar aspirations will continue, transcend, or reverse fossil-propelled industrial capitalism. If solar PV technology is based on ecologically unequal exchange, industrial societies shifting away from fossil fuels will probably require intensified global asymmetries to maintain their level of consumption.

The prerequisites of the Industrial Revolution: Colonialism, capitalism, and fossil fuels

There is no doubt that the Industrial Revolution marks the beginning of historically unprecedented changes in human-environmental relations. Much of the recent work in environmental history considers the Industrial Revolution as the analytical focal point *par excellence* for understanding the roots of the global environmental problems of today (Haberl et al., 2011; Barca, 2011; Steffen, et al. 2015a; Hornborg, 2015; Malm, 2016). However, as these studies show, more than fundamentally altering the environment on a global scale, the Industrial Revolution marked the beginning of an entirely new form of social-ecological regime. This is an important point, because it is crucial to acknowledge how today's global environmental challenges emerged in tandem with specific social relations and cultural ideas that took shape with the historically new means to harness highly energy-dense fossil energy.

As in the other two major energy transformations in history, the taming of fire and the Neolithic Revolution, it is difficult to isolate the exact causality behind the emergence of the industrial social-ecological regime in a satisfactory way (Weisdorf, 2005). This is not to say that scholars have not attempted the task of doing so. To date, causal explanations range from the classical notion of human (notably British) engineering ingenuity in the design of the steam engine following the Enlightenment, to the British factory owners' desire to dominate labor in the process of accumulating more capital (see Landes, 1969; Barca, 2011; Malm, 2016). Western scholars have typically thought of the industrial revolution as something emerging first in Britain around 1760, as an effect of some cultural, social, or ecological factor internal to Britain. This approach still dominates today, even if numerous historians have made much effort to demonstrate the flaws in such reductive and Eurocentric approaches (Frank, 1966; Wolf, 2010[1982]; Denemark and Thomas, 1988; Pomeranz, 2000; Inikori, 2002; Moore, 2003; Barca, 2011; Marks, 2015; Hornborg, 2015). Acknowledging that the emergence of industrialism in Britain was contingent upon international relations – as exemplified by the increasing role of the international market, the slave trade, and raw material imports from colonies – implies in turn that any attempt to understand the birth of the industrial regime must be sensitive to historical patterns established well before the year 1760. These include understanding capitalism and colonialism as a world strategy for ecological appropriation, emerging already in the late 15th century. Here, we shall try to understand colonialism and capitalism as two interconnected prerequisites for the emergence of the industrial regime. In addition to these prerequisites, it is widely acknowledged that the industrial regime could not emerge without burning fossil fuels to propel machines used in the mass-production of commodities for the world market.

Colonialism and capitalism as prerequisites for the Industrial Revolution

If industrialism refers to "an inclination toward mass production of commodities," then we have good reason to think that the industrial regime could not emerge without an already significant level of social-political complexity (Hornborg, 2015: 863). This is so because mass production cannot exist without the mass extraction of matter-energy inputs and a large-scale system of labor orchestration. For the ecological economist Robert Ayres (2016: 389), "[e]nergy (exergy) *availability* was the main engine of growth from the start of the Industrial Revolution." However, this energy availability was not represented by the fossil fuels lying dormant in the Earth's crust, but rather the access to copious amounts of biomass from the world peripheries without which fossil fuels would be impossible to extract and burn.[28] From this, we can deduce that the industrial regime must have emerged from a "successful" agrarian social metabolism that drew resources from an immense land base. As some environmental historians have shown, such complexity was generated through colonial expansion of European imperial powers, which appropriated natural resources and displaced entropy around the globe through means of trade, warfare, and slavery (Wallerstein, 2011a; Crosby, 1986; Pomeranz, 2000; Moore, 2003; Hornborg, 2006).

Environmental historian Jason Moore (2003, 2007) has thoroughly examined the mechanisms and root causes of the capitalist world-system and its relation to early European colonialism. Drawing on the work of Immanuel Wallerstein, Moore provides an interdisciplinary interpretation of the rise of capitalism that considers "nature and society as mutually relational" (2003: 357). In seeking a "synthesis of theory and history for the study of large-scale socio-ecological change over the *long duree*," Moore's early work on the origins of capitalism is an indispensable contribution to the environmental history of social-ecological regimes (ibid. 308). According to Wallerstein and Moore, the capitalist world economy emerged out of the social-ecological crisis in 15th century European feudalism that had "overstepped the socio-ecological limits to continued expansion" (Moore, 2003: 313, see also Wilkinson, 1973). For Wallerstein (2011: 37), the most plausible explanation for this crisis was that "[a]fter a thousand years of surplus appropriation under the feudal mode, a point of diminishing returns had been reached." Feudalism, in the process of producing a surplus for the ruling strata, tended not to reinvest in the soil, which eventually led to soil exhaustion and diminishing returns (Moore, 2003: 330; Wallerstein 2011: 23).

In the crisis of feudalism, ecological factors such as climatological change and the Black Death were important catalysers for the emergence of capitalism. The Black Death, in particular, was a significant event because it fundamentally altered the power structure of feudal Europe through changes in

---

[28] Large-scale industrial operations to manufacture machines, construct railways, extract coal, and transport commodities across the world required a substanital amount of workers and raw materials. Both the food for this workforce (including both wage laborers and slaves) and many of the raw materials themselves implied substantial amounts of biomass. This includes biomass in the form of sugar from South -and Central America, cotton from North America, and wheat and wood from the Baltic (see below). As concluded by Inikori (2002: 478), "the claim, that technological development ... caused the growth of overseas sales instead of the other way round, is contrary to the clear evidence from the northern countries that led the technological change in cottons, woolens, and metals." In short, technological development and industrialization was contingent on biomass and raw material importation.

demography. The effects in Europe were devastating, leading to the death of 40-60% of the population. In turn, this had serious repercussions for the production of surplus for the managerial elites, who found themselves without the provisions generated through serf labor. The dissolution of "the feudal equivalent of the 'reserve army of labor'" implied that the peasants bargaining position drastically improved (Moore, 2003: 314). To put it crudely, the "supply" of peasant serfs drastically diminished, thereby increasing their perceived value. The result was that "Europe's peasantry waged the class struggle much more effectively than heretofore, squeezing the seigneurs, who in turn squeezed the states, who were forced to recognize the former's voice in policy-making" (ibid. 2003: 317). Since the European peasantry resisted increased exploitation, often in outright rebellion, "Europe's ruling strata" came to favor "'outer' rather than 'inner' expansion" to satisfy their need for surplus and political power (Wallerstein, 2011a; quoted in Moore, 2003: 316).

Internal reforms, such as converting arable land to pasturage in Castile and England, were attempted in the hope of increasing the production of surplus value by producing wool for export. In the end, these were not very effective and "transatlantic expansion was the path of least resistance" (Moore, 2003: 316). Meanwhile, stories of a new world in the west were spreading. Christopher Columbus, in a speech to the Court in Madrid, gave an alluring account of his travels to what he believed to be a group of islands just east of Asia:

> Hispaniola is a miracle. Mountain and hills, plains and pastures, are both fertile and beautiful … the harbors are unbelievably good and there are many wide rivers of which the majority contain gold … There are many spices, and great mines of gold and other metals (Zinn, 1995: 3).

Columbus's choice of words in describing Hispaniola (known by the indigenous peoples as Haiti or Quizqueia) was not accidental. Nor was it romantic. It was a description of a financial opportunity for commerce and surplus production. Fertile lands, good harbors and wide rivers were all optimal conditions for resource exploitation and extraction. Precious metals such as gold and silver were extremely desirable goods on the emerging world market and were therefore likely to attract investment opportunities from commercial city-states such as Genoa, who financed the Iberian colonial expansion. Silver, in particular, was highly sought after due to an enormous Chinese demand stemming from Chinese financial reforms (from ca. 1400) that remonetized the economy from paper and copper coinage to silver as a medium of accounting and store of value (Pomeranz, 2000: 159-162).

In Europe, the increased quantities of bullion extracted from the Americas, such as gold and silver, functioned as a foundation for the emerging international market. As grain prices went up in one part of Europe, for example, the bullion functioned as a means for purchasing grain from elsewhere in Europe, thereby stabilizing prices in a common market sphere. As such, Wallerstein argues, increased access to bullion operated as a "hedge" and "sustained the thrust of the expansion, protecting [the] still weak system against the assaults of nature" (2011[1974]: 45-46, 76). The result was the emergence of a more resilient form of world-commerce operating with a world division of labor under the logic of commodification, i.e., the capitalist system (ibid. 77).

World trade in luxury goods, or "preciosities", such as silk, carpets, and spices had existed for some time, but it had done little to alter or affect regional metabolisms in Europe to the degree that it upset domestic power relations (Wallerstein, 2011a: 41-42). In China, in contrast, the intensified production of silk (among other goods) for international trade contributed to considerably changing social and ecological conditions (Abu-Lughod, 1989). With the expanding capitalist market, trade in staples such as wheat, wood, and sugar proved to have tangible material effects both in the regions that benefited from the trade and in those regions that carried the consequences. Wheat and wood imported from the Baltic (part of Europe's "internal Americas") freed up land in core regions that could be converted to pastures for draft animals and livestock, while simultaneously feeding a growing labor force and serving as raw material for house- and shipbuilding. Sugar, an emerging food staple in the core, was first planted by the Portuguese with slave labor on the island of Madeira, and this model was exported to the Americas where it was expanded and intensified to provide increased revenues for the newly formed coalitions between the merchant classes, the bankers, and the ruling classes of Europe. Sugar, in particular, was intimately tied to slave labor and both the colonial production of sugar and silver (and later cotton and tobacco) were extremely destructive and inhumane processes. The detrimental effects of sugar plantations led to what Moore (2003) calls "sequential exploitation," whereby the ruthless treatment of landscapes and slaves through extractive mono-cropping forced colonial plantation capitalists to move from region to region throughout the Americas in order to maintain profitable yields.

From a wider, world-economic point of view, this degradation occurred for the benefit of those who could enjoy the final products. Early capitalist expansion and colonialism was ultimately a process whereby "[n]utrients [and all manner of resources] flowed from country to city in the New World, and thence from urban centers in the periphery to the core" (Moore, 2003: 334; see also Hornborg, 2006; Clark and Foster, 2009; Infante-Amate and Krausmann, 2019). As we have seen, the accumulation of resources and raw materials in the world core were used to increase living standards for a growing middle class, to gain political influence, to develop technological infrastructure, and to ramp up the manufacture of cheap commodities for the world market (Hornborg, 2006). The result was not only detrimental social and ecological effects in the peripheries, but also that some European nations, such as Britain, could uphold a metabolic throughput larger than the biocapacity of their domestic land base (Pomeranz, 2000).

Even in colonial centers, however, the material bounty collected from around the world was unequally distributed. In core regions of the world, such as Britain, the "country to city" flow of nutrients was a central aspect of the emergence of capitalist class relations, ultimately contingent upon the "enclosure acts" by which landowners displaced peasants from their land to be used as sheep pasture (Foster, 2000: 172; Hornborg, 2015). The displaced peoples congregated in the cities where they made up the new class of the proletariat, a "reserve army of labor" condemned as serfs for capitalist industrial manufacturing (Marx, 1990[1867]). The new capitalist class gaining influence through the process of commodity production eventually grew powerful enough to challenge the tributary-based state system and so the power structure was recomposed (Wolf, 2010[1982]: 265-266).

In this way, the rise of capitalism was inseparable from European colonialism and world commerce. Since its inception, then, capitalism has been contingent upon a world division of labor upholding an unequal distribution of social-ecological benefits and burdens (Wallerstein, 2011a; Moore, 2003, 2007; Hornborg, 2006, 2013). In effect, "where earlier ecological crises had been local, capitalism globalized them. And it did so at a pace that outstripped all previous existing historical systems" (Moore, 2003: 303; see also Clark and Foster, 2009). Capitalism, in this sense, is inherently global in character, defined by the world social relations that allowed for the rise and continuation of resource accumulation among European imperial powers. Compared to previous empires, capitalism could (and did) draw on resources from around the globe (Wolf, 2010[1982]). According to Moore (2003), this distinctive feature was the foundation for a completely new form of world-economy in which the European capitalist resource base greatly exceeded its predecessors both in absolute and relative terms. This was, in other words, a historically unique social condition distinct from feudalism.[29] In Marx's words (1990[1867]: 915):

> The discovery of gold and silver in America, the extirpation, enslavement and entombment in mines of the indigenous population of that continent, the beginnings of the conquest and plunder of India, and the conversion of Africa into a preserve for the commercial hunting of blackskins, are all things which characterize the dawn of the era of capitalist production. These idyllic proceedings are the chief moments of primitive accumulation.

The term "primitive accumulation" is used here to denote the "prehistory and the *precondition* of capital" (Foster, 2000: 173, emphasis added). It was only within a highly exploitative world economy that the resources necessary for industrialization could be acquired, maintained, and increased.

Fossil fuels as a prerequisite for the industrial regime

Even if industrial mass-production was first propelled by hydropower, fossil energy played a definite role for the industrial regime, such as it developed in the 19th and 20th century (Malm, 2016). Beyond the role of coal as a source of energy in 19th century steam-powered manufacturing, fossil gas and oil were later pivotal for the development of industrial agriculture based on artificial fertilizer and for a range of artificial material compounds that replaced naturally occurring materials (Smil, 2001, 2016b).

To understand the importance of fossil energy for the historical development of the industrial regime, we need first an informed understanding of what fossil energy is. This begins with an acknowledgement that fossil fuels originate as organic material that has been transformed over millions of years under conditions of enormous pressure and high heat in the crust of the Earth. This organic material was once the bustling ecosystems of prehistoric plants and animals that captured direct energy from the sun through photosynthesis and

---

[29] Such a definition of capitalism differs from positions that considers institutionalized wage labor, class-based ownership of the means of production, or even the combustion of fossil fuels as core defining features of capitalism. The famous Wallerstein-Brenner debate signifies a core dispute regarding the scale of the level and unit of analysis for understanding capitalism, where Brenner has challenged Andre Gunder Frank's and Wallerstein's analytical focus on exchange and class relations at the level of the emerging colonial world economy (Brenner, 1977). I have sided with Wallerstein, who provides a basis for considering the rise of industrialism as fundamentally intertwined with world strategies for environmental load displacement prior to the fossilization and mechanization of the industrial manufacturing process (for this position, see also Denemark and Thomas, 1988; Bunker and Ciccantell, 2005a; Hornborg, 2006; Barca, 2011).

built themselves from material found in the air, water, and soil. Over several hundred million years, layer upon layer of dead organic material accumulated in anaerobic environments (such as swamps). These layers were then buried under each other and pushed down in the Earth's crust where they were subjected to extreme heat and pressure that eventually transformed them into the coal, oil, or fossil gas that industrialists extract today. As such, fossil fuels represent millions of years' worth of "buried sunshine" that is highly energy-dense (Dukes, 2003). The fact that modern humans orchestrate collective efforts to release the energetic potential of this fossilized solar energy in the blink of an eye, by geological standards, helps to explain the unique historical condition of the industrial regime today.

Swedish journalist Therese Uddenfeldt pedagogically appeals to our sensory experiences as she explains the fundamental difference between direct solar energy and fossil energy. She writes (2016: 20, my translation),

> A simple experiment: First, reach out with one of your hands into a beam of sunshine and enjoy. Then put a piece of burning coal in the other. In the first hand, you experience the effects of direct sunshine. In the second hand, concentrated sunshine is in the process of melting your skin. What you experience is the difference between how much direct sunshine and concentrated sunshine can accomplish.

Note that the difference between the two energy sources is not a difference in original energy source, i.e. sunshine. Coal, however, is a concentrated form of sunshine that is highly energy dense. The high energy density in the coal is contingent upon the time it took for it to accumulate and compress in the Earth's crust, and the space for the original sunshine to hit the Earth and to be sequestered by ancient photosynthesizing plants. The sheer scales and timespans in question make it impossible for humans to imitate the formation of fossil fuels without great energetic costs (see e.g., Nikiforuk, 2012: 96). It is, in other words, energetically futile to attempt to produce artificial fossil energy carriers in the hopes that these could maintain any human social metabolism. This is why fossil fuels are considered non-renewable, as it simply takes too long for them to be renewed through the biogeochemical processes described above. Access to fossil fuels and the great energetic potential they embody is by all practical accounts a historically one-time opportunity (for a discussion, see Love and Isenhour, 2016).

The non-renewability of fossil energy carriers does not preclude the fact that they are highly lucrative sources and substitutes for both space and time (Hornborg et al., 2019). Space and time, both represented in fossil energy, correspond to the two categories of land and labor that had a primary significance for the expansion and increased complexification of social metabolisms in the agrarian regime (Sieferle, 2001). Let us briefly look at these two categories in turn.

Fossil energy as compressed space. In Uddenfeldt's "simple experiment," it becomes easier to understand how the transition from the reliance upon direct sunshine to the reliance upon coal altered the relation to land with the industrial regime. Simply put, the lump of coal held in the second hand can be understood to represent numerous concentrated hands of the first kind. In the terminology of ecological economics, the coal is said to contain a lot of "embodied land," i.e., the energetic potential of land areas. As the reliance upon coal grew (first in Britain), the social metabolism increasingly came to rely upon the land embodied in the fossil fuels extracted from mines. The historian Edward Wrigley (1988) famously thought of the British industrialization as a transition from an "organic economy" to a "mineral-based economy" that burst the solar income constraint of the agrarian regime limited by access to land (for a critique, see Malm, 2016). Studies that are more recent have come to similar conclusions of how fossil fuels represent access to space (Sieferle, 2001; Bridge, 2010; Huber and McCarthy, 2017). Geographer Gavin Bridge (2010) considers the geography of the industrial regime as a "geography of holes," with reference to how extractive sites of coal, oil, and fossil gas are comparatively small in relation to the amount of energy potential that is extracted.

The concept of "power density," as developed by Vaclav Smil (2006, 2010, 2015), also captures the relation between land and fossil fuels. In short, power density is a measure of how much space is needed for any given means of capturing energy (W/m^2). The concept is primarily used for understanding the challenges in transitioning away from fossil fuels, but it is equally useful for understanding what it implied to transition to fossil fuels in the first place. For example, Smil (2015: 3-4) has calculated that harvesting oak or beech has a power density of 0.22 W/m^2, while a British coal mine in the 1770s produced fuel with a power density of nearly 1,200 W/m^2.[30] Again, this shows that the industrial regime fundamentally altered the human relation to land and the environment. Given this situation, it becomes evident that there is a fundamental difference between the agrarian regime and the industrial regime regarding the access to the energy necessary for the metabolic process.

---

[30] These calculations only account for the land occupied by the mine itself (10,000 m^2), i.e., not the land embodied in the mechanical infrastructure, the capital, or the labor.

Whereas the agrarian regime is highly dependent on access to quantities of (preferably fertile) land for the production of consumable biomass, the industrial regime is less dependent upon quantities of land for access to energy, but increasingly reliant upon what we may call "qualitative" lands or "holes" rich in stocks of fossil fuels.

The consequence of the very high energy density of coal was that it allowed matter-energy throughputs to be increased beyond the biocapacity of local environments, including the flow of energy harnessed through waterpower or wind power. Even if fossil energy did not cause the Industrial Revolution, access to fossil energy meant that the "social metabolism [could] be greatly increased without decimating the base of human nutrition" (Weisz et al., 2001: 129).[31]

Fossil energy as compressed time. Uddenfeldt's experiment is also an entry for understanding how fossil energy relates to time and labor. As for land, the scorching heat burning the skin of the second hand can be understood as a concentration of millions of years' worth of sunshine. Apart from embodied land, fossil fuels represent also high concentrations of embodied time. The very essence of industrialism as an inclination towards the mass production of commodities under the capitalist logic of accumulation was founded upon this new energy-time relation. Andrew Nikiforuk (2012: 26) uncovers how early industrial capitalists marveled at the capacity for work embodied in coal as "two pounds of coal could … lift a man to the summit of Mont Blanc without any human toil." The time embodied in coal was used to speed up the manufacturing process and reduce the time for traveling and transportation of goods and materials (Hagens, 2020). For example, prior to the industrialization

---

[31] A bit of caution is warranted on the basis that the transition to fossil fuels was not simply a transition from biomass to coal, but also a transition from water energy to fossil energy in key early industrial industries such as the cotton manufacturing industry (Malm, 2016). It is nevertheless crucial that we understand the extraction of fossil fuels and industrial technology as an alternative means for increasing matter-energy throughput that is distinct from the territorial expansion in the agrarian regime. This, however, does not imply that the conquest of territories was halted with the Industrial Revolution. Quite the contrary, the increased access to energy was still contingent upon an increased access to materials extracted from environments in remote lands for building and maintaining highly complex forms of (energy) infrastructures in the core (Bunker and Ciccantell, 2005a; Hornborg, 2006). In this sense, fossil energy was not substitutive of, but additive to, colonial strategies for matter-energy appropriation (Barca, 2011; Hornborg, 2015). As is becoming increasingly clear in scholarly work, fossil energies did not prevent the logic of capitalism, rather it cemented capitalist relations of production, wage labor, and the spread of the world market (Bunker and Ciccantell, 2005a; Huber, 2008, 2015; Malm, 2016).

of the manufacturing process it took up to 50,000 human labor hours to spin 50 kg of cotton. With the fossilization of the cotton industries, the process of spinning the same amount of cotton took only 135 hours (Hornborg 2010: 122).

Coal, however, could not be fed to human or animal bodies in the hope of converting its potential energy into useful work. These "prime movers"[32] were contingent upon biomass (food, such as grain) to do work. To convert fossil energy, another category of prime mover was necessary. The steam engine, built for this purpose, was first developed by the Spanish mining administrator Jerónimo de Ayanz, who employed it to pump water out of the silver mine in northern Seville, Spain, 1606. It was in Britain, however, that the steam engine made its true commercial breakthrough (Headrick, 2009: 91-110). The eventual dependency on coal in industrial manufacturing was coupled with a combined dependence on steam engines (Smil, 2016b). One could not exist without the other. In the transition from the agrarian to the industrial regime, to put it succinctly, coal was to machinery what biomass was to animals (Hornborg, 2014). The increased reliance upon the coal-machinery combination was biophysically favorable given its massive energetic potential, but also because it meant that human and animal nutrition did not compete directly with the access to energy for other purposes, such as manufacturing and transportation (Weisz et al., 2001).

The consequences of the Industrial Revolution: Fossil dependency, world division of labor, ecological crisis, and modernity

As we have seen, colonialism, capitalism and fossil fuels generated the conditions for a rapidly expanding social metabolism. The consequences of this were nothing short of a revolution with far-reaching repercussions in many aspects of human (and non-human) life. Let us now turn to some of the arguably most important consequences.

Fossil dependency as a consequence of the Industrial Revolution

In *Fossil Capital*, Malm (2016: 288) concludes that at a certain stage in the development of capital, fossil fuels became an indispensable part of capitalist

---

[32] Defined as components converting energy sources into motive power, also known as "energy converters" (see Giampietro and Mayumi, 2008).

production of surplus value "*across the [entire] spectrum of commodity production*," in which each round of appropriation generating money was coupled to an increased burning of sources of fossil energy. While most scholars have been content with pointing out how fossil energy facilitated a transgression of the local solar income constraint of the agrarian regime, Malm argues that coal was favored by British cotton manufacturers because it could facilitate capitalist relations of production in which the workers were separated from the means of production, thereby lowering the cost of labor and the price of the British cotton textiles.

The first obvious problem with fossil dependency is that fossil energy carriers are non-renewable. Therefore, by all practical accounts, extracting and burning fossilized sources of energy is a one-time historical opportunity that is subjected to diminishing energy returns. Economist Stanley Jevons was early to point this out in relation to the importance of coal to the continued expansion of the British Empire. In *The Coal Question*, Jevons lamented over how digging deeper would only cause the price of British coal to increase, something that would in turn raise the prices of domestically manufactured goods on the world market and undermine the competitiveness of British manufacture. Import of coal from the colonies, Jevons continued, would also raise prices of British manufactures and so he concluded that the British Empire was doomed to end with the diminishing returns on coal. In this, Jevons was early to uncover the general pattern of industrial metabolism operating with diminishing EROI (Jevons, 1865; today, see Hall and Klitgaard, 2012; Hall et al., 2014).

Since fossil energy carriers are non-renewable, depending on them metabolically is inseparable from an imperative to expand the depth and reach of the social metabolism. Typically, the most easily accessible and lucrative sources of fossil energy carriers are extracted first, which means that it becomes increasingly expensive to continue the reliance upon a specific fossil fuel (Hall and Klitgaard, 2012). Historically, relying upon coal as a non-renewable energy carrier thereby incentivized British capitalists to develop and build networks of railways and trade routes that allowed for the extraction of coal in even the most distant areas throughout the world (Debeir et al., 1991; Malm, 2016b).

Given the fact that infrastructure and old extractive equipment quickly become obsolete or inadequate in the face of the recurrent challenges to dig deeper, travel further, or extract faster, industrial capitalism has been forced to constantly renew its means of metabolic throughput. The diminishing EROI of fossilized energy carriers has thereby given rise to a dynamic non-equilibrium in the industrial regime where the social-technical means for appropriation constantly needs to be developed. Alongside "[t]he need of a constantly expanding market for its products" this has led "the bourgeoisie over the entire surface of the globe" in search for fossil fuels (Marx and Engels, 1969[1848]; Malm, 2018a). This expanding process is a biophysical imperative in the industrial regime. Essentially, the expansive quest for increased quantities of energy, material resources, and labor for the production of ever-cheaper commodities demands that industrial capitalism enters new areas of nature or society, something that in turn requires novel technologies. In this sense, "primitive accumulation" is not a historical one-time event, but an ongoing logic of capital expansion that constantly generates new markets and new spheres of appropriation (Luxemburg, 2003[1913]; Harvey, 2003; Bunker, 2007). Considering this imperative, it is legitimate to consider to what degree solar PV technology provides an escape from this or whether it is chiefly a way to exploit nature or society further.

To understand this movement in history, Andreas Malm (2018a) historicizes the entry of new fossil energy carriers in relation to what economists call "long waves" of economic development. Throughout the 19th and 20th centuries, in short, the economic surges in the industrial regions of the world have been supported and upheld by either novel ways of extracting and burning fossil energy or upon the discovery and commercialization of entirely new fossil energy carriers (table 1). Complementary figures from Smil (2016a) show that humans and draft animals, propelled by biomass, were the dominant prime movers at the onset of the Industrial Revolution. This, however, changed fast with the coming of the 20th century as the industrial metabolism gained momentum.

Table 1. Long waves of fossil development in the industrial regime.
Adapted from Malm (2018a) and revised with reference to Smil (2016a).

Economic waves	Upswing	Downswing	Dominant prime mover(s)	New prime movers	Industries and input	Dominant energy carrier(s)	New energy carriers
First wave	1780-1825	1825-1848	Humans and draft animal	Water-powered mechanization, stationary steam engine	Cotton and iron	Biomass	Coal
Second wave	1848-1873	1873-1896	Humans and draft animal, steam engines	Mobile steam engine	Railways, machine-tools, cotton, iron	Biomass	Coal
Third wave	1896-1914	1914-1945	Steam engines	Steam turbines, electric generators	Electrical equipment, engineering, chemicals, steel	Coal	Crude oil, fossil electricity
Fourth wave	1945-1973	1973-1992	Internal combustion engine, electric generators	Nuclear reactors, gas turbines	Automobiles, aircrafts, refineries, petrochemicals	Crude oil, coal, fossil gas	Fossil gas, nuclear electricity
Fifth wave	1992-2008	2008-?	Internal combustion engine, electric generators	Solar PV modules, wind turbines, etc.	Computers, software, microprocessors, fracking	Crude oil, coal, fossil gas	Tar sands, shale oil, renewable electricity

These long waves of fossil development are commonly mistaken for energy transformations in two regards. First, it is often assumed that absolute quantities of a previously dominant energy carrier are decreasing when another rises to prominence. The rising prominence of crude oil, for example, is easily mistaken as indicating a decrease in the burning of coal. Coal burning is, in fact, increasing even today (Gellert and Ciccantell, 2020). The same applies to the rapid expansion of solar PV technology, which does not prevent the expansion of fossil energy, including crude oil and fossil gas (IEA, 2020f). Second, the transition from one type of fossil energy to another (e.g., from coal to oil) is often mistaken for an energy transformation comparable to shifts in socio-metabolic regimes (e.g., Fouquet and Pearson, 2012; Sovacool, 2016). However, energy sources such as petroleum, fossil gas, tar sands, and shale oil are all non-renewable sources that support a qualitatively similar human-environmental relation. These energy carriers are all made from "buried sunshine" and contingent upon mechanical prime movers. The shift from one fossilized source of energy to another, therefore, is more analogous to shifting plants to forage among hunter-gatherers or species to domesticate among agrarians. These transitions do not fundamentally challenge – but rather support – the continuation of the metabolic logic of the respective socio-ecological regime.

The fact that the introduction of new fossil energy carriers supports the industrial regime is perhaps most clearly illustrated in how the fourth wave of economic development after the Second World War ushered in a massive increase in the metabolic throughput of industrial societies – a historical event now known as "the Great Acceleration" (Steffen et al., 2011, 2015a). Access to and burning of oil in combustion engines facilitated this drastic acceleration of industrial metabolism from 1945 and onward. Oil is an extremely energy dense source of fossil energy with even higher energy values (40-44 MJ/kg) than coal (18-25 MJ/kg) (Smil, 2016b: 12). In world peripheries and world cores alike, it is hard to overestimate the developmental impact of oil extraction and consumption (Mitchell, 2011). Still today, gross domestic production (GDP) of the world is intimately connected to oil extraction and dissipation – if the world's oil extraction falls one percent, the world's GDP also falls one percent (Ayres, 2016: 382-389). Moreover, the period between 1950 and 2010 saw perhaps the greatest expansion of societal metabolism in world history, with primary energy use increasing 500%, real GDP increasing by 600%, fertilizer consumption reaching 160 million tonnes per year from practically zero, and world population soaring from 2.5 billion to 7 billion (Krausmann et al., 2009; Steffen et al., 2015a).

Like any form of fossilized energy source, however, oil is also subjected to diminishing EROI (Hall and Klitgaard, 2012). From the start, oil dependency was questioned based on this fact. The most famous warning came 1956 from Shell-employed geologist Marion King Hubbert who estimated that the U.S. domestic production of petroleum would follow a bell-shaped curve (the Hubbert curve) that he expected would peak in the early 1970s. Hubbert's calculations were first met with skepticism from Shell and the oil industry. However, when the peak in production came in 1971 the tone changed from skepticism to praise. The debate around what today is known as "peak oil" largely sprang from Hubbert's surprisingly accurate predictions of the U.S. oil production peak in the early 1970s. The U.S. domestic peak oil contributed to the 1973 oil crisis by making the U.S. more dependent upon international oil reserves and therefore vulnerable to Arab oil embargos motivated by U.S. interventions in the Middle East. While U.S. demand for oil was eventually saturated, some economists believe that something like the Hubbert curve may be applicable to global oil production today (Höök et al., 2009; Hall and Klitgaard, 2012; Ayres, 2016).

Today, however, the total amount of oil produced continues to increase even if so-called "conventional oils" are subjected to diminishing returns. This, some argue, is because oil industries are turning to less lucrative and much dirtier forms of oil, such as tar sands or shale oil, which become cost-effective when the EROI of conventional oils diminish (Ayres, 2016). As the EROI of conventional oils diminish, a larger portion of society's resources must be allocated to oil extraction. Many of the world's governments now provide the necessary resources in the form of subsidies (Erickson et al., 2017). In this way, the extraction and burning of oil continues to increase, despite the global peak in conventional oil production. Crucially, however, this occurs at substantial real-world costs to global and local environments and communities in the form of more frequent devastating weather events, displacement, and loss of biodiversity (Nduagu and Gates, 2015; Parson and Ray, 2016; Ayres, 2016).

The ecological crisis as a consequence of the Industrial Revolution

With access to energy-dense coal, oil, and fossil gas, human-environmental relations were fundamentally altered. As put by Uddenfeldt (2016: 61, my translation), industrial societies "were not just separated from nature in a philosophical sense, but for real. Free, unbound, and independent." The notion that the development of more advanced technologies made industrial societies free and independent from nature is a surprisingly common assertion (e.g., Landes,1969; Asafu-Adjaye et al., 2015). Among ecological modernists, this leads to the contradictory position that "technologies … have made humans less reliant upon the many ecosystems that once provided their only sustenance, even as those same ecosystems have often been left deeply damaged" (Asafu-Adjaye et al., 2015: 8). However, the premise that industrial societies have decoupled from nature is a fundamental mistake.

First, industrial societies are utterly dependent upon stocks of fossil energy, raw materials, and fertile lands that either originate from or represent aspects of nature. This nature dependency is in fact increasing. Between 1900 and 2009, industrial capitalism generated a tenfold increase in material extraction (Krausmann et al., 2018). Similarly, between 1970-2010 both material and energy throughput increased threefold (UNEP, 2016; BP, 2020). *Human appropriation of net primary production* (HANPP) is a measure of how much of the world's potential natural vegetation is currently being appropriated by humans. A recent study calculated that 28% of the world's productive surface has been claimed for human land use (agriculture, infrastructure, etc), a doubling of HANPP in the 20th century (Haberl et al., 2007; Krausmann et al., 2013). Similarly, the ecological footprint of industrial societies has drastically increased over the last century, and the sum total of humanity's ecological footprint has been larger than the Earth's biocapacity since the 1970s (Wackernagel et al., 2002; WWF, 2018). The industrial-capital colonization of environments is in turn intimately connected to the massive loss of biodiversity during the 20th century (Haberl et al., 2011; Barnosky et al., 2011; Dawson, 2016; IPBES, 2019). In particular, the loss of natural habitat due to agricultural intensification has been identified as the biggest threat to global biodiversity (WWF, 2018).

Second, the industrial regime has massive impacts on the natural world through pollution. To quote ecological economist Clive Spash (2017: 9), pollution "is an inevitable part of the economic process, not an avoidable externality that disappears if the prices are 'right'." Any metabolizing system "pollutes" its environment. Typically, however, the pollution of non-human organisms is considered food for fellow species within the ecosystem. In contrast, the millions of artificial chemicals produced in the industrial regime are not the natural foods of other species. Instead, they are often poisonous. However, it is the immense scale and rapidity with which industrial societies dissipate matter-energy that should be the primary cause for concern. The sheer quantities of pollution from the industrial metabolism makes it practically impossible for the ecosystems of the Earth to absorb and sequester the material in time. This is most starkly illustrated by how Earth's nutrient cycles, including the carbon cycle and the nitrogen cycle, have been overburdened by pollution from 20th-century industrial metabolism.

Concerning the nitrogen cycle, the Haber-Bosch process is the single largest cause of the intensification of nitrates into the air and water, something associated with numerous ecological problems including eutrophication and acidification (Smil, 2001; Rockström et al., 2009). Similarly, the carbon cycle has been affected by the anthropogenic emission of greenhouse gases, leading to concentrations of CO_2 in the atmosphere that now cause a dramatic increase in global temperatures (IPCC, 2014a, 2018). Current levels of CO_2 in the atmosphere must therefore drastically be reduced to avoid catastrophic changes to Earth's life-supporting systems (IPCC, 2018; Steffen et al., 2018). As put by Malm (2018b), "nature comes roaring back" in the form of increased frequency of extreme weather events such as droughts and floods, rising sea levels, loss of coral reefs, and considerably harder conditions for plant cultivation (IPCC, 2018). Already today, the effects of climate change are disproportionally felt by the poor and most vulnerable people in the world system (IPCC, 2014b; Harrington et al., 2016; Byers et al., 2018). To keep global temperatures below 1.5 degrees relative to pre-industrial levels, no more than 275 $GtCO_2$ must be emitted in the period 2016-2100 (Rogelj et al., 2018). Merely during the years 2011-2015, however, as much as 200 $GtCO_2$ were released (ibid.). The emissions embodied in the known fossil energy reserves have been estimated to amount to roughly 2900 $GtCO_2$ (McGlade and Ekins, 2015). With vested economic interests capitalizing on these lucrative fossil assets, it is unlikely that the Earth system will be spared further detrimental changes unless a radical transition towards another socio-ecological regime occurs (Foster, 2013).

The impacts of all past civilizations fade in comparison to the "world-eater" that is industrial capitalism (Hagens, 2020; Dunlap and Jakobsen, 2020). No other energy transformation in history has had such an all-pervasive effect on the natural world as the Industrial Revolution. It is not difficult to understand the industrial regime's problematic relation to the environment against the definition of industrialism as an inclination towards the mass production of commodities and capitalism as a global system of exchange driven by the social aspiration to accumulate and profit *ad infinitum* (Foster, 2000; Hornborg, 2015). As we have seen, nothing comes from nothing (chapter two). This means that the ever-increasing mass production of commodities is coupled with an ever-increasing mass extraction of the necessary matter-energy (Adams, 1982). At the other end of the social metabolism, mass pollution also has a considerable effect upon the biosphere in the form of accumulation of numerous artificial chemicals and greenhouse gases. In this sense, the development of the world core over the 19th and 20th centuries is inseparable from the destruction and alteration of natural environments that are now threatening the continuation of life on an unprecedented scale (Steffen et al., 2011, 2015b; Dawson, 2016; Wiedmann et al., 2020).

In this context, it is absurd to suggest that industrial capitalism is becoming increasingly independent from nature. In the midst of a historical situation characterized by increasing extraction, production, consumption, and pollution, i.e., metabolizing, of an ever-increasing amount of matter-energy, the industrial metabolism is now fundamentally altering nature's nutrient cycles that have been stable for thousands of years (Foster et al., 2010). With this in mind, it seems more correct to say that societies' dependence upon nature is rapidly *increasing*. Nature's processes are now so deeply affected by industrial capitalism that it has raised debates regarding humans as the major force in a new geological epoch (cf. Malm and Hornborg, 2014). Even if ecomodernists characterize the suggested Anthropocene as a historically "great" achievement (Asafu-Adjaye, 2015), the unequivocal hallmark of this epoch is the destruction of millions of years' worth of evolution and biodiversity through human interference in Earth's life-supporting systems. While the tendency to alter environments at the point of civilizational collapse has occurred in the past, never before has the Earth system been altered so radically by any human metabolic interaction. This, ultimately, is a situation uniquely attributable to the industrial regime.

World division of labor as a consequence of the Industrial Revolution

The industrial regime has facilitated social and economic improvements that have generated greater freedom and independence in certain aspects of life compared to some earlier societies. For instance, never before have so many been able to consume so many goods and enjoy so much material wealth or been so educated. Never before was it possible to travel vast distances at incredible speeds or communicate with another person on the other side of the globe in real time. In part due to modern medicine, human health conditions have now also returned to levels equivalent to those of the Upper Pleistocene (Gowdy, 2020). Politically, industrialization and access to fossil fuels have been shown to correlate with social revolutions, some of which swept away despotism and introduced more democratic forms of governance (Fischer-Kowalski et al., 2019). The world, some insist, is getting better and better (e.g., Pinker, 2018; Rosling, 2018). But this is not the case for everyone. With all the evidence at hand, industrial capitalism is still characterized by a world division of labor that shares burdens and benefits unequally (Martinez-Alier, 2002; Roberts and Parks, 2007; Hornborg, 2013; Milanovic, 2013, 2016; Harrington et al., 2016; Oxfam 2017; WWF, 2018; Chakraborty et al., 2018; Scheidel and Schaffartzik, 2019). Crucially, this discrepancy is not due to differences in technological progress or cultural sophistication, but a result of the historically developed condition with roots in Western colonial expansion and capitalist relations of production (Wolf, 2010[1982]; Bunker, 1985).

Despite all its advantages to beneficiary regions and classes, industrial capitalism does not challenge the world division of labor. Why not? The short answer is that this world division is a *sine qua non* of the regime itself. In other words, without this division, it would grind to a halt. Global discrepancies in environmental burdens and benefits are not simply a consequence of the industrial regime, but a necessary condition for the continued development and technological progress in core regions (Hornborg, 2001, 2016; Jorgenson et al., 2009). Without a means to access highly dense forms of energy and massive quantities of high-quality raw materials scattered throughout the world, it is likely the world-economic cores would not be able to maintain a continually increasing level of matter-energy throughput. Industrial capitalism, in the end, does not challenge the world division of labor because it would then undermine its own capacity to develop technologies that could penetrate nature and social life in novel ways to establish new market outlets for capital investment and profit. This means that ecologically unequal exchange is not a side effect of industrial metabolism, but a necessary aspect of its reproduction (Hornborg, 2013; cf. Andersen, 2013).

The mechanisms by which it is possible to maintain this relation include a) securing necessary resources through military means or b) trading resources under price differences that provide favorable terms of trade in a biophysical sense (see chapter four; Hornborg, 1998; Pérez-Rincón, 2006; Jorgenson and Clark, 2009; Downey et al., 2011). Examples of the former include the U.S. invasion of Iraq in 2003 that secured U.S. access to lucrative oil reserves. Timothy Mitchell (2011) has brilliantly shown how democratic governance in core regions of the world are dependent upon anti-democratic governance in peripheral regions, such as Iraq, that facilitates the flow of petroleum—and so its social benefits –from periphery to core. Examples of the latter include a wide range of historical and contemporary cases of ecologically unequal exchange as well as neoliberal schemes such as “structural adjustment programs” that deregulate and force open publicly controlled environments and resources of impoverished and indebted countries to the world market at low prices (e.g., Jorgenson, 2010; Noble, 2017; Frey et al., 2019).

While this social condition generates enormous wealth in core regions of the world, it simultaneously impedes wealth generation in peripheral regions (Jorgenson et al., 2009). We can therefore conclude that fossil fuels both extend and deepen capitalist relations of production through a process that is perhaps best described as “ecological imperialism” (Huber, 2008; Clark and Foster, 2009; Foster et al., 2010; Malm, 2016; Hornborg, 2016). Ultimately, then, the industrial regime reproduces the same world division of labor upon which it was founded.

The modern worldview as a consequence of the Industrial Revolution

For some time, anthropologists have insisted that people in world economic cores are just as susceptible to so-called magical beliefs as premodern peoples (Latour, 1993; Stivers, 1999; Hornborg, 2016). This insight challenges the conventional self-image of modern culture as having been liberated from supposedly false beliefs concerning the world (Hornborg, 2015: 866). The industrial regime is no historical exception when it comes to questionable cultural imaginaries, even if the dominant narrative of the Industrial Revolution relies upon this claim (Landes, 1969). Studies in emerging fields such as "energy humanities" have shown how often arguably irrational cultural imaginaries are formed and upheld through processes reliant upon fossil fuels in industrial societies (Boyer, 2011; Huber, 2015; Love and Isenhour, 2016; Wilson et al., 2017; Daggett, 2019; Folkers, 2021). Questions regarding how fossil fuels have affected modern culture include a broad range of issues, from the modern notion of freedom (Huber, 2015) to something as innocent as the celebration of New Year (Uddenfeldt, 2016). As suggested by Wilson et al. (2017: 8), "just as politics has been shaped by and in reaction to oil, so, too, have many of our most important concepts and theories." For the purpose of this thesis, I will highlight only two such issues, the immaterial conception of the economy and the modern conception of technology.

Ecological economists have for a long time critiqued neoclassical economists for failing to recognize biophysical nature as an essential foundation for the economic process (Georgescu-Roegen, 1971, 1975; Daly and Farley, 2011; Hall and Klitgaard, 2012; Spash, 2017). Scholars from other fields have more recently also pointed out that the neoclassical school of economics emerged in tandem with the increased access to and burning of fossil fuels during the late 19th and early 20th centuries (Mitchell, 2011; MacDuffie, 2014; Wilson et al., 2017). With the access to extremely lucrative and seemingly nature-independent sources of fossil fuels, economic theories became less concerned with physical production factors (e.g., land, labor, energy, materials) (Mitchell, 2011: 247). This is somewhat paradoxical, because the rise of the neoclassical school around 1860-1870 (the Marginalist Revolution) is commonly understood as based upon insights from the physical sciences. The crucial point, as pointed out by ecological economists and historians, is that the insights from thermodynamics were only adopted *metaphorically*, with little interest for understanding the biophysical basis of the economy (Mirowski, 1989; Walker, 2020). To Jevons, for example, the economic notion of utility was understood as parallel to the physicist's notion of gravity, and value as parallel to energy (Mirowski, 1989: 219). The failure to realize how the economic process is *actually* subjected to the law of entropy, Georgescu-Roegen (1975) argued, was intimately connected to the mechanistic-epistemological inclination in neoclassical economics, through which the economy is understood as a perpetual motion machine operating independently from an outside environment. Thus, fossil fuels, the Earth's species, and nature's biogeochemical cycles were misconstrued as somehow "external" to the economy, all while economists took pride in the scientific basis of their discipline.

The notion of the economy as nature-independent arose in tandem with the notion that mechanical artifacts are inherently productive. If the wealth generated by the economy does not originate from labor, land, or material resources, it must have some other origin. As we have seen, instrumental descriptions attribute the productive potential to human scientific knowledge (e.g., Landes, 1969). Even today, it is common to attribute the productive potential of machines to scientific knowledge or even to the machines themselves rather than attributing it to the natural origin of the matter-energy that it transforms. The failure to realize the distinction between "energy converters" and "energy carriers/sources" still confuses modern economic analyses of the Industrial Revolution and technological progress (Giampietro et al., 2008; Hornborg and Roos, 2020). This is a situation in which the productive potential of technologies appears to originate only from the prime mover assembled in society, when it is in fact also contingent upon the primary source of energy derived from nature. One of the results of this, as we have seen, is the common belief that "innovation" or "engineering design," quite independent of any environmental concern, is a sufficient condition for developing new technologies. One important result of this is the rise of the notion that it is possible to leave the industrial regime without setting off wider social-ecological changes that challenge its technological development.

The new metabolism: Continuing, transcending, or reversing the industrial regime?

As stated in the introduction to this chapter, some scholars point out that leaving the fossil regime implies a metabolic transformation that is comparable to the Neolithic and Industrial Revolutions. We now have a historically rooted understanding of what this actually means, beyond merely implying a shift in the dominant energy carrier. I have given an overview of how the Industrial Revolution gave rise to historically novel social, cultural, and ecological relations. What social, cultural, and ecological relations and conditions are we then to expect from the now much-anticipated transformation away from fossil energy? To be sure, given the major changes associated with such major energy transformations, "it is probably as difficult for us to imagine a sustainable society as it was for people in the 16th century to imagine the industrial society today" (Haberl et al., 2011: 11). We have no way of knowing exactly what the future will look like. Most likely, history will make fools of anyone who attempts any such prediction. There are, nevertheless, current processes and events that can be put under scrutiny to begin to understand some of the prerequisites of the new social metabolism.

Putting aside the dip in fossil energy throughput during the first year of the corona pandemic, there is little to suggest that the industrial regime based on fossil fuels is undergoing a process of fundamental metabolic transformation (Krausmann et al., 2018; UNEP, 2016; Foster et al., 2020; IEA, 2021). Even if the consumption of electricity generated through renewable energy technologies is increasing, fossil energy carriers still supply 80-90% of the world's primary energy (Smil, 2016c; Voosen, 2018; BP, 2020). Since diminishing energy throughput is antithetical to corporate investments in fossil energy reserves and social-political complexity at large, it also seems reasonable to expect that the push for higher levels of fossil energy throughput will persist if no radical action is taken (Tainter, 2006; Foster, 2013; Hall et al., 2014; Carroll and Daub, 2018). This becomes clear in the light of recent studies, which show how the installation of renewable energy technologies tend to add to, not replace, already fossil-dominated energy mixes (York, 2012; Marques et al., 2018; York and Bell, 2019; Hornborg et al., 2019; Hagens, 2020). We might nevertheless be witnessing the beginning of an energy addition in which the economic imperative of endless accumulation pushes society to increase both fossil energy and renewable energy simultaneously.

There are several concerns that call into question whether renewable energy technologies can support industrial levels of energy-matter throughput in the absence of fossil energy subsidies or a world division of labor. The central question today concerning energy transformation is therefore whether the development of renewable energy technologies is currently in the process of continuing, transcending, or reversing the industrial regime. Let us look at each in turn.

Continuing the industrial regime: The conventional position is that the increased installation of renewable energy technologies represents the emergence of a more sustainable human-environmental relation that will continue the industrial regime. In this view, declining prices of renewable energy and increasing technological efficiencies are commonly referred to as signs of the emergence of a sustainable and universal form of industrial capitalism (UN-Energy, 2012, UNEP, 2011; UNDP, 2016). However, in relation to the technological continuum, the social-ecological prerequisites for the existence of renewable energy technologies are systematically ignored or downplayed. In effect, the installation of renewable energy technologies commonly take on the discursive role of a "technological fix" that bypasses the necessity for significant social, cultural, or biophysical changes that are otherwise associated with transforming the industrial regime (Goldstein, 2018; Johnston, 2020). Arguably, this position only holds as far as colonialism and the metabolism of fossil energy are analytically separated from industrialism (Barca, 2011). In conventional interpretations, the Industrial Revolution was made possible historically through British engineering design applied to harness natural forces (Landes, 1969; cf. Barca, 2011; Hornborg, 2015). By extension, scientific knowledge is considered the causal prime mover of energy transformations. Since industrialism itself arose out of human ingenuity, it follows that it can be made sustainable through the application of better scientific knowledge and technological design. Because of this, no material prerequisite, such as a particular energy source or a particular social relation is seen as necessary for the continuation of industrialism (table 4). Designs and technological improvements of renewable energy technologies, nuclear reactors, and/or fossil energy converters are considered the novel scientific knowledge upon which the new metabolism will be based. In this sense, current levels of production and consumption can be extended ad infinitum without further harm to the biosphere or people throughout the world.

Transcending the industrial regime: The second position sees the conditions and trajectories of the current historical moment as a moral obligation to transform industrial capitalism into a new metabolism that maintains industrial levels of matter-energy throughput under more just social relations. This stance argues that the post-fossil era must necessarily be post-capitalistic (e.g., Huber, 2008; Malm, 2016; cf. Bosch and Schmidt, 2019). This is shown, in part, by demonstrating how fossil energy carriers were necessary for the emergence and lock-in of the capitalist division of labor within Britain during the Industrial Revolution (Huber, 2008; Malm, 2016). As argued by Andreas Malm (2016), early British cotton manufacturers employed fossil-propelled machinery because it provided a means for superior control over workers through its (seemingly) landscape-independent character.[33] Still today, Malm (2013, 2016, 2018) argues, capitalism cannot exist without fossil energy because its biophysical characteristics are essential for the mobility of

---

[33] Fossil fuels, once they are extracted, are highly transportable energy carriers that can be used to power machinery in almost any location. This sets them apart from biomass, waterpower, and wind power. This landscape-independent character, however, is illusory, since the effects of fossil fuels upon the landscape is today returning in the form of extreme weather events (not to mention the desolate landscapes generated from the extraction of coal or tar sands).

transnational corporations relying upon the relocation of factories to regions with low prices for manufacturing in order to stay competitive on the world market. It follows that if we wish to leave fossil energy in the ground to mitigate environmental problems such as climate change, capitalism needs to be radically transformed.

This transformation can occur through the development and installation of renewable energy technologies that are qualitatively different from fossil energy carriers by virtue of being more integrated in landscapes (Malm, 2016, 2018). Renewable energy technologies, as such, are antithetical to the capital accumulation of transnational corporations because these corporations necessitate fossil fuels to move extraction processes and manufacturing facilities across the world with impunity. It cannot be expected that actors, whose primary interest consists in accumulating capital, should develop renewable energy technologies, since maintaining high rates of profit requires low wages in the world economy, which can only be facilitated by fossil energy carriers. What is needed instead is the active and purposeful intervention of powerful states that can connect the comparative advantage of different national energy-landscapes in international super grids harnessing renewable or nuclear sources of energy (Malm, 2016, 2018). Through central planning, a more sustainable and greener metabolism can arise that challenges the social-ecological relations of industrial capitalism (Schwartzman, 1996). Crucial to this position is that the energy transformation will only occur through an increased matter-energy throughput (Schwartzman, 2012; Phillips, 2015). This change will necessarily arise from a social telos connected to a revolutionary class that considers the social metabolism not as an engine for profit or capital accumulation (e.g., Huber, 2019). The industrial regime will therefore be transcended simultaneously as the social relations of capitalism. In this sense, through a purposeful and rapid revolution, industrial levels of production and consumption can be extended justly throughout the world without further harm to the biosphere.

Reversing the industrial regime: The third position considers the industrial regime as a historical parenthesis that is fundamentally contingent upon fossil energies that are now showing signs of diminishing energy returns (Hall and Klitgaard, 2012; Hornborg, 2014, 2020; Love and Isenhour, 2016). This is supported by a number of points showing how leaving fossil fuels in the ground will reintroduce some of the major characteristics of the agrarian regime.

Similar to the second position, those who think that the industrial regime is being reversed recognizes the landscape-dependent character of renewable energy sources as a feature that sets them apart from fossil energies. As we have seen, the power densities of renewable energy sources such as solar PVs and biofuels are low in comparison to fossil energy carriers (Smil, 2010, 2015; Prieto and Hall, 2013; Ferroni and Hopkirk, 2016; Capellán-Pérez et al., 2017). This also applies to unconventional oils, such as tar sands and shale oil (Cleveland and O'Connor, 2011; Smil, 2015). Compared to the industrial regime, the new metabolism is therefore predicted to be vastly more dependent on direct surface areas for maintaining current (or higher) levels of energy throughput (Scheidel and Sorman, 2012; Huber and McCarthy, 2017). The same applies to both mineral and energy requirements (Hall and Klitgaard, 2012; Hall et al. 2014; Ferroni and Hopkirk, 2016; de Castro and Capellán-Pérez, 2020; Feltrin and Freundlich, 2008; de Castro et al., 2013; McLellan et al. 2016; Tokimatsu et al. 2017; Rhodes, 2019; Vakulchuk et al., 2020).

Contrary to the second position, the comparatively large biophysical demand to generate renewable energy is not understood as antithetical to global capitalism. The point here is a subtle one: While fossil fuels reduced the costs of relocating factories to regions with low wages, it is the resultant wage and price differences in the economy, not fossil fuels per se, which determine the continued success of capital accumulation. As history shows, there are other means for creating and upholding regional or global price differences, including enslavement or indebtment. To the extent that current price differences are maintained (or deepened), the real costs for generating renewable energy is a relative issue contingent upon wages and prices in a particular region. Since the industrial regime arose from colonialism and the price differences enforced through slavery and military domination, there is a possibility that capitalist relations of production will continue in a new metabolism energized again by renewable energy sources.

A throughput as large as in today's affluent societies is likely to require enormous amounts of resources. Without access to subterranean stocks of energy (fossil fuels), these resources must be extracted from current ecosystems located above the Earth's crust. This leads to the question whether current levels of consumption will be maintained in core regions at the expense of peripheral regions of the world. This would effectively reverse the Industrial Revolution by making core countries increasingly dependent upon embodiments of labor and resources in international trade. The larger relative land requirements per unit of energy implied by biofuels and solar PV energy indicate that the new metabolism may necessitate ecologically unequal exchange (see e.g., Hermele, 2014; Hornborg, 2014; Hornborg et al., 2019). To the extent that this is true, it is unlikely that a matter-energy throughput as large as in today's affluent societies is an ambition that is environmentally sustainable or socially just, even if it propelled by renewable energy. This non-universality contrasts to the first and second positions' visions of a new metabolism that will distribute high energy-matter throughput equally throughout the world through the development of renewable industrial mega-projects.

At times, it is unclear whether the different positions above argue what their respective authors *want* to happen or what they sincerely *think* will happen. This may be thought of as the distinction between a utopian and an analytical lens. Both lenses must arguably be combined if we wish to establish an at once desirable and credible vision of the new metabolism. That is to say, any social-technical aspiration must be understood together with the social-ecological conditions necessary to realize it. In the end, "people make their own history, but not exactly as they please" (Foster et al., 2010: 38). It is with this in mind that we next turn to the global industrial manufacturing of solar photovoltaic modules.

4. From alternative technology to world commodity: Ecologically unequal exchange and the commercialization of solar PV technology 2002-2018

“*Solar power is no longer alternative energy*.”

Dustin Mulvaney

In this chapter, I will look at “the boom” in solar PV manufacturing that is widely celebrated as making solar energy a commercially viable option. The purpose is to examine the global political relations that are associated with the commercialization solar PV technologies. In the previous chapter, we have seen how the Industrial Revolution arose with the increased use of coal to propel machines for mass production in Britain and how this industrialization was historically inseparable from specific matter-energy flows whereby resources were asymmetrically transferred between world regions. This chapter seeks to understand the relation between ecologically unequal exchange and the commercialization of solar power 2002-2018 based on the possibility that solar PV technology might not be a challenge to but a continuation of the industrial regime,. Before we turn to this matter, let us briefly look at the history of solar PV technology, such as it is commonly narrated.

Solar PV technology is based on the photovoltaic effect.[34] The effect has been known ever since French physicist Edmond Becquerel discovered it in his father’s laboratory in 1839. By the beginning of the 20th century, Albert

---

[34] In essence, the photovoltaic effect is a physiochemical effect that generates an electric potential when light hits two (or three) layers of material with polarized electric charges (typically silicone doped with phosphorus or boron).

Einstein was awarded the Nobel Prize for discovering the laws of the photoelectric effect and the quantum theory of light that proved important for the advent of modern solar PV cells. Still, it took a few more decades before the solar PV cell was applied. The first practical PV cell was developed by scientists in Bell Labs in New Jersey, more than a hundred years after the first discovery of the PV effect. This development was demonstrated in 1954 and utilized only a few years later to power the U.S. satellite Explorer 6. In the late 20th century, PV cells proved usable in a number of contexts, ranging from powering pocket calculators to space satellites. While this invited the aspiration to develop an advanced post-industrial society propelled entirely by renewable energy from the sun, scaling up solar PV technology remained an elusive project of the future.

It was not until the oil crisis of the 1970s that public discourse in industrialized nations entertained the notion to scale up renewable energy technologies. Solar technology represented an alternative to fossil fuels, which were increasingly perceived as unreliable for long-term societal stability. Energy security was a prominent argument for renewable energy at the time, but a number of visionaries pointed out that renewable energy technologies were superior to fossil fuels both on social and environmental grounds (for an overview, see Mittlefehldt, 2018). Environmentalists such as Murray Bookchin (2009[1964]) and Barry Commoner (1979) argued that solar technology would decentralize power and end poverty. The perhaps most influential spokesperson for renewables (at least in the US) was Amory Lovins, who in 1976 introduced the idea of the "soft energy path" (Lovins, 1976, 1979). Lovins argued for a society relying on energy captured directly from the sun and the wind. Such a society, he argued, would at once be more efficient and provide a technological basis for reduced resource consumption. Lovins was directly influenced by the work of Ernst Schumacher who in *Small is Beautiful* argued for "intermediate technology" (what was later called "appropriate technology"). Schumacher defined this famous concept as follows:

> I have named it *intermediate technology* to signify that it is vastly superior to the primitive technology of bygone ages but at the same time much simpler, cheaper, and freer than the super-technology of the rich. One can also call it self-help technology, or democratic or people's technology - a technology to which everybody can gain admittance and which is not reserved to those already rich and powerful (Schumacher, 1993[1973]: 127, emphasis in original).

In comparison to nuclear power, solar technology was considered an appropriate technology, at once more democratic and environmentally friendly. With the increasing awareness of the detrimental effects of anthropogenic climate change, the argument for renewable energy technologies took on a new dimension by the end of the 1990s (Hake et al., 2015). The new argument was that societies could reduce the dangerous greenhouse emissions by installing solar technology. The discourse on renewable energy was reinvigorated. Herman Scheer, an influential German visionary and green-wing politician soon laid out a vision for a future society sustaining on energy harnessed directly in local environments that was at once more efficient, community empowering, and environmentally friendly (see Scheer, 2005, 2007).

Today, the fundamentally underlying attitude and feeling is that solar PV technology is still an appropriate, democratic, environmentally friendly, and empowering technological option (see chapter one). But it is important to recognize that these visions and arguments for solar power were articulated at a time when actual manufacturing and installations of solar PV modules remained modest and small-scale. As expressed in an article from *Science Magazine* two years ago, “the recent rapid declines in PV system pricing illustrate that we are entering an era in which PV already is or will soon become cost-competitive with conventional electricity generation in many parts of the world” (Haegel et al., 2019). Over the last 20 years, the installation of solar PV capacity has soared beyond most expectations and solar PV modules are rapidly becoming commodities available for advanced societies in the world economy.

How did this occur? More importantly, what does this commercialization mean for social-ecological visions assuming that solar PV technology is a democratic and environmentally friendly technology? If, as Schumacher (1993[1973]: 127) contended, “the technology of mass production is inherently violent, ecologically damaging, self-defeating in terms of non-renewable resources, and stultifying for the human person,” is there a contradiction in producing “appropriate technologies” *en masse* for increased mass-consumption of commodities? Arguably, while the biophysical condition of solar PV technologies has changed with the introduction of mass manufacturing, the inherited techno-political visions of the 1970s have essentially remained unchanged.

In this chapter, I first give a brief account of the Chinese PV manufacturing boom. I then provide a review of the most common explanations for the boom and show how they rest on the assumption that technology is immaterial, as unpacked in chapter two. This will be followed by an empirical investigation into the presence of ecologically unequal exchange between Germany and

China during the time of the boom. (The reason why I focus on these two countries will soon become apparent.) I then discuss the implications in a final part which deals with how the Chinese boom in solar PV manufacturing and trade was contingent on material world relations characterized by asymmetric flows of resources and what this means for global peripheries as the world economy further increases its aspirations for solar PV technology. Given the results of this investigation, I conclude that societies propelled by solar PV technology are not by default antithetical to social aspirations for endless accumulation and that ecologically unequal exchange may be inherent to large-scale solar PV development.

The boom: An explosive dawn for commercial solar PV technology

Over the last two decades, the global solar photovoltaic market has developed in a way that has reshaped the meaning of solar PV technology. The most apparent consequences of this development have been that prices of crystalline solar PV modules plunged, while global installations of PV systems soared. Between the years 2000 and 2012 the price per watt peak (Wp) manufacture fell from 3.7 USD to 1 USD, only to plunge to 0.25 USD/Wp in 2018 (Yu et al., 2016; Haegel et al., 2019). Meanwhile, cumulative global installations of PV capacity soared from a modest 1.2GW in 2000 to a momentous 500GW in 2018 (Yu et al., 2016; Jäger-Waldau, 2019). Notably, the added capacity in the year 2018 alone was equivalent to the world's historical cumulative capacity up until 2012 (figure 5). This period of industrial frenzy has aptly been called a "boom" in the global PV market. Judging from forecasting scenarios, the manufacture and installation of PV technologies is believed to increase over the two coming decades, with installations possibly doubling in the coming five years (Jäger-Waldau, 2019; SF-UNEP/BNEF, 2020).

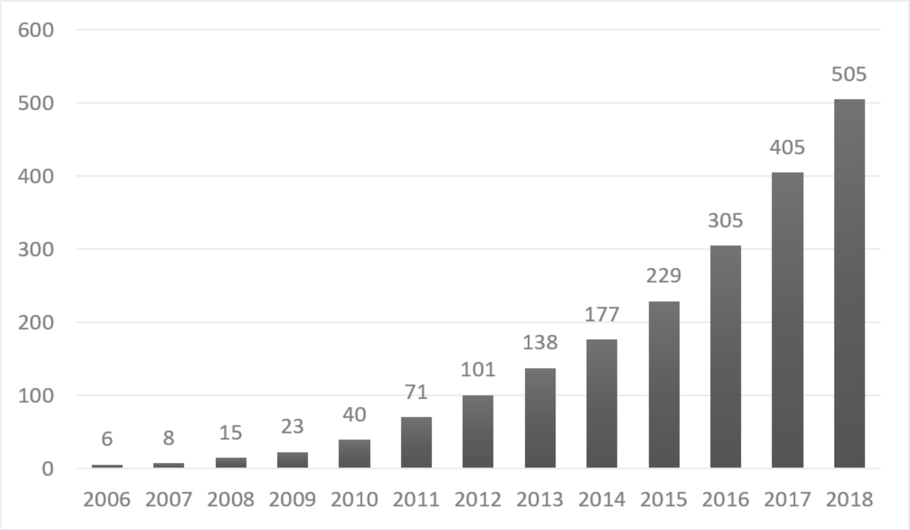


Figure 5. World total installations of solar photovoltaic capacity 2006-2018.
Data source REN21 (2016, 2019).

There is little doubt that the boom in the global solar PV industry correlates with the entrance of China into the international market as a manufacturing and exporting nation, motivated and encouraged by European demand (Zhang and He, 2013; Quitzow, 2015; Fialka, 2016; Yu et al., 2016; Nemet, 2019). Dustin Mulvaney, in his recent book *Solar Power: Innovation, sustainability, and environmental justice*, considers the emergence of the entrance of China as “arguably the most significant story in renewable energy over the past decade” (2019: 224). To be sure, even if Chinese firms have only been engaged in industrial solar PV production since the mid-1980s, the significance of Chinese industry cannot be underestimated. Compared to U.S. industries that pioneered the development of the solar PV cell in the 1950s, Chinese actors were latecomers to the PV industry. While the Chinese manufacture of crystalline solar cells increased considerably during the 1990s, the Chinese PV market was then almost exclusively geared towards small off-grid rural electrification projects that did not facilitate much industrial growth (Zhang and He, 2013: 394).

This situation gradually changed with the growing international demand for solar PV technologies driven by a progressive German energy politics, starting with the red-green coalition formed in 1998. As part of the long red-green effort to phase out nuclear power and transition to a renewable energy mix, the coalition offered generous feed-in tariffs (FITs) supported by the Renewable Energy Act (EEG) in 2000. This resulted in a remarkable increase in global solar PV demand and installation (Hake et al., 2015). Despite amendments to the act in 2009 to reduce FITs, German demand continued to soar and soon Germany was the largest PV market in the world, representing 50 percent of world PV module demand. With this demand, there was a need for a large increase in production that German solar PV corporations could not meet (despite fiscal support). This represented an opportunity for Chinese entrepreneurs to start up, or shift, to production for the global solar PV industry to turn considerable profits (Nemet, 2019). Soon, German equipment providers selling manufacturing equipment established links with Chinese PV manufacturers exporting solar PV modules back to Germany (Quitzow, 2015).

As noted in an article in *Scientific American*, "Germany … provided the capital, technology and experts to lure China into making solar panels to meet the German demand," and "'the Chinese took it'" (Fialka, 2016). Encouraged by European (mostly German, but also Spanish) demand and armed with low-cost labor, cheap coal-propelled manufacturing, and generous government loans, Chinese companies initiated the "explosive increase" in global solar PV module manufacturing by the mid-2000s (Yu et al., 2016: 466). China quickly rose as the largest solar PV manufacturer in the world, producing nearly 30 percent of all solar PV modules in 2007. In 2011, this figure had increased to 60 percent and in 2018 to 64 percent (Jäger-Waldau, 2019: 2). By 2017, 95 percent of the world production of solar PV modules was located in Asia (Mulvaney, 2019: 224). Meanwhile, "China's solar-electric panel industry dropped world prices by 80 percent" (Fialka, 2016). Between the years 2008 and 2009, after a period of polysilicon shortage, the price on silicon PV cells dropped by almost 50 percent (figure 6).

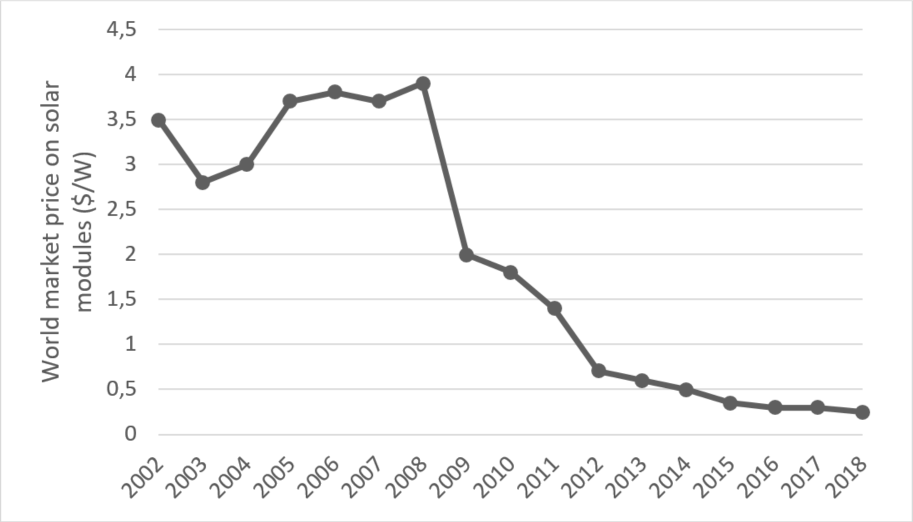


Figure 6. Avarage selling prices of solar PV modules, 2002-2018.
Data from Nemet (2019) and Haegel et al. (2019).

As of 2006, a whole 96 percent of China's PV production was geared towards the international market (i.e. exported) (Yu et al., 2016: 466). However, as international demand diminished due to trade regulations and the financial crisis of 2008, the Chinese government responded in its 11th five-year plan (2006-2010) by increasing domestic demand in a series of national PV-financing programs, such as the "Golden Sun Demonstration Program." Following these plans, China also became the largest *consumer* of solar PV technologies by 2015, even surpassing Germany as the previous leader in solar PV installations (REN21, 2019). Today, China is unrivaled in both the production and installation of solar PV modules, even if at least half of the modules manufactured in China are still produced for export.

The effects of the boom were systemic. Most notably, it upset international relations between China and other nations in the world, as Chinese solar manufacturing companies effectively shattered all competition and glutted the global market with cheap products. The four largest solar manufacturers in Germany (Q-Cells, Solar Millennium, Solon, and Solarhybrid) and no less than sixteen U.S. solar companies (including BP Solar, Evergreen Solar, SolarWorld, and SolarPower) closed down, off-shored production to Asia or were sold as a result of the rise of Chinese manufacturers (DW, 2012; Mulvaney, 2019: 226). In Japan, a staggering 65 solar-related companies filed for bankruptcy and had to close down (REN21, 2017: 70). The German government, who was offering generous FITs as incentive for increased rooftop installations, was threatened with heavy financial costs as installations soared. In an effort to defend the national economy and German manufacturing profits and jobs (and by extension, the German consumer base), it decided to reduce funding in its FIT program. Later, the European Commission levied import tariffs and anti-dumping fees on a majority of cheap solar PV technologies imported from China. This was met by fierce opposition from some European solar corporations and ENGOs such as WWF and Greenpeace, who saw it as an obstacle to a rapid transition to renewable energy (Reuters, 2017).

In the U.S., some solar corporations successfully lobbied for import tariffs on Chinese solar PV modules to protect their businesses. This resulted in Chinese PV products being subjected to tariff fees of up to 250 percent (Mulvaney, 2019: 236). When these measures were implemented, it sparked an outright "trade war" between China and the U.S., in which each accused the other of anti-free trade measures (Mulvaney, 2019: 230-239). Consequently, in part to avoid European and U.S. tariffs and in part due to other factors contributing to increasing production costs (e.g., labor prices), large Chinese solar companies such as Trina Solar relocated their factories to Southeast Asian countries including Thailand and Vietnam (Roselund, 2016; Watt et al., 2019; Sinn, 2019).

Another effect of the boom was the noticeable increase in demand for materials needed in the manufacturing of solar PV modules. In terms of materials, the mono- and poly-crystalline PV technologies that make up around 90 percent of the global PV market requires solar grade silicon, silver, lead, and nickel (Grau et al., 2011: 3; WB, 2017). In comparison, less commercially viable technologies such as thin-film technologies require more specific material compounds, including tellurium, indium, cadmium, and zinc, which are often higher in toxicity (WB, 2017; Exter et al., 2018; Muteri et al., 2020). Much attention has been paid specifically to silver, which is a potentially scarce material for a large-scale development of the now commercially viable PV technologies (Piano and Mayumi, 2017). One recent study has shown that the booming production of solar PV technologies caused a definite increase in global silver prices (Apergis and Apergis, 2019). Similarly, solar grade polysilicon production boomed with the rapidly expanding solar PV industry and China's initiative to create a domestic polysilicon production industry (Bernreuter, 2020).

The sheer amount of materials mined and processed for the rapidly expanding solar PV industry has become a basis for social and environmental concern. Silver has been found in high concentrations in various Chinese municipalities (Chen et al., 2020), where it has shown to be a driver of eutrophication and terrestrial eco-toxicity (Muteri et al., 2020: 17). Polysilicon production has also been pointed out as hazardous for workers and environments due to dangerous chemicals such as silicone tetrachloride and hydrofluoric acid leaking into environments. In an article in *Nature*, Yang et al. (2014) reported that Greenpeace and the Chinese Renewable Energy Industries Association found that two thirds of all solar companies in China failed to meet the national environmental regulations. This was reported even after the scandal of 2011, when rest-products from a solar-panel factory in Haining City were discovered to have severely polluted the Mujiaqiao River. The company, Jinko Solar, had been dumping toxic wastewater into the city river that killed a considerable amount of fish (Chan, 2011). This was met by a local uprising against the factory that was suppressed only after three days by the Chinese police's "heavy-handed tactics" (ibid.).

In addition to this, there are several environmental, health, and safety hazards throughout the production chain of solar PV technologies that are less regulated in Chinese factories (SSTI, 2016; Wang and Feng, 2014). These hazards allow for production at lower prices. LCA analyses frequently find that low-cost production in Chinese PV industries is associated with higher (up to double) social-ecological impacts in comparison to U.S. or European industries (Dubey et al., 2013; Yue et al., 2014; Stamford and Azapagic, 2018). These include, most notably, much higher energy consumption and greenhouse gas emissions. It is no secret that China's rapid ascent as a global economic superpower is linked to its low-cost labor force and massive burning of coal to propel its industries (Thomson, 2003; Wang et al., 2011; Malm, 2013). Consequently, as PV production companies relocated from Europe and the U.S., the carbon footprint of solar PV modules increased drastically.

In the case of the boom in solar PV production, some have argued that relocating the production of solar PV modules to China resulted in "energy cannibalism" in which the energy and emissions payback has been offset by aggregate growth in annual solar PV module production (Pearce, 2009; Decker, 2015). The annual amount of energy dissipated and greenhouse gases emitted in the production of solar PV modules is cancelling out the annual mitigating potential embodied in the installed PV technologies. Taking into consideration factors such as solar insolation, geographic distribution, LCA accounts and more, Decker (2015) arrives at the conclusion that the maximum sustainable growth rate for the now global solar industry is 16 percent per year. Based on these figures, one important effect of the boom is that the manufacturing and installation of solar PV technologies may itself have facilitated – not mitigated – increased energy consumption and greenhouse gas emissions (cf. York, 2012; York and Bell, 2019; Gellert and Ciccantell, 2020).

In light of these social-ecological conditions, recent research has begun to seek ways for mitigating environmental injustices throughout the production chains of solar PV technologies (e.g., Mulvaney, 2019). These, however, typically do not focus on understanding whether the observed social and environmental problems were necessary conditions for meeting the German demand and the low manufacturing costs. Even Decker (2015), who provides a highly critical analysis, does not consider how the price differences between U.S/European nations (notably Germany) and China may have been a necessary condition for it to occur in the first place. While we should seek to "ensure that solar energy commodity chains evolve in a just and sustainable way" (Mulvaney, 2019: 248), and "carefully select locations for production and installation" (Decker, 2015), we must ask whether such interventions would impede the expansion of solar PV technologies.

This means that we should ask what characterized the international relation between Germany and China over the course of the boom in solar PV technology. Why, in other words, could Germany not supply its own solar PV technologies? Why did Germany outsource the manufacture of its energy-political vision? If Germany possessed the "capital, technology and the experts," then why could German companies not employ these assets to ramp up its own domestic production? In this chapter, I argue that the world division of labor between Germany and China – characterized by an ecologically unequal exchange – may have been a key condition for the global market boom for solar PV in 2000-2018. However, before we consider this interpretation, we shall look at some of the already existing explanations for the boom and their underlying philosophical assumptions.

Current explanations for the boom: An infatuation with immaterial factors

The present explanations for the boom all draw on frameworks that understand technology as an ontologically immaterial phenomenon. The solar PV boom and the plunging prices are, according to these explanations, supposed to have sprung forth from ideas. These explanations can be found among a variety of sources represented by both academics and non-academics. The following explanations are not exhaustive, but they provide a general overview of the conventional interpretations of the boom.

Instrumental explanations: The boom originated from increases in scientific knowledge

The first explanation is the conventional notion that breakthroughs in scientific knowledge and engineering design contributed to the plunging prices in solar PV technology. This explanation centers on the notion that efficiency improvements push down prices per unit produced by allowing more to be done with less. This explanation focusing on efficiency takes at least two forms. The first form emphasizes how improved engineering design of the *technological artifact* improves efficiencies and thereby reduces prices. Examples of this includes findings in a study from MIT showing that increases in module efficiency may have contributed up to 25 percent of the decline in prices between 1980 and 2012 (Kavlak et al., 2018). However, the same study pointed out that the increase in solar power plant size and policies likely had larger effects on the drop in prices from 2001 onwards.

The second form emphasizes the increases in efficiency in the wider sphere of installation and manufacturing that comes from applied, or practical, knowledge over time (e.g., Haegel et al., 2019). The underlying assumption here is that the more frequently something is done, the more efficiently and cheaper it can be done. This is referred to as the Experience Curve (or Henderson Curve) explaining and modelling how increases in production correlate with more efficient practices over time. Aaron Bastani, in his *Fully Automated Luxury Communism*, falls back on this model in explaining the plunge in solar PV module prices. Here it is worth quoting Bastani (2019: 47-48) at length.

> [T]he most important area where one sees the experience curve at work is with the price of photovoltaic (PV) cells. … Here progress correlates almost perfectly to what Henderson would have predicted, with the cost of PV falling 20 per cent every time capacity doubled over the last sixty years. When the technology was deployed for the first time aboard NASA’s Vanguard 1 satellite in 1958, each panel was able to generate a maximum half a watt of energy at a cost of many thousands of dollars each. By the mid-1970s, that figure had fallen dramatically to $100 per watt … Yet by 2016 the price-performance ratio of solar had been transformed, with a watt of energy from solar array costing as little as fifty cents … *and with global solar capacity doubling every two years … a virtuous cycle between increased capacity and ever-falling prices has been established* (emphasis added).

Here we can see how the knowledge derived from larger amounts of PV modules installed is itself understood as a driver for the increased PV module demand. In other words, lower prices driven by increased knowledge are creating an increase in demand for solar PV technologies (i.e. knowledge -> efficiency -> lower prices -> demand -> installations -> knowledge). However, as we have seen in the case of the boom in the global PV market between 2000 and 2018, the demand was clearly driven by German political interests, not by progress in PV engineering design. Other than reiterating technological determinism, where knowledge via technological progress is believed to determine social change, this explanation fails to explain why German companies, who possessed expert knowledge in solar PV manufacturing, were outcompeted by Chinese entrepreneurs who had previously produced as dissimilar products as water purification products, cosmetics (Suntech), or household detergents (Trina Solar) (Nemet, 2019: 148-150).

This is not to say that knowledge and designs that are more efficient did not have any effect on PV module prices during the years 2000 to 2018. But the claim that increased experience in the wider sphere of manufacturing and installation were key mechanisms driving the boom contradicts the actual events. To be sure, ideas surrounding solar PV technology served a discursive function for German red-green politics, but this had been the case already since the early 1970s (Hake et al., 2015). What changed just prior to the boom was not any spectacular increase in knowledge or technological breakthrough in cell efficiency, but a shift in power in favor of red-green politics that advocated solar PV technologies over nuclear power and fossil fuels. This, of course, together with China's rise as manufacturer of the world.

Chinese governance: The boom originated from planned Chinese policy and government support

The second explanation focuses on how the powerful central state of China strategically planned and implemented measures to develop its PV manufacturing industry. This explanation stems from considerations on how China, sometimes described as a "developmental state" or as an "environmental authoritarian" state, implemented top-down measures to support PV manufacturing companies located within its borders (Gilley, 2012; Chen and Lees, 2016). This explanation bears some resemblance to Feenberg's critical theory of technology, which highlights the importance of different social forms in designing and developing particular technologies. However, rather than being concerned with the design of a specific technological artifact, this explanation for the global boom in PV installation focuses on how the

Chinese government, operating with social-political interest disparate from Western nations driven by corporate profit-maximization provided a unique environment for solar PV manufacturing to flourish.

Writing for *Aljazeera*, Larry Beinhart (2018) argues that it was Chinese development policies and planning that catalyzed the rise of PV manufacturers in China, which ultimately led to the global commercialization of solar PV technology. These policy designs, modelled from South Korea, include the nationalization of commercial banks and state control over credit, which allowed its "solar industry to prosper as part of a long-term, well-thought-out industrial development strategy" (ibid.). Beinhart points out that in comparison to China, the U.S. were "against ... an articulated, thoughtful, deliberate industrial policy." This, Beinhart points out, explains why China and not the U.S. is now the global leader in the solar PV market. As with the case of German demand, this explanation emphasizes how policies, driven by different forms of governance with specific social-political interests, influence the prospects for solar PV development.

The notion that the Chinese government supported solar PV manufacturers from a position of a "well-thought-out industrial development strategy" can be questioned on the basis that the Chinese government generally lacked an interest in PV manufacturing until Chinese firms appeared in Western stock exchange around 2008 (Nemet, 2019: 138-139). Notably, the interest of the Chinese government was kindled only after Chinese manufacturers produced a majority of the world's PV modules (Yu et al., 2016: 466). The Chinese government, it seems, was *reactive* in the development of the solar PV manufacturing industry that was crucial to meet German demand. The Chinese Renewable Energy Law of 2005, which is commonly pointed out as a core mechanism by which the Chinese government supported the solar PV industry, was at the time geared towards increasing domestic demand and installation and did not seem to have any direct importance for manufacturers (Martinot, 2010). The law can be understood as the Chinese equivalent to the German EEG, developed with expert help from both Denmark and Germany. In addition to this, Nemet (2019: 148), who recently documented the development in his *How Solar Energy Became Cheap*, explains how pioneering Chinese corporations, such as Suntech, relied on foreign direct investment from Western corporations such as Goldman Sachs for their economic success. Only after the economically successful establishment of Chinese PV manufacturers did the Chinese government take an active interest in their continuation.

While Beinhart provides an important comparison between China and the U.S., this raises the question why German companies – who also benefitted from generous government policies – could not scale up to meet German consumer demand (see Grau et al., 2011). Here, the economic impact of the financial crisis in 2008 may have played a larger role than differences in governance. In Germany and other European nations, government support (such as FITs) had to be cut down as economies went into recession (Yu et al., 2016). In contrast, the Chinese economy was not affected in the same way by the crisis, in part due to its strength in the world economy and in part due to previous experiences with financial crises (Li et al. 2012). Consequently, even at the height of the crisis in Europe in 2008, China's government had the capacity to strengthen policies for increasing domestic PV installation. At this time, Chinese development banks also offered generous loans for solar companies struggling to turn a profit (Dong et al., 2015a). The degree to which the role of China in the world economy was strong due to its particular form of governance (state capitalism) is debatable. It would seem, however, that the different world-economic positions of Germany and China provide a better explanation for why the development of a world-scale solar PV manufacturing capacity occurred in China and not in Germany (as I discuss below).

International co-evolution: The boom originated from increased knowledge exchange

The third explanation focuses on how the global solar PV market emerged from a complex international network of entrepreneurs, corporations, and government actors engaged in knowledge exchange (Nahm and Steinfeld, 2014; Quitzow, 2015; Quitzow et al., 2017). This explanatory framework acknowledges that China's capacity to scale PV manufacturing was an important reason why a commercially viable solar PV industry could emerge. While it is sometimes acknowledged that prices in material input factors, such as wages, rent, energy, and materials had an initial significance for the Chinese capacity to meet German demand, this framework considers "knowledge" (sometimes referred to as innovation or expertise) as the supreme input factor shaping the dynamics of the global PV market. Curiously, even the Chinese capacity for mass manufacturing is here understood as something originating from knowledge as opposed to originating from specific material conditions characteristic of the Chinese economy, such as the heavy reliance on coal (Goodrich et al., 2013).

In contrast to the purely instrumental explanation above, the knowledge in question is not understood to originate from scientific expertise or engineering design, but from actors making up an international network of knowledge exchange. In other words, the boom did not occur because Chinese actors were unique in their ability to innovate or scale-up manufacturing but because an international network of knowledge exchange emerged in which European, Australian, and U.S. actors could trade knowledge with Chinese manufacturers and vice versa. Helveston and Nahm (2019: 395) conclude, for example, that

> Chinese manufacturers gain technological know-how from advanced foreign incumbents, and the foreign partners feed the manufacturing and scale-up solutions their Chinese partners identify back into up-stream R&D activities.

In this explanation, knowledge exchange typically constitutes a win-win situation where each actor or nation has something to benefit from engaging in knowledge transfer (sometimes called “technology transfer”) to optimize or improve their respective manufacturing capabilities. This means that there was no unique event, condition, or knowledge within China or among Chinese corporations that drove the boom in global solar PV manufacturing. Certainly, the Chinese capacity to scale was important, but the emerging PV industry, as put by Quitzow (2015: 143) was “a co-evolutionary process of mutual cumulative causation,” where the knowledge exchange between Chinese and German actors co-created the boom.

Importantly, these studies acknowledge that the co-evolution underlying the emerging PV industry did not necessarily imply that the exchanges were always equal or just. As pointed out by Nahm and Stenfield (2014), solar PV products that are “made in China” typically benefit U.S. and European firms who, unlike their Chinese partners, do not have to navigate substantial financial or environmental risks. In this explanatory framework, a world division of labor is sometimes mentioned in passing, but quickly downplayed with reference to manufacturing automation or the rapid increase in Chinese technical know-how. For example, Helveston and Nahm (2019: 796) argue in their concluding remarks that even if world assymmetries are present today, “[t]he division of labor between Western inventors and Chinese manufacturers is not fixed or inevitable.” This is true, but it should not deter us from questioning to what degree a world division of labor was a necessary condition for solar PV commercialization, and to what degree it may be a permanent (albeit geographically mobile) condition for modern technological progress in general.

That is to ask, could the boom have occurred without this particular division of labor? If yes, then, why did it not? Helveston and Nahm (ibid.) continue by saying that, “in a global marketplace such as energy technology, it is unlikely that the entire value chain for a complex, manufactured product would lie entirely within national boundaries.” Again, this is certainly true, but it should not deter us from questioning why certain parts of the supply chain – typically primary sectors – are systematically placed in lower-wage, peripheral or semi-peripheral regions of the world (see e.g., Muradian and Martinez-Alier, 2001; Pérez-Rincón, 2006; Ciccantell and Smith, 2009). To turn a blind eye to the world division of labor under which the solar PV boom occurred is arguably to miss the most important historical condition under which solar PV technologies were commercialized.

Overall, in focusing on how *efficiency improvements*, *governance*, or *knowledge exchange* creates conditions for increased production, most explanations omit the role of particular human-environmental relations and the energy and material flows that make up the physical production of solar PV technologies. This is especially peculiar if we consider the vast amount of evidence pointing at a strong historical and physical correlation between mass production (i.e., industrialism) and the access to fossil fuels (see chapter three).

Ecologically unequal exchange between Germany and China 2002-2018: Trading German PV manufacturing machines for Chinese solar PV modules

As we have seen, the relation between Germany and China had a particular significance for the boom in production of solar PV modules between 2000 and 2018. As some studies have already suggested, it makes little sense to understand China and Germany as isolated countries in this historical context (see section above). Rather, it may be best to understand that these countries, along with their associated actors, make up a particular relation that itself catalyzed the boom. Paradoxically, to understand such a relation, we must understand some basic qualitative differences between the countries that allow for such a relation to emerge (relations, as I have argued in chapter two, being characterized by both separation and connection). This implies that we should seek to understand that each country in the modern world economy, even if unique, develops in a co-evolutionary process. Crucially, however, such a relation must be understood to constitute not only innovative knowledge or governing orders, but also biophysical flows of matter-energy. Knowledge and governance is certainly important, but neither exist apart from a transformation of matter-energy (see e.g. Strumsky et al., 2010). Therefore, the question is what kind of material relation that emerged historically between Germany and China and what role this relation played in the boom of the global PV market. To understand this, we will first very briefly look at the history of each country and then calculate the material relations that catalyzed the boom itself. Finally, I will discuss ecologically unequal exchange as a historical necessity for solar PV technology becoming a commercially viable option in the 21st century.

Ecologically unequal exchange between China and Germany

From a world-systems perspective, Germany is a core country and China is a semi-peripheral country. Ranked by the World Bank as a high-income economy, Germany is known for its internationally strong vehicle industry, medical industry, and the production of machinery for export. Measured in monetary exchange value, the Observatory for Economic Complexity (OEC) ranks Germany as one of the most complex and largest exporting nations in the world. This ranking is linked to a very specific historical past. Germany was one of the first countries to transition from an agrarian to an industrial regime, with a rapid increase in the use of fossil energy during the 19th century (Fischer-Kowalski et al., 2019). Already by the 1860s, over 50 percent of the energy throughput in the German economy was fossil-based (Molina and Toledo, 2014: 337). In addition to this, Germany has a colonial legacy, spanning roughly from the onset of the Scramble for Africa (1880) to the end of the First World War (1918). At the height of its power in 1914, the German Empire could draw on resources from an additional 10.6 million square kilometers and 55.5 million inhabitants outside its borders (ibid. 225). Germany's early industrialization combined with its colonial legacy has no doubt shaped the country's contemporary profile in the world economy (see e.g., Infante-Amate and Krausmann, 2019). Despite its turbulent 20th century history, with economic depression, two world wars, fascism, and the cold war period, Germany is today a strong state and a top actor competing for increased economic power in the world economy.

Today, Germany boasts ambitious environmental targets and some of the most promising trajectories for 'sustainable development' according to conventional discourse (UNEP, 2011). However, the quantifiable difference between Germany's climate targets and actual environmental mitigations – the so-called "emissions gap" – remains wide (CAT, 2020b). Germany's environmental loads far exceed the carrying capacity of the German land base and globally sustainable footprints per capita (WWF, 2018). In part, the conventional narrative is kept alive because Germany is importing much of its energy-matter throughput via international trade. Several studies have documented how Germany as a core, high-income country, relies upon a net import of matter-energy in the world economy (Giljum and Eisenmenger, 2004; Jorgenson, 2009; Dorninger and Hornborg, 2015). While Germany is a net exporter in terms of monetary exchange value, the country is a net importer of embodied matter-energy. Germany's ambitious environmental politics is thereby associated with an environmental load displacement, whereby Germany exports a considerable amount of the environmental degradation resulting from its economic development to other countries. From a biophysical perspective, then, Germany exhibits a clear core-like position in the world economy.

Now we turn to China. According to the World Bank, China ranks as an "upper middle income" country. Currently, China is the largest exporting nation in the world, mainly exporting machinery (broadcasting equipment and computers), textiles, and a vast range of other commodities. China has an immensely rich cultural and material history. The region of contemporary China is associated with some of the earliest and most complex civilizations in history and at least a dozen dynasties well before the 20th century. World-system and dependency scholars Kenneth Pomeranz and Andre Gunder Frank have argued against a Eurocentric understanding of history by stressing the central role of China in the formation of the modern world economy, not the least with reference to the Chinese demand for silver as a core incentive for early European colonialism (see chapter three).

Despite China's central role in the early modern period, the country was late to industrialize. Several explanations exist as to why China did not industrialize earlier, or simultaneously with western European nations. Pomeranz (2000), for example, suggests that China's deteriorating relations to its peripheries contributed to halting its industrialization. To this, we could add the deteriorating social conditions in China imposed by the British Empire with the forceful opening of the Chinese markets for opium trade. The two opium wars that followed established relations between China and European colonial powers that benefitted the British Empire (e.g., Clark and Foster, 2009). With impediments such as these, combined with the fall of the Chinese Empire in 1911, two world wars, and the stumbling Maoist attempt at industrialization through the Great Leap Forward, Chinese industrialization did not take off until well into the 20th century, a whole century after Germany and other western European countries (Fischer-Kowalski et al., 2019). The economic reforms of 1978 are typically pointed out as a key turn-around event that served as a new foundation for modernization and industrialization in China. Since then, China has quickly risen as the second most powerful economy in the world.

During this time of rapid economic growth, China has been fundamentally dependent on coal as the energetic basis for its expanding industries. Energy expert Vaclav Smil (2016: 275) explains that "China's total coal output more than quadrupled between 1980 (907 Mt) and 2013 (3.97 Gt), when it accounted for almost as much as the rest of the world production put together." Even if the relative amount of coal in the Chinese energy mix is slowly being reduced, Chinese industries continue to burn larger and larger amounts of coal every year to propel its increasing economic activity, which provides massive amounts of commodities to the world. Given its high fossil fuel dependence and the vast amounts of extraction of other non-renewable resources, China is often described as one of the worst polluters in the world. The Climate action tracker, for instance, categorizes China's efforts at decarbonization as "highly insufficient," estimating that the Chinese emissions reduction targets are in a range that would warm the Earth to a detrimental 3°C–4°C above pre-industrial levels (CAT, 2020a). In a highly globalized economy, however, it is problematic to place blame simply upon the Chinese government for this trajectory, since the country is an arena for a number of national and international actors with economic interests in producing cheap commodities for a global market (Malm, 2013; Dong et al., 2015b; Shen, 2017). Considerable parts of the environmental damages from Chinese production processes benefit other countries or actors by virtue of commodities being exported to other world regions or providing profits for non-Chinese actors.

In a study assessing the physical trade between China and 186 other countries in the world economy it was found that developed regions (including the EU) displace their environmental loads to China through trade (Yu et al., 2014). This environmental load included embodied greenhouse gas emissions (CO_2 and SO_2) as well as embodied water and embodied land. The same study concluded that China in turn exports some of its own environmental loads to less developed regions of the world, including Southeast Asian and African countries. China, seen from a biophysical world-systems perspective, thereby exhibits both core- and periphery-like processes, marking it as a semi-periphery in the world economy. Several other studies have confirmed the Chinese role as semi-periphery, as it simultaneously *exports* embodied greenhouse gas emissions, embodied energy, embodied land, and embodied material while it *imports* embodied forests, embodied land, and embodied water (Yu et al., 2014; Peng et al., 2016; Tian et al., 2017; Shandra et al., 2019).

Given their respective roles in the world economy, it is not surprising that direct trade relations between China and Germany have been shown to facilitate an ecologically unequal exchange whereby embodied matter-energy is transferred to Germany (Tian et al., 2017). It is interesting to note that the most relevant trade sectors between China and Germany, considered in physical measurements, included the German export of "machinery" to China and the Chinese export of "electrical and optical equipment" to Germany (Tian et al., 2017). This means that the German export of machinery, such as cars, PV equipment, and similar products, has a biophysical significance for the Chinese economy, while electrical equipment, such as computers and solar PV modules, have a physical significance for the German economy.

LCA-based methods for calculating ecologically unequal exchange

As we have already seen how the world economic relation between Germany and China is characterized by ecologically unequal exchange at the nation-scale, the goal here is to calculate the presence of unequal exchange in the trade in products specific to the global solar PV market between 2000 and 2018 and discuss its significance. While the most common methods for calculating the occurrence of ecologically unequal exchange typically focus on specific industrial sectors, entire economies, or even world economic regions, I will here follow a method based on Life Cycle Analysis (LCA), by which it is possible to assess ecologically unequal exchange in trade with specific commodities (Oulu, 2015). This is the first step in the wider goal to understand the significance of ecologically unequal exchange for the commercialization of solar PV technology.[35]

Following Oulu (2015), LCA-based calculations on ecologically unequal exchange have two basic parts. First is to calculate the embodied resources and impacts of the individual commodities traded and second is to calculate the bulk exchange of these commodities in the world economy relative to a fixed market price. This includes at least four sub-phases.

- First, a scope definition should be provided wherein the functional unit, system boundaries, and units of measurements are articulated.
- This is followed by an inventory analysis wherein the resource intensity per functional unit is determined and presented.
- Third, an impact assessment is made wherein unequal exchange is determined via a comparison of the resource intensity per unit of exchange value.

---

[35] This method is chosen in part because this thesis is an attempt at understanding the ontology of PV technology.

- Finally, the implications of the results are discussed. The remaining part of the chapter will follow this systematization.

To compare the ecological exchange implicated in two commodities in the solar PV market, the functional units were defined as follows: One Chinese solar multi-crystalline silicone solar photovoltaic module[36] and one German solar photovoltaic manufacturing machine.[37] The system boundaries were set to include measurements traced from the extraction of the necessary matter-energy to the assembly of the final product (figure 7 and 8). Since we are here narrowly concerned with the exchange of finished products, environmental impacts associated with the usage, disposal, and recycling phases are considered outside the system boundaries. Only domestic resources and greenhouse gas emissions are taken into account (for solar PV, see Dong et al. 2015b). For this study, the units of measurement include embodied land, embodied labor, embodied energy, and embodied CO_2 emissions. These units of embodiments were then related to quantities and monetary exchange values (USD) of the respective commodities, derived from the UN database COMTRADE (2020) and the Trend economy (2020) database on commodity exchanges.

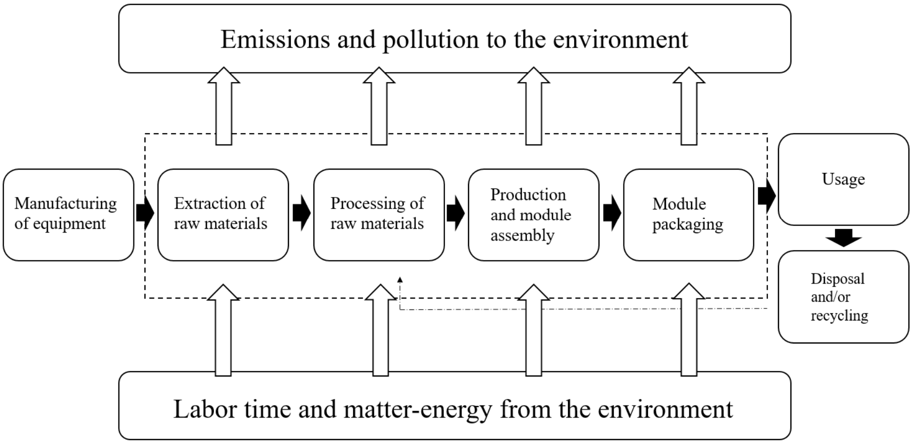


Figure 7. System boundary for a Chinese multi-crystalline silicone (m-Si) solar PV module.

---

[36] Properties: 1,482 x 992 x 35 mm (1,47 m^2), 16.8 kg, 54 cells (6 x 9), lifespan 25 years, 200 Wp.

[37] Properties: 2,500 kg, lifespan 30 years (OpenLCA, 2020).

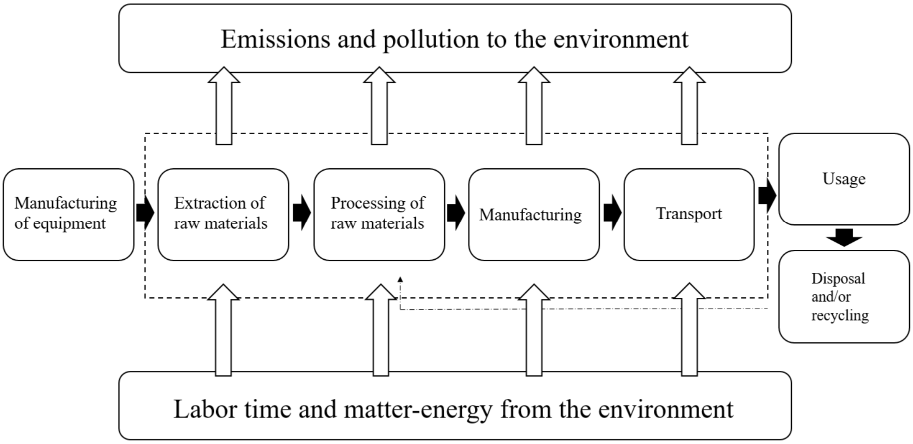


Figure 8.System boundary for a German solar photovoltaic manufacturing machine.

Table 2 summarizes the resource intensity of a Chinese solar PV module. Methodologically, the resource intensity in the life-cycle inventory table is presented as if it is static in time. This means that variations in resource intensity associated with changes in the manufacturing process have not been taken into consideration. In order to avoid portraying the resource intensity as larger than it was during the last years of the boom, the inventory table is based on LCA-analyses published as recently as possible (typically from 2013 onwards). Contrary to what is often assumed, the LCA-analyses reviewed shows that resource efficiencies in manufacturing may not have changed considerably over the last twenty years. For instance, one review reveals that CO_2 emissions and energy use in the production of solar PV systems were in some cases higher in 2017 and 2018 than 20 years earlier (Ludin et al., 2018). This may in turn be linked to observations that increased automation in manufacturing implies higher energy expenditures per commodity produced even if it lowers the amount of necessary labor hours (Hagens, 2020) or that economies of scale are offset by “diseconomies of space” (Bunker and Ciccantell, 2005b; Ciccantell and Smith, 2009).

Table 2. Life-cycle inventory table for a Chinese solar multi-crystalline silicone (m-Si) solar photovoltaic module.

Process/input	Energy (MJ)	Land (m^2)[c]	Labor (h)[d]	Emissions (kg CO_2-eq.)
Extraction of raw materials	2552[a]	57	0.35	0.6[b]
Processing of materials	2071[a]	44	0.87	186.1[b]
Production and assembly	1382[a]	29	3.26	88.9[b]
Module packaging	1512[b]	31.5	N/A	167.6[e]
Total	**7517**	**161.5**	**4.47**	**443.2**

[a] Data from Wong et al. (2016).

[b] Data from Dong et al. (2015b).

[c] Calculations based on energy values from Wong et al. (2016) and Dong et al. (2015b) converted into land hectares with a coefficient (1.56 W/m^2) calculated from land requirements of China's solar PV industry (table 12). The coefficient includes indirect land requirements of the necessary labor and capital, but excludes the land for carbon sequestration.

[d] Data from Llera et al. (2013). Considering a 1800h work year in China.

[e] Data from Dong et al. (2015b). Includes some emissions associated with assembly of the aluminum frame not previously included.

Table 3 summarizes the resource intensity of a German solar photovoltaic manufacturing machine. Ironically, it is notoriously difficult to access life-cycle data on machinery, perhaps because there is a limited interest in understanding machines as material artifacts (see chapter two). The LCA accounts on machinery that do exist focus almost exclusively on variations in production efficiency in the usage phase by examining variations in machine design (so-called "eco-design"). These typically do not contain any measurements of resource expenditures or environmental impacts of the machines themselves. The most significant exception to this trend can be found in research on energy flows in agricultural systems (e.g., Fluck, 1992; Pimentel, 2006; Bochtis et al., 2019). In these studies, energy embodiments associated with the manufacture of machinery are sometimes considered relevant for the overall energy expenditure of a particular food product or a particular agricultural system. Usually, such measurements are based on energy intensities per kg of machinery. In literature on ecological footprints, it is also possible to find coefficients concerning land embodiments for different industrial sectors (e.g. Hubacek and Giljum, 2003). The life-cycle inventory for the German manufacturing machine draws upon these studies.

Table 3. Life-cycle inventory table for a German solar photovoltaic manufacturing machine.

Process/input	Energy (MJ)[a]	Land (m^2)[b]	Labor (h)	Emissions (kg CO_2-eq.)[d]
Extraction and processing of raw materials	1,286,500	8,276	N/A	74,617
Manufacturing	61,000	385	N/A	3,538
Transportation	3,225	20	N/A	187
Total	**1,350,725**	**8,681**	**849**[c]	**78,342**

[a] Data from Bochtis et al. (2019).

[b] Calculations based on energy values from Bochtis et al. (2019) converted into land hectares with a coefficient (4,93 W/m^2) calculated from land requirements of Germany's solar PV industry (table 12). The coefficient includes indirect land requirements of the necessary labor and capital, but excludes the land for carbon sequestration.

[c] Calculated by dividing the annual turnover of Germany's manufacturing and equipment industry with the amount of jobs focused on export in the sector (Kolbe, 2011; Dauth et al. 2017). Considering a 1,350h work-year in Germany.

[d] Calculated with a coefficient of Germany's carbon intensity (0.058 kg/MJ) (Worldometer, 2020; BP, 2019a).

The next step was to apply the resource intensities associated with each commodity to aggregate quantities traded between Germany and China during the time of the boom. Tables 4 and 5 summarize the associated flows implied in the Chinese export of solar PV modules to Germany and the German export of solar PV manufacturing machinery to China. The results show an unequal exchange whereby net transfers of embodied energy, embodied land, embodied labor, and embodied emissions are flowing from China to Germany (Figure 9, 10, 11, 12). In all embodiments calculated, the biophysical exchange implicated in trade with these two commodities shows a considerable asymmetry as of 2013. Even prior to this period, a notable (yet smaller) asymmetry was present that started accelerating in 2006. Figure 13 provides a closer look at the trends in the crucial early years 2002-2010.

Table 4. Trade volumes and embodied resources in Chinese export of solar PV modules to Germany 2002-2018.

Year	Chinese solar PV module exports to Germany		Embodied resources			
	Export (kg)	Prices (USD)	Energy (GJ)	Land (ha)	Labor (h)	Emissions (tonnes CO_2-eq.)
2002	117,206	15,655,463	52,442	113	31,177	3,092
2003	129,521	20,093,089	57,953	124	34,453	3,417
2004	1,234,167	145,459,891	552,216	1,186	328,288	32,559
2005	3,963,096	458,772,870	1,773,248	3,809	1,054,184	104,550
2006	6,976,314	802,959,450	3,121,482	6,704	1,855,700	184,042
2007	31,539,586[a]	1,387,741,794	14,112,072	30,310	8,389,530	832,050
2008	65,828,307[a]	3,134,085,716	29,454,218	63,261	17,510,330	1,736,617
2009	158,658,712[a]	3,776,077,334	70,990,254	152,471	42,203,217	4,185,575
2010	375,570,340	7,663,736,157	168,045,193	360,923	99,901,710	9,907,921
2011	327,077,931	5,704,730,963	146,347,749	314,322	87,002,730	8,628,643
2012	211,272,309	2,131,681,388	94,531,682	203,033	56,198,434	5,573,575
2013	59,025,716	592,278,908	26,410,466	56,724	15,700,840	1,557,157
2014	58,083,459[a]	345,596,582	25,988,863	55,818	15,450,200	1,532,300
2015	75,283,694[a]	313,933,004	33,684,936	72,348	20,025,463	1,986,059
2016	111,149,346[a]	396,803,166	49,732,663	106,815	29,565,726	2,932,231
2017	100,319,671[a]	358,284,551	44,887,081	96,438	26,692,198	2,646,528
2018	155,734,982[a]	463,406,970	69,682,131	149,710	41,436,627	4,108,437

Sources: Data from COMTRADE (2020), commodity codes 854140 and 854150. Embodied resources, including indirect land requirements, calculated by author.

[a] Data on export (kg) missing from COMTRADE (2020). Calculated based on prices (USD) from COMTRADE (2020) and $/W from Nemet (2019: 156-157). A price of $0.3/W in 2017 was deduced from price trends displayed in Nemet (2019: 156) and a price of $0.25/W was considered for the year 2018 (Nemet, 2019: 156; Haegel et al., 2019).

Table 5. Trade volumes and embodied resources in German export of solar PV manufacturing equipment to China 2002-2018.

Year	German solar PV machine exports to China		Embodied resources			
	Export (kg)	Prices (USD)	Energy (GJ)	Land (ha)	Labor (h)	Emissions (tonnes CO_2-eq.)
2002	106	38,000	57	0.03	36	3
2003	2,500	909,000	1,350	1	849	78
2004	7,300	3,843,000	3,944	3	2,479	229
2005	10,900	3,321,000	5,889	4	3,702	342
2006	28,100	12,458,000	15,182	10	9,543	881
2007	853,900	130,479,000	461,354	297	289,984	26,758
2008	1,9849,44	300,227,011	1,072,445	689	674,087	62,202
2009	2,448,306	312,712,046	1,322,795	850	831,445	76,722
2010	8,884,239	1,187,604,272	4,800,065	3,085	3,017,087	278,404
2011	11,555,939	1,944,456,603	6,243,558	4,013	3,924,397	362,126
2012	4,453,060	391,886,514	2,405,944	1,546	1,512,259	139,545
2013	2,214,644	277,799,826	1,196,550	769	752,093	69,400
2014	2,934,083	322,045,392	1,585,256	1,019	996,415	91,945
2015	2,379,973	285,157,862	1,285,876	826	808,239	74,581
2016	5,321,773	418,854,750	2,875,301	1,848	1,807,274	166,767
2017	5,892,225	613,486,356	3,183,510	2,046	2,001,000	184,643
2018	5,009,753	606,865,365	2,706,719	1,740	1,701,312	156,990

Sources: Data from COMTRADE (2020) commodity code 8486 and Trend economy (2020) commodity code 903082. Embodied resources, including indirect land requirements, calculated by author.

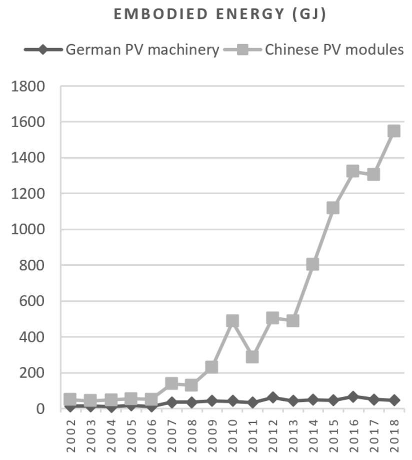


Figure 9. Exchange of embodied energy per 10,000 USD.

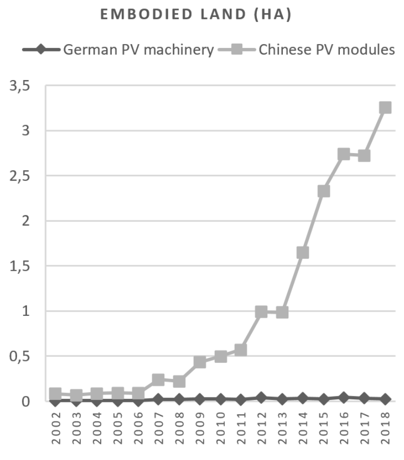


Figure 10. Exchange of embodied land per 10,000 USD.

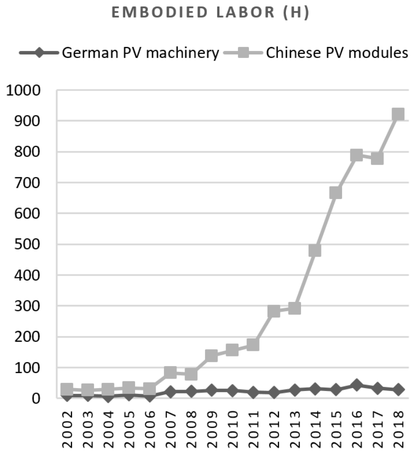


Figure 11. Exchange of embodied labor per 10,000 USD.

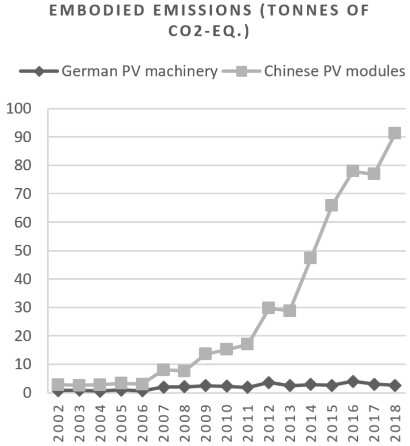


Figure 12. Exchange of embodied emissions per 10,000 USD.

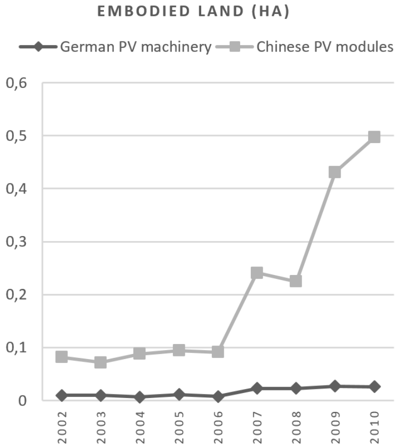


Figure 13. Exchange of embodied land per 10,000 USD, 2002-2010.

A closer look at asymmetry emerging in 2006.

At the peak of asymmetry in 2018, the exchange implied a net transfer of 1,459 GJ, 3.2 hectares of embodied land, 866 embodied labor-hours, and embodied greenhouse gases equivalent to 86 tonnes of CO_2 from China to Germany for every 10,000 USD exchanged. The drop in solar PV module prices is likely a factor contributing to these biophysical trends (cf. Nemet, 2019: 156), because lower prices on solar PV modules relative to prices on PV machinery implies that less embodied resources are traded for more embodied resources. The fact that German machinery has not followed the same price trajectory as Chinese solar PV modules is likely the underlying reason for the intensification of ecologically unequal exchange.

Was ecologically unequal exchange a necessity for solar PV commercialization?

The results above indicate that trade in the solar PV market was indeed ecologically unequal between Germany and China between the years 2002 and 2018. The emerging solar PV industry represents a technological expansion in which Germany displaced the environmental loads and work loads of its politically motivated energy transition to China. Let us now return to the question of whether ecologically unequal exchange was a necessary condition for the boom in the global solar PV market that transformed alternative solar technology into a fully-fledged world market commodity. This includes answering the questions whether Germany could reasonably have provided the energy, land, labor-hours, and carbon sink potential domestically and whether trade with China was a condition for fulfilling Germany's solar PV aspirations. Following this, I will also provide two brief notes on the implications of this finding for modern solar PV aspirations and in relation to current trends in the world economy.

At the peak of asymmetry in 2018, for an exchange of 463,406,970 USD worth of PV modules and PV equipment respectively (the total amount spent on Chinese solar PV modules by Germany), Germany gained a total amount of 67,615,260 GJ of embodied energy, 148,381 hectares of embodied land, and 20,069 embodied person-year-equivalents from China. In addition, 3,989,852 tonnes of CO_2-eq. were emitted in China for the "benefit" of Germany. Based on the observation that Germany's primary energy supply, total surface area, and total population is significantly greater than the volumes of resources embodied in trade with China, it seem that Germany could theoretically have provided the necessary energy, land, and labor-hours domestically. However, we should recognize that that these figures represent a significant volume of resources in relation to electricity capacity. If we take into consideration that the 463,406,970 USD exchanged in 2018 represent 1,854 MW solar PV capacity,[38] then an equivalent of 0.009% of Germany's electricity capacity[39] required the equivalent of 0.005% of its energy supply,[40] 0.004% of its surface area,[41] the labor of 0.00027% of its population,[42] and greenhouse gases equivalent to 0.005% of its annual emissions.[43] Since these figures account only for the resources embodied in trade with China, the total amount of resources required is in fact higher.[44] This is a significant amount of resources *per electricity capacity installed*, confirming that solar PV modules require larger amounts of resources than is conventionally assumed.

This finding imply that Germany's solar aspiration would probably imply high economic costs if the energy, land, and labor had to be supplied domestically. This possibility can be tested by calculating the cost of the solar PV modules (USD/W) based on German wages and energy prices. In 2018, China exported solar PV modules to Germany at a total exchange value of 463,406,970 USD (table 5). The total amount of labor-hours embodied was 41,436,627 (table 5). With Chinese manufacturing wages of 6.2 USD/hour, these labor-hours cost 256,907,087 USD (Trading economics 2021). With German manufacturing wages of 28 USD/hour, the same amount of labor hours would have cost 1,160,225,556 USD (Salary explorer, 2021). Thus, the total price on the solar PV modules installed by Germany would have increased to 1,366,725,439 USD (0.74 USD/W) if they were manufactured with German wages. Additionally, the embodied energy to manufacture the solar PV modules amounted to 69,682,131 GJ (table 5). With Chinese electricity prices of 0.08 USD/kWh and German electricity prices of 0.38 USD/kWh (Statista, 2021), the prices on the solar PV modules would increase by 5,806,844,250 USD if they were manufactured in Germany.[45] This means that the solar PV modules that Germany imported from China at an exchange value of 463,406,970 USD would cost 7,173,569,689 USD if they were manufactured with German wages

---

[38] Considering a price of 0.25 USD/W (Nemet, 2019: 157).

[39] Germany's total power generation capacity was 154,100 MW in 2011 (Fraunhofer, 2020).

[40] Calculations based on figures from AGEB (2019).

[41] Germany's surface area is 35,738,600 hectares.

[42] The 40,137,492 labor-hours are equivalent to 22,299 people if we assume a 1,800 long work-year. In 2018, Germany's total population was 80.33 million (Koptyug, 2020).

[43] Germany emitted 731,300,000 million tonnes CO2-eq. in 2018 (BP, 2020: 13).

[44] The figures do not account for expenditures associated with installing the PV modules, maintaining the modules, and managing the waste of the massive infrastructure.

[45] The price of the Chinese electricity was 1,548,491,800 USD (69,682,131 GJ * 0.08 USD/kWh) and the price of the Germany electricity was 7,355,336,050 USD (69,682,131 GJ * 0.38 USD/kWh). The difference between them is 5,806,844,250 USD.

and energy prices. This means that prices on solar PV modules would be at least 15 times higher if they were produced in Germany rather than China.[46] This represents an increase in PV prices from 0.25 USD/W to 3.87 USD/W, a price that is equivalent to the situation just prior to the boom, around the year 2000 (Nemet, 2019: 156). This demonstrates that the global solar PV boom was essentially based on ecologically unequal exchange. From this, we can conclude that ecologically unequal exchange was indeed a necessity for Germany to begin realizing its techno-political aspirations.

Since conventional economics does not take biophysical flows of embodied resources into account, it is unlikely that the boom was initiated based on economic arguments for environmental load displacement. Rather, the opportunity for environmental load displacement was most likely expressed as favorable manufacturing prices in Asia relative to Germany. The gap in manufacturing costs between Germany and China were so large that even the world's most established solar PV companies – such as German Q-Cells – who had been leading PV manufacturing for decades and had maximized opportunities for low cost manufacturing within Europe, still could not scale up manufacturing to saturate the growing German demand (Nemet, 2019: 118-123). To a large degree, this insufficiency was due to high raw material costs (ibid.). In Asia, by comparison, resources and labor could be accessed at decidedly lower prices. For this reason, a few years before Q-Cells was sold to the Korean corporation Hanwha Solar, the company built a production line in Malaysia in the hope of increasing its global competitiveness.

Quite opposite to what proponents of the Experience curve suggests, this shows that lower relative manufacturing costs was a key necessity for scaling up manufacturing in solar PV modules and not the other way around. This can be explained by the fact that an increase in scale (i.e., "scaling up," or "growth," or even "complexity") can only occur with an absolute increase in matter-energy throughput in highly ordered structures (Georgescu-Roegen, 1975; Tainter, 1988; Hall and Klitgaard, 2012). In turn, such an increase necessitates lower prices on matter-energy inputs for ventures bound within the cycle of capital accumulation. In the case of the global PV boom, the relative price difference in energy, raw materials, and labor between China and Germany served precisely this purpose of allowing higher energy-matter throughputs at lower prices. Far from exhibiting unique Ricardian comparative

---

[46] We should bear in mind that these figures do not include prices on carbon emissions or expenses associated with the land requirements. If these were calculated, it would likely imply that the prices of the solar PV modules would be even higher if they were manufactured in Germany.

advantages in knowledge on how to scale up, firms in China had the "absolute advantage" of access to cheap and unregulated use of fossil fuels, lower wages, cheap or unregulated land, and cheap materials necessary to produce larger amounts of solar PV modules at low prices (i.e., scaling up production).

In relation to this, we should recall that relative price differences in resources and wages in different geographical regions is a core mechanism through which ecologically unequal exchange occurs (Emmanuel, 1972; Hornborg, 1998; Pérez-Rincón, 2006). This is reflected in how the annual environmental load displacement increased with the successively lower prices on solar PV modules in China relative to German solar PV machinery. As we see between the years 2011-2013, for instance, even if export (in kg) increased, the volume of embodiments increased per unit of exchange value. This shows that price differences – not amounts of mass exchanged – is the central determinant for the rates of ecologically unequal exchange (see also the years 2004-2006). This drop in manufacturing prices in China relative to those of Germany exemplifies what economists call "deteriorating terms of trade" whereby an ever-increasing quantity of export is needed every year to balance the same amount of import. For the purpose of maintaining a regular export income flow, Chinese and foreign manufacturers in China were compelled to produce ever more solar PV modules to the beat of an ever-faster rhythm of natural resource extraction, increased pollution, and more cost-effective manufacturing processes. Increased environmental degradation and efficiency improvements can here be understood as an effect of market conditions and the never-ending quest for profit maximization under capitalism.

Even if the radical drop in prices in Chinese solar PV modules in 2002-2018 is conventionally understood in a positive light, it masks an uneven biophysical relation that was as much a necessary condition for the boom as scientific knowledge, knowledge-exchange in manufacturing, or strong government support. For simultaneously as extraction and manufacturing soared in China, the German economy reaped the benefit of the increased import of embodied resources (in the guise of *seemingly* social-ecologically benign solar technologies) that further contributed to the modernization and complexification of its social metabolism. In this way, ecologically unequal exchange enabled the emergence of a global low-cost solar PV market inseparable from underlying questions concerning environmental sustainability and uneven distribution of work, resources and pollution in the world economy.

Implications for modern solar PV aspirations

These calculations indicate that the commercialization of solar PV technology was linked to a particular global political relation without which an expanding global solar PV market could not be established. As we have seen, discourses that consider solar PV technologies as a democratic or appropriate technology have so far remained silent about this form of global political relation (in chapter six I discuss why this is so). Visions of a post-industrial metabolism driven by solar energy captured from local rooftops or solar parks must arguably re-consider the politics of solar PV technology based on this recently acknowledged reality of a global division of labor in solar PV manufacturing. Large-scale solar PV development is today far from an "appropriate technology" or a "tool for conviviality" (Illich, 1973; Schumacher, 1999[1973]). In fact, the results are suggestive of Ivan Illich's (1973: 11) conviction that a technology that grows beyond a certain scale tend "to frustrate the end for which they were originally designed." Equally distant is the popular vision of local energy democracies facilitating energy security and greenhouse gas mitigation, for example as argued by Herman Scheer (2005, 2007) and Naomi Klein (2014). To be sure, these technological visions and their outlook on technology still hold relevance, but only to the extent that the materiality of the global economy is ignored. As I have argued, however, to omit this aspect is to miss a fundamental part of what technology is (chapter two).

This omission can only be remedied by taking into consideration the biophysical past of technologies. This is easily done by recognizing that technologies do not spring forth from nothing. While it is possible to argue that solar PV technologies required ecologically unequal exchange even prior to the boom in the global solar PV market (e.g. by virtue of being manufactured in Eastern Germany and installed in Western Germany), the commercialization that is characteristic of the boom is linked to a qualitatively specific global political relation whereby a net transfer of resources from a semi-peripheral nations (China) proved necessary to fulfill the aspirations of a core nation (Germany).

The ecologically unequal exchange between Germany and China that provided the foundation for the emerging solar PV market demonstrates how an instrumental notion of technology, exemplified in German policy, was vital for the emerging global asymmetries. The Renewable Energy Act (EEG), geared towards incentivizing mass installation of PV modules, was especially important to this end. It rested upon an understanding of renewable energy technologies, such as solar PV modules, as exempt from so-called "external costs" (BMU, 2000: 16-17). It is clear that fossil energy carriers were understood to have problematic socio-ecological impacts that are not reflected in their price. The EEG was meant to remedy this situation by "internalizing" the "costs" of fossil fuels, while simultaneously making renewable energy technologies more cost competitive on the market through subsidies (feed-in-tariffs). This solution, however, never took into consideration that renewable energy technologies also have definite socio-ecological impacts in the world, similar to fossil technologies. In effect, as installation of renewable energy technologies were economically incentivized, the socio-ecological impacts associated with solar PV modules increased. In this sense, the narrow view of solar PV technology (i.e. as exempt from a biophysical past) facilitated the global asymmetries between Germany and China. As theorized in chapter two and three, this demonstrates how the conventional, fetishized understanding of solar PV technology sustains the global relations of industrial capitalism. These are the very same social relations, we might add, from which the fetishized view of technology and commodities emerged.

Implications for the solar PV technology of tomorrow: China's aspirations for the world economy

It is important to note that the rapid rise of the global solar PV market has not been fast enough to meet installation targets set in the Paris agreement (Halveston and Nahm, 2019: 796). Despite reaping the benefits of Chinese low-cost solar PV modules, Germany has only met 50% of its intended targets of installing 98 GW worth of solar PV capacity by 2030 (Enkhardt, 2019a). According to an article in *Nature*, an additional 500 GW of solar PV capacity is expected worldwide already by 2023. The same article suggests that "scaling in production … is something that China … is certainly capable of in the future" (Nature editorial, 2019: 623). As world leaders race for an increase in PV manufacturing and installation, it is important to understand the underlying biophysical relations that are linked to the continuation of such mega-industrialization. The result uncovered in this chapter may shed theoretical light on some of China's changing trade relations with neighboring its countries.

China has articulated one of the world's most ambitious aspirations for a future industrial economy propelled by renewable energy. The degree to which this aspiration will be fulfilled remains unclear but given its record of accomplishment of manufacturing and installing solar PV modules, it should be taken seriously. In a speech to the UN in October 2016, Liu Zhenya, the former chairman of the State Grid Corporation of China spelled out the vision for the international organization Global Energy Interconnection Development and Cooperation Organization (GEIDCO) whose mission is to develop the installation of a global renewable electricity grid under the flag of sustainable development. As reported by Fialka (2016) in *Scientific American*, Liu Zhenya laid three phases of the global mega project that would eventually "transmit solar, wind and hydroelectric-generated power from places on Earth where they are abundant to major population centers, where they are often not." First, individual nations will redesign their electricity grids. Second, international efforts will be mobilized to build cross-national grids. Third, power lines and undersea cables will be built to connect cross-national grids across the globe. Liu Zhenya continued to argue that this would create a win-win situation in which sunny regions such as Africa and Central America could export clean energy to major cities that have the biggest need for the energy. In the end, Zhenya claimed, "the world will turn into a peaceful and harmonious global village with sufficient energy, green lands and blue sky." Questions concerning matter-energy requirements, their social distribution, and social-ecological impacts were conspicuously absent.

From what we learn in the case of the boom of the solar PV market, it quickly becomes illusory if social-cultural aspirations – such as Liu Zhenya's – are separated from their associated matter-energy requirements, social distribution, and social-ecological impacts in the world. Here it is important to remember the ecologically asymmetric relations between China and world economic peripheries that may come to increase in significance and magnitude with aspirations such as Lie Zhenya's (Yu et al., 2014; Peng et al., 2016; Tian et al., 2017; Shandra et al., 2019). Already, studies have shown that the Chinese PV industry will have to import many of the materials used in solar PV manufacturing from elsewhere in order to further scale up its solar PV manufacturing (Wang et al., 2019). Simultaneously, Chinese firms are relocating their manufacturing facilities to Southeast Asian countries while attempting to create new export markets in semi-peripheral and peripheral countries (Shen and Power, 2017). In line with this, Yu et al. (2016: 471) suggest that new demand may be explored in less-developed regions that could benefit from increased electrification and green growth. The question, however, is what Chinese firms would demand in turn and what biophysical trade relations this would imply. Taken together, the Chinese social-cultural aspirations for a globally interconnected electricity grid harnessing renewable energy and the biophysical implications of such an endeavor points to the increasing relevance of understanding the distributive problems of advanced solar PV technologies and the anticipated new metabolism.

The solar boom: The vision and the reality

At least since the early 1970s, utopian visions in which modern societies sustain themselves on the direct energy of the sun has informed the collective imagination of developed nations. These visions were articulated in a time when actual manufacturing and installations of renewable energy technologies remained small-scale and modest. Today, however, solar PV technology is no longer an alternative technology. Over the last two decades, a boom in solar PV manufacturing and installation has occurred that has transformed solar PV technology into a commercial commodity. This boom, motivated and encouraged by European (notably German) demand, started with the increasing significance of coal-propelled China into the international market as a manufacturing and exporting nation. So far, explanations for this boom have focused on solar PV technology simply as an immaterial phenomenon. The consequences of the preoccupation with idealist explanations are that the underlying social-ecological relations of the commercialization have remained invisible.

This chapter has shown that the boom itself – understood as a trade relation between China and Germany – was characterized by an intensification of ecologically unequal exchange whereby Germany could displace an ever-increasing amount of the environmental burdens associated with the realization of its social-cultural vision of an industrial society sustaining itself on renewable energy sources to China. Without this relation, presented as an option due to relative price differences between the nations, Germany would not have been able to fulfill its goals of installing solar PV capacity without compromising the stability of its domestic economy and the condition of its domestic environment. These results support the hypothesis that a net transfer of resources, flowing from one social group to another, is a necessary social relation for realizing conventional aspirations to capture energy directly from the sun through the means of solar PV technology.

Even if solar PV modules can be installed to facilitate local democratic communities that embrace democratic ways of being, this chapter shows that there is an additional political dimension to solar PV technologies at the scale of the world economy. This political dimension, characterized by a world division of labor, likely intensified with the commercialization of solar PV technology over the last two decades. Recent changes in the now global solar PV industry are thereby associated with a transformation of solar PV technology that current visions for a future sustainable society relying on renewable energy sources has yet to catch up to. This is likely to become an ever-greater concern in need of attention in a world economy where major actors continue to advocate for an ever-faster installation of ever-more solar PV technology.

5. The political ecology of the technological boundary: On the inherent politics of large-scale solar PV development

"*The solar advocate's belief that solar technologies are compatible with democracy pertains to the way they complement aspects of society removed from the organization of those technologies as such.*"

Langdon Winner

Drawing boundaries is a powerful political act. Consider the enclosure acts in England (circa 1600-1900) that gave rise to the proletariat through widespread privatization of the commons, or the Valladolid debate in Spain in the mid-16th century that came to justify war against Native Americans on the erroneous belief that they were categorically different from Christian Europeans (so-called "natural slaves"). In both cases, a categorical boundary was drawn and enforced to justify social relations of power, i.e., capitalism and colonialism respectively. Importantly, there was nothing inherent in the English landscapes that forced the landowners to draw the new property boundaries. Nor were there any inherent biological differences between Americans and Europeans that could justify colonial exploitation and war. The resulting social relations – proletariat/capitalist and slave/colonizer – were not material categories, but socially and historically constructed ones.

In the context of drawing boundaries for political purposes, it is interesting to see how cognitive scientists distinguish what they call "artificial" versus "natural" categories:

> By natural object categories we mean categories with lexical entries (e.g., bird) whose instances correspond to entities in the world (e.g., robin, turkey, pigeon). Artificially constructed categories typically involve novel stimuli where the

> constituent features or properties of examples are familiar, but where the experimenter [or boundary drawer] specifically manipulates the properties of examples and the assignment of examples to categories to create some particular category structure of interest. Neither the examples nor the categories need necessarily correspond to real-world entities (Medin and Heit, 1999: 101-102).

In the examples above, two artificially constructed categories (property and natural slave) were developed for political purposes (capital accumulation and resource exploitation), through the drawing and enforcing of boundaries (enclosure and othering) that were not naturally encouraged in the world. The possibility that humans can cognize categories that have no counterparts in the physical world is at once helpful and politically charged. On the one hand, it allows for deductive learning and hypothesis testing (i.e., establishing *a priori* categories that are then tested). On the other hand, in the lack of relations to "real-world contexts," artificial categories can miss or purposefully leave out important aspects of the world, sometimes with far-reaching political consequences (Medin and Heit, 1999: 103).

An illustrative example of the latter is the partition of the African continent during "the scramble for Africa," where European colonial powers during the Berlin congress 1884-85 drew artificial boundaries to agree over what colonial power owned what territory. This was done with little regard for the real-world context, such as physical features of landscapes (including rivers, forest areas, mountains, etc.) or already established social-political entities or cultural groups (Griffiths, 1986). The awkward straight lines of many African states today is but one reminder of the scant regard in colonial Europe for the continent and its peoples. Still today, more than a hundred years later, Africa's inherited political geography influences its politics and serves as a catalyst for numerous political-ecological conflicts, including trans-boundary resources disputes (Okumu, 2010) and ethnic wars (Michalopolous and Papaioannou, 2016).

The latter examples demonstrate Alfred Korzybski's (2000[1933]: 58) observation that "a map is not the territory it represents." That is to say, the representation (or categorization) of a thing is not the same as the thing itself. However, the representation (the map) can be truer to the thing (the territory) the more attentive one is to the real-world context. What aspects of reality should be included in the representation, however, is a notoriously political question. Current debates regarding the feasibility of "green growth" illustrates this very clearly. Evaluations of the notion of "green growth" are intimately tied up in questions concerning the categorization of economies, where "decoupling" of economic activity from matter-energy throughput is more likely experienced if the boundary of what constitutes an economy is narrowly drawn at the regional or national level and/or if indirect biophysical costs are omitted from the analysis (Jiborn et al., 2018; Kan et al., 2019; Hickel and Kallis, 2019). This is a situation in which two sets of categorizations of what constitutes "the economy" typically lead to two sets of conclusions regarding the phenomenon of "decoupling" and the sustainability of "green growth." Whereas the more narrowly defined categorization – of the economy as a national or regional entity – sometimes confirms the presence of relative decoupling, the more widely defined categorization – of the economy as an international phenomenon – tends to disprove it. The logical conclusion, as pointed out in several studies, is that national or regional decoupling occurs, but that it occurs through mechanisms of environmental load displacement, such as ecologically unequal exchange (Jorgenson and Clark, 2012; Isenhour and Feng, 2014; Parrique et al., 2019). This conclusion can only be reached by considering the economic process as a wider, international category. However, this is methodologically foreclosed in most studies on decoupling.[47]

The question of how to draw boundaries around what constitutes technology (or, technologies) are well known, albeit contested, within philosophy of technology (see chapter two). The instrumental definition of technologies, as neutral tools to be employed for different social-political purposes, has been thoroughly criticized. One path-breaking study in this regard, edited by Wiebe Bijker, Thomas Hughes and Trevor Pinch (1989), established that technologies are deeply social both in how they arise from and shape social interactions. The instrumentalist view, from this perspective, is objectivistic and narrow because it captures only a miniscule proportion of what constitutes the vital components of a particular technology. From this critique emerged the systems view of technology, primarily related to the work of Thomas Hughes (1986), who extended the boundary of technological artifacts by recognizing how they were inseparable from a system consisting of organizations and things such as "manufacturing firms, utility companies, and investments banks … books, articles, and university teaching and research programs" as well as "regulatory law" and "natural resources" (ibid. 51). Crucially, the interaction of each component was understood to "contribute directly, or through other components, to the common system goal" (ibid.). Technological artifacts, in

---

[47] In a substantial review (N=11,500 screened, n=835 analyzed) of "decoupling", Wiedenhofer et al. (2020) concluded that as few as 8% of all studies included consumption-based environmental loads occurring outside the national boundary.

this sense, are component parts emerging from and within a specific systemic telos.[48]

The widely accepted systems view of technology redefines in what sense technologies are considered political. As suggested by Dusek (2006: 36), if we include "advertising, propaganda, government, administration, and all the rest, it is easier to see how the technological system can control the individual, rather than the other way around."[49] The choice of including or excluding certain aspects of technological systems is a political act because it defines who or what is relevant to consider. To understand this, it is worth quoting Hughes (1986: 55) at length:

> The definer or describer of a hierarchical system's choice of level of analysis from physical artifact to world system can be noticeably political. For instance, an electric light and power system can be so defined that externalities or social costs are excluded from the analysis. Textbooks for engineering students often limits technological systems to technical components, thereby leaving the student with the mistaken impression that problems of system growth and management are neatly circumscribed and preclude factors often pejoratively labelled "politics." On the other hand, neoclassical economists dealing with production systems often treat technical factors as exogenous. Some social scientists raise the level of analysis and abstraction so high that it matters not what the technical content of a system might be.

On the one hand, then, technologies can be so narrowly defined that aspects of great importance are omitted from the analysis. On the other hand, technologies can be so broadly defined that they lose sight of any meaningful relation between the system telos and the technologies within it. Winner (1980: 122) warned early that "the corrective," i.e., to draw the technological boundary very wide, could lead to the erroneous conclusion that technical artifacts do not matter at all. Somewhat provocatively, he contends that this conclusion validates what social scientists tend to think of the study of technology in general, "namely, that there is nothing distinctive about the study of technology in the first place" and that they therefore "can return to their standard models of social power … and have everything they need" (ibid. 122).

---

[48] This telos is generated by the historically developed relations of production and upheld by the social aspirations of powerful actors. Today, it pertains to the drive for infinite capital accumulation (see chapter three).

[49] ANT scholars, such as Latour (1988), carried this position to an extreme, suggesting that technological artifacts themselves have agency by virtue of their consequential interaction with humans.

In response to this, Winner (1980) has offered the to-date most thorough analysis of how political artifacts themselves can be considered political.

Winner's (1980) thoughts on the politics of artifacts can be presented as three ways in which technologies can be political.[50] First, a technological artifact can acquire politics by virtue of being nested in a particular political context that is not necessary for its existence. This is a situation in which tweaking the design, rearranging the political context, or mitigating a particular effect of the technology does not change the device in any significant way. Technologies, in this sense, can nevertheless be political because their existence can be linked to the political aims of the owners or designers (Winner 1980: 130). In such cases, the technological artifact is both an embodiment of and a tool for the establishment of a particular social relation, but it is not inherently so, since it might exist as a "roughly similar device" also within other social-political contexts. Winner does not name this form of politics, but we could simply call it "acquired" politics on the basis that the particular politics is granted exogenously by the system telos, e.g. from the organizational networks that are in control of the design process (see e.g. Feenberg, 1991). In this sense, technologies are political in the sense that they can – but do not have to – be employed to further specific social-political relations or agendas (e.g., research, commerce, war, or capital accumulation).

Second, Winner's analysis reveals the existence of so-called "inherently political technologies" that are contingent upon specific social relations of power.[51] Winner (1980: 130) divides these inherently political technologies into two sub-categories. For ease of reference, we may call them "strong inherent politics" and "weak inherent politics."

1. *Strong inherent politics*: Technologies that require particular social-political relations to exist in the physical world. Railways, nuclear power, and atom bombs, Winner suggests, are technologies that require engineering and military experts operating under hierarchical chains of command that make sure the system is predictable and safe (ibid. 130-32). These technologies require a "social environment to be structured in a particular way in much the same sense that an

---

[50] Winner defines the political as "arrangements of power and authority in human associations as well as the activities that take place within those arrangements" (1980: 123).

[51] A relation of power is broadly understood as a situation in which one group or individual has a disproportionate capacity to form decisions or carry out actions affecting another group or individual. Power, as the capacity to form decisions and carry out actions, is both social and physical (Russell et al., 2011).

automobile requires wheels in order to turn" (ibid. 130). The social-political relation, in short, is a necessary condition (or part) of the technological artifact or technological project. Engels, we can recall, argued that industrialism in general, or what he called "the factory system," embodied such an inherent politics (see chapter three).

2. *Weak inherent politics*: Technologies that are strongly compatible with particular social-political relations. In this political form, a technology does not strictly require a particular social-political context, but it does encourage it. Here, Winner briefly discusses solar energy technology as an example of a technology that many consider to be strongly compatible with a more democratic and egalitarian society, based upon how it encourages decentralized ways of harnessing energy that is at once more "accessible, comprehensible and controllable" (ibid. 130).

As the introductory quote to this chapter suggests, Winner himself is somewhat reserved regarding the weak inherent politics of solar energy technology, because this categorization analytically excludes the system's context through which solar technologies are actualized in the world. That is to say, *the perceived democratic potential of solar energy technologies may depend upon how the boundary of the technology is drawn*. In this chapter, I assess the inherent politics of large-scale solar PV projects as it relates to the perceived boundary of what technology is. The aim of this analysis, following Winner, is not to tease out the trade-offs of a particular technology concerning number of jobs, pollution, or potential revenues in a sort of cost-benefit analysis, but to examine the "important consequences for the form and quality of human associations" as a result of the pursuit of solar PV technology, particularly as it relates to the current formation of the new metabolism (Winner, 1980: 131; see chapter three).

This chapter will attempt to answer and discuss the question of whether and in what sense large-scale solar photovoltaic technology projects are inherently political. This will be considered in relation to two biophysical measurements, those of "energy return on energy investment" (EROI) and "power density." First, I attempt to show how methodological disagreements in the study of EROI illustrate how specific ways of drawing the technology boundary is intertwined with different notions of how solar PV technologies are understood as political. Following this, I turn to the "power density" measure and show that the large-scale solar PV projects proposed by four leading solar countries (China, Germany, India, and Italy) are inherently political by virtue of necessitating displacement of land requirements in the world-system. In the discussion, I make the claim that the low EROI and low power density of solar

PV technologies should not be understood as something that renders a large-scale transition to solar PV technology impossible, but that it raises important questions of justice, ecological sustainability, and social relations of power in the emerging metabolism.

The boundary debate in the study of energy return on energy investment (EROI)

All ordered structures, including all living things, require an inflow of energy from their environment in order to sustain themselves in the world (see chapter two). Among dissipative structures – identified by the ability to reproduce their own structure – some of this energy is necessarily dissipated in the search for energy. The myriad of organisms in nature, all dissipative structures, represent a great variety of strategies by which energy is dissipated in the search for energy. They are nevertheless all subjected to a common rule, namely that they need to acquire more energy than they dissipate during their search for energy. To be sure, many animals and even some humans skilled in the art of fasting can go long periods without energy inputs. But even if many organisms have ways of buffering energy access, e.g., through fat storage, the fact that they need to acquire more energy than they dissipate remains true over their lifetime. Importantly, it is not enough that the organism obtains the exact same amount of energy that it dissipates, since the transformation of one energy form to another necessarily implies a loss of useful energy. The digestion of food, for instance, requires that a certain amount of energy be dissipated. In the case of organisms, some energy also needs to be designated to building their own body (e.g., maintaining healthy cells, growing, healing), providing for the continuation of the species (e.g., reproducing, nursing, courting) and enjoyment (e.g., playing, socializing, etc.).

The concept of "energy return on energy investment" (EROI) captures this biophysical condition of dissipative structures and presents it as a measurable ratio (figure 14). In its most elementary form, it is understood as the ratio of the energy returned to the energy invested of a particular energy technology (or energy strategy).

$$\mathbf{EROI} = \frac{\mathbf{ENERGY\ RETURNED}}{\mathbf{ENERGY\ INVESTED}}$$

Figure 14. A simple rendition of how to measure energy return on energy investments.

The strength of the measure lies partly in its capacity to test some basic biophysical necessities of energy strategies. As I have already mentioned, every energy technology necessitates a higher energy return than the energy invested in building and maintaining that strategy, simply as a way of surviving. This means that the EROI of any energy technology needs to be larger than 1:1 (expressed as “one to one”) to be regarded as an energy strategy with the capacity to harness energy from nature. Hall et al. (2009: 29-30) go as far as suggesting that this imperative should be regarded as an “iron ‘law’ of evolutionary energetics,” the so-called “law of minimum EROI.” The fact that dissipative structures need to dissipate energy not only for the sake of acquiring energy, means that the EROI of any viable energy strategy needs to be higher than 1:1. There must be some net energy surplus to sustain other necessary practices of the dissipative structure. Hall et al. (2009: 45) have suggested that 3:1 is the bare minimum EROI for sustaining larger human societies. Recent studies (de Castro and Capellán-Pérez, 2020: 4) suggest that an EROI of 10-15:1 is necessary for sustaining advanced industrial societies, with high quality modern healthcare, well developed transportation infrastructure, and more. Lambert et al. (2013), in a study on the relation between EROI and life quality, conclude that a high EROI in a society correlates with few underweight children, high health expenditure per capita, high access to water among rural populations, and high gender equality.

The non-linear character of the EROI measure means that there is a more significant difference between 2:1 and 5:1 than there is between 20:1 and 50:1. The “net energy cliff” illustrates the relation between EROI, the percentage of energy required to invest in a specific energy strategy, and the percentage of energy returned to society, or the organism (figure 15). An energy technology with an EROI of 2:1, for example, means that 50% of society’s energy is dissipated in the procurement of energy. The remaining 50% can be allocated to other ends. In contrast, an energy strategy with an EROI of 10:1 demands only 10% of society’s energy for energy procurement, while the remaining 90% can be allocated to other ends. The difference between 10:1 and 50:1 is merely a few percentages. In line with Carnot’s theorem, no matter how high the EROI is, a certain percentage of the energy surplus is always necessary for energy procurement.

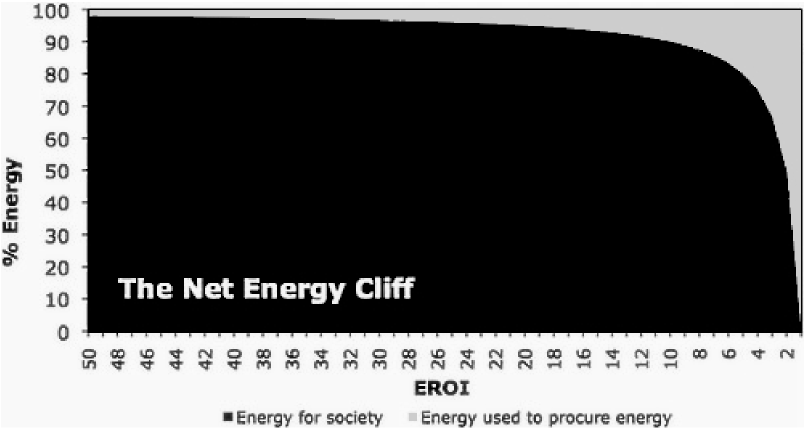


Figure 15. The Net Energy Cliff.
Adopted and reworked from Murphy and Hall (2010: 108).

The measure of EROI is primarily applied to the study of human energy strategies, i.e. energy technologies, where it serves the purpose of assessing the viability of different energy technologies in relation to particular ends. Since the concept rose to prominence, it has triggered two core debates among researchers. These demonstrate the problematic character of the measure. The first of these debates arose from the concern that the production of biofuels, such as ethanol from corn, might require more energy than the final ethanol fuel can deliver to society (Giampietro et al., 1997; Pimentel, 2003; Pimentel and Patzek, 2005). However, the low EROI meant not simply that corn ethanol and other biofuels might not be able to deliver a net energy to society, but also that they would require energy subsidies from other fuels, such as coal and fossil gas, which would contribute to an increase in greenhouse gas emissions. These studies also pointed out the link between a low EROI and the requirement of large amounts of land under intensive industrial cultivation means that biofuels compete with food production and contribute to significant deforestation and soil degradation. A substantial amount of literature and activism then emerged around understanding and combating the environmental impacts of biofuel production, particularly as they were disproportionally felt in the global peripheries (e.g., Shiva, 2008; Dauvergne and Neville, 2010; Martinez-Alier, 2011; Hermele, 2014).

Contra to this, Farrell et al. (2006) offered an apologetic view, suggesting that the EROI of biofuels might be higher than the break-even point at 1:1 and that they therefore displayed some positive potential in applications for environmental ends (see also Cleveland et al., 2006). This positive potential, however, would only come under future technological improvements, such as "sustainable agriculture and cellulosic ethanol production" (Farrell et al., 2006: 508). Even with the development of new biofuels and continued claims of technological improvements, biofuels remain the least efficient energy technology of industrial societies to date (see Murphy and Hall, 2010; Hall et al., 2014; Chiriboga et al., 2020). Meanwhile, environmental, and social-political implications have largely been ignored in favor of instrumentalist preoccupations with artifact improvement.

The second debate concerns the EROI of solar PV technologies. In this debate, the major question has been whether the EROI of solar PV technologies is generally high enough to sustain advanced industrial societies. While Prieto and Hall (2013) were early to demonstrate the importance of this question, the kindle of the recent debate was a study by Ferroni and Hopkirk (2016) showing that solar PV systems in regions with moderate solar insolation (such as Switzerland) had an EROI less than 1:1. In these authors' words, solar PV systems can thereby be understood as "non-sustainable energy sink[s] or a non-sustainable net energy loss" (ibid. 343). This was soon met with a comprehensive response from Raugei et al. (2017) pointing out a number of methodological issues and suggesting that the actual EROI of solar PV systems was in fact an order of magnitude higher than Ferroni and Hopkirk's study showed. The response in turn by Ferroni et al. (2017) rebutted these methodological concerns in a manner that allows us to point out some core issues in the debate.

The debate seems at heart to concern the issue of what boundaries are appropriate for an EROI analysis of solar PV technology. The boundary problem is a well-known problem among EROI scholars, and it featured also in the biofuel debate. However, it arguably became more prominent in the solar debate. If we look at the disagreement more closely, we can see that Ferroni et al. (2017: 499) repeatedly indicate that they think Raugei et al. (2017) adopt a narrow understanding of PV technology by "confin[ing] themselves within unrealistic boundaries" for understanding the transition away from fossil energy. Raugei et al. (2017), on the other hand, seem more concerned with making sure that different energy technologies can be subjected to comparison under the same technological boundary. To put it simply, while Ferroni and Hopkirk's (2016) study is concerned with the biophysical reality of transitioning away from fossil energy, Raugei et al. (2017), in their critique, is concerned with establishing a methodological consistency by drawing a narrow, well-defined, technological boundary. Raugei (2019) has elsewhere made the remark that this narrow boundary is drawn for the purpose of providing clear proposals for policy makers.

This exemplifies a case in which the particular *aim* of the study or research program informs what technological boundary is appropriate (for discussion, see Carbajales-Dale et al., 2015; Palmer and Floyd, 2017).

It has long been recognized within the study of EROI that a more widely drawn technological boundary gives a lower EROI ratio and vice versa (Murphy and Hall, 2010; Hall et al., 2014; Capellán-Pérez et al., 2019). Subsequently, numerous types of technological boundaries have been suggested for different aims. These boundaries vary primarily in how to understand the numerator (energy invested). These include, from narrowest to widest, the following technological boundaries (see Hall et al., 2014; Capellán-Perez et al., 2019; de Castro and Capellán-Perez, 2020):

a) Standard EROI ($EROI_{st}$): This boundary represents the narrowest technological boundary. It includes the direct energy dissipated on site and the indirect energy dissipated in the manufacturing of the infrastructure used on site.

b) Point of use EROI ($EROI_{pou}$): Apart from the energy dissipated directly on site and in the manufacturing of infrastructure used on site, this boundary includes also the energy required for delivering a certain energy carrier to a particular point of use (including refinery, processing, transportation, maintenance of electric grid, etc.).

c) Extended EROI ($EROI_{ext}$): This boundary considers the energy dissipated for getting, delivering and using a given energy carrier. This boundary also extends further back in the production chain by considering the energy embodied in the necessary labor time and capital investment.

This shows how the very same energy technology can be understood in many different ways depending on what technological boundary is chosen. While this fact is taken as evident within the EROI literature, from a philosophical point of view it is an interesting finding. It means that even the physical performances of technological systems can be understood very differently based on how they are demarcated. The different boundaries above thereby represent different epistemologies, but ultimately suggest routes to an alternative ontology of technology. The first point I wish to make in this chapter is that the boundary of solar PV technology may influence not only its calculated efficiency, but also – by extension – the way in which solar PV technology is understood as inherently political. To begin to understand this, we can look at the results of different EROI calculations of solar PV technology under different technological boundaries.

Table 6. Energy return on energy investment for solar PV technology under three different technological boundaries.

Technological boundary	$EROI_{st}$	$EROI_{pou}$	$EROI_{ext}$
Solar PV technology	7.7-38:1[a]	3.5:1[b]	0.82-4.5:1[c]

[a](Raugei et al. 2012; Bhandari et al., 2015; de Castro and Capellán-Peréz, 2020)
[b](de Castro and Capellán-Peréz, 2020)
[c](Weißbach et al., 2013; Ferroni and Hopkirk, 2016; de Castro and Capellán-Peréz, 2020)

Table 6 shows how the expansion of a technological boundary implies a decrease in calculated EROI ratios. This is an expected result. These different boundaries and their results can be understood as corresponding to different demarcations of the technological continuum (see chapter two). All the EROI measures take into consideration the energy dissipated for the manufacturing of the infrastructure of solar PV technologies prior to the actualization of the modules. All the boundaries to some degree preclude fetishisation. Even the narrowest $EROI_{st}$ measure is a way of understanding the relation between past energy investments and present and future energy returns. In this way, the concept is an acknowledgement that energy is not created from human ingenuity (i.e. a recognition of the first law of thermodynamics). However, each measure does so differently and under different assumptions regarding technology. Since $EROI_{pou}$ is uncommon in the study of solar PV technology, I will focus on the goals, conclusions, and assumptions derived from $EROI_{st}$ and $EROI_{ext}$ respectively.

$EROI_{st}$

Among those favoring the $EROI_{st}$ boundary, the goal, as we have seen, is often explicitly to offer a comparison between solar PV technologies and fossil energy technologies for policy makers. The results, usually concluding that the EROI for solar PV technologies is fairly high, have so far been that solar PV technologies do indeed offer a viable option for replacing fossil energy carriers and for sustaining advanced industrial societies. However, when confronted with the fact that the technological boundary is narrowly drawn, the replies sometimes reveal fetishized understandings of technological progress. For example, in their critique of the $EROI_{ext}$ boundary, Raugei et al. (2017: 378) write:

> It is crucial to recognize that extending the EROI boundaries beyond the inclusion of the physical inputs required for the production and operation of one unit of energy output from the analysed energy system also gradually shifts the goal of the analysis from the (comparative) assessment of its *intrinsic net energy performance* … to the assessment of the ability of the analysed system to support the entire societal demand for the type of energy carrier it produces (emphasis added).

This is a view in which the technological artifact is of primary importance because it is believed that it can exist and perform tasks apart from its wider systemic context. The phrase “intrinsic net energy performance” reveals the assumption that energy technologies have productive capacities that should be understood as separate from their wider social-ecological conditions. While the necessary past social-ecological conditions are taken into consideration to some degree, they are narrowly considered.

As in the case of biofuels, the view in which the boundary is narrowly drawn serves the ideological function of covering for potential technological inefficiencies with reference to a taken-for-granted improvement of an exogenous system. If a particular technology shows a low EROI value, then this is not taken as a wider cause for concern but seen as an opportunity for further technological progress. For example, Raugei et al. (2012: 580) argue, “technological improvements are expected to continue providing incremental life cycle energy efficiency gains to the existing PV technologies, and even radically more efficient, third-generation devices might become available in the long run.” However, the energy necessary for such technological progress is not considered relevant for the EROI analysis, which remains confined to the study of the energy technology’s “intrinsic net energy performance” (ibid. 581). Thus, energy consumption associated with such processes as the design and research for improved cell efficiency, the search and extraction of promising raw materials, added transportation routes, additional refining and processing of materials, added links in the commodity chains, etc., are all seen as independent from the technological progress that they are advocating. Meanwhile, we know that the search and extraction of new and higher quantities of materials for the transition to a new metabolism is having very real and politically laden consequences for communities and ecosystems worldwide (see e.g., Hein et al., 2014; Yenneti, et al., 2016; Church and Crawford, 2018; Sonter et al., 2020).

Raugei et al. (2017: 382-83) refute the need for including such “associated environmental externalities” in the EROI measure, while simultaneously stressing the importance of keeping up-to-date regarding technological improvements and data in the case of “rapidly evolving technologies such as PVs.” This selective view is symptomatic of “machine fetishism” whereby the technological artifact (e.g., PV module) and improvements upon it are understood as independent from the wider social-ecological relations and conditions that it necessitates. This, in short, is a view that is blind to the wider political-ecological implications of solar PV technologies and their development during the formation of the new metabolism. Within the overarching goal of providing recommendations for policy makers, studies employing the EROI_{st} boundary thereby primarily serve the political purpose of uncritically legitimizing the large-scale production of solar PV technologies under any social-ecological condition.

$EROI_{ext}$

Among those who favor the EROI_{ext} boundary, the goal is often directed to the question of whether solar PV technologies can be employed to sustain advanced industrial societies (Prieto and Hall, 2013; Pickard, 2014; Ferroni and Hopkirk, 2016; Capellán-Peréz et al., 2019; de Castro and Capellán-Perez, 2020). Among these studies, comparison between electricity generated from solar PV technologies and fossil energy is of minor importance, because it is already clear that a transition away from fossil energy is both necessary and desirable. Since the last 200 years of rapid industrialization have proven the viability for fossil energy technologies to support the emergence (but not necessarily continuation) of advanced industrial societies, a comparison is not strictly relevant for the aim of these studies. Rather, what is truly pressing is the question whether renewable energy technologies, such as solar PVs, can support global industrialism. The question at stake is the very continuation of high-energy modernity (see chapter three). To understand this, the technology boundaries must necessarily be widely drawn to give a more complete picture of the associated energy investments and necessary energy returns.

The methodological difficulties in studying the energy dissipated along the production chains around the globe remains a complex problem, but the results of studies on the EROI_{ext} of solar PV technologies are nevertheless surprisingly similar. Most studies seem to reach the conclusion that the EROI_{ext}, ranging from 0.82:1 to 4:1, is too low for maintaining advanced industrial societies (see table 1). Even among the most favorable estimations (4:1), the net energy available to society would amount to no more than roughly 70% of all energy metabolized (see figure 15). Roughly 30% of all global societal efforts (including all jobs, infrastructure, research, etc.) would need to be geared towards the energy sector in such a scenario.

Several conclusions can be drawn from these findings. Some have concluded that solar PV technologies can be a viable option for sustaining industrial societies, but only if they are complemented with fossil energy carriers (Prieto and Hall, 2013; Hall et al., 2014). This, as they often note, defeats the purpose of rapidly installing solar PV technologies in the hope of mitigating catastrophic climate change. In the scenario of a rapid transition relying upon solar PV technology, the low EROI implies that an enormous amount of energy and materials would need to be metabolized during the transition phase (Capellán-Peréz et al., 2019).[52] Such an increase in metabolic throughput is antithetical to greenhouse gas emissions reduction targets aiming to remain below a global warming of 2°C, which is why the rapid transition has to be geared towards a degrowth trajectory that aims to reduce aggregate metabolic throughput (Sers and Victor, 2015; Capellán-Peréz et al., 2019). This paradoxical situation, wherein the energy transformation is reliant upon an increased matter-energy throughput problematic for reaching the emissions targets, has been called “the energy-emissions trap”and the “transformation paradox” (Sers and Victor, 2015; Heikkurinen, 2019). Capellán-Peréz et al. (2019:18) similarly conclude that there is a “trade-off between urgent climate mitigation and viability of the [economic] system,” essentially showing that the proposed trajectory for “green growth” based on the Environmental Kuznetz Curve hypothesis is detrimental for mitigating climate change. Studies employing the $EROI_{ext}$ boundary thereby serve the political purpose of questioning the sustainability of the large-scale production of solar PV technologies under specific economic imperatives (e.g. growth).

I would like to suggest that both these interpretations have their shortcomings when it comes to the emerging metabolism and its global politics. On the one hand, the claim that technologies harbor an intrinsic productive potential can only be true from a fetishized perspective that purposefully ignores the wider global politics of the emerging solar PV industry. On the other hand, the assertion that solar PV technologies cannot be installed to further advanced industrial societies under the label “green growth” seems to be at odds with the boom in both the manufacturing and installation of solar PV modules over the last two decades (see chapter four). The synthesis of these two conclusions, I would argue, is that the low $EROI_{ext}$ of solar PV technologies can partly be circumvented by select social groups if the associated energy investments are displaced elsewhere. The high $EROI_{st}$ of solar PV technologies can be understood as evidence of this possibility. In such a way, the continued use of fossil energy and the continuation of global environmental inequality would make solar PV technologies viable for certain groups at the expense of other groups in the world-system.

---

[52] Given the 20-30-year life span of solar PV modules, this situation is likely a continuing problem if the energy system reliant upon solar PV technology should become mature under capitalism.

Therefore, while it may be true that "inequality makes the metabolic system less efficient," a world division of labor[53] may actually serve to increase the EROI of solar PV technologies in certain parts of the world through displacement of material-, labor-, and energy-intensive production processes to other parts of the world (quote from de Castro and Capellán-Peréz, 2020: 6). As shown in the previous chapter, much of the energy dissipated for the German solar boom came from processes outside the national boundary, notably China. This indicates that a country or social group may enjoy higher energetic benefits from the installation of solar PV systems as long as they can outsource the associated energy and land investments to other countries or social groups.

The main point here is that physical inefficiencies are substitutable for global social inequalities in the transition to solar PV technology. This view, crucially, can only be understood from a widely drawn technological boundary that also takes into consideration world trade in resources and world division of labor. This view is in agreement with the generic conclusions drawn among those studying solar PV technology under the $\mathrm{EROI}_{\mathrm{ext}}$ boundary but adds the question for *whom* the "green growth" trajectory is problematic. If, as some studies suggest (Isenhour, 2016), the policy makers of core regions of the world experience "green growth" from the fetishized perspective of the $\mathrm{EROI}_{\mathrm{st}}$ boundary, then this can be understood as a cultural impediment to successfully mitigating climate change at a global scale. The transition would, under such circumstances, seem successful for the globally rich (i.e., from their own perspective), while actually depending on increased energy throughput and greenhouse gas emissions displaced to other parts of the world-system.

With reference to the low $\mathrm{EROI}_{\mathrm{ext}}$ of solar PV technology, it remains unclear whether environmental load displacement is not only possible, but also *necessary* for the success of large-scale solar PV technology projects. That is to ask, given their low physical efficiency, do large-scale solar PV technology projects embody a "strong inherent politics" by necessitating environmental load displacement in the world-system? With reference to the definition of "strong inherent politics" above, we can rephrase this question in terms of whether a world division of labor is a necessary condition for (or part of) large-scale solar PV projects in the absence of fossil subsidies. To answer this question, we will leave the realm of energy and turn to the calculation of land requirements for the proposed plans for installing solar PV modules in four countries.

---

[53] Understood as global differences in wages, rent, and pricing of natural resources.

Power density extended: Calculating the necessary land for the solar aspirations of China, Germany, India, and Italy[54]

Apart from requiring energy, all organisms and their energy strategies occupy space in the world. The concept of power density, developed by Vaclav Smil (2006, 2015), formalizes this condition in a simple measure designating the horizontal land area needed per watt of energy (expressed as W/m^2) (figure 16). In Smil's own words, power density is a means of "quantifying [the] power that is received and converted (or that is potentially convertible) per unit of land, or water, surface" (2015: 14-15). Similar to EROI, power density is a powerful indicator because of its simplicity and wide applicability. However, it also hides complexities in how to measure the denominator and numerator, which is dependent upon a wide range of contextual factors (Smil, 2015: 23-40). In the case of the denominator (power), this includes factors such as solar insolation of the particular geographical region, PV cell conversion efficiencies, panel direction, risks of direct damage, entropic degradation over time, and more. These are all factors that *in situ* reduce the theoretical peak power capacity (Wp) of a particular energy infrastructure. For instance, in the case of a modern wind turbine operating under laws of aerodynamics, the efficiency is never higher than 0.59 * Wp (Smil, 2015: 19). In the case of the numerator, variations depend upon whether only the surface area of the solar PV modules or the aggregate surface area, including the spacing between the panels or turbines, is considered (de Castro et al., 2013; Smil, 2015: 36-40). However, the land required for the necessary labor and capital should also be included as relevant for the numerator (Hornborg et al., 2019).

$$\textbf{POWER DENSITY} = \frac{\textbf{POWER (ENERGY FLOW PER UNIT OF TIME, W)}}{\textbf{SURFACE AREA (m}^2\textbf{)}}$$

Figure 16. Simple rendition of how to calculate "power density."

The measure has so far mostly been used in the study of societal energy technologies for understanding the limits to surface areas in the transition away from fossil energy. At root of many assessments over the global implications of transitioning away from fossil energy lie concerns over the low "power

---

[54] This part contains reworked excerpts from Hornborg et al. (2019).

density” of renewable energy technologies (Scheidel and Sorman, 2012; de Castro et al. 2013; Piano and Mayumi, 2017; Capellán-Peréz et al., 2017). Calculations have shown that renewable energy technologies have a relatively low power density in comparison to fossil energy technologies (table 7). Compared to fossil energy technologies such as coal or oil, renewable energy technologies such as solar PVs require substantially more surface areas per unit of energy generated. This applies even to solar PV technologies, which display the highest power density among renewables.

Table 7. The power density of selected energy technologies.
Based on (Smil, 2006, 2015).

Energy technology	Power density (W/m^2)
Coal, oil, fossil gas	100-24,000
Nuclear	20-4,000
Solar PV power	9-13
Water and wind power	<10
Biofuels	<1

Following this troubling fact, critical geographers have pointed out that the transition away from fossil energy through mass installation of renewable energy technologies may “necessitate new and uneven power relations over land, energy, and territory that will not necessarily point to ‘just’ transitions to ‘sustainability’” (Huber, 2015: 9; McCarthy, 2015; Huber and McCarthy, 2017). Indeed, studies have shown how the import of biofuels and other “green” commodities produced in the world periphery or semi-periphery sometimes represents significant displacements of environmental loads in the world-system (Bonds and Downey, 2012; Hermele, 2014). A global political ecology of biofuels is emerging from nations’ efforts to transition away from fossil energy while aspiring to maintain an increasing matter-energy throughput.

With solar PV technologies in mind, Huber and McCarthy (2017: 666, emphasis added) contend that

> the geographies of industrial-scale renewable energy production might involve just as many ‘extractive peripheries’ or ‘sacrifice zones’ as current geographies of fossil fuel extraction, while their siting and the distribution of the energy produced there, and of its costs and benefits, would be no less *inherently political*.

To transition away from fossil energy, they continue, would imply that access to land become elevated as “the centre of energy struggles,” as it once was under the agrarian regime (ibid.; see also Scheidel and Sorman, 2012; cf. Malm, 2016). Notably, this understanding of solar PV technologies as inherently political contrasts to the more common view wherein the social-ecological problems associated with solar PV technologies are classified as "unintended consequences" or injustices in the "solar energy commodity chains" that can be engineered away (Andersen, 2013; Mulvaney, 2019; Hernandez et al., 2019). In this latter view, there is nothing inherently political with the technologies themselves. So far, however, this has not been empirically tested in relation to large-scale solar PV projects.

Power density extended: Principles and how to calculate it

In order to test whether large-scale solar PV projects are inherently political, the necessary surface area to realize a country's solar aspiration can be converted into a percentage of the entire country's surface area, which can then be related to the aspired percentage of solar PV capacity in the country's energy mix. Theoretically, this will reveal the extent to which large-scale solar PV technology projects can be considered as necessarily embodying a "strong inherent politics" by virtue of requiring an amount of surface area that would seriously restrict the country's economy (e.g., food production). This land requirement might also be higher than is feasibly available within a country's borders (e.g., MacKay, 2009).

Crucially, Smil's calculations of power densities only account for the immediate physical potential of a given technological infrastructure and not its total sociometabolic ''footprint'' including indirect spatial requirements. In Smil's account, technologies are drawn to coincide with the physical extent of the infrastructure rather than the total sociometabolic system that reproduces it. This corresponds to the technological boundary of the EROI_{st} measure. We can call it "power density standard" (power $\text{density}_{\text{st}}$). In relation to the technological continuum, the power $\text{density}_{\text{st}}$ measure considers a given energy technology narrowly as an object in the present. Still, the physical space covered by an infrastructure for harnessing fossil or renewable energy only represents a fraction of the space required to generate the necessary capital to build solar PV infrastructure. Smil estimates that electricity generation from PV solar modules has a power $\text{density}_{\text{st}}$ of 10–20 W/m^2 (Smil, 2015). This figure accounts for the space occupied by the surface of the solar modules only. When the aggregate space demanded by solar parks on site are taken into consideration the power density declines to 4–9 W/m^2 (Smil, 2015: 49–61). We may call this "power density aggregate" (power $\text{density}_{\text{ag}}$). This measure takes into consideration spacing between the solar PV modules, the infrastructure's "right of way", access roads, service buildings, and space not used on the site. Refining this boundary for solar PV technology, de Castro et al. (2013) examine six newly constructed solar parks in Europe and North America and arrive at an average power density$_{ag}$ of 4.28 W/m^2. The most land-efficient solar park in Spain reaches a power density$_{ag}$ no higher than 5.55 W/m^2 (table 8). For the calculations of the direct land requirements in this chapter, I will assume an average power density$_{ag}$ of 5 W/m^2. Considering the relation between technological boundary and EROI, I expect to find that power density$_{ext}$ will be lower than both power density$_{st}$ and power density$_{ag}$ (see table 7).

Table 8. PV technology and its measured "power density standard" and "power density aggregate." "Power density extended" has not yet been calculated.

Technological boundary	Power density$_{st}$	Power density$_{ag}$	Power density$_{ext}$
Solar PV technology	10-20	3.7-5.5	?

Sources: de Castro et al. (2013), Smil (2015), Capellán-Peréz et al. (2017).

The requisite labor and capital costs for solar development ultimately also represent land requirements. As both labor and capital have incontrovertible spatial correlates in the land areas required to reproduce and generate them, a calculation of the land requirements of a given technology would be incomplete without including the spatial demands corresponding to the inputs of labor and capital in the technology's construction and operation. This corresponds to assumptions regarding the technological boundary made in the study of EROI$_{ext}$ (Prieto and Hall, 2013; Ferroni and Hopkirk, 2016; de Castro and Capellán-Perez, 2020). In line with these approaches, an assessment of the conditions for a renewable energy transition must attend to the total spatial demands of the labor and capital required to construct and maintain a massive technological infrastructure capable of replacing fossil fuel technologies. To build energy technologies is not simply a matter of applying engineering knowledge to certain physical forces of nature, but of accumulating a material infrastructure for harnessing such forces. The human labor and raw material for this infrastructure are spatially dispersed in a global political economy of social-ecological exchanges that are notoriously difficult to trace (see the example from Nager IT as provided in chapter two).

To indicate the magnitude of demands on surface area, the person-years of labor time needed for a country's PV development can be multiplied with the average ecological footprints of the workers inside and outside that nation's borders. The required labor time could then be translated into hectares. While these ecological footprints would exist regardless of whether the workers produced and maintained solar panels, a country's planned PV capacity—i.e., the solar panels themselves—cannot exist without a supply of labor time representing eco-productive space under the given historical circumstances. The labor demand for solar PV manufacturing, installation, and servicing ranges from 18,400 (IEA, 2017; IRENA, 2017) to 37,286 (DOE, 2017) to 53,028 labor-hours per MW. Based on a somewhat conservative average of these figures I will assume an estimate of 35,000 labor-hours per MW throughout the entire global commodity chain. These labor-hours are dispersed in the world economy according to different tasks throughout the commodity chain (table 9). The ecological footprints of the aggregate labor-hours vary by country depending on what labor tasks in the commodity chain are conducted domestically and what tasks are outsourced to other nations.

Table 9. Employment distribution in select events throughout the global commodity chain of a solar PV module.

Based on Llera et al. (2013: 266).

Select labor tasks in the PV module commodity chain[55]	Percentage of labor-hours (%)	Geography
Projects/studies	1	Domestic/international
Silicon processing	3	Domestic/international
Cell manufacturing	8	Domestic/international
Module assembly	30	Domestic/international
Solar tracker	22	Domestic/international
Elect. Components and inverters	9	Domestic/international
Installation	21	Domestic
Operation	6	Domestic
Total	**100**	**-**

How do we calculate the spatial correlates of the extraction, transport, and manufacturing of the component parts of solar PV modules? The main obstacle to doing this is that economic exchange is conventionally measured in money. However, this complication can be overcome if we recognize that energy consumption and real GDP are causally linked (Warr and Ayres, 2010; Ayres, 2016; Sultan and Alkhateeb, 2019). Based on this observation, I use a method that translates money into energy and then translates energy into land (see also Prieto and Hall, 2013; Hornborg et al., 2019). Let us look at each translation in turn:

a) *Money to energy*. As the GDP of a country is proportional to its energy consumption, the money to energy ratio is straightforward (Ayres, 2016: 382-386). In physics, all production processes are

---

[55] Llera et al. (2013) do not account for the labor necessary for the raw material extraction.

transformations of materials, which require energy. Real GDP is a measure of a given economy's total production output (be it in goods or services). Since all production processes are transformations of materials that require energy, energy consumption is inextricably connected to GDP. As Hagens (2020: 6, footnote 2) put it, "Money is a claim on energy, materials, and many other things. But every single good and service which generates GDP requires some energy conversion." In short, energy is a physical production factor without which economic activity would simply not be possible.

b) *Energy to land*. The best available estimate of how much land is embodied in energy is the carbon footprint. This has been calculated by Wackernagel and Monfreda (2004), who estimate that the carbon footprint of fossil fuels is 1,050-1,900 ha/MW. This means that for every MW worth of fossil fuel infrastructure, 1,050 to 1,900 hectares of land is required. I will use the median figure 1,475 ha/MW. Importantly, this figure includes both the land for the physical infrastructure and the land for sequestering the carbon emissions accociated with the output of that infrastructure. Today, 84% of industrial energy is generated from fossil fuels, which means that I will calculate 84% of the capital investment as having a spatial correlate (BP, 2020).[56] This method of calculating the footprint of fossil fuels includes the surface areas needed for carbon sequestration through reforestation, which make up most of the footprint (99.998%). These surface areas may not strictly speaking be necessary for the operation of large-scale solar PV projects, but they are nevertheless required for their long-term sustainability.

Estimating the direct land requirements as well as the indirect land requirements of the necessary labor and capital required in the global commodity chains will provide an estimate of what we may call "power density extended" (power density$_{\text{ext}}$) (figure 17). This measure, when adjusted to the life span of the solar PV modules, can be used to assess the possible necessity for a country to rely upon a net importation of resources from the global economy in order to construct, install, and maintain a significant PV infrastructure over time.

---

[56] Since other energy sources have spatial correlates too, this means that the full footprint of the capital investment in PV is not calculated.

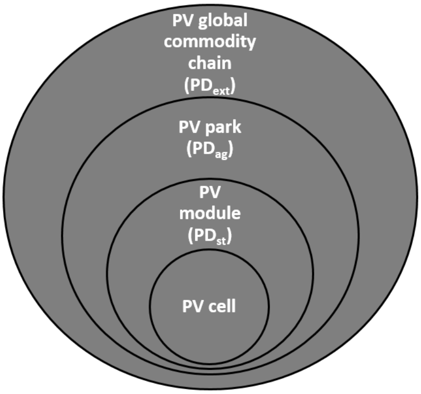


Figure 17. The gradually expanding scope of the power density numerator (surface area). Ranging from an instrumental focus on the PV cell to an extended focus considering the global PV commodity chain. PD = power density.

It is with this in mind that we will turn to the necessary surface area associated with four countries' solar PV aspirations. For generating results that can be discussed in relation to the emerging metabolism, I have chosen four countries based on their leading role in solar PV installation. These are China, Germany, India, and Italy (see IEA, 2020a). While many countries aspire to expand the share of renewable energy in their national energy mix, governments favoring market-based strategies rarely present detailed plans on how to achieve it, as would be expected. Japan, which is a leader in solar PV installation, has been excluded from the analysis due to the lack of explicit and detailed future energy targets. The countries analysed below have either documented their official plans or otherwise outsourced strategy plans to an affiliated organisation, which I consult. First, I give a brief description of each country's global energopolitical context, followed by a description of the country's current solar PV aspirations and project plans. Second, I calculate the power density$_{ext}$ in order to relate the land requirements to the available surface area within the country's borders. This allows me, ultimately, to draw some conclusions regarding the "inherent politics" of solar PV technologies, regardless of a specific country's internal social relations of production.

China's aspiration for an "ecological civilization" by 2050

China is by far the most ambitious country when it comes to the installation of solar PV modules. In 2015, China surpassed Germany in total installed PV capacity and since then the expansion of solar PV technology has grown by leaps and bounds. In 2019, China installed more PV capacity than the EU and US combined (IEA, 2020a). Despite recent disruptions in the commodity chain due to the pandemic, China continued to install solar PVs in 2020 and is now expecting a "strong recovery" for solar demand (Shaw, 2020; Bellini, 2020a). However, China is also by far the largest polluter on the planet, currently housing half of the world's coal power capacity and being responsible for emitting almost a third of all greenhouse gases world-wide (Ritchie and Roser, 2017a; CAT, 2020a). China's relentless appetite for coal is only increasing, with an additional 150 GW coal capacity currently under construction domestically and an additional 100 GW financed internationally (Shearer et al., 2019; CAT, 2020a). While the soaring installation of solar PV modules may induce some hope for the environmentally concerned, the latter development is detrimental to any serious effort to mitigate China's – and so the world's – impact on the biosphere (CAT, 2020a). As concluded by Shearer et al. (2019: 4), China's "power generation alone will be more than three times as large as the global limit on coal power use determined by the IPCC to keep warming well below 2°C."

China's proclivity towards fossil energy has put the country under international pressure. This may have been one of the reasons why president Xi Jinping recently pledged that China now plans on becoming carbon neutral before 2060 (Sengupta, 2020). China has previously been participating in international negotiations and pledged to reduce its impacts under the Paris Agreement, even agreeing to a "climate pact" with President Obama to peak its emissions by 2030 (Magill, 2020). While China's targets under the Paris Agreement are reportedly far too modest for maintaining warming below 2°C , Xi Jinping proclaimed that the ambition to peak China's emissions by 2030 will be strengthened (CAT, 2020a). Despite Xi Jinping's recent announcement to the world, the Chinese government has remained silent on *how* to achieve its ambitions. If Liu Zhenya's speech to the UN in 2016 is any guideline, then the Chinese strategy will operate simultaneously nationally and internationally (see chapter four). China is currently active in international mega-industrialization through its "Belt and Road initiative" aiming to connect nations at a world scale through massive expansion of infrastructure, including roads, railways, and sea routes. China's ambitions for a renewable world, as we have seen, also stretch far beyond the borders of China. It remains to be seen, however, whether Zhenya's vision will come to fruition.

While China's international influence is unmistakable, its national targets for phasing out fossil energy through installation of renewable energy technologies is ambitious, but vague. The most concrete formulation of

China's ambition can be found in a "roadmap study" by the Energy Research Institute (ERI) of the Chinese National Development and Reform Commission, an executive branch of the Chinese government (ERI, 2015). The study by ERI lays out a "high renewable energy penetration scenario" by 2050 with a stepping stone target for 2030 that aspires to inaugurate an "ecological civilization … complying with and protecting the nature" (2015: 1). The scenario is highly ambitious, with greenhouse gas emissions peaking before 2025 and the entire economy entering a degrowth trajectory by 2025, effectively proposing to reduce its total energy throughput between 2025 and 2050. The focus of the study is on the electricity sector and solar power and wind power are clearly favored in the proposed scenario. The roadmap suggests that the installation of coal capacity will rise until 2025 and thereafter slowly reduce (perhaps as old plants are decommissioned).

The study sets a goal for the electricity sector for the year 2030, which will be the basis for my calculations (table 10). In ERI's (2015: 12) "high renewable energy penetration scenario," 1,048 GW solar capacity will be installed by 2030 and nearly 2,700 GW by 2050. Between 2015 and 2030, a total addition of 999,785 MW, rounded to 1,000 GW, of solar PV capacity is proposed.

Table 10. Actual and projected annual electricity output per energy source in Chinas's national electricity system under a "high renewable energy penetration scenario."

Energy technology	2015 (MW)	2015 (%)	2030 (MW)	2030 (%)
Coal	822,495	54	1,052,150	26
Oil	1,166	<1	1,012	<1
Fossil gas	94,273	6	130,119	3
Hydropower[a]	305,589	20	522,063	13
Wind	114,880	7.5	1,103,944	28
Solar	42,025	3	1,048,858	26
. Of which is PV	(41,731)	-	(1,041,516)	-
Nuclear	42,790	3	66,000	2
Biomass	77,838	5	18,794	<1
Other[b]	21,232	1.5	58,203	1
Total	**1,522,288**	**100**	**4,001,143**	**100**

Source: ERI (2015).

[a] Including "pumped hydro storage."

[b] Including geothermal, ocean, waste, biogas, and chemical energy storage.

Calculating the direct land requirements of China's plan to massively increase its solar capacity by installing an additional 1,000 GW, we can begin by calculating the power density$_{ag}$ with the coefficient above (5 W/m^2). This yields the figure 20,000,000 ha, representing the surface areas occupied by the solar PV modules, as well as the spacing between them, access roads and empty land within the park fencing.

As for labor, we can begin by noting how the increased automatisation in solar PV manufacturing has led to a decrease in labor hours over the last two decades. This explains the relatively small percentage of labor hours (8%) designated to the task of "cell manufacturing" in the commodity chain of solar PV modules (table 5). This reduction, however, should not be confused with the increasing trend to outsource the manufacturing facilities to peripheral nations such as Vietnam and Indonesia (see chapter four). That said, Chinese corporations, such as GCL System Integration, are also investing heavily in domestic manufacturing capacity, boasting plans to manufacture the largest solar module factory in the world that will be located in the eastern Chinese province of Anhui (Bellini, 2020b). Given this situation, it is hard to foresee how much of the anticipated 1,000 GW will be manufactured domestically contra internationally. Based on this qualitative assessment, I will assume that 85% of the solar PV modules emerge within a completely domestic commodity chain, while the remaining 15% are manufactured and assembled in Vietnam and Indonesia.

The total 1,000 GW multiplied by the total labor-hours throughout the commodity chain (see above) amounts to 35,000 million labor-hours. Assuming a 2,000-hour long work-year, these labor-hours represent 17,500,000 person-year equivalents, 85% of which are located in China and 15% of which are in part (38%) located in Vietnam/Indonesia. With an average ecological footprint in China of 3.6 ha and the average ecological footprint in Vietnam (2.1) and Indonesia (1.7) of 1.9 ha, this amounts to a requirement of 59,697,500 ha associated with Chinese workers and 1,745,625 ha associated with Vietnamese and Indonesian workers. Measured this way, this gives a total land requirement of 61,443,125 ha.

As for the capital investment, the International Finance Corporation estimates that the cost of solar parks is approximately 1.74 million US dollars per MW (IFC, 2015). IFC's benchmarks include labor costs but exclude costs related to FITs, interest payments, insurance, construction of access roads, administration costs, the construction of a potential backup storage system, and repairs following events such as floods, hurricanes, and wildfires. Subtracting the labor costs (120,000 per MW) and adding 0.5 million US dollars per MW for some of the above-mentioned expenses (see Hornborg et al., 2019; cf. Prieto and Hall, 2013; Ferroni and Hopkirk, 2016) yields an estimate of 2.12 million dollars per MW. Using this coefficient, the Chinese ambition to install an additional 1,000 GW corresponds to 2.12 trillion US dollars.

Given that 1,823,200 million US dollars (i.e. 84%) of capital investments in PV represent around 13.8% of China's GDP[57] and that China's total use of fossil energy is around 23,301 TWh per year (2,003,512 ktoe; IEA, 2020b), the country's investment in PV can be taken to represent the use of approximately 3,728 TWh of fossil energy. Dividing this fossil energy by 8,766 hours in a year and converting the quotient into MW, we get 366,747 MW. Considering a footprint of 1,475 ha/MW, this figure corresponds to 540,951,825 ha.

Table 11. Direct and indirect land requirements of ERI's (2015) renewable energy scenario by 2030. Also shows the power density$_{ext}$ calculated.

Solar PV	Direct land requirements (ha)	Indirect land requirements, labor (ha)	Indirect land requirements, capital (ha)	Total (ha)
Aggregate	20,000,000	61,443,125	540,951,825	622,394,950
Annual	20,000,000	2,457,725	21,638,073	44,095,798
Power density$_{ext}$ (W/m^2)	0.16			

If China's trajectory towards an "ecological civilization" progresses in such a way that China succeeds in reaching its 2030 targets, then 25% of its electricity capacity will be made up by solar PV modules by 2030. The success of this target is associated with direct and indirect land requirements amounting to 622,394,950 ha (table 11). To generate 25% of China's total electricity output[58] through this added infrastructure would implicate approximately 63% of China's total surface area.[59] The annual indirect land requirements would amount to roughly 24,095,798 ha during the 25-year long lifespan of the solar PV modules. Adding this to the direct land requirements (20,000,000 ha) means that an amount of land equivalent to 4.6% of China's total surface area (44,095,798 ha) will need to be designated to solar PV development every year. Even if the percentage of renewable energy capacity has increased since 2015, solar PV modules covers no more than 1.2% of China's total energy consumption (BP, 2019b). This means that, if carbon sequestration were included within the system's boundaries, it would implicate a surface area more than the entire country to sustain a Chinese economy exclusively propelled by electricity generated from solar PV technology.

---

[57] China's GDP was 11,064.67 billion US dollars in 2015 (Worldometer, 2020b).

[58] This is the percentage represented by the *added* solar PV capacity.

[59] China's total surface area is 9,597,000 km^2.

Germany's coal phase-out and renewable electricity plan

Germany has long been recognized as a global leader in solar power, only recently surpassed by China in installed solar PV capacity. Similar to China, however, Germany is still heavily reliant upon a range of fossil energy sources, including coal, oil, and fossil gas. The country's increasing fossil dependency has partly been blamed on the phase-out of nuclear power under the *Energiewende* with the aim to transition to a clean and low-carbon energy mix by 2050 (Bruninx et al., 2013; cf. Kunze and Lehmann, 2019). Despite Germany's high success in installing renewable energy technologies, the country relies heavily on energy imports. As much as 64% of Germany's total energy consumption is imported. The country's use of oil and fossil gas are both heavily reliant (at least 97%) upon import, primarily from Russia (Gazprom) and Norway (BMWI, 2020). Oil and fossil gas, moreover, constitute the two largest primary energy carriers for the German economy, making the country highly dependent on the international market for its energy throughput.

In contrast, the largest domestic energy source consists of coal (both lignite and bituminous). Historically, coal was a key energy source for German industrialization and development. Today, while Germany's ambition is to phase out coal, new coal-fired power stations are still being built (Meza, 2020) and the persistent proclivity towards coal for electricity generation is being met by widespread grassroots mobilization and protests.

In efforts to mitigate climate change, ensure energy security, and stave off unrest, the government approved the Climate Action Plan 2050 (*Klimaschutzplan 2050*) in 2016. The plan aims to make the country carbon neutral by 2050, while increasing the share of renewable energy in the energy mix (BMUB, 2016). After the UN summit (COP25) in 2019, Greta Thunberg and 15 other young activists filed a lawsuit against the five biggest polluters, including Germany, for breaching the Convention on the Rights of the Child on the basis that these countries were promoting fossil energy and thereby compromising the lives of current and future children. Perhaps as a response to these accusations, Germany adopted a climate policy package the same year, which included a plan for reaching the interim targets for 2030, lifting the 52 GW PV cap and confirming a Climate Action Law. The most exciting of these developments is arguably the law that aims to phase out coal by 2038, starting with the shutdown of four coal power plants in Rhineland already by the 31st of December, 2020 (Wettengel, 2020).

Until recently, it was believed that Germany would miss its climate targets set for 2020 to reduce greenhouse gases to 40% of its 1999 levels (Enkhardt, 2019b). The Climate action tracker, however, projects that Germany will now likely reach its targets as a direct consequence of the reduced industrial production and energy demand during the pandemic (CAT, 2020b). Nevertheless, the efforts of the German government are not deemed compatible with a 1.5°C pathway, largely because the proposed actions come too late, with too many compromises and with too vague guidelines for the project plans (ibid.).

The most concrete scenario projections for Germany's 2050 plan have been developed by the climate think-tank Agore Energiewende, which provides three possible scenarios for Germany's energy mix in 2030 depending on policy decisions (AER, 2018). Out of these, the scenario "coal phase-out + 65% renewable energy" is the one most aligned with the current government's position and promises (table 12). In this scenario, an additional 50 GW PV capacity will be installed by 2030, a target explicitly mentioned by the German government (Enkhardt, 2019a). This means, in essence, that solar PV capacity will double over a period of 13 years. This target scenario will serve as the basis for my calculations.

Table 12. Projected annual electricity output per energy source in Germany's national electricity system under the scenario "coal phase-out + 65% target (KA65)."

Energy technology	2017 (MW)	2017 (%)	2030 (MW)	2030 (%)
Coal	46,000	21	16,000	6
Oil	2,000	1	6,000	2
Fossil gas	30,000	14	33,000	12
Nuclear	10,000	5	0	0
Wind	57,000	27	98,000	37
Solar PV	43,000	20	93,000	35
Hydro	10,000	5	10,000	4
Biomass	8,000	4	5,000	2
Other	7,000	3	5,000	2
Total:	**213,000**	**100**	**266,000**	**100**

Source: AER (2018).

Turning to the land requirements of Germany's ambition to double its solar PV capacity, we can begin by calculating the direct land requirements according to the power density$_{ag}$ above (5 W/m^2). Applying this figure to the 50 GW solar PV infrastructure equals an even 1,000,000 ha. This designates the surface area necessary for the solar PV parks, including the solar PV modules, spacing between them, and access roads.

Apart from the direct land requirements, there are also the indirect land requirements of labor and capital. Let us look at labor first. As we saw in the previous chapter, Germany's rapid installation of solar PV modules hinged in large part on the access to cheap Chinese raw materials, fossil energy, and labor. Still in 2020, Germany is dependent upon this relation as 80% of all modules installed are imported to Germany from Asia (notably China) (Wirth, 2020). These 80%, however, are both installed and operated in Germany. Assuming that the remaining 20% of the modules are manufactured in Germany, albeit with Chinese polysilicon, the German aspiration to install an additional 50 GW of solar PV capacity until 2030 will require approximately 350,000,000 labor-hours, 58% of which will be work in low-wage nations like China and 42% of which will be work done in Germany.[60] Related to the ecological footprint of an average Chinese and German worker, 203,000,000 labor-hours from China represents 197,622 hectares and 147,000,000 labor-hours from Germany represents 533,556 hectares.[61] This amounts to a total of 898,956 hectares for Germany's target to install 50 GW by 2030.

Calculating the land requirement of the capital investment, I apply the same method of calculation as described above in the case of China. This involves using the IFC (2015) benchmarks on the costs of utility-scale solar parks, albeit with a subtracted cost of the labor and the added costs of processes not included by IFC. The estimate reached above was 2.12 million US dollars per MW. In the case of Germany's 2030 aspiration to install 50 GW solar PV capacity, this corresponds to 106,000 million US dollars. The portion of this capital that derives from fossil energy (84%) is 89,040 million US dollars, which corresponds to 2.4% of Germany's GDP at the time of the proposal.[62] In the same year, Germany's total fossil energy use was roughly 2,904 TWh (IEA, 2020c). The country's investment in PV can thereby be taken to represent the use of approximately 69,696,000 MWh of fossil energy. Converted into MW, we get 7,951 MW, which corresponds to a footprint of 11,727,725 ha.

---

[60] Assuming that an equivalent of 8,000 MW solar PV capacity is manufactured in China, but that 28% of the associated labor-hours are performed in Germany (research, installation, operation) and that the remaining 2,000 MW capacity is produced in Germany with 3% of associated labor-hours performed in China (silicon production).

[61] The average ecological footprints of the German and Chinese populations in 2016 were 4.9 and 3.6 global hectares per person and year (GFN, 2019). I have calculated a work year of 1,300 labor-hours in Germany in 2016 and a 2,000-hour work-year for Chinese laborers (OECD, 2019).

[62] Germany's GDP (nominal) in 2017 was 3,693.2 billion US dollars (Worldometer, 2020c).

Table 13. Direct and indirect land requirements in Germany's target scenario "KA65."
Also shows the associated power density$_{ext}$.

Solar PV	Direct land requirements (ha)	Indirect land requirements, labor (ha)	Indirect land requirements, capital (ha)	Total (ha)
Aggregate	1,000,000	898,956	11,727,725	13,717,681
Annual	1,000,000	35,958	469,109	1,505,067
Power density$_{ext}$ (W/m^2)	**0.36**			

As we have seen, Germany's target is to provide 35% of its electricity from solar PV modules by 2030. Out of this percentage, the added 50 GW would contribute to roughly 17% of Germany's total capacity for electricity generation (half of the total installed capacity in 2030). We can now see that this ambition to install an additional 50 GW of solar PV capacity would require access to 13,717,681 ha, which is equivalent to a power density$_{ext}$ of 0.36 (table 13).

Given that the total surface area of Germany is 357,386 km^2, Germany's ambition to generate 17% of the country's electricity through solar PV capacity would implicate an amount of land equivalent to 38% of its total surface area. Over the course of the 25-year long lifespan of the solar PV modules, the annual indirect land requirements are 505,067 ha (1/25 of 12,626,681 ha[63]), However, not only the indirect land requirements, but also the direct land requirements will be required each year. The total annual land requirement, 1,505,067 ha, amounts to 4.2% of Germany's total surface area. If we take into consideration that renewable energy supplied 14.8% of Germany's primary energy in 2019, 1.6% of which was generated from solar PVs, this means that it took 4.2% of Germany's land surface to supply 1.6% of its energy in 2019 (AGEB, 2020). Thus, in the case of a scenario in which Germany's entire energy supply comes from renewable energy technologies, such as solar PVs, it would likely require a surface area greater than that of the entire country.

India's path towards energy independency through 2030

The "rise of India" can largely be attributed to the country's massive burning of domestic coal and imported oil (Chikkatur and Sagar, 2009; Chacko, 2015). Today, India is the world's third largest coal producer (after China and the U.S.) and second largest coal consumer (after China), consuming a massive 5,172 TWh in 2019 (Ritchie and Roser, 2017b; BP, 2020). The Indian

---

[63] This is the sum of the indirect land requirements of labor and capital divided by the average life span of the solar PV modules (25 years) (see table 9).

economy is also importantly geared towards burning imported oil from Iraq, Saudi Arabia, and Iran. This is linked to the changing nature of the Indian state in the beginning of the 2000s, which reframed the country's energy situation in terms of "energy security" for economic growth, increased welfare, and international competitiveness (Chacko, 2015). Access to oil and coal were two key energy carriers that became central to achieve this aspiration. Given its very modest oil reserves, India's increased economic growth over the last years has been contingent upon multilateral cooperation in the international arena, including an active involvement in curbing piracy on the Somalian coast in order to secure reliable supplies of oil (Chacko, 2015). However, relying on oil imports and diminishing coal reserves bodes ill for long-term energy security and ecological sustainability (Chikkatur and Sagar, 2009; CAT, 2020c).

In a nutshell, the current focus of the Indian government is to simultaneously expand its coal and renewable energy capacity (Spencer et al., 2020). This may seem like a contradictory pathway, but reflects the government's prioritization of energy security and economic growth in an internationally competitive context. On the one hand, India can be understood as an international leader and role model for the energy transformation under a government that has pledged 500 GW of renewable capacity by 2030, leading to more than 60% renewable energy in its electricity mix. On the other hand, the Indian government's increasing dependence upon coal can be understood as not consistent with the Paris agreement and possibly detrimental for tackling climate change (Shearer et al., 2017; CAT, 2020c). Regardless of how we interpret this situation, India is set on continuing its economic development through green technology and growth to saturate the rising demand for electricity in its urban centers.

These developments will likely alter the Indian energy landscape as well as international energy politics. As stated by a recent commentator, "if India can convert even a tiny portion of the 150,000 gigawatts of natural solar radiation that it's bombarded with per year into cost-effective electricity, it will not only transform the energy and manufacturing landscape of the world's largest democracy but also dramatically alter the geopolitical equation of Asia" (Sinha, 2020). The hope, as stated in the article, is that India will manage to both manufacture, produce, and consume renewable energy within its borders independently from Chinese manufacturers and interests. This aspiration came partly as a response to the crippling supply chains of Chinese solar PV modules in the wake of the COVID-19 pandemic. For this end, the Modi government is currently making ready land for over 40 solar parks throughout India. The question, however, is whether India's solar ambitions can be implemented in democratic ways. Already, studies have revealed how the development of solar energy mega-projects in India dispossesses vulnerable communities for the benefit of capital coalitions through the enclosure of commons and extra-legal land politics (Yenneti et al., 2016; Stock and Birkenholtz, 2019a, 2019b). Apart from this, it is also unclear to what degree the large-scale development of solar PV technology can fit into a nationally confined energy system not reliant upon international markets.

As in the case of Germany, the Indian government does not provide target scenarios of their own. However, statistics over the government's ambitions can be found in a pathway study provided by the New Delhi-based Energy and Resources Institute (Spencer et al., 2020). In their own words, the point of the study is to "outline what is required to take the share of VRE [solar power and wind power] to levels greater than 30% of generation by 2030" (ibid. 1). The model provides two scenarios, the "Baseline Capacity Scenario" with 36% of electricity generation from renewable energy technologies and the "High Renewable Energy Scenario" with 64% from renewable sources (table 14). The latter scenario is aligned with the Modi government's target for 500 GW renewable capacity by 2030. In this scenario, the total amount of renewable generation capacity amounts to 505 GW (adding hydro, wind, solar and biomass/waste). In analyzing the requirements of these targets, the study reveals that India's future energy mix will likely require a substantial amount of battery storage. Since I do not estimate the land requirements of battery storage in the other cases, I will intentionally leave out the labor and raw materials necessary for this infrastructure and focus only on the direct and indirect land requirements associated with the additional 184.3 GW PV capacity modelled in the "High Renewable Energy Scenario."

Table 14. Actual and projected annual electricity output per energy source in India's national electricity system under the "High Renewable Energy Scenario."

Energy technology	2019-20 (MW)	2019-20 (%)	2030 (MW)	2030 (%)
Coal, oil, gas	231,000	62	263,000	33
Hydropower	51,000	14	84,000	11
Wind	38,000	10	169,000	22
Solar	35,000	9	229,000	29
. Of which is PV[a]	33,250	(9)	217,550	(28)
Nuclear	7,000	2	17,000	2
Biomass, waste	10,000	3	23,000	3
Total	**372,000**	**100**	**785,000**	**100**

Source: Spencer et al. (2020). Figures from the "High Renewable Energy Scenario."

[a] Assuming 95% of the solar power capacity from PV (see IRENA, 2017: 56).

Now turning to the calculations, we can begin by applying the power density$_{ag}$ coefficient (5 W/m^2) to the additional 184.3 GW solar PV capacity now planned in India. This amounts to 3,686,000 ha necessary for the direct infrastructure, including spacing and other open surfaces within the park limits.

As for the indirect land requirements of labor, despite efforts on behalf of the Indian government to favor domestic manufacturing of solar PV modules, most of the solar PV modules installed in India are imported from China (Gupta, 2020). As much as 85% of the solar PV modules are imported from China, Vietnam, or Thailand (Gupta, 2019; MERCOM, 2020). Given these developments and ambitions, I will assume that India will be able to reach a domestic production of 30% of the annual installed capacity during the next 10 years. The remaining 70% will be calculated as if they are imported from China, where labor-tasks related to research, silicon processing, cell manufacturing, module assembly, manufacturing of solar tracker, and various electrical components are located (63% of all labor in commodity chain). Even if the solar PV modules are imported from China, they are installed and operated with Indian labor (27% of labor in commodity chain). The total 184.3 GW multiplied by the total labor-hours throughout the commodity chain amounts to 3,225,250 person-year equivalents. Out of these labor-years, 56% will be located in India and 44% will be located in China. When multiplied with the ecological footprint per capita of the two countries, this amounts to 2,163,498 ha for the Indian labor and 5,120,406 for the Chinese labor. In sum, the indirect land requirement of the labor for India's solar PV aspiration amounts to 7,283,904 ha.

Using the coefficient of 2.12 million dollars per MW, India's capital investment in solar PV modules amounts to a sum of 390,716 million US dollars. The proportion of this money that can be said to derive from fossil energy (84%) is 328,201 million US dollars, which corresponds to 11.4% of India's GDP.[64] In the same year, India's total fossil energy supply was 7,762 TWh (667,385 ktoe; IEA, 2020d). India's investment in solar PV development can thereby be taken to represent the combustion of approximately 885 TWh of fossil energy. Converted into MW, this amounts to 100,958 MW with a footprint of 148,913,050 ha.

---

[64] India's GDP (nominal) was 2,875.14 billion US dollars in 2019 (Trading economics, 2020).

Table 15. Direct and indirect land requirements for India's 2030 target.
Also shows the power density$_{ext}$ calculated.

Solar PV	Direct land requirements (ha)	Indirect land requirements, labor (ha)	Indirect land requirements, capital (ha)	Total (ha)
Aggregate	3,686,000	7,283,904	148,913,050	159,882,954
Annual	3,686,000	291,356	5,956,522	9,933,878
Power density$_{ext}$ (W/m^2)	**0.12**			

If these calculations are accurate, then India's aspiration to install an additional 184.3 GW solar PV capacity will have a total land requirement of 159,882,954 ha (table 15). This added capacity, which will make up 23% of India's total electricity generating capacity, will implicate a surface area equivalent to 49% of India's total surface area.[65] Over the 25-year long lifespan of the PV modules, the indirect land requirements amount to 6,247,878 ha per year (1/25 of 156,196,954 ha indirect land requirements). Thus, the annual requirements (including the direct land) amounts to 9,933,878 ha, which is equivalent to 3% of India's total surface area. Today, the latest data indicate that solar power in India – including PV and CSP – contribute to 0.9% of the country's total energy consumption (BP, 2019c).

Italy's solar development and commitment to the Belt and Road initiative

Italy has a long history of being dependent upon imported fossil energy. Still today, the country's primary energy supply is made up of over 83.7% fossil energy, primarily in the form of crude oil imported from Azerbaijan, Iraq, Russia, and other countries (Ritchie and Roser, 2020; Statista, 2020). In recent years, however, Italy has increasingly turned to renewable energy for satisfying its energy demand, even if the proportion of renewable energy in its primary energy supply remains modest. For a time, during the solar PV boom, Italy was the world's leading nation in solar power. Today, within the EU, it is second only to Germany with an installed capacity of roughly 20,000 MW. Nevertheless, with a large share of fossil energy, Italy's efforts to mitigate climate change ranks as "insufficient" alongside the other EU member states (CAT, 2020d).

In the beginning of the 2010s, the two Italian energy corporations Enel Green Power and Terna were part of the Germany-initiated DESERTEC project that was intended to provide electricity to Europe via high-voltage direct current

---

[65] India's total surface area is 3,287,000 km^2.

transmission generated in the Saharan desert. The ideological trigger for the massive project was a thesis (May, 2005) claiming that only a fraction of the land of the highly insolated Saharan desert could supply the entire world's energy need. The energy need of all the countries in Europe could be saturated from an even smaller surface area. At the time of the proposal, DESERTEC was seen as a promising solution to environmental problems, energy security and peak oil. As one commentator put it, as "an apolitical techno-fix, it promises to overcome these problems without fundamental change, basically maintaining the status quo and the contradictions of the global system that led to these crises in the first place" (Hamouchene, 2020). The non-political essence of the proposals eventually led to splits within the project, separating those who saw it as a way to satisfy European demand and those seeing the project as the beginning of a truly international and democratic power grid. The basis of the failure of the wider project coalition, however, was the marked drop in prices of renewable energy technologies during the time of the solar PV boom (ibid.). Still today, however, some of the DESERTEC partners are in continued collaboration with the aim to generate solar power (mostly through CSP) from the Saharan desert.

With the decline of the DESERTEC project and increased collaboration with Asian markets, Italy is now in close collaboration with Chinese developers working on the massive Belt and Road initiative. In 2019, the Chinese corporation Jetion Solar signed a deal with the Italian state-owned fossil corporation Eni to install 1 GW solar PV power in the country (Hall, 2019). This deal reportedly came as a reward for Italy's agreement to be part of the initiative that will encompass solar PV projects spanning from South East Asia to Europe. In turn, Italy is starting to establish manufacturing facilities in China (Hutchins, 2019). In a stroke of historical repetition, Italy is once again connected to eastern Asia via the historical route of the "Silk Road." Ironically, then, while the Italian government reportedly see the European Green New Deal as a "an opportunity for Europe to become a key geopolitical actor," such an opportunity might become contingent upon a global political economy with core actors in Eastern Asia (Coratella, 2020).

In the midst of these developments, three ministries of the Italian government presented the joint Integrated National Energy and Climate Plan that targets to supply 55% of the country's electricity generation from renewable energy sources in 2030 (table 16). To achieve this, Italy plans to develop an additional 31,438 MW PV capacity. This figure is the basis for the calculations below.

Table 16. Actual and projected annual renewable electricity capacity in Italy's national electricity system under the "Integrated National Energy and Climate Plan."

Energy technology	2017 (MW)	2017 (%)	2030 (MW)	2030 (%)[a]
Hydropower	18,863	12	19,200	11
Geothermal	813	0	950	0
Wind	9,766	6	19,300	12
Solar	19,682	13	52,000	30
. Of which is PV	(19,682)	(13)	(51,120)	(30)
Bioenergy	4,135	3	3,760	2
Total:	**53,259**	**34**	**95,210**	**55**

Source: NECP (2019: 69-70). Does not include fossil technology capacity (coal, oil, fossil gas, etc.), hence the "missing" percentages.

[a]Pertains to the estimated electricity generated (not the generation capacity).

Taking the power density$_{ag}$ of 5 W/m^2 as an estimate, the additional 31,438 MW PV capacity needed to generate 30% of the annual electricity in Italy would require 628,760 ha of land directly (table 17). As for labor, during the boom of the global solar market, Italy relied to a high degree upon imported solar PV modules from China. During this time, around 85% of Italy's demand for solar PV modules was met through international trade (Terzini et al., 2011; Cai et al., 2017). There is little to suggest that this situation will change in the near future. I will therefore assume that 15% of Italy's planned solar PV capacity will be manufactured domestically and that the remaining 85% will be manufactured in China (albeit installed and operated in Italy). Italy's 2030 target will require approximately 550,165 labor-years, 208,791 of which will be work in Italy and 341,374 being labor embodied in imported materials and components from China. These figures represent a land requirement equivalent to 918,681 ha (Italy) and 1,228,946 ha (China) respectively. The land embodied in the required labor-time thereby amounts to 2,147,627 ha in total.

Concerning capital investment, Italy's plan to install 31,438 MW of solar PV capacity translates into 66,649 million US dollars (2.12 m$/MW). Given that 55,985 million US dollars (i.e. 84%) of Italy's capital investment in PV technology represent around 2.8% of Italy's GDP[66] and that Italy's total fossil energy supply is around 1429 TWh per year (122,894 ktoe; IEA, 2020e), the country's investment can be taken to represent the use of 40 TWh of fossil energy. Dividing this fossil energy by 8,766 hours and converting it from energy consumption to energy capacity (MW), we get 4,563 MW. Considering the footprint of fossil energy (1,475 ha/MW), this corresponds to 6,730,426 ha.

---

[66] Italy's GDP was 1994 billion US dollars in 2017 (Worldometer, 2020d).

Table 17. Direct and indirect land requirements for Italy's 2030 target
Also shows the power density$_{ext}$ calculated.

Solar PV	Direct land requirements (ha)	Indirect land requirements, labor (ha)	Indirect land requirements, capital (ha)	Total (ha)
Aggregate	628,760	2,147,627	6,730,426	7,361,959
Annual	628,760	85,905	269,217	983,882
Power density$_{ext}$ (W/m^2)	**0.43**			

In total, the direct and indirect land requirements of Italy's ambition to install 31,438 MW PV capacity amounts to 7,361,959 ha. These figures yield a power density$_{ext}$ of 0.43. This added capacity, which represents 18% of Italy's electricity capacity in 2030, would necessitate an amount of land that is equivalent to 24.4% of Italy's total surface area[67] The indirect land requirements in the necessary labor and capital, however, are dispersed over time. Over the 25-year long lifespan of the solar PV modules, these land requirements (8,878,053 ha) are equivalent to 355,122 ha per year. If we also consider the direct land requirements as annual, the total annual land requirements (983,882 ha) amount to roughly 2.5% of Italy's total surface area. Today, electricity generation represents 21% of Italy's total energy consumption (IEA, 2020e). To the degree that this remains the same in 2030 (despite NECP's ambitious targets), the 18% of electricity generated through the added solar PV capacity represents 3.8% of Italy's final energy consumption and the associated power density$_{ext}$.

The political ecology of the technological boundary: The case of large-scale solar PV development

I will now discuss some of the most central implications of these results. First, the calculations suggest that the power density$_{ext}$ of large-scale solar PV projects is likely somewhere between 0.12-0.43 W/m^2. This is an order of magnitude lower than the values reached with the power density$_{ag}$ boundary (table 18). This means that solar PV technology, when understood from a broad systems perspective, requires a substantially higher amount of land per watt capacity. Since no equivalent to the "net energy cliff" has been developed for the power density measure, it is difficult to determine exactly at what value a

---

[67] Italy's total land surface area is 391,338 km^2.

particular technology can be considered to require a land subsidy.[68] In this chapter, I have taken the relation between a country's total surface area and the surface area necessary to provide that country's energy as relevant for understanding the inherent global politics of solar PV technology. The inherent politics of solar PV technology is found in the relation between the social aspirations and the biophysical conditions to fulfill them, i.e. in the mismatch between the socially motivated ends and the biophysical means or limits.

Table 18. Solar PV technology and its measured "power density standard," "power density aggregate," and "power density extended."

Technological boundary	Power density$_{st}$	Power density$_{ag}$	Power density$_{ext}$
Solar PV technology	10-20	3.7-5.5	0.12-0.43

Sources: de Castro et al. (2013), Smil (2015), Capellán-Peréz et al. (2017) and author's calculations.

So, do the inherent politics of solar PV technology depend upon how the technological boundary is drawn? Table 19 shows the results above in relation to the same calculations under the power density$_{st}$ boundary. Here we can see that the differences between the two boundaries are significant. If we look at electricity generation, the solar aspirations of all countries seem favorable from the perspective of the power density$_{st}$ boundary; to generate between 17-25% of the countries' electricity would require only 0.3-1.4% of their respective total surface area. In contrast, from the perspective of the power density$_{ext}$ boundary, all the aspirations seem more problematic; to generate 17-25% of a country's electricity supply would necessitate 2.5-4.6% of a country's total surface area. This means that it could implicate up to 25.6% of an entire country's surface area to generate 100% of the electricity from PV technology. If we recognize that electricity only constitutes a small portion of a country's total energy supply, then we can see that there is a significant difference between the boundaries. In all cases but Italy, the percentage of the countries' surface area that is needed for the PV electricity is *higher* than the percentage of PV electricity in the total energy mix. This means that it would require more surface area than the geographical territory of the entire country if 100% of the total energy supply is generated from solar PV technology. Notably, the power density$_{st}$ boundary cannot detect this possibility.

---

[68] Future studies could seek to understand at what power density$_{ext}$ value the energy technology would have repercussions for other sectors of a country (such as food production) to the extent that relying upon the energy technology becomes unfeasible or undesirable.

Table 19. Land requirement related to solar PV energy generated from the viewpoint of two technological boundaries.

Technological boundary	**Power density$_{st}$**	**Power density$_{ext}$**
Energy generated by PV (%)	Annual land requirement (%)[a,b]	Annual land requirement (%)[a]
China		
25 % of electricity, or, 1.2% of total energy supply	0.5-1	4.6
Germany		
17% of electricity, or, 1.6% of total energy supply	0.7-1.4	4.2
India		
23% of electricity, or, 0.9% of total energy supply	0.3-0.6	3
Italy		
18% of electricity, or, 3.8% of total energy supply	0.4-0.8	2.5

[a] Percentage of the country's total surface area.
[b] Calculated by considering a power density of 10-20 W/m^2.

Interpreted this way, the results confirm that conventional solar aspirations require more land than the total available surface area if 100% of the *electricity* is generated through solar PV technology (see also MacKay, 2009). If not just a country's electricity, but its total primary energy is supplied through solar PV technology, the results demonstrate that this will be practically difficult without a net import of embodied labor, embodied land, or raw material. This is so even if the indirect land requirements are dispersed over the life span of the solar PV modules. Even if a country such as Italy could theoretically keep its solar energy production within its borders, the question is how the very high land requirements would compete with other claims on land and the natural habitat of local species.

The calculations suggest that large-scale solar PV technology projects are probably inherently political by virtue of necessitating or encouraging ecological appropriation in the world-system. This means that the large-scale solar PV ambitions of China, Germany, India, and Italy are probably unfeasible if they are not coupled to either fossil subsidies, an ecological appropriation from other parts of the world economy, or both.[69] The major point here,

---

[69] Since the direct land requirements increase with additional installations of solar PV capacity, this inherent politics of solar PV technology will probably not be mitigated. While some countries, such as Japan, are now installing solar PV modules on water surfaces, this leads to a dynamic whereby increasing installations within the border of a country puts further pressure on that country, thereby encouraging extraction, manufacturing, and labor displacements. Technological progress in cell efficiency, as far as it is dependent upon an increasingly complex commodity chain, is not by default a solution because it is associated with increased

however, is that the recognition of this political-ecological condition of solar PV technology depends upon how the boundary is drawn.

The solar future: The vision and the reality

The above calculations indicate that each country's solar PV aspiration make demands on land that far exceeds the extent of the solar modules themselves.[70] In each case, this demand is so large that the geographical territory within each country's borders is insufficient to accommodate the envisioned solar PV development. From this we could conclude that a net import of resources from elsewhere is a necessary condition for successfully realizing large-scale solar PV visions. Such environmental load displacement, as we saw in the previous chapter, occurs through an ecologically unequal exchange that follows from relative price differences in the world economy. Such an exchange is ultimately upheld through disproportionate distribution of dismal working conditions, negligent environmental regulations, and a copious burning of fossil energy (notably coal) in the world economy. Under these conditions and assumptions, the large-scale solar PV projects of China, Germany, India, and Italy all necessitate a highly politicized world division of labor as much as they necessitate polysilicon, engineers, electrical components, or direct sunshine. In this view, a world division of labor is an integral part of the new metabolism as far as it is based on large-scale construction of solar PV parks.

But do the solar PV projects analysed above really necessitate such a world division of labor, as opposed to strongly encouraging it? What I have demonstrated is that large-scale solar PV projects necessitate a biophysical subsidy, as was concluded by Georgescu-Roegen already 40 years ago:

> The truth is that any present recipe for the direct use of solar energy is a "parasite," as it were, of the current technology, based mainly on fossil fuels. All the necessary equipment (including the collectors) are produced by recipes based on sources of energy other than the sun's. And it goes without saying that, like all parasites, any solar technology based on the present feasible recipes would subsist only as long as its "host" survives (Georgescu-Roegen, 1978: 19).

---

biophysical expenses (e.g., new material components, added manufacturing techniques, added trade routes, more labor, etc.) (Bunker, 2007; Gutowski et al., 2009; Strumsky et al., 2010).

[70] In this, I would like to add, solar modules are no different than other industrial means of harnessing energy, such as fossil energy.

Several points in this quote are worth considering. First, as we saw in chapter three, the Industrial Revolution was successful precisely because feeding coal to machines provided access to copious amounts of "buried sunshine," ultimately representing large amounts of buried land. The fact that solar PV technology requires large surface areas could therefore theoretically be "solved" with a fossil energy subsidy. A country could theoretically develop a significant solar PV infrastructure if it was constructed with the help of fossil energy. Indeed, this seems to be the primary form of subsidy in modern Chinese manufacturing today. Also, in both China's and India's PV pathways, fossil energy consumption is projected to increase. Considering this, the large-scale development of solar PV technology does not strictly necessitate a world division of labor, but encourages it in cases where fossil energy is scarce or otherwise considered undesirable, i.e., it embodies a "weak inherent politics."

This conclusion, however, overlooks the fundamental political ecology of fossil energy in the world economy. To think that large-scale solar PV projects merely *encourage* a world division of labor by necessitating fossil energy is to forget that the access, use, and pollution of fossil fuels are politically charged processes intertwined with a world division of labor (Huber, 2008; Mitchell, 2011; Schaffartzik et al., 2014; Malm, 2016; Warlenius, 2016).[71] Since solar PV modules show the greatest promise among the low-carbon alternatives when it comes to power density$_{st}$, it is unlikely that the biophysical subsidy could come from other renewable energy technologies. Seen from this perspective, large-scale solar PV projects embody a "strong inherent politics" because they necessitate a biophysical subsidy that could be granted through ecologically unequal exchange or through continued extraction and burning of fossil fuels. This means that large-scale solar PV development necessitate a world relation of power through which resources are unevenly distributed.

This leaves us with two technological boundaries with two distinct implications for interpreting the ontology of solar PV technology and the emerging metabolism. Considering this thesis's research question (RQ2), which boundary is more realistic for assessing solar PV technology as an option for a socially just and ecologically sustainable world?

In the introductory paragraph to this chapter, both the Enclosure acts in Britain and the Valladolid debate in Spain justified social relations of power (capitalism and colonialism) by enforcing what cognitive scientists call "artificial" categories, i.e., categories that do not correspond to entities in the world. Out of the two technological boundaries, or categorizations, the

---

[71] The same can be said for nuclear power.

narrower boundary of technology may seem to correspond more to the natural world than the broader boundary of technology as a system. After all, you might say, "here is the computer," and you might think of the computer as a technology. However, I would like to argue that the narrow definition is in fact more "artificial," because it excludes processes that are vital for the technology to exist in the world. There is after all no such thing as a functioning computer without a continuous electricity input, or a solar PV module without raw material extraction. The widely drawn boundary actually includes *more* of the biophysical world and should therefore be understood as a more realistic category.

It remains, however, that the broader category is not widely recognized in most people's everyday interaction with technological artifacts. The narrow definition of technology as an artifact remains more intuitive. This is a problem because it is precisely in this more intuitive and narrow understanding of technology that the feeling of a mystical technological power can take root and bloom (Hornborg, 2001, 2016). Anthropologists and historians have noted how modern technological faith is a type of magical thinking, where magic enters in the space between a collective wish and its fulfillment (Stivers, 1999). In the case of solar PV technology, magical thinking enters in instances where engineers and policy makers justify technological inefficiencies or environmental injustices with reference to a future progress in design. Recurring sentiments such as "if PV cells are redesigned, they can become more land-efficient in the future," or "if the commodity chain is altered, the technology can become more just," may in fact be expressions of such magical thinking. Such views are ultimately contingent on understanding solar PV modules as artifacts separate from the wider processes that generate them, rather than seeing these processes as necessary for their existence. Such views overlook the fundamentally material – and so social – ontology of technology (see chapter two). In effect, technological faith may implicitly and unintentionally justify social relations of power that are as much part of the technology as any material component that cannot be engineered away.

Similar to the Enclosure Acts and the Valladolid debate, these relations are encouraged and upheld through a cultural category that may seem correct, but which hides relations of power. With this in mind, it seems that the broader categorization of solar PV technology as intertwined with a world economy is more realistic if the aim is to establish a socially just and ecologically sustainable world. Given that the word "technology" is a fetishization of the complex sociotechnical systems emerging at the time of the Industrial Revolution (Marx, 2010; chapter two), it is only fitting that the word is defetishized in the transformation away from fossil fuels. That said, it is crucial to remember that the conventional notion of power density$_{st}$ is the dominant boundary today, regardless of whether it is in some way irrational or problematic.

What does it mean to say that large-scale solar PV projects embody a strong inherent politics? Why does it matter and to whom? To understand the consequences of this, we can begin by recognizing that the strong politics informed by the extended boundary leads to a recognition of the incongruence between the proposed visions and the implications of their actual fulfillment. As we have seen, the contrast between the conception of technology and what technology *is* can unwittingly legitimize social relations of power and further exploitation of the natural world. In the case of China, the vision is to inaugurate an ecological civilization in which the world can flourish. Simultaneously, China's massive Belt and Road initiative is likely to draw on resources from throughout the world in a manner analogous to the imperial colonial era of the 1800s. India, as we have seen, is seeking to become energy independent by turning to large-scale solar PV projects. Simultaneously, India's vision can only be fulfilled via international collaborations that facilitate an import of vital raw materials, embodied labor, and embodied land from countries such as China, Thailand, and Indonesia. The German government is planning to phase out its domestic coal production by 2038 and plans to become more energy independent through the installation of renewable energy technologies. Simultaneously, this will necessitate a net import of resources from countries in the world economy that are currently *expanding* domestic coal production. Italy, meanwhile, is seeking higher energy independence and decarbonization. Simultaneously, it is seeking to achieve this through participation in a historically unprecedented infrastructure initiative aimed at expanding international exchange relations. In each case, admirable visions of an environmentally benign post-carbon transition are counteracted in their practical application.

The important consequence of this inconsistency between vision ("the map") and practical application ("the territory") is that the unfolding of the new metabolism is allowed to add to the social-ecological problems of the old, purely fossil-based, regime. The twist, however, is that the dismal working conditions, negligent environmental regulations, and copious burning of fossil energy can now be glossed over with reference to a progress in the development of renewable energy technologies. Ultimately, such progress may be an illusion maintained under narrowly drawn technological boundaries that fail to acknowledge the global political implications of the physical inefficiencies. Meanwhile, as the world gets warmer and the EROI of fossil energy carriers start slipping down the net energy cliff, the real risk is that different social groups start blaming each other for the atrocities and catastrophes of the world based on perceived differences. The resulting conflicts may in turn lead to justifications for further resource appropriation. To avoid this, it is highly relevant to align modern solar PV visions with the ecological reality of the world by recognizing what technology actually *is*.

6. The world and the solar module: Ecologically unequal exchange and the ontology of technology

> "*In order to reconquer the machine and subdue it to human purposes, one must first understand it and assimilate it. So far, we have embraced the machine without fully understanding it.*"
>
> Lewis Mumford

This thesis set out with the hypothesis that solar PV technology is conventionally perceived in ways that are incongruent with the physical conditions of its existence. Through philosophical, historical, and empirical considerations of solar PV technology, I have now shown that the social and ecological conditions of its existence are indeed more complex than is generally assumed. In particular, I have shown how ecologically unequal exchange is a likely prerequisite for solar PV technology and how this condition is repeatedly overlooked by researchers, policy makers, corporations, and governments who are working towards a low-carbon transition. Thus, solar PV technology has been embraced without a full understanding of its global prerequisites. We see the mushroom but not the mycelium, so to speak. In these final pages, I provide a summary of the conclusions and revisit the larger philosophical question of what technology ultimately *is*. In the text, I have marked the sentences that provide answers to the thesis's three sets of research questions (RQ1, RQ2, and RQ3).

The world in the solar module: Solar PV technology as ecologically unequal exchange

This thesis has shown that contemporary solar aspirations tend to require an ecologically unequal exchange through which embodied labor and matter-energy flow from one social group to another (RQ1). This condition may be inherent in large-scale solar PV technology projects, such as they are now being pursued by industrialized nations. The fact that Germany appropriated a notable amount of embodied resources from China in order to realize its solar PV aspirations during the period 2002-2018, is testimony to the significance of this relation. So is the fact that the solar aspirations of leading solar nations, including China, Germany, India and Italy, require an amount of land that would make a complete low carbon energy transition unfeasible without substantial biophysical subsidies. Such biophysical subsidies could be obtained either by continuing to extract and burn fossil fuels or by exchanging commodities at favorable prices, as Germany did during the crucial period 2002-2018.[72][73]

This finding shows how fulfilling large-scale development of solar PV technology necessitates global asymmetries as much as they necessitate polysilicon, electrical components, engineers, or direct sunshine (RQ1). While solar PV modules may be employed with or without specific social or ecological goals in mind, I have highlighted how the very existence of the modules may require social asymmetries in resource distribution. Solar PV technology can thus be categorized as “authoritarian” in Mumford’s sense and as “inherently political” in Winner’s sense (Mumford, 1964; Winner, 1980). This implies that solar power is intertwined with global political economy just as much as fossil fuels. The difference is that the politics of fossil fuels pertains primarily to these fuels as energy carriers (coal, oil, gas), whereas the politics surrounding solar PV modules primarily pertains to the massive amount of material infrastructure necessary for capturing the dispersed and intermittent

---

[72] Theoretically, such a subsidy could also be obtained through tribute payments or by appropriating resources through plunder (e.g., Wallerstein, 2004: 28). Since solar PV technology is the most land efficient renewable energy technology, it is unlikely that a biophysical subsidy could come from other renewable energy technologies such as wind, water, or geothermal.

[73] Even prior to this period, a division of labor was evident in Germany’s solar PV industry, but it was then confined to relative price differences within the nation, i.e., between the western and eastern parts of the country.

flow of direct sunshine.[74] Since these requirements stem from the physical circumstances of capturing large amounts of direct sunshine through technically sophisticated and materially voluminous artifacts, it is not likely that this condition could be transformed even under new relations of production. In Marxist terminology, the relations of production and the means of production are inseparable. Globally asymmetric resource transfers appear to be an integral part of the envisioned socio-ecological regime based on capturing large amounts of energy with solar PV technology.

This conclusion has consequences for whether further pursuits of solar PV technology contributes to a continuation, transcending, or reversal of the industrial regime (see chapter three). Conventional interpretations of nature, technology, history, and development anticipate that progress in solar PV technologies will contribute to a world in which climate change and global injustices are being mitigated, while industrialism and affluent high-energy lifestyles *continue*. Such perspectives tend to overlook the fact that technological artifacts are contingent on both the natural world and the world economy. This neglect is most apparent in the common assertion that solar power is "free", "abundant", and problem-free (e.g., Schwarzman, 1996; Bastani, 2019; McKibben, 2019). The fact that solar PV projects require large capital investments and large amounts of land, energy, and material per unit of energy harnessed suffices to invalidate this assertion. Solar power is not free and abundant. Solar PV infrastructure comes at the expense of the natural world and emerges within a context of world inequalities, as shown by the fact that the drop in prices in solar PV modules over the last twenty years occurred because manufacturers took the initiative to exploit international wage -and price differences.

A point raised by those who believe that solar PV technology presents a way to *transcend* the industrial regime is that the energy harnessed from solar power cannot be used to power the global transport system currently propelled by easily transportable and highly energy dense energy carriers, such as oil (see chapter three). This is so because solar PV energy, given its landscape-dependent character, cannot be used to transport manufacturing facilities to regions in the world where wages are low without great economic costs. This, so the argument goes (Malm, 2013, 2016), will put an end to a two-hundred-year-old arbitrage in which capitalists have had the power to shape the

---

[74] To be sure, installation and operation of fossil infrastructure is also a significant and highly politicized issue. In comparison to solar PV technology, however, the infrastructure necessary for fossil extraction is relatively small per unit of energy harnessed (Smil, 2015).

demands and regulations of global manufacturing by threatening to move production facilities. As this thesis shows, however, ending this exploitation of the world peripheries might in fact increase prices on solar PV modules and halt the rate of installation. Fulfilling global economic aspirations for solar power would then undermine the process of capital accumulation *and* the societal prerequisites for solar PV technology.

Importantly, *price differences* are the key determinant for the availability of solar PV modules in the world economy. Ecologically unequal exchange, whereby matter-energy flows from one region to another, will occur only if wages and prices on raw materials and carbon sinks are higher in one region than in another. In effect, if global transportation can be maintained, albeit in a more costly form, perhaps utilizing battery power and wind power, then the conditions for producing solar PV modules might still be upheld even in the absence of fossil fuels. The higher costs in transportation would not render trade impossible, but it would make the commodities traded less available for the many. In such a context, the larger the price differences in the world economy, the more affordable is solar PV modules in wealthier regions of the world. Therefore, in the absence of fossil fuels, it is likely that intensified global asymmetries are necessary for societies (or specific social groups within them) aspiring to maintain high-energy lifestyles. Thus, the question is not if a new socio-ecological regime is possible or not, but rather for whom and how many it will be available. The following section discusses what this says about solar aspirations based on the premise that solar PV technology is a feasible option for a socially just and ecologically sustainable world.

The solar module in the world: Fetishism in conventional solar visions

I now wish to reflect on some of the issues I raised in the introduction. Let us recall that ETC's solar park in Katrineholm was a showcase for demonstrating how easy and affordable it is to "save the world" by purchasing solar PV cells and organizing citizen energy cooperatives. This combination of solar power and local democracy, so the argument went, had already been demonstrated in Germany. We now know that a reason why a large share of Germany's electricity could by generated by democratically organized renewable energy cooperatives was because Germany benefitted from asymmetric resource transfers in the world economy. It is peculiar how easy it was to spend a whole day in the solar park without encountering any information about these global asymmetries. As I walked around the park, my attention was directed to the various types of solar cells and to information about their technical properties. Thus, the solar modules were exhibited as being *in* the world but not *of* the world. The solar modules had undergone a process of fetishisation through which knowledge about the early stages of their commodity chain had been erased and replaced by posters focusing on their features as technical artifacts. Following Marx's definition of fetishism, this was "nothing but the definite social relation between men themselves which [assumed] here, for them, the fantastic form of a relation between things" (1990[1867]: 165).

The closest to a mention of global asymmetries was a paragraph on one of the information signs by the park's row of thin film solar panels. With a headline in capital letters saying "thin film was the melody of the future", the sign read:

> A few years ago, thin film was thought to become the dominant solar technology. These 7 kW German thin film panels are typical: glass panels with a micro-thin film inside which generates electricity. Many people thought that the "old technology" - silicon solar cells - would be replaced by this type.
>
> But instead, *silicon solar cells dominate the world market. These cells have simply become cheaper*. Now they are even made with all-black backgrounds so that they look like thin film. Thin film needs about 25-30 percent more surface area than silicon solar cells to produce the same amount of electricity.
>
> Of course, many thin film producers say that it is a better product because it can handle clouds better than silicon. We have tried this in the park and reality is our judge.
>
> We have not been able to see any difference between thin film and silicon solar cells for the whole year. Both technologies are equally good (Appendix B, my translation and emphasis).

By acknowledging the existence of a world market, the author of the sign came close to recognizing the global asymmetries that I have examined. However, nothing on the sign suggested anything as politically charged as Chinese low-wage labor, fossil-propelled manufacturing, deregulated mineral extraction, or repression of local resistance. Except for David's meditation on Chinese wages, nothing in the park suggested that the words "cells have simply become cheaper" actually referred to a highly political global asymmetry.

The relation between global asymmetries and PV prices is sometimes acknowledged. When it is acknowledged, however, it is also typically downplayed or ignored. In chapter four, we saw an unwillingness to consider global asymmetries in prices as a social prerequisite for the solar boom in 2002-2018. In chapter five, we saw how the requisite social asymmetries were downplayed by drawing a narrow boundary around what constitutes technology. The unwillingness to integrate global asymmetries as a prerequisite for solar PV modules is obvious in the case of ETC's solar park, where the issue is acknowledged but not communicated. All this suggests that some people who are now pursuing solar PV technology are aware of the relation between the global asymmetries and prices of solar modules, but knowingly disregard it (RQ2). Why? I can see at least three interrelated explanations for why this fetishization of PV technology occurs.

a) *Alienation*. The fetishized perspective reflects an everyday experience of technologies wherein the biophysical past of the artifact is seldom seen as relevant. The conventional perspective on solar PV technology is encouraged by the fact that PV modules are commodities produced in a highly complex world economy. Thus, the world economic system itself encourages a fetishized perspective as an aspect of alienation. For this reason, people may be aware of the relation between global asymmetries and technology but struggle to integrate the connection in their everyday lives.

b) *Power*. Fetishization may be a strategy for legitimizing the pursuit of power. We should recall that ETC's park was founded on the aspiration to become a political force of consequence. Similarly, the leading solar nations' ambitions to install massive amounts of solar PV modules were regularly justified with reference to greater national energy autonomy (chapter five). In the case of China, solar PV development was also associated with the ambition to become an "ecological civilization" with great influence over the trajectory of the world economy. By omitting the negative effects of solar PV development, these pursuits for social-physical power appear as more legitimate.

c) *Ideology*. Recognizing the global social conditions of technology clearly challenges the conventional perception of what technology is (Hornborg, 1992, 2016; Hornborg and Roos, 2021). Conventional solar visions typically assume that solar PV technologies can be employed to solve problems. However, because technologies necessitate global asymmetries, they tend to solve problems for some at the expense of others and are better understood as entropy displacers (see chapter two). Ultimately, this understanding of technology does not fit into the worldview according to which solar PV technology is predestined to encourage socially just and environmentally friendly ways of living. As ideology, fetishism may derive from a deep-seated desire or socially encouraged conviction that "prevents, [or] renders even unnoticeable, contrary evidence or argument" (Pippin, 1994: 96). This is reminiscent of Heidegger's notion of "Enframing" as something which prevents a person from entering into "a more original revealing [i.e., how things come to be] and hence to experience the call of a more primal truth" (1954: 28).

d) *Denial*. The notion that global inequality is a prerequisite for solar PV modules may be threatening to people who perceive themselves as morally good people advocating PV technology to achieve virtuous ends. In such a context, adopting the fetishized perspective may be a strategy to protect oneself from threatening information. Cohen's (2001: 51) definition of denial as "the maintenance of social worlds in which an undesirable situation … is unrecognized, ignored or made to seem normal" seems to apply to the case of solar PV fetishism. An "interpretative denial," in which threatening information is distorted, might be applicable to some of the explanations of the solar boom and the physical inefficiencies of solar technology (Wullenkord and Reese, 2020: 5). In turn, an "implicatory denial" might apply to the case of ETC, in which a fact was recognized but "not integrated into everyday life or translated into action" (Ibid: 6).

The wider effect of this solar technology fetishism is that it obscures the global asymmetries of the emerging energy regime (RQ2).

A few years ago, one study concluded that ExxonMobil Corporation had purposefully misled the public regarding climate change and its existential implications (Supran and Oreskes, 2017). ExxonMobil, it turns out, had shared scientifically correct assessments of climate change internally but communicated skepticism and denial in public media in order to avoid stranded fossil assets. The question is whether the strategic omission of the global distributive dimension of solar PV technology may one day be compared to ExxonMobil's strategic denial of climate change. It is arguably too early to predict the wider biogeochemical implications of the new energy regime and its effects on ecosystems (cf. Lenton et al., 2016; Rehbein et al., 2020; Sonter et al., 2020). Solar-generated electricity still comprises only 1.2% of global energy consumption (BP, 2020: 9, 55). However, with ambitious efforts to massively increase the share of solar power in the world economy, we had better consider its prerequisites already today, so that we can envision and put into practice the new energy regime with full awareness of the conditions of pivotal technologies such as solar PVs.

Leaves, trees, roots: An analogy for understanding technology and the ecological crisis

To discuss the ontology of technology, I have found it helpful to start with the analogy of a tree. In this analogy, the leaf is to the solar module what the root system is to the world economy. A leaf and a solar module can both harness the energy in direct sunshine but neither of them can exist without a root system or a world economy, respectively. To omit the biophysical past of solar PV modules as an essential aspect of what technology *is* (i.e., fetishizing it), is similar to omitting the root system from the conception of what constitutes a tree. The analogy also highlights how the root system and the world economy are both hidden from view, even if we know that they both exist. By demonstrating how solar PV modules necessitate ecologically unequal exchange, I have highlighted how a specific root system is necessary for the existence of the leaf. To be more concrete, I have demonstrated how solar modules and global asymmetries in the world economy are two aspects of an inseparable whole, i.e., solar PV technology (RQ3). These are inseparable in a way that corresponds to the inseparability of the relation between the leaves and the roots of a tree. These respective parts can be analytically but not physically separated without compromising the survival of the tree. This metaphor suggests that today's world division of labor is an inherent part of solar PV technology.

Is it correct, then, to compare technology with an organism? I would argue that technology is better understood as an organ, rather than the organism itself (cf. Ellul, 1964). A technology made up of leaves and roots is not comparable to an organism, but rather a metabolic strategy for reproducing it. In a similar sense, we can think of technologies as the historically developed metabolic organs of society. This, I would argue, is what Marx was reaching for when he asserted that technology is the human equivalent to "the formation of the organs of plants and animals, which serve as the instruments of production for sustaining their life" (1990[1867]: 493, footnote 4). Marx had a social rather than individualist understanding of humans, which means that he understood technologies as the social organs by which human collectives interact with their environment. As demonstrated by Lewis Mumford (1954, 1964, 1967), such social organs – which he called “megamachines” – have existed for a long time in human history. However, as we have seen, it was only with the rise and acceleration of the industrial regime that the modern social organs were fetishized and labelled technology. Modern technologies – simultaneously cultural fetishes and material realities – are organs of the industrial metabolism, which implicate a world division of labor in the same sense that the leaf implicates a root system (RQ3).

As parts of solar PV technology, it is noteworthy that both the photoelectric effect and the world division of labor owe their generative potential to the phenomenon of polarization. It might turn out that technologies in general owe their productive potential to polarizations that may or may not be confined to the technological artifact (RQ3). Notably, for the purpose of retaining the feasibility or desirability of a technology, the ineffectiveness of one polarization (the photoelectric effect) may be compensated by taking advantage of another (global asymmetries). Given that the most fundamental polarization is of a physical kind (unequal distribution of matter-energy), it cannot be dissolved, merely shifted around among social groups, biogeochemical cycles, and ecosystems. This represents the core of the issue concerning shifting away from fossil fuels by means of advanced technologies, since the underlying matter-energy throughput will merely be transformed in kind, not magnitude. As far as climate change is mitigated by way of solar PV technology without addressing this throughput, the risk is that climate change will be replaced by another eco-existential concern of equal magnitude (albeit of a different kind).

This forces us to seriously consider to what degree a long-term sustainable relation to the biosphere can be reached through an endless expansion of the technosphere, as implied in proposals for “green” growth or various “green” technologies, and to what degree it can only be reached by a progressive degrowth with attention to well-being, justice, and ecological limits. Rapid and extensive efforts to install solar PV technology and other renewables may encourage a world with less greenhouse gas emissions. In the process, however, these efforts generate other problems in the Earth system that affected communities, activists, and researchers are only starting to understand (see chapter one). It is abundantly clear that fossil fuels are finite and non-sustainable energy carriers that the world’s actors must immediately stop burning in order to halt the detrimental effects of climate change (IPCC, 2014a, 2018). Therefore, the pressing question is not whether the ecological effects of fossil fuels present a better or worse ecological situation than the effects of solar power. Rather, the question is whether a socially just and ecologically sustainable world is currently being pursued through solar power and other renewables. At the very least, I have shown that this is a more complex question than is generally assumed. Large-scale solar PV development, in particular, may generate problems that in the long-term may be as detrimental to the biosphere as climate change.

References

Abu-Lughod, Janet L. 1989. *Before European hegemony: The world system A.D. 1250-1350*. New York and Oxford: Oxford University Press.

Adams, Richard N. 1982. *Paradoxical harvest: Energy and explanation in British history, 1870-1914*. Cambridge University Press.

Adler, David, Power Wargan, and Sona Prakash, eds. *2019. The Green New Deal for Europe: A blueprint for Europe's just transition*. Second edition. The Green New Deal for Europe.

AER. 2018. Stromsektor 2030 – Energiewirtschaftliche Auswirkungen von 65%Erneuerbare Energien und einer Reduktion der Kohleverstromung imEinklang mit den Sektorzielen des Klimaschutzplans. Kurzstudie.

AGEB. 2019. *Energy consumption in Germany 2018*, edited by Hans-Joachim Zeising.

AGEB. 2020. *Arbeitsgemeinschaft Energiebilanzenlegt Bericht zum Energieverbrauch 2019 vor.* Nr. 02.

Allen, Repko F., and Rick Szostak, eds. 2017. *Interdisciplinary research: Process and theory*. Third edition. Los Angeles: Sage.

Amin, Samir. 1972. *Unequal development*. New York: Monthly Review Press.

Andersen, Otto. 2013. *Unintended consequences of renewable energy: Problems to be solved*. London: Springer.

Apergis, Iraklis, and Nicholas Apergis. 2019. Silver prices and solar energy production. *Environmental science and pollution research* 26: 8525-8432.

Asafu-Adjaye, John, Linus Blomqvist, Stewart Brand, Barry Brook, Ruth DeFries, Erle Ellis et al. 2015. *An ecomodernist manifesto*.

Ayres, Robert. 2016. *Energy, complexity, and wealth maximization*. Cham: Springer.

Barca, Stefania. 2011. Energy, property, and the industrial revolution narrative. *Ecological economics* 70: 1309-1315.

Barnosky, Anthony D., Nicholas Matzke, Susumu Tomiya, Guinevere O.U. Wogan, Brian Swartz, Tiago B. Quental, Charles Marshall, Jenny L. McGuire, Emily L. Lindsey, Kaitlin C. Maguire, Ben Mersey, and Elizabeth A. Ferrer. 2011. Has the earth's sixth mass extinction already arrived? *Nature* 471: 51-57.

Bastani, Aaron. 2019. *Fully automated luxury communism.* London and New York: Verso.

Bates, Daniel. 2001. *Human adaptive strategies: Ecology, culture, and politics*. Boston: Allyn and Bacon.

Bateson, Gregory. 2000[1972]. *Steps to an ecology of mind.* Chicago and London: The University of Chicago Press.

Beinhart, Larry. 2018. Why China, and not the US, is the leader in solar power. *Aljazeera*. Published 22-08-2018. https://www.aljazeera.com/opinions/2018/8/22/why-china-and-not-the-us-is-the-leader-in-solar-power/. Accessed 03-03-2020.

Bellini, Emiliano. 2020a. "China entering post-FIT era with solid prospects." PV magazine. Published 17-06-2020. https://www.pv-magazine.com/2020/06/17/china-entering-post-fit-era-with-solid-prospects/. Accessed 23-09-2020.

Bellini, Emiliano. 2020b. "World's biggest PV module factory." *PV magazine*. Published 30-03-2020. https://www.pv-magazine.com/2020/03/30/worlds-biggest-pv-module-factory/. Accessed 23-09-2020.

Bennet, Jane. 2010. *Vibrant matter: A political ecology of things*. Durham and London: Duke University Press.

Bernreuter, Johannes. 2020. *The polysilicon market outlook 2020: Technology, capacities, supply, demand, prices*. Bernreuter research: Polysilicon market reports.

Bhandari, Khagendra P., Jennifer M. Collier, Randy J. Ellingson, and Dfne S. Apul. 2015. Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis. *Renewable and sustainable energy reviews* 47: 133-141.

Bhaskar, Roy, and Berth Denermark. 2006. Metatheory, interdisciplinary and disability research: A critical realist perspective. *Scandinavian journal of disability research* 8(4): 278-297.

Bhaskar, Roy. 1991. Materialism. In *A dictionary of Marxist thought*, edited by Tom Bottomore, Laurence Harris, V.G. Kiernan, and Ralph Miliband, 369-373. Second edition. Oxford: Blackwell.

Bijker, Wiebe, Thomas Hughes, and Trevor Pinch, eds. 1989. *The social construction of technological systems: New directions in the sociology and history of technology*. Cambridge and London: The MIT Press.

Blok, Vincent. 2017. Earthing technology: Towards an eco-centric concept of biomimetic technologies in the Anthropocene. *Techné: Research in philosophy of technology* 21(2-3): 127-149.

BMU. 2020. *Act on granting priority to renewable energy sources (renewable energy sources act)*. Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. Alexanderplatz 6, 10178 Berlin, Germany.

BMUB. 2016. *Climate action plan 2050: Principles and Goals of the German government's climate policy*. Berlin: Druck- und Verlagshaus Zarbock GmbH and Co. KG.

BMWI. 2020. Oil imports and crude oil production in Germany. Federal ministry of economics affairs and energy. https://www.bmwi.de/Redaktion/EN/Artikel/Energy/petroleum-oil-imports-and-crude-oil-productions-in-germany.html. Accessed 24-09-2020.

Bochtis, Dionysis, Claus Aage Grrøn Sørensen, and Dimitrios Kateris. 2019. Energy inputs and outputs in agricultural operations. In *Operations management in agriculture*, edited by Dionysis Bochtis, Claus Aage Grrøn Sørensen, and Dimitrios Kateris, 187-196. London: Academic Press.

Bonds, Eric, and Liam Downey. 2012. "Green" technology and ecologically unequal exchange: The environmental and social consequences of ecological modernization in the world-system. *American Sociological Association* 18(2): 167–186.

Bookchin, Murray. 1964[2009]. Ecology and revolutionary thought. *The anarchist library*. https://theanarchistlibrary.org/library/lewis-herber-murray-bookchin-ecology-and-revolutionary-thought.

Bosch, Stephan, and Matthias Schmidt. 2019. Is the post-fossil era necessarily post-capitalistic? – The robustness and capabilities of green capitalism. *Ecological economics* 161: 270-279.

Boyer, Dominic. 2011. Energopolitics and the anthropology of energy. *Anthropology news* 52(5): 5-7.

BP. 2019a. *BP statistical review of world energy*. 68th edition.

BP. 2019b. *BP statistical review – 2019: China's energy market in 2018*. BP energy economics.

BP. 2019c. *BP statistical review – 2019: India's energy market in 2018*. BP energy economics.

BP. 2020. *BP statistical review of world energy*. 69th edition.

Brenner, Robert. 1977. The origins of capitalist development: A critique of Neo-smithian Marxism. *New Left Review* 104: 25-92.

Bridge, Gavin. 2010. The hole world: Scales and spaces of energy extraction. *New geographies 2: Landscapes of energy*: 43-51.

Bruninx, Kenneth, Darin Madzharov, Erik Delarue, and William D'haeseleer. 2013. Impact of the German nuclear phase-out on Europe's electricity generation—A comprehensive study. *Energy Policy* 60: 251-261.

Buchan, David. 2012. *The Energiewende – Germany's gamble*. Oxford: Oxford institute for energy studies.

Bunker, Stephen G. 1985. *Underdeveloping the Amazon: Extraction, unequal exchange, and the failure of the modern state*. Chicago and London: University of Chicago Press.

Bunker, Stephen G. 2007. Natural values and the physical inevitability of uneven development under capitalism. In *Rethinking environmental history: World-system history and global environmental change*, edited by Alf Hornborg, J.R. McNeill, and Joan Martinez-Alier, 239-358. Lanham and New York: AltaMira.

Bunker, Stephen G., and Paul S. Ciccantell. 2005a. *Globalization and the race for resources*. Baltimore: Johns Hopkins University Press.

Bunker, Stephen G., and Paul S. Ciccantell. 2005b. Matter, space, time, and technology: How local processes drives global systems. *Research in rural sociology and development* 10: 23-44.

Burkett, Paul. 2013. Lukács on science: A new act in the tragedy. *Historical materialism*, 21(3): 3-15.

Byers, Edward, Matthew Gidden, David Leclère, Juraj Balkovic, Peter Burek, Kristie Ebi, et al. 2018. Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environmental Research Letters* 13: 055012.

Cai, Mattia, Niccolò Cusumano, Arturo Lorenzoni, and Federico Pontoni. 2017. A comprehensive ex-post assessment of RES deployment in Italy: Jobs, value added and import leakages. *Energy policy* 110: 234-245.

Capellán-Pérez, Iñigo, Carlos de Castro, and Iñaki Arto. 2017. Assessing vulnerabilities and limits in the transition to renewable energies: Land requirements under 100% solar energy scenarios. *Renewable and sustainable energy reviews* 77: 760-782.

Capellán-Pérez, Iñigo, Carlos de Castro, and Luis Javier Miguel González. 2019. Dynamic energy return on energy investment (EROI) and material requirements in scenarios of global transition to renewable energies. *Energy strategy reviews* 29: 100399

Carbajes-Dale, Michael, Marco Raugei, Vasilis Fthenakis, and Charles Barnhart. 2015. Energy return on investment (EROI) of solar PV: An attempt at a reconciliation. *Proceedings of the IEEE* 103(7): 995-999.

Carroll, William K., and Shannon Daub. 2018. Corporate power, fossil capital, climate crisis: Introducing the Corporate Mapping Project. *Studies in political economy* 99(2): 111-113.

Carton, Wim. 2019. "Fixing" climate change by mortgaging the future: Negative emissions, spatiotemporal fixes, and the political economy of delay. *Antipode* 51(3): 750-769.

Cassegård, Carl. 2017. Eco-Marxism and the critical theory of nature: Two perspectives on ecology and dialectics. *Distinktion: Journal of social theory* 18(3): 314-332.

Castillo-Mussot, Marcelo del, Pablo Ugalde-Vèlez, Jorge Antonio Montemayor-Aldrete, Alfredo de la Lama-García, and Fidel Cruz. 2016. Impact of global energy resources based on energy return on their investment (EROI) parameters. *Perspectives on global development and technology* 14: 290-299.

CAT. 2020a. China. *Climate action tracker.* https://climateactiontracker.org/countries/china/. Accessed 24-09-2020.

CAT. 2020b. Germany. *Climate action tracker.* https://climateactiontracker.org/countries/germany/. 24-09-2020

CAT. 2020c. India. *Climate action tracker.* https://climateactiontracker.org/countries/india/. Accessed 27-09-2020

CAT. 2020d. EU. *Climate action tracker.* https://climateactiontracker.org/countries/eu/. Accessed 27-09-2020

Chacko, Priya. 2015. The new geo-economics of a "rising" India: State transformation and the recasting of foreign policy. *Journal of contemporary Asia* 45(2): 236-344.

Chakraborty, Jayjit, Timothy W. Collins, and Sara E. Grineski. 2018. Exploring the environmental justice implications of hurricane Harvey flooding in greater Houston, Texas. *American journal of public health* 109(2): 244-250.

Chan, Royston. 2011. China quells village solar pollution protests. *Reuters*. https://www.reuters.com/article/us-china-solar-plant-protest/china-quells-village-solar-pollution-protests-idUSTRE78H0FL20110918. Accessed 14-04-2020.

Chan, Wing-Cheuk. 2005. On Heidegger's interpretation of Aristotle: A Chinese perspective. *Journal of Chinese philosophy* 32(2): 539-557.

Chen, Geoffrey C. and Charles Lees. 2016. Growing China's renewable sector: A developmental state approach. *New political economy* 21(6).

Chen, Ying, Yuziang Mao, Maoyong Song, Yongguang Yin, Guangliang Liu, and Yong Cai. 2020. Occurrende and leaching of silver in municipal sewage sludge in China. *Exotoxicology and environmental safety* 189: 109929.

Chikkatur, Ananth P., and Ambuj D. Sagar. 2009. Rethinking India's coal-power technology trajectory. *Economics and political weekly* XLIV(46): 53-58.

Chiriboga, Gonzalo, Andrés De La Rosa, Camila Molina, Stefany Velarde, and Ghem Carvajal C. 2020. Energy return on investment (EROI) and life cycle analysis (LCA) of biofuels in Ecuador. *Heliyon* 6: e04213.

Chohan, Usman W. 2019. A green new deal: Discursive review and appraisal. *Notes on the 21st Century* (CBRI).

Church, Clare, and Alec Crawford. 2018. *Green conflict minerals: The fuels of conflict in the transition to a low-carbon economy*. International institute for sustainable development. 111 Lombard Avenue, Winnipeg, Canada.

Ciccantell, Paul S., and David A. Smith. 2009. Rethinking global commodity chains: Integrating extraction, transport, and manufacturing. *International journal of comparative sociology* 50(3-4): 361-384.

Clark, Brett, and John B. Foster. 2009. Ecological imperialism and the global metabolic rift: Unequal exchange and the guano/nitrates trade. *International journal of comparative sociology* 50(3-4): 311-334.

Clark, Brett, John Bellamy Foster, and Richard York. 2007. The Critique of Intelligent Design: Epicurus, Marx, Darwin, and Freud and the materialist defense of science. *Theory and society* 36: 515-546.

Clausius, Rudolf. 1867. *The mechanical theory of heat with its applications to the steam-engine and to the physical properties of bodies*. London: J. van Voorst.

Cleveland, Cutler J., and Peter A. O'Connor. 2011. Energy return on investment (EROI) of oil shale. *Sustainability* 3: 2307-2322.

Cleveland, Cutler J., Charles A. S. Hall, Robert A. Herendeen, Nathan Hagens, Robert Costanza, Kenneth Mulder, Lee Lynd, Nathanael Greene, Bruce Dale, Mark Laser, Dan Lashof, Michael Wang, et al. 2006. Energy returns on ethanol production. *Science* 312(5781): 1746-1748.

Cohen, Stanley. 2001. *States of denial: Knowing about atrocities and suffering*. Cambridge: Polity Press.

Commoner, Barry. 1979. *The politics of energy*. New York: Random House.

COMTRADE, U.N. 2020. https://comtrade.un.org/data/. Accessed 03-2020.

Cook, Earl F. 1976. *Man, energy, society*. Texas A. and M.University, College of Geosciences, College Station, TX.

Coratella, Teresa. 2020. The European green deal: A political opportunity for Italy. European Council on Foreign Relations. Published 17-02-2020. https://www.ecfr.eu/article/commentary_the_european_green_deal_a_political_opportunity_for_italy. Accessed 24-09-2020.

Crosby, Alfred W. 1986. *Ecological imperialism: The biological expansion of Europe, 900-1900*. Cambridge: Cambridge University Press.

Dale, Gareth. 2019. Degrowth and the Green New Deal. *The Ecologist*. Published 28-10-2019. https://theecologist.org/2019/oct/28/degrowth-and-green-new-deal. Accessed 05-22-2020.

Daly, Herman E. 1996. Beyond growth: The economics of sustainable development. Boston: Beacon Press.

Daly, Herman E., and Joshua Farley 2011. *Ecological economics: Principles and applications*. Second edition. Washington, Covelo and London: Island Press.

Darwin, Charles. 2011[1859]. *The origin of species*. London: Harper.

Dauth, Wolfgang, Sebastian Findeisen, and Jens Suedekum. 2017. *Trade and manufacturing jobs in Germany*. IZA institute of labor economics. IZA DP No. 10469.

Dauvergne, Peter, and Kate J. Neville. 2010. Forests, food, and fuels in the tropics: The uneven social ecological consequences of the emerging political economy of biofuels. *Journal of peasant studies* 37(4): 631-660.

Dawson, Ashley. 2016. *Extinction: A radical history*. New York and London: OR Books.

de Castro, Carlos, and Iñigo Capellán-Pérez. 2020. Standard, point of use, and extended energy return on energy invested (EROI) from comprehensive material requirements of present global wind, solar, and hydro power technologies. *Energies* 13: 3036.

de Castro, Carlos, Margarita Mediavilla, Luis Javier Miguel, and Fernando Frechoso. 2013. Global solar electric potential: A review of their technical and sustainable limits. *Renewable and sustainable energy reviews* 28: 824-835.

Debeir, Jean-Claude, Jean-Paul Deléage, and Daniel Hémery. 1991. *In the servitude of power: Energy and civilization through the ages*. London and New Jersey: Zed Books.

Decker, Kris De. 2015. How sustainable is PV solar power? *Low-tech magazine*. https://www.lowtechmagazine.com/2015/04/how-sustainable-is-pv-solar-power.html. Accessed 14-04-2020.

Deggett, Cara. 2019. *The birth of energy: Fossil fuels, thermodynamics, energy and the politics of work*. Durham: Duke University Press.

Denemark, A. Robert, and Kenneth P. Thomas. 1988. The Brenner-Wallerstein Debate. *International studies quarterly* 32(1): 47-65.

Dewey, John. 2008. *The middle works of John Dewey, volume 10, 1899-1924: Journal articles, essays, and miscellany published in the 1916-1917 period*. Carbondale: Southern Illinois University Press.

Diaz-Maurin, François, and Mario Giampietro. 2013. A "grammar" for assessing the performance of power-supply systems: Comparing nuclear energy to fossil energy. *Energy* 48: 162-177.

Diaz-Maurin, François, and Zora Kovacic. 2015. The unresolved controversy over nuclear power: A new approach from complexity theory. *Global environmental change* 31: 207-216.

DOE. 2017. U.S. *Energy and employment report January 2017*. Washington, DC: United States Department of Energy.

Dong, Wenjuan, Ye Qi, and Stephen Spratt. 2015a. *The political economy of low-carbon investment: The role of coalitions and alignments of interest in the green transformation in China*. Evidence report no 160: Policy anticipation, response and evaluation.

Dong, Yang, Jingru Liu, Jianzin Yang, and Ning Ding. 2015b. Life-cycle assessment of China's multi-crystalline silicone photovoltaic modules considering international trade. *Journal of cleaner production* 94: 35-45.

Dorninger, Christian, Alf Hornborg, David J. Abson, Henrik von Wehrden, Anke Schaffartzik, Stefan Giljum, John-Oliver Engler, Robert L. Feller, Klaus Hubacek and Hanspeter Wieland. Global patterns of ecologically unequal exchange: Implications for sustainability in the 21st century. *Ecological economics* 179: 106824.

Dorninger, Christian, and Alf Hornborg. 2015. Can EEMRIO analyses establish the occurrence of ecologically unequal exchange? *Ecological economics* 119: 414-418.

Downey, Liam, Eric Bonds, and Katherine Clark. 2011. Natural resource extraction, armed violence and environmental degradation. *Organization environment* 23(4): 417-445.

Drengson, Alan R. 1995. *The practice of technology: Exploring technology, ecophilosophy, and spiritual disciplines for vital links*. Albany: SUNY Press.

Dubey, Swapnil, NIlesh Y. Jadhav, and Betka Zakirova. 2013. Socio-economic and environmental impacts of silicon based photovoltaic (PV) technologies. *Energy procedia* 33: 322-334.

Dukes, Jeffrey S. 2003. Burning buried sunshine: Human consumption of ancient solar energy. *Climatic change* 61(1): 31-44.

Dunlap, Alexander, and Jostein Jakobsen. 2020. *The violent technologies of extraction: Political ecology, critical agrarian studies and the capitalist worldeater*. Cham: Palgrave Macmillan.

Dunlap, Alexander. 2019. End the "green" delusions: Industrial-scale renewable energy is fossil fuel+. https://www.versobooks.com/blogs/3797-end-the-green-delusions-industrial-scale-renewable-energy-is-fossil-fuel. Accessed 2020-05-29.

Dusek, Val. 2006. *Philosophy of technology: An introduction*. Oxford: Blackwell.

DW. 2012. Keeping solar power hopes alive. *DW*. https://www.dw.com/en/keeping-solar-power-hopes-alive/a-15882915. Accessed 20-02-2020.

Eiseley, Loren. 1969. *The unexpected universe*. San Diego: Harcourt, Brace and World.

Ellul, Jacques. 1964. *The technological society*. New York: Vintage.

Emmanuel, Arghiri. 1972. *Unequal exchange: A study of the imperialism of trade*. New York: Monthly Review Press.

Engels, Frederick. 1964[1925]. *Dialectics of nature*. Third edition. Moscow: Progress Publishers.

Engels, Frederick. 1972[1874]. On Authority. In *Marx-Engels reader*, edited by Robert C. Tucker, 730-733. Second edition. New York: W.W. Norton and Co.

Enkhardt, Sandra. 2019a. German government wants 98 GW of solar by 2030. *PV magazine*. https://www.pv-magazine.com/2019/10/09/german-government-wants-98-gw-of-solar-by-2030/. Accessed 13-04-2020.

Enkhardt, Sandra. 2019b. Germany lifts cap on solar FIT program with new Climate Change Act. *PV magazine*. Published 23-09-2019. https://www.pv-magazine.com/2019/09/23/germany-lifts-cap-on-solar-fit-program-in-climate-change-act/. Accessed 24-09-2020

ERI. 2015. *China 2050 high renewable energy penetration scenario and roadmap study*. Energy Research Institute National Development and Reform Commission and Energy Foundation.

Erickson, Peter, Adrian Down, Michael Lazarus, and Doug Koplow. 2017. Effects of subsidies to fossil fuel companies on United States crude oil production. *Nature energy* 2: 891-898.

Exter, van Pieter, Sybren Bosch, Branco Schipper, Benjamin Sprecher and René Kleijn. 2018. *Metal demand for renewable electricity generation in the Netherlands: Navigating a complex supply chain*. Metabolic, Copper8, and Universitet Leiden.

Farrell, Alexander E., Richard J. Plevin, Brian T. Turner, Andrew D. Jones, Michael O'Hare, and Daniel M. Kammen. 2006. Ethanol can contribute to energy and environmental goals. *Science* 311(5760): 506-508.

Feenberg, Andrew. 1991. *Critical theory of technology*. New York: Oxford University Press.

Feenberg, Andrew. 2008. Critical Theory of Technology: An Overview. In *Information technology in librarianship: New critical approaches*, edited by Gloria Leckie, and John Buschmanm 31-46. Westport CT: Libraries Unlimited.

Feenberg, Andrew. 2009. What is philosophy of technology? In *International handbook of research and development in technology education*, edited by Alister Jones, and Marc J. de Vries, 159-166. Rotterdam: Sense.

Feenberg, Andrew. 2014. *The philosophy of praxis: Marx, Lukács and the Frankfurt school*. London and New York: Verso.

Feltrin, Andrea, and Alex Freundlich. 2008. Material considerations for terawattlevel deployment of photovoltaics. *Renewable Energy* 33(2): 180-185.

Ferroni, Ferruccio, Alexander Guekos, and Robert J. Hopkirk. 2017. Further considerations to: Energy return on energy invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation. *Energy policy* 107: 498-505.

Ferroni, Ferruccio, and Robert J. Hopkirk. 2016. Energy return on energy invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation. *Energy Policy* 94: 336-344.

Fialka, John. 2016. Why China is dominating the solar industry. *Scientific American*. https://www.scientificamerican.com/article/why-china-is-dominating-the-solar-industry/. Accessed 03-03-2020.

Fischer-Kowalski, and Helmut Haberl. 2007. Conceptualizing, observing and comparing socioecological transitions. In *Socioecological transitions and global change*, edited by Marina Fischer-Kowalski, and Helmut Haberl, 1-30. . Cheltenham and Northampton: Edward Elgar.

Fischer-Kowalski, Marina, Elena Rovenskaya, Fridolin Krausmann, Irene Pallua, and John R. Mc Neill. 2019. Energy transitions and social revolutions. *Technological forecasting and social change* 138: 69-77.

Fischer-Kowalski, Marina, Simron J. Singh, Christian Lauk, Alexander Remesch, Lisa Ringhofer, and Clemens M. Grünbühel. 2011. Sociometabolic transitions in subsistence communities: Boserup revisited in four comparative case studies. *Research in human ecology* 18(2): 147-158.

Fischer-Kowalski, Marina. 2011. Analyzing sustainability transitions as a shift between socio-metabolic regimes. *Environmental innovation and societal transitions* 1: 152-159.

Fluck, Richard, ed. 1992. *Energy in world agriculture*. Amsterdam : Elsevier.

Folkers, Andreas. 2021. Fossil modernity: The materiality of acceleration, slow violence, and ecological futures. *Time and society* 30(2): 1-24.

Footprint network. 2019. http://data.footprintnetwork.org/#/?. Accessed 17-07-2020.

Foster, John Bellamy, Brett Clark, and Richard York. 2010. *The ecological rift: capitalism's war on the earth*. New York: Monthly Review Press.

Foster, John Bellamy. 2000. *Marx's ecology: Materialism and nature*. New York: Monthly Review Press.

Foster, John Bellamy. 2013. The fossil fuels war. *Monthy review*. https://monthlyreview.org/2013/09/01/fossil-fuels-war/. Accessed 30-07-2020.

Fouquet, Roger, and Peter J.G. Pearson. 2012. Past and prospective energy transitions: Insights from History. *Energy policy* 50: 1-7.

Frank, Andre G. 1966. The development of underdevlopment. *Monthly review* 18(4): 17-31.

Franquesa, Jaume B. 2018. *Power struggles: Dignity, value, and the renewable energy frontier in Spain*. Bloomington: Indiana University Press.

Fraunhofer. 2020. Net installed electricity generation capacity in Germany. Updated 30-11-2020. https://energy-charts.info/charts/installed_power/chart.htm?l=enandc=DE. Accessed 02-12-2020.

Frey, Scott R., Paul k. Gellert, and Harry F. Dahms, eds. 2019. Ecologically unequal exchange: Environmental justice in comparative and historical perspective. Cham: Palgrave Macmillan.

Fu, Yinyin, Xin Liu, and Zengwei Yuan. 2015. Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China. *Journal of cleaner production* 86: 180-190.

Geels, Frank W. 2012. A socio-technical analysis of low-carbon transitions: Introducing the multi-level perspective into transport studies. *Journal of transport geography* 24: 471-482.

Geels, Frank W. 2014. Regime resistance against low-carbon transitions: Introducing politics and power into the multi-level perspective. *Theory, culture and society* 31(5): 21-40.

Geller, Paul K., and Paul S. Ciccantell. 2020. Coal's persistence in the capitalist world-economy: Against teleology in energy 'transition' narratives. *Sociology of development* 6(2): 194-221.

Georgescu-Roegen, Nicholas. 1971. *The entropy law and the economic process*. London: Oxford University Press.

Georgescu-Roegen, Nicholas. 1975. Energy and economic myths. *Southern economic journal* 41(3): 347–381.

Georgescu-Roegen, Nicholas. 1978. Technology assessment: The case of the direct use of solar energy. *Atlantic economic journal* 6: 15-21.

GFN. 2019. Ecological footprint explorer. http://data.footprintnetwork.org/#/. Accessed 21-09-2020.

Giampietro, Mario, and Kozo Mayumi. 2008. Complex systems thinking and renewable energy systems. In *Biofuels, solar and wind as renewable energy systems*, edited by David Pimentel, 173-213. Dordrecht: Springer.

Giampietro, Mario, and Kozo Mayumi. 2015. *The biofuel delusion: The fallacy of large scale agro-biofuels production*. New York: Routledge.

Giampietro, Mario, Sergio Ulgiati, and David Pimentel. 1997. Feasibility of large-scale biofuel production. *Bioscience* 48(9): 587-600.

Giljum, Stefan, and Nina Eisenmenger. 2004. North-South trade and the distribution of environmental goods and burdens: A biophysical perspective. *Journal of environment and development* 13(1): 73-100.

Gilley, Bruce. 2012. Authoritarian environmentalism and China's response to climate change. *Environmental politics* 21(2): 287-307.

Goldstein, Jesse. 2018. Planetary improvement: Cleantech entrepreneurship and the contradictions of green capitalism. Cambridge and London: The MIT Press.

Goodrich, Alan C., Douglas M. Powell, Ted L. James, Michael Woodhouse, and Toni Buonassisi. 2013. Assessing the drivers of regional trends in solar photovoltaic manufacturing. *Energy and environmental science* 6: 2811.

Gowdy, John M. 1994. Progress and environmental sustainability. *Environmental ethics* 16: 41-55.

Gowdy, John M. 2020. Our hunter-gatherer future: Climate change, agriculture and uncivilization. *Futures* 115: 102488.

Grau, Thilo, Molin Huo, and Karsten Neuhoff. 2011. *Survey of photovoltaic industry and policy in Germany and China*. DIW discussion papers no. 1132. Deutsches Institut für Wirtschaftsforschnug, Berlin.

Griffiths, Ieuan. 1986. The scramble for Africa: Inherited political boundaries. *The geographical journal* 152(2): 204-2016.

Gupta, Uma. 2019. Solar cells using imported blue wafers will not qualify as domestically manufactured: MNRE. *PV magazine*. Published 22-10-2019. https://www.pv-magazine-india.com/2019/10/22/solar-cells-using-imported-blue-wafers-will-not-qualify-as-domestically-manufactured-mnre/. Accessed 23-09-2020.

Gupta, Uma. 2020. PV imports to face 20-25% customs duty in India. Published 26-06-2020. https://www.pv-magazine.com/2020/06/26/pv-panel-imports-to-face-20-25-customs-duty-in-india-from-august/. Accessed 23-09-2020.

Gutowski, Timothy G., Matthew S. Branham, Jeffrey B. Dahmus, Alissa J. Jones, Alexandre Thiriez, and Dusan P. Sekulic. 2009. Thermodynamic analysis of resources used in manufacturing processes. *Environmental science and technology* 43: 1584-1590.

Haberl, Helmut, K. Heinz Erb, Fridolin Krausmann, Veronica Gaube, Alberte Bondeau, Christoph Plutzar, et al. 2007. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *PNAS* 104(31): 12942-12947.

Haberl, Helmut, Marina Fischer-Kowalski, Fridolin Krusmann, Joan Martinez-Alier, and Verena Winiwarter. 2011. A socio-metabolic transition towards sustainability? Challenges for another great transformation. *Sustainable development* 19(1): 1-14.

Haegel, Nancy M., Harry Atwater Jr., Teresa Barnes, Christian Breyer, Anthony Burrell, et al. 2019. Terawatt-scale photovoltaics: Transform global energy. *Science* 364(6443): 836-838.

Hagens, Nathan J. 2020. Economics for the future – Beyond the superorganism. *Ecological economics* 169: 106520.

Hake, Jürgen-Friedrich, Wolfgang Fischer, Sandra Venghaus, and Christoph Weckenbrock. 2015. The German Energiewende—History and status quo. *Energy* 92: 532-546.

Hall, Charles A. S., Stephen Balogh, and David J. R. Murphy. 2009. What is the minimum EROI that a sustainable society must have? *Energies* 2: 25-47.

Hall, Charles A.S., and Kent A. Klitgaard. 2012. *Energy and the wealth of nations: Understanding the biophysical economy*. New York: Springer.

Hall, Charles A.S., Jessica G. Lambert, and Stephen B. Balogh. 2014. EROI of different fuels and the implications for society. *Energy policy* 64: 141-152.

Hall, Max. 2019. Belt and Road to bring 1 GW of solar to Italy. *PV magazine*. Published 01-10-2019. https://www.pv-magazine.com/2019/10/01/belt-and-road-to-bring-1-gw-of-solar-to-italy/. Accessed 02-10-2020.

Hamouchene, Hamza. 2020. Desertec: What went wrong. *EcoMENA*. Published 23-07-2020. https://www.ecomena.org/desertec/. Accessed 26-09-2020.

Hansen, James, Puschker Kharecha, Makiko Sato, Valerie Masson-Delmotte, Frank Ackerman, David J. Beerling, Paul J. Hearty, et al. 2013. Assessing "dangerous climate change": Required reduction of carbon emissions to protect young people, future generations and nature. *PLoS ONE* 8(12): e81648.

Hao, Feng. 2020. A study of ecologically unequal exchange for 89 countries between 1990 and 2015. *The social science journal*, 57(2): 245-257.

Haraway, Donna. 1991. *Simians, cyborgs and women: The reinvention of nature*. New York: Routledge.

Harrington, Luke J., David J. Frame, Erich M. Fischer, Ed Hawkins, Manoj Joshi and, Chris D. Jones. 2016. Poorest countries experience earlier anthropogenic emergence of daily temperature extremes. *Environmental research letters* 11: 055007.

Harris, Marvin. 1980. *Cultural materialism: The struggle for a science of culture*. New York: Vintage.

Harris, Marvin. 1997. *Culture, people, nature*. New York: Longman.

Harvey, David. 2003. *The new imperialism*. Oxford and New York: Oxford University Press.

Headrick, Daniel R. 2009. *Technology: A world history*. Oxford and New York: Oxford University Press.

Headrick, Daniel R. 2010. *Power over peoples: Technology, environments, and Western imperialism, 1400 to the present*. Princeton and Oxford: Princeton University Press.

Heard, Benjamin P, Barry Brook W., T.M.L Wigley, and Corey J.A. Bradshaw. 2017. Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. *Renewable and sustainable energy reviews* 76: 1122-1133.

Heidegger, Martin. 1977[1954]. The Question Concerning Technology and Other Essays. New York and London: Garland Publishing.

Heikkurinen, Pasi, and Toni Ruuska, eds. 2021. *Sustainability beyond technology: Philosophy, critique, and implications for human organization*. Oxford: Oxford University Press.

Heikkurinen, Pasi, Jenny Rinkinen, Timo Järvensivu, Kristoffer Wilén, and Toni Ruuska. 2016. Organising in the Anthropocene: An ontological outline for ecocentric theorising. *Journal of cleaner production* 113: 705-714.

Heikkurinen, Pasi. 2018. Degrowth by means of technology? A treatise for an ethos of releasement. *Journal of cleaner production* 197: 1654-1665.

Heikkurinen, Pasi. 2019. Degrowth: A metamorphosis in being. *Environment and planning E: Nature and space* 2(3): 528-547.

Hein, James R., Kira Mizell, Andrea Koschinsky, and Trace A. Conrad. 2014. Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. *Ore geology reviews* 51: 1-14.

Helmholtz, Herman von. 2001[1862]. On the conservation of force: Introduction to a series of lectures delivered in the winter of 1862-1863. In *Scientific papers: The Harvard classics*, edited by Charles Eliot. New York: P.F. Collier and Son.

Helveston, John, and Jonas Nahm. 2019. China's key role in scaling low-carbon energy technologies. *Science* 366(6467): 794-796.

Hermele, Kenneth. 2014. *The appropriation of ecological space: Agrofuels, unequal exchange and environmental load displacement.* Abingdon and New York: Routledge.

Hernandez, Rebecca R., Alona Armstrong, Jennifer Burney, Greer Ryan, Kara Moore-O'Leary, Ibrahima Diédhiou, et al. 2019. Techno-ecological synergies of solar energy produce outcomes that mitigate global change. *Nature sustainability* 2(7): 560-568.

Hickel, Jason and Giorgos Kallis. 2019. Is Green Growth Possible? *New political economy*: 1-18.

Hickman, Larry. 2014. Putting Pragmatism (especially Dewey's) to Work. In *Philosophy of technology: The technological condition*, edited by Scharff, C. Robert, and Val Dusek, 406-425. Second edition. Chichester: Blackwell.

Höök, Mikael, Robert Hirsch, and Kjell Aleklett. 2009. Giant oil field decline and their influence on world oil production. *Energy polics* 37(6): 2262-2272.

Hornborg, Alf, and Andreas Roos. 2021. Technology as capital: Challenging the illusion of the neutral machine. In *Capitalising on the sun: Critical perspectives on the global solar economy*, edited by Dustin Mulvaney, Jamie Cross and Benjamin Brown. Johns Hopkins University Press. Forthcoming.

Hornborg, Alf, Gustav Cederlöf, and Andreas Roos. 2019. Has Cuba exposed the myth of "free" solar energy? Energy, space, and justice. *Environment and planning E: Nature and space* 2(4): 989-1008.

Hornborg, Alf, J.R. McNeill, and Joan Martinez-Alier, eds. 2007. *Rethinking environmental history: World-system history and global environmental change.* Lanham and New York: Altamira Press.

Hornborg, Alf. 1992. Machine fetishism, value, and the image of unlimited good: Toward a thermodynamics of imperialism. *Man* 27: 1–18.

Hornborg, Alf. 1998. Towards an ecological theory of unequal exchange: Articulating world systems theory and ecological economics. *Ecological economics* 25(1): 127-136.

Hornborg, Alf. 2001. *The power of the machine: Global inequalities of economy, technology, and environment.* Walnut Creek, CA: Altamira Press.

Hornborg, Alf. 2003. The unequal exchange of time and space: Towards a non-normative ecological theory of exploitation. *Journal of ecological anthropology* 7(1): 4-10.

Hornborg, Alf. 2006. Footprints in the cotton fields: The Industrial Revolution as time-space appropriation and environmental load displacement. *Ecological economics* 59(1): 74-81.

Hornborg, Alf. 2009. Zero-sum world: Challenges in conceptualizing environmental load displacement and ecologically unequal exchange in the world-system. *International journal of comparative sociology* 50: 237-262.

Hornborg, Alf. 2010. *Myten om maskinen: Essäer om makt, modernitet och miljö*. Borgå: Daidalos.

Hornborg, Alf. 2013. *Global ecology and unequal exchange: Fetishism in a zero-sum world*. London: Routledge.

Hornborg, Alf. 2014. Why solar panels don't grow on trees: Technological utopianism and the uneasy relation between Marxism and Ecological Economics. In *Green utopianism: Perspectives, politics and micro-practices*, edited by Johan Hedrén, and Karin Bradley, 76-97. New York: Routledge.

Hornborg, Alf. 2015. Industrial societies. *International encyclopedia of the social and behavioral sciences* 11: 863-867.

Hornborg, Alf. 2016. *Global magic: Technologies of appropriation from ancient Rome to Wall Street*. London: Palgrave Macmillan.

Hornborg, Alf. 2017. Artifacts have consequences, not agency: Toward a critical theory of global environmental history. *European journal of social theory* 20(1): 95-110.

Hornborg, Alf. 2021. Reversing the industrial revolution: Theorizing the distributive dimensions of energy transitions. In *Sustainability beyond technology: Philosophy, critique, and implications for human organization*, edited by Heikkurinen, Pasi, and Toni Ruuska, 182-197. Oxford: Oxford University Press.

Hubacek, Klaus, and Stefan Giljum. 2003. Applying physical input-output analysis to estimate land appropriation (ecological footprints) of international trade activities. *Ecological economics* 44: 137-151.

Huber, Amelie, Santiago Gorostiza, Panagiota Kotsila, María J. Beltrán, and Marco Armiero. 2016. Beyond "socially constructed" disasters: Re-politicizing the debate on large dams through a political ecology of risk. *Capitalism nature socialism* 28(3): 48-68.

Huber, Matthew T. 2008. Energizing historical materialism: Fossil fuels, space and the capitalist mode of production. *Geoforum* 40(1): 105-115.

Huber, Matthew T. 2013. *Life blood: Oil, freedom, and the forces of capital*. Minneapolis: University of Minnesota Press.

Huber, Matthew T. 2019. Ecological politics for the working class. *Catalyst* 3(1).

Huber, Matthew T., and James McCarthy. 2017. Beyond the subterranean energy regime? Fuel, land use and the production of space. *Transactions of the institute of British geographers* 42(2): 655-668.

Huber, Matthew. 2015. Theorizing energy geographies. *Geography compass*: 1-12.

Huesemann, Michael, and Joyce Huesemann. 2011. *Techno-fix: Why technology won't save us or the environment*. Gabriola, B.C.: New Society.

Hughes, Thomas. 1989. The evolution of large technological systems. In *The social construction of technological systems: New directions in the sociology and history of technology*, edited by Wiebe Bijker, Thomas Hughes, and Trevor Pinch, 51-82. Cambridge and London: The MIT Press.

Hutchins, Mark. 2019. Italy’s FuturaSun opens 500 MW module fab in China. *PV magazine*. Published 01-07-2020. https://www.pv-magazine.com/2019/07/01/italys-futurasun-opens-500-mw-module-fab-in-china/. Accessed 24-09-2020.

IEA. 2017. *Snapshot of global photovoltaic markets*. Report IEA-PVPS T1-31:2017. Paris: Photovoltaic Power Systems Programme of the International Energy Agency.

IEA. 2020a. *Snapshot of global photovoltaic markets*. Report IEA-PVPS T1-37:2017. Paris: Photovoltaic Power Systems Programme of the International Energy Agency.

IEA. 2020b. Total energy supply (TES) by source, China (People's Republic of China and Hong Kong China) 1990-2018. https://www.iea.org/data-and-statistics?country=CHINAREGandfuel=Energy%20supplyandindicator=TPESbySource. Accessed 09-12-2020.

IEA. 2020c. Total energy supply (TES) by source, Germany 1990-2019. https://www.iea.org/data-and-statistics?country=GERMANYandfuel=Energy%20supplyandindicator=TPESbySource. Accessed 09-12-2020.

IEA. 2020d. Total energy supply (TES) by source, India 1990-2018. https://www.iea.org/data-and-statistics?country=INDIAandfuel=Energy%20supplyandindicator=TPESbySource. Accessed 09-12-2020.

IEA. 2020e. Total energy supply (TES) by source, Italy 1990-2019. https://www.iea.org/data-and-statistics?country=ITALYandfuel=Energy%20supplyandindicator=TPESbySource. Accessed 09-12-2020.

IEA. 2020f. *World energy outlook 2020*. Paris: IEA Publications.

IEA. 2021. Global energy review: CO2 emissions in 2020. Understanding the impacts of covid-19 on global CO2 emissions. *IEA*. Published 02-03-2021. https://www.iea.org/articles/global-energy-review-co2-emissions-in-2020 Accesssed 12-03-2021.

IFC. 2015. *Utility-scale solar photovoltaic power plants: A project developer’s guide*. Washington, DC: International Finance Corporations.

Illich, Ivan. 1973. *Tools for conviviality*. Glasgow: Collins.

Infante-Amate, Juan, and Fridolin Krausmann. 2019. Trade, ecologically unequal exchange and colonial legacy: The case of France and its former colonies (1962-2015). *Ecological economics* 156: 98-109.

Inikori, Joseph E. 2002. *Africans and the industrial revolution in England: A study in international trade and economic development*. Cambridge: Cambridge University Press.

IPBES. 2019. *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the intergovernmental science-policy platform on biodiversity and ecosystem services*. IPBES secretariat, Bonn, Germany.

IPCC. 2014a. *Climate Change 2014: Synthesis report*. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change. IPCC, Geneva, Switzerland.

IPCC. 2014b. Livelihoods and poverty. In *Climate change 2014 – Impacts, adaptation and vulnerability: Part A: Global and sectoral aspects: Working group II contribution to the IPCC fifth assessment report*, 793-832. Cambridge: Cambridge University Press.

IPCC. 2018. Summary for policymakers. In *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty*. IPCC, Geneva, Switzerland.

IRENA. 2017. *Renewable energy and jobs – Annual review 2017*. Abu Dhabi: International Renewable Energy Agency.

Isenhour, Cindy, and Kuishuang Feng. 2014. Decoupling and displaced emissions: On Swedish consumers, Chinese producers and policy to address the climate impact of consumption. *Journal of cleaner production* 134: 320-329.

Isenhour, Cindy. 2016. Unearthing human progress? Ecomodernism and contrasting definitions of technological progress in the Anthropocene. *Economic anthropology* 3: 315-328.

Jäger-Waldau, Arnulf. 2019. Snapshot of photovoltaics – February 2019. *Energies* 12: 769.

Jahn, Thomas, Matthias Bergmann, and Florian Keil. 2012. Transdisciplinarity: Between mainstreaming and margnialization. *Ecological economics* 39: 1-10.

Jeffries, Elisabeth. 2017. Nationalist advance. *Nature climate change* 7: 469-471.

Jensen, Derrick, Lierre Keith, and Max Wilbert. 2021. *Bright green lies: How the environmental movement lost its way and what we can do about it*. Monkfish Book Publishing. Forthcoming.

Jevons, William Stanley. 1865. *The coal question. An inquiry concerning the progress of the nation and the probable exhaustion of our coal-mines*. London and Cambridge: Macmillan. https://archive.org/details/coalquestionani00jevogoog.

Jiborn, Magnus, Astrid Kander, Viktoras Kulinois, Hana Nielsen, and Daniel D. Moran. 2018. Decoupling or delusion? Measuring emissions displacement in foreign trade. *Global environmental change* 49: 27-34.

Johnston, Sean F. 2020. *Techno-fixers: Origins and implications of technological faith*. Montreal and Kingston: McGill-Queen's University Press.

Jorgenson, Andrew K. 2009. The sociology of unequal exchange in ecological context: A panel study of lower-income countries, 1975-2000. *Sociological forum* 24(1): 22-46.

Jorgenson, Andrew K. 2010. World-economic integration, supply depots, and environmental degradation: A study of ecologically unequal exchange, foreign investment dependence, and deforestation in less developed countries. *Critical sociology* 36(3): 453-477.

Jorgenson, Andrew K., and Brett Clark. 2009. The economy, military, and ecologically unequal exchange relationship in comparative perspective: A panel study of the ecological footprints of nations, 1975-2000. *Social problems* 56(4): 621-646.

Jorgenson, Andrew K., and Brett Clark. 2012. Are the economy and the environment decoupling? A comparative international study, 1960-2005. *American journal of sociology* 118(1): 1-44.

Jorgenson, Andrew K., Kelly Austin, and Christopher Dick. 2009. Ecologically Unequal Exchange and the Resource Consumption/Environmental Degradation Paradox: A Panel Study of Less-Developed Countries, 1970-2000. *International journal of comparative sociology* 50(3-4): 236-284.

Kabasakal, Bekir, and Tamer Albayrak. 2012. Effects of nuclear power plants accidents on biodiversity and awareness of potential nuclear accident risk near the eastern border of Turkey. *Fresenius environmental bulletin* 21(11b): 3434-3436.

Kallis, Giorgios, and Richard B. Norgaard. 2010. Coevolutionary ecological economics. *Ecological economics* 69: 690-699.

Kallis, Giorgios. 2019. Degrowth is utopian, and that's a good thing. *Resilience*. Published 30-04-2019. https://www.resilience.org/stories/2019-04-30/degrowth-is-utopian-and-thats-a-good-thing/. Accessed 06-11-2020.

Kan, Siyi, Bin Chen, and Guiqian Chen. 2019. Worldwide energy use across global supply chains: decoupled from economic growth? *Applied energy* 250: 1235-1245.

Kapp, Ernst. 2018[1877]. *Elements of a philosophy of technology: On the evolutionary history of culture*. Minneapolis and London: University of Minnesota Press.

Kavlak, Goksin, James McNerney, and Jessica E. Trancik. 2018. Evaluating the causes of cost reduction in photovoltaic modules. *Energy policy* 123: 700-710.

Kim, Song-Young, and Elizabeth Thurbon. 2015. Developmental environmentalism: Explaining South Korea's ambitious pursuits of green growth. *Politics and society* 43(2): 213-240.

Klein, Naomi. 2014. *This changes everything: Capitalism vs. the climate*. New York: Penguin Random House Knopf Canada.

Kline, Ronald. 1995. Construing 'Technology' as 'Applied Science': Public Rhetoric of Scientists and Engineers in the United States, 1880-1945. I*sis: A journal of the history of science* 86: 194-221.

Kolbe, Marko. 2011. *Industrial overview 2011: The machinery and equipment industry in Germany*. Germany trade and invest, no. 13692.

Koptyug, Evgeniya. 2020. Development of population numbers in Germany from 1990 to 2019. *Statista*. Published 28-09-2020. https://www.statista.com/statistics/672608/development-population-numbers-germany/. Accessed 02-12-2020.

Korzybski, Alfred. 2000[1933]. *Science and sanity: An introduction to non-Aristotelian systems and general semantics*. New York: Institute of General Semantics.

Kostakis, Vasilis, Andreas Roos and Michel Bauwens. 2016. Towards a political ecology of the digital economy: Socio-environmental implications of two competing value models. *Environmental innovation and societal transitions* 18: 82-100.

Krausmann, Fridolin, Christian Lauk, Willi Haas, and Dominik Wiedenhofer. 2018. From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900-2015. *Global environmental change* 52: 131-140.

Krausmann, Fridolin, Helga Weisz, and Nina Eisenmenger. 2016. Transitions in sociometabolic regimes throughout human history. In *Social ecology: Society-nature relations across time and space*, edited by Helmut Haberl, Marina Fischer-Kowalski, Fridolin Krausmann, and Verena Winiwarter, 63-92. New York: Springer.

Krausmann, Fridolin, Karl-Heinz Erb, Simone Gingrich, Helmut Haberl, Alberte Bondeau, Veronika Gaube, et al. 2013. Global human appropriation of net primary production doubpled in the 20th century. *PNAS* 110(25): 10324-10329.

Krausmann, Fridolin, Simone Gingrich, Nina Eisenmenger, Karl-Heinz Erb, Helmut Haberl, and Marina Fischer-Kowalski. 2009. Growth in global materials use, GDP and population during the 20th century. *Ecological economics* 68(10): 2696-2705.

Kunze, Conrad, and Paul Lehmann. 2019. The myth of the dark side of the Energiewende. In *The European dimension of Germany's energy transition. Opportunities and conflicts*, edited by Erik Gawel, Sebastian Strunz, Paul Lehmann and Alexandra Purkus, 255-263. New York: Springer.

Lambert, Jessica G., Charles A. S. Hall, Stephen Balogh, Ajay Gupta, and Michelle Arnold. 2013. Energy, EROI and quality of life. *Energy policy* 64: 153-167.

Landes, David S. 1969. *The unbound Prometheus: Technological change and industrial development in Western Europe from 1750 to the present*. Cambridge and New York: Cambridge University Press.

Lange, Frederick A. 1925. *The history of materialism*. New York: Harcourt.

Last, Cadell. 2015. Human metasystem transition (HMST) theory. *Journal of evolution and technology* 25(1): 1-16.

Latour, Bruno. 1988. Mixing humans and nonhumans together: The sociology of a door-closer. *Social problems* 35(3): 298-310.

Latour, Bruno. 1993. *We have never been modern*. Cambridge, MA: Harvard University Press.

Latour, Bruno. 1996: On actor-network theory: A few clarifications. *Soziale welt* 47(4): 369-381.

Law, John, and Annemarie Mol. 1995. Notes on materiality and sociality. *The sociological review* 43(2): 274-294.

Law, John. 1999. After ANT: Complexity, naming and topology. *The sociological review* 47(S1): 1-14.

Law, John. 2009. Actor network theory and material semiotics. *The new blackwell companion to social theory*: 141-158.

Lawrence, Kirk S. 2009. The thermodynamics of unequal exchange: Energy use, CO_2 emissions, and GDP in the world-system, 1975-2005. *International journal of comparative sociology* 50(3-4): 335-359.

Layton, Edwin T. 1974. Technology as knowledge. *Technology and culture* 15(1): 31-41.

Lenton, M. Timothy, Peter-Paul Pichler, and Helga Weisz. 2016. Revolutions in energy input and material cycling in earth history and human history. *Earth system dynamics* 7: 353-370.

Levidow, Les, Theo Papaioannaou, and Kean Birch. 2012. Neoliberalizing technoscience and environment: EU policy for competitive, sustainable biofuels. In *Neoliberalism and technoscience: Critical assessments*, edited by Luigi Pellizzoni and Marja Ylönen, 159-186. London and New York: Routledge.

Li, Linuye, Thomas D. Willett, and Nan Zhang. 2012. The effects of the global financial crisis on China's financial market and macroeconomy. *Economics research international*: 961694.

Likavčan, Lukáš, and Manuel Scholz-Wäckerle. 2018. Technology appropriation in a de-growing economy. *Journal of cleaner production* 197: 1666-1675.

Llera, E., S. Scarpellini, A. Arandra, and I. Zabalza. 2013. Forecasting job creation from renewable energy deployment through a value-chain approach. *Renewable and sustainable energy reviews* 21: 262-271.

Lotka, Alfred J. 1956. *Elements of mathematical biology*. New York: Dover Publications.

Love, Thomas, and Cindy Isenhour. 2016. Energy and economy: Recognizing high-energy modernity as a historical period. *Economic anthropology* 3: 3-16.

Lovins, Amory B. 1976. Energy strategy: The road not taken? *Foreign affairs*. https://www.foreignaffairs.com/articles/united-states/1976-10-01/energy-strategy-road-not-taken. Accessed 14-04-2020.

Lovins, Amory B. 1979. *Soft energy paths: Towards a durable peace*. New York: Harper and Row.

Lucretius, Titus C. 2007. *The nature of things*. London: Penguin Books.

Ludin, Norasikin Ahmad, Nur Ifthitah Mustafa, Marlia M. Hanafiah, Mohd Adib Ibrahim, Mohd Asri Mat Teridi, Suhaila Sepeai, Azami Zaharim, and Kamaruzzaman Sopian. 2018. Prospects of life cycle assessment of renewable energy from photovoltaic technologies: A review. *Renewable and sustainable energy reviews* 98: 11-28.

Lukács, Georg. 1968[1923]. *History and class consciousness: Studies in Marxist dialectics*. MIT Press.

Luxemburg, Rosa. 2003[1913]. *The accumulation of capital*. London and New York: Routledge.

Lyon, Thomas P., and A. Wren Montgomery. 2015. The means and ends of greenwash. *Organization and environment* 28(2): 223-249.

MacDuffie, Allen. 2014. *Victorian literature, energy, and the ecological imagination*. Cambridge and New York: Cambridge University Press.

MacGregor, Wise. 1991. Intelligent agency. *Cultural studies* 12(3): 410-428.

Mach, Ernst. 1911. *History and root of the principle of the conservation of energy*. Chicago: The Open Court.

MacKay, David J. C. 2009. *Sustainable energy: Without the hot air*. Cambridge: UIT.

Magill, Bobby. 2020. China could cut coal (mostly) by 2050. *Scientific American*. Published 20-04-2015 https://www.scientificamerican.com/article/china-could-cut-coal-mostly-by-2050/ Accessed 24-09-2020

Malm, Andreas, and Alf Hornborg. 2014. The geology of mankind? A critique of the Anthropocene narrative. *The Anthropocene review* 1(1): 62-69.

Malm, Andreas. 2013. China as chimney of the world: The fossil capital hypothesis. *Organization environment* 25(2): 146-177.

Malm, Andreas. 2016. *Fossil capital: The rise of steam power and the roots of global warming*. London: Verso.

Malm, Andreas. 2018a. Long waves of fossil development: Periodizing energy and capital. *Mediations* 31(2): 17-40.

Malm, Andreas. 2018b. *The progress of this storm: Nature and society in a warming world*. London: Verso.

Mander, Jerry. 1992. *In the absence of the sacred: The failure of technology and the survival of the Indian nations*. San Francisco: Sierra Club.

Markard, Jochen, Rob Raven, and Bernhard Truffer. 2012. Sustainability transitions: An emerging field of research and its prospects. *Research policy* 41: 955-967.

Marks, Robert B. 2015. *The origins of the modern world: A global and environmental narrative from the fifteenth to the twenty-first century*. Fourth edition. Lanham: Rowman and Littlefield.

Marques, António Cardoso, José Alberto Fuinhas, and Diogo André Pereira. 2018. Have fossil fuels been substituted by renewables? An empirical assessment for 10 European countries. *Energy policy* 116: 257-265.

Martinez-Alier Joan and Heinz Schandl. 2002. Special section: European environmental history and ecological economics. *Ecological economics* 41: 175-176.

Martinez-Alier, Joan. 1987. *Ecological economics: Energy, environment and society*. Oxford and Cambridge: Blackwell.

Martinez-Alier, Joan. 2002. *The environmentalism of the poor: A study of ecological conflicts and valuation*. Cheltenham: Edward Elgar.

Martinez-Alier, Joan. 2011. The EROI of agriculture and its use by the Via Campesina. *The journal of peasant studies* 38(1): 145-160.

Martinot, Eric. 2010. Renewable power for China: Past, present, and future. Front. Energy Power Eng. *China* 4(3): 287-294.

Marx, Karl. 1990[1867]. *Capital: A critique of political economy*. London: Penguin.

Marx, Karl. 2000[1841]. *The difference between the Democritean and Epicurean philosophy of nature*. http://marxists.anu.edu.au/archive/marx/works/1841/dr-theses/index.htm. Accessed 11-10-2020.

Marx, Karl. 2000[1844]. *Economic and philosophic manuscripts of 1844*. https://www.marxists.org/archive/marx/works/1844/manuscripts/preface.htm. Accessed 11-10-2020.

Marx, Leo. 2010. Technology: The emergence of a hazardous concept. *Technology and culture* 51(3): 561-577.

May, Nadine. 2005. *Eco-balance of a solar electricity transmission from North Africa to Europe*. Technical University of Braunschweig.

McCarthy, James. 2015. A socioecological fix to capitalist crisis and climate change? The possibilities and limits of renewable energy. *Environmental and planning A* 47: 2485-2502.

McGlade, Christophe, and Paul Ekins. 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2°C. *Nature* 517(7533): 187-190.

McKibben, Bill. 2019. If the world ran on sun, it wouldn’t fight over oil. *The guardian*. Published 18-09-2019. https://www.theguardian.com/commentisfree/2019/sep/18/climate-crisis-oil-war-iraq-saudi-attack-green-energy?fbclid=IwAR0prXxroXRD83FDQgbaNv8METigaalLFYvf89JcjZB0JLctWqr-bPSYgM4. Accessed 30-11-2020.

McLellan, Benjamin C., Eiji Yamasue, Tetsuo Tezuka, Glen Corder, Artem Golev, and Diamen Giurco. 2016. Critical minerals and energy-impacts and limitations of moving to unconventional resources. *Resources* 5(19): 5020019.

Medin, Douglas L., and Evan Heit. 1999. Chapter 3 — Categorization. In *Cognitive science*, edited by Benjamin Martin Bly, and David E. Rumelhart, 99-143. San Diego: Academic Press.

Merchant, Carolyn. 1980. *The death of nature: Women, ecology, and the scientific revolution*. New York: Harper.

MERCOM. 2020. Q1 2020 India solar market update – 1,080 MW installed in Q1 2020. MERCOM India.

Meza, Edgar. 2020. Controversial new coal plant in Datteln 4 test runs disrupt German power prices. *Clean energy wire*. Published 19-05-2020. https://www.cleanenergywire.org/news/controversial-new-coal-plant-datteln-4-disrupts-germanys-green-power-sector. Accessed 20-09-2020.

Michalopolous, Stelios, and Elias Papaioannou. 2016. The long-run effects of the scramble for Africa. *American economic review* 106(7): 1802-48.

Milanovic, Branko. 2013. Global income inequality in numbers: In history and now. *Global policy* 4(2).

Milanovic, Branko. 2016. Global inequality: A new approach for the age of globalization. *Panoeconomicus* 63(4): 493-501.

Miller Tyler G., and Scott E. Spoolman. 2009. *Living in the environment: Concepts, connections and solutions*. Sixteenth edition. Belmont: Brooks/Cole.

Miller, Ian, Paul Warde, Ariane Tanner, J.R. McNeill et al. 2019. Forum: The environmental history of energy transitions. *Environmental history* 24: 463-533.

Mirowski, Philip. 1989. *More heat than light: Economics as social physics: Physics as nature's economics*. Cambridge and New York: Cambridge University Press.

Mitcham, Carl. 1994. *Thinking through technology: The path between engineering and philosophy*. Chicago and London: The University of Chicago Press.

Mitchell, Timothy. 2011. *Carbon democracy: Political power in the age of oil*. London and New York: Verso.

Mittlefehldt, Sarah. 2018. From appropriate technology to clearn energy economy: Renewable energy and environmental politics since the 1970s. *Journal of environmental studies and sciences* 8: 212-219.

Molina, Manuel González De, and Víctor M. Toledo. 2014. *The social metabolism: A socio-ecological theory of historical change*. Cham: Springer.

Moore, Jason. 2003. The modern world-system as environmental history? Ecology and the rise of capitalism. *Theory and society* 32: 307-377.

Moore, Jason. 2007. Silver, ecology, and the origins of the modern world, 1450-1640. In *Rethinking environmental history: World-system history and global environmental change*, edited by Alf Hornborg, J.R. McNeill, and Martinez-Alier J., 123-142. Lanham, MD: AltaMira Press.

Mulvaney, Dustin. 2013. Opening the black box of solar energy technologies: Exploring the tensions between innovation and environmental justice. *Science as culture* 22(2): 230-237.

Mulvaney, Dustin. 2019. *Solar power: Innovation, sustainability and environmental justice*. Oakland: University of California Press.

Mumford, Lewis. 1954. *Technics and civilization*. London: Routledge and Kegan Paul LTD.

Mumford, Lewis. 1964. Authoritarian and democratic technics. *Technology and culture* 5(1): 1-8.

Mumford, Lewis. 1967. *The myth of the machine: Technics and human development*. New York: Harcourt Brace Jovanovich.

Muradian, Roldan, and Joan Martinez-Alier. 2001. Trade and the environment: From a 'southern' perspective. *Ecological economics* 36: 281-297.

Murphy, David J., and Charles A. S. Hall. 2010. Year in Review—EROI or energy return on (energy) invested. *Annals of the New York academy of sciences* 1185(1): 102-118.

Muteri, Vincenzo, Maurizio Cellura, Domenico Curto, Vinenzo Franzitta, Sonia Longo, Marina Mistretta, and Maria Laura Parisi. 2020. Review on life cycle assessment of solar photovoltaic panels. *Energies* 13: 252.

Nahm, Jonas, and Edward S. Steinfeld. 2014. Scale-up nation: China's specialization in innovative manufacturing. *World development* 54: 288-300.

Nain, Preeti, and Arun Kumar. 2020. Ecological and human health risk assessment of metals leached from end-of-life solar photovoltaics. *Environmental pollution* 267: 115393.

NASA. 2017. Earth at night. Published 07-08-2017. https://www.nasa.gov/topics/earth/earthday/gall_earth_night.html. Accessed 27-10-2017.

Nature editorial. 2019. China brings solar home. *Nature energy* 4: 623.

Nduagu, Experience I., and Ian D. Gates. 2015. Unconventional heavy oil growth and global greenhouse gas emissions. *Environment science technology* 49(14): 8824-8832.

NECP. 2019. *Integrated national energy and climate plan*. Ministry of economic development, ministry of the environment and protection of natural resources and the sea and ministry of infrastructure and transport.

Nemet, Gregory. 2019. *How solar energy became cheap: A model for low-carbon innovation*. London and New York: Routledge.

Ngram Viewer. 2020a. Technology, technique, machine, 1800-2019, English (2019), case-insensitive, smoothing of 5. *Google books ngram viewer*. http://books.google.com/ngrams. Accessed 05-12-2020.

Ngram Viewer. 2020b. Technologie, technique, machine, 1800-2019, French (2019), case-insensitive, smoothing of 5. *Google books ngram viewer*. http://books.google.com/ngrams. Accessed 05-12-2020.

Ngram Viewer. 2020c. Technology, technique, maschine, 1800-2019, German (2019), case-insensitive, smoothing of 5. *Google books ngram viewer*. http://books.google.com/ngrams. Accessed 05-12-2020.

Nikiforuk Andrew. 2012. *The energy of slaves: Oil and the new servitude*. Vancouver and Berkley: Greystone Books.

Nissani, Moti. 1997. Ten cheers for interdisciplinarity: The case for interdisciplinary knowledge and research. *The social science journal* 34(2): 201-216.

Noble, Mark D. 2017. Chocolate and the consumption of forests: A cross-national examination of ecologically unequal exchange in cocoa exports. *Journal of world-systems research* 23(2): 236-268

Norberg-Hodge, Helena. 2019. *Local is our future: Steps to an economics of happiness*. Totnes and East Hardwick: Local Futures.

OECD. 2011. *Towards green growth: A summary for policymakers*. https://www.oecd.org/greengrowth/48012345.pdf.

OECD. 2019. Average annual hours actually worked per worker: Total employment. *OECD.stat*. https://stats.oecd.org/Index.aspx?DataSetCode=ANHRS#. Accessed 20-09-2020.

Okumu, Wafula. 2010. Resources and border disputes in Eastern Africa. *Journal of eastern African studies* 4(2): 279-297.

Oldfield, Jonathan D., and Denis J.B. Shaw. 2013. V.I. Vernadskii and the development of biogeochamical understandings of the biosphere, c. 1880s-1968. *The British journal for the history of science* 46(2): 287-310.

OpenLCA. 2020. Electronic component machinery production, unspecified (GLO). https://nexus.openlca.org/search/query=machinery%20electronic%20equipment!Country=Germany!Price=%3C10. Accessed 02-12-2020.

Oulu, Martin. 2015. The unequal exchange of Dutch cheese and Kenyan roses: Introducing and testing an LCA-based methodology for estimating ecologically unequal exchange. *Ecological economics* 119: 372-383.

Oxfam. 2017. *An Economy for the 99%.* Oxfam briefing paper. Oxford: Oxfam House.

Palmer, Graham, and Joshua Floyd. 2017. An exploration of divergence in EPBT and EROI for solar photovoltaics. *Biophysical economics and resource quality* 2:15.

Parrique, Timothée, Jonathan Barth, François Briens, Christian Kerschner, Alejo Kraus-Polk, Anna Kuokkanen, and Joachim H. Spangenberg. 2019. *Decoupling debunked: Evidence and arguments against green growth as a sole strategy for sustainability*. European environmental bureau.

Parson, Sean and Emily Ray. 2016. Sustainable colonization: Tar sands as resource colonialism. *Capitalism nature socialism* 29(3): 68-86.

Pearce, Joshua M. 2009. Optimizing greenhouse gas mitigation strategies to suppress energy cannibalism. *Second climate change technology conference,* may 12-15, Hamilton, Ontario, Canada.

Pearse, Rebecca, and Steffen Böhm. 2014. Ten reasons why carbon markets will not bring about radical emissions reduction. *Carbon management* 5(4): 325-337.

Pellizzoni, Luigi. 2011. Governing through disorder: Neoliberal environmental governance and social theory. *Global environmental change* 21: 795-803.

Pellmar, Terry C., and Leon Eisenberg, eds. 2000. *Bridging disciplines in the brain, behavioural, and clinical sciences*. Washington D.C.: National Academy Press.

Peng, Shuijun, Wencheng Zhang, and Chuanwang Sun. 2016. "Environmental load displacement" from the north to the south: A consumption-based perspective with a focus on China. *Ecological economics* 128: 147-158.

Pérez-Rincón, Mario Alejandro. 2006. Colombian international trade from a physical perspective: Towards an ecological "Prebisch thesis." *Ecological economics* 59(4):

Phillips, Leigh, and Michal Rozworski. 2020. Planning the future. *Social science collective*. Accessed 03-02-2021.

Phillips, Leigh. 2015. *Austerity ecology and the collapse-porn addicts: A defence of growth, progress, industry and stuff.* Winchester and Washington: Zero Books.

Phillips, Leigh. 2020. Planet of the anti-humanists. *Jacobin*. Published 05-04-2020. https://jacobinmag.com/2020/05/planet-of-the-humans-michael-moore-documentary-climate-change/. Accessed 06-11-2020.

Piano, Samuel L., and Kozo Mayumi. 2017. Toward an integrated assessment of the performance of photovoltaic power stations for electricity generation. *Applied energy* 186: 167–174.

Pickard, William F. 2014. Energy return on energy invested (EROI): A quintessential but possibly inadequate metric for sustainability in a solar-powered world? *Proceedings of the IEEE* 102(2): 1118-1122.

Pimentel, David, and Tad W. Patzek. 2005. Ethanol production using corn, switchgrass, and wood: Biodiesel production using soybean and sunflower. *Natural resources research* 14(1): 65-76.

Pimentel, David. 2003. Ethanol fuels: Energy balance, economics, and environmental impacts are negative. *Natural resources research* 12(2): 127-134.

Pimentel, David. 2006. Impacts of organic farming on the efficiency of energy use in agriculture. An organic center state of science review. https://www.organic-center.org/reportfiles/ENERGY_SSR.pdf.

Pinker, Steven. 2018. *Enlightenment now: The case for reason, science, humanism, and progress*. London: Penguin.

Pippin, Robert R. 1994. On the notion of technology as ideology: Prospects. In *Technology, pessimism, and postmodernism*, edited by Yaron Ezrahi, Everett Mendelsohn and Howard Segal, 99-113. Dordrecht: Springer.

Podobnik, Bruce. 2005. *Global energy shifts: Fostering sustainability in a turbulent age*. Philadelphia: Temple University Press.

Pomeranz, Kenneth. 2000. *The great divergence: China, Europe, and the making of the modern world economy*. Princeton and Oxford: Princeton University Press.

Prieto, Pedro A., and Charles A. S. Hall. 2013. *Spain's photovoltaic revolution: The energy return on investment*. New York: Springer.

Quitzow, Rainer, Joern Huenteler, and Hanna Asmussen. 2017. Development trajectories in China's wind and solar energy industries: How technology-related differences shape the dynamics of industry localization and catching up. *Journal of cleaner production* 158: 122-133.

Quitzow, Rainer. 2015. Dynamics of a policy-driven market: The co-evolution of technological innovation systems for solar photovoltaics in China and Germany. *Environmental innovation and societal transitions* 17: 126-148.

Rabinbach, Anson. 1992. *The human motor: Energy, fatigue, and the origins of modernity*. Berkley and Los Angeles: University of California Press.

Raugei, Marco, Pere Fullana-i-Palmer, and Vasilis Fthenakis. 2012. The energy return on energy investment (EROI) of photovoltaics: Methodology and comparisons with fossil fuel life cycles. *Energy policy* 45: 576-582.

Rehbein, Jose A., James E. M. Watson, Joe L. Lane, Laura J. Sonter, Oscar Venter, Scott C. Atkinson, and James R. Allan. 2020. Renewable energy development threatens many globally important biodiversity areas. *Global change biology* 26(5): 3040-3051.

REN21. 2016. *Renewables 2016: Global status report*. https://www.ren21.net/wp-content/uploads/2019/05/REN21_GSR2016_FullReport_en_11.pdf.

REN21. 2017. *Renewables 2017: Global status report*. https://www.ren21.net/wp-content/uploads/2019/05/GSR2017_Full-Report_English.pdf.

REN21. 2019. *Renewables 2019: Global status report*. https://www.ren21.net/wp-content/uploads/2019/05/gsr_2019_full_report_en.pdf.

Reuters. 2017. EU countries oppose duty extension on Chinese solar panels. *Euractiv*. https://www.euractiv.com/section/energy/news/eu-countries-oppose-duty-extension-on-chinese-solar-panels/. Accessed 20-02-2020

Rhodes, Christopher J. 2019. Endangered elements, critical raw materials and conflict minerals. *Science progress* 102(4): 304-350.

Rice, James. 2007. Ecological unequal exchange: Consumption, equity, and unsustainable structural relationships within the global economy. *International journal of comparative sociology* 48(1): 43-72.

Ritchie, Hannah, and Max Roser. 2017a. CO_2 and Greenhouse Gas Emissions. *Our world in data*. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions. Accessed 24-09-2020.

Ritchie, Hannah, and Max Roser. 2017b. Fossil fuels. *Our world in data*. https://ourworldindata.org/fossil-fuels. Accessed 27-09-2020.

Ritchie, Hannah, and Max Roser. 2018. Energy. *Our world in data*. https://ourworldindata.org/energy. Accessed 15-09-2020.

Roberts, Timmons J., and Bradley Parks. 2007. *A climate of injustice: Global inequality, north-south politics, and climate policy*. Cambridge, MA: The MIT Press.

Rockström, Johan, Will Steffen, Kevin Noone, Åsa Persson, Stuart F. Chaplin III, Eric F. Lambin, Timothy M. Lenton, Marten Scheffer, Carl Folke, et al. A safe operating space for humanity. *Nature* 461: 472-475

Rogelj, Joeri, Alexander Popp, Ketherine V. Calvin, Gunnar Luderer, Johannes Emmerling, et al. 2018. Scenarios towards limiting global-mean temperature increase below 1.5°C. *Nature climate change 8*: 325-332.

Roos, Andreas. 2021. Earthing philosophy of technology: A case for ontological materialism. In *Sustainability beyond technology: Philosophy, critique, and implications for human organization*, edited by Pasi Heikkurinen and Toni Ruuska, 58-98. Oxford: Oxford University Press.

Roselund, Christian. 2016. Trina solar begins module production in Thailand. *PV magazine*. https://www.pv-magazine.com/2016/03/29/trina-solar-begins-module-production-in-thailand_100023919/#ixzz47Nb5oGHs. Accessed 20-02-2020.

Rosling, Hans. *Factfulness: Ten reasons we're wrong about the world – and why things are better than you think*. New York: Flatiron.

Ruagei, Marco, Sgouris Sgouridis, David Murphy, Vasilis Fthenakis, Rolf Fischknecht, Christian Breyer, Ugo Bardi, Charles Barnhart, Alastair Buckley, Michael Carbajes-Dale, Denes Csala, MAriska de Wild-Scholten, Garvin Heath, Arnulf Jæger-Waldau, Christopher Jones, Arthur Keller, Enrica Leccisi, Pierluigi Mancarella, Nicola Pearsall, Adam Siegel, Wim Sinke, and Philippe Stolz. 2017. Energy return on energy invested (ERoEI) for solar photovoltaic systems in regions of moderate insolation: A comprehensive response. *Energy policy* 102: 377-384.

Russell, Bertrand. 2001[1912]. *The problems of philosophy*. Oxford: Oxford University Press.

Russell, Edmund, James Allison, Thomas Finger, John K. Brown, Brian Balogh, and W. Bernard Carlsson. 2011. The nature of power: Synthesizing the history of technology. *Technology and culture* 52(2): 246-259.

Ruuska, Toni, Pasi Heikkurinen and Kristoffer Wilén. 2020. Domination, power, supremacy: Confronting anthropolitics with ecological realism. *Sustainability* 12(7): 2617.

Salary explorer. 2021. Factory and manufacturing average salaries in Germany 2021. http://www.salaryexplorer.com/salary-survey.php?loc=81&loctype=1&job=33&jobtype=1. Accessed 08-03-2021.

Schaffartzik, Anke, Andreas Mayer, Simone Gingrich, Nina Eisenmenger, Christian Loy, and Fridolin Krausmann. 2014. The global metabolic transitions: Regional patterns and trends in global material flows, 1950-2010. *Global environmental change* 26: 87-97.

Scharff, C. Robert, and Val Dusek, eds.. *Philosophy of technology: The technological condition*. Second edition. Chichester: Wiley Blackwell.

Scheer, Hermann. 2005. *The solar economy: Renewable energy for a sustainable global future*. London and Sterling, VA: Earthscan.

Scheer, Hermann. 2007. *Energy autonomy: The economic, social and technological case for renewable energy*. London and Sterling, VA: Earthscan.

Scheidel, Arnim and Alevgul H. Sorman. 2012. Energy transitions and the global land rush: Ultimate drivers and persistent consequences. *Global environmental change* 22: 588-585.

Scheidel, Arnim and Anke Schaffartzik. 2019. A socio-metabolic perspective on environmental justice and degrowth movements. *Ecological economics* 161: 330-333.

Schmidt, Alfred. 2014[1971]. *The concept of nature in Marx*. London and New York: Verso.

Schrödinger, Erwin. 1945. *What is life? The physical aspect of the living cell.* London: Cambridge University Press.

Schumacher, Ernst F. 1993[1973]. *Small is beautiful: A study of economics as if people mattered*. London: Vintage.

Schwartzman, David, and Peter Schwartzman. A rapid solar transition is not only possible, it is imperative! *African journal of science, technology, innovation and development* 5(4): 297-302.

Schwartzman, David. 1996. Solar communism. *Science and society* 60(3): 307-331.

Schwartzman, David. 2012. A critique of degrowth and its politics. *Capitalism nature socialism* 23(1): 119-215.

Sengupta, Somini. 2020. China, in pointed message to U.S., tightens its climate targets. *The New York Times*. Published 22-09-2020. https://www.nytimes.com/2020/09/22/climate/china-emissions.html. Accessed 25-09-2020.

Sers, Martin R., and Peter A. Victor. 2015. The energy-emissions trap. *Ecological economics* 151: 10-21.

SF-UNEP/BNEF. 2020. *Global trends in renewable energy investment 2020*. 60322 Frankfurt am Main, Germany.

Shandra, John M., Michael Restivo, and Jamies M. Sommer. 2019. Appetite for destruction? China, ecologically unequal exchange, and forest loss. *Rural sociology*: 1-30.

Shaw, Vincent. 2020. China added almost 4 GW of solar in first quarter despite Covid-19. *PV magazine*. Published 20-05-2020. https://www.pv-magazine.com/2020/05/20/china-added-almost-4-gw-of-solar-in-first-quarter-despite-covid-19/. Accessed 23-09-2020.

Shearer, Christine, Aiqun Yu, and Ted Nace. 2019. *Out of step: China is driving the continued growth of the global coal fleet*. Global energy monitor.

Shearer, Christine, Robert Fofrich, and Steven J. Davis. 2017. Future CO_2 emissions and electricity generation from proposed coal-fired power plants in India. *Earth's future* 5: 408-416.

Shen, Wei. 2017. Who drives China's renewable energy policies? Understanding the role of industrial corporations. *Environmental development* 21: 87-97.

Shepard, Paul. 1967. Whatever happened to human ecology? *Bioscience* 17(12): 891-894+911.

Shiva, Vandana. 2008. *Soil not oil: Environmental justice in an age of climate crisis*. London: Zed Books.

Sieferle, Rolf P. 2001. *The subterranean forest: Energy systems and the Industrial Revolution*. Cambridge: White Horse Press.

Sinha, Dhruv. 2020. Why India is the new hotspot for renewable energy investors. *Indiaincgroup*. https://indiaincgroup.com/why-india-is-the-new-hotspot-for-renewable-energy-investors/. Accessed 23.09-2020.

Sinn, Dann. 2019. Companies look to shift supply chain to Southeast Asia. *Citigroup Inc.* https://www.citibank.com/commercialbank/insights/asean-supply-chain-changes/en/?linkId=69579292. Accessed 14-04-2020.

Smil, Vaclav. 2001. *Enriching the earth: Fritz Haber, Carl Bosch, and the transformation of world food production*. Cambridge and London: The MIT Press.

Smil, Vaclav. 2006. 21st century energy: Some sobering thoughts. *OECD observer* 258/259: 22-23.

Smil, Vaclav. 2009. The Iron Age and coal-based coke: A neglected case of fossil-fuel dependence. *Master resource*. Published 17-09-2009. https://www.masterresource.org/smil-vaclav/a-forgotten-case-of-fossil-fuel-dependence-the-iron-age-requires-carbon-based-energy-like-it-or-not/. Accessed 28-12-2020.

Smil, Vaclav. 2010. Power density primer: Understanding the spatial dimension of the unfolding transition to renewable electricity generation (Part I – definitions).

Smil, Vaclav. 2015. *Power density: A key to understanding energy sources and uses*. Cambridge, MA: MIT Press.

Smil, Vaclav. 2016a. *Still the Iron Age: Iron and steel in the modern world*. Oxford and Cambridge: Butterworth-Heinemann.

Smil, Vaclav. 2016b. *Energy and civilization: A history*. Cambridge and London: The MIT press.

Smil, Vaclav. 2016c. Examining energy transitions: A dozen insights based on performance. *Energy research and social science* 22: 194-197.

Smith, Merritt R., and Leo Marx, eds. 1994. *Does technology drive history? The dilemma of technological determinism*. Cambridge and London: The MIT Press.

Sonter, Laura J., Marie C. Dade, James E. M. Watson, and Rick K. Valenta. 2020. Renewable energy production will exacerbate mining threats to biodiversity. *Nature communications* 11: 4174.

Soper, Kate. 1995. *What is nature?* Oxford: Wiley-Blackwell.

Sovacool, Benjamin K. 2011. *Contesting the future of nuclear power: A critical global assessment of atomic energy*. New Jersey and London: World Scientific.

Sovacool, Benjamin K. 2016. The history and politics of energy transitions: Comparing contested views and finding common ground. WIDER working paper, no. 2016/81.

Spaargaren, Gert, and Arthur P. J. Mol. 2013. Carbon flows, carbon markets, and low-carbon lifestyles: Reflecting on the role of markets in climate governance. *Environmental politics* 22(1): 174-193.

Spash, Clive, ed. 2017. *Routledge handbook of ecological economics: Nature and society*. London and New York: Routledge.

Spencer, Herbert. 1904. Essays, scientific, political, and speculative. New York: D. Appleton and Company.

Spencer, Thomas, Neshwin Rodrigues, Raghav Pachouri, Shubham Thakre, and G. Renjith. 2020. *Renewable power pathways: Modelling the integration of wind and solar in India by 2030*. The Energy and Resources Institute.

Spivey, Hudson. 2020. Governing the fix: Energy regimes, accumulation dynamics, and land use changes in Japan's solar photovoltaic boom. *Annals of the American association of geographers* 110(6): 1690-1708.

SSTI. 2016. Health and safety concerns of photovoltaic solar panels. https://www.ssti.us/wp/wp-content/uploads/2016/09/Health_and_Safety_Concerns_of_Photovoltaic_Solar_Panels_2010_OR.pdf. Accessed 14-04-2020.

Stamford, Laurence, and Adisa Azapagic. 2018. Environmental impacts of photovoltaics: The effects of technological improvements and transfer of manufacturing from Europe to China. *Energy technology* 6: 1146-1160.

Stanford, Kyle P. 2006. Instrumentalism: Global, local, and scientific. In *The Oxford handbook of philosophy of science*, edited by Paul Humphreys, 318-336. New York: Oxford University Press.

Statista. 2020. Value of crude oil imported to Italy during the 1st quarter of 2020, by country of origin. *Statista*. https://www.statista.com/statistics/789168/volume-of-crude-oil-imported-by-country-of-origin-in-italy/ . Accessed 30-09-2020.

Statista. 2021. Global electricity prices for households in 2020, by select country. *Statista*. https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/. Accessed 08-03-2021.

Steffen, Will, Jacques Grindevald, Paul Crutzen, and John McNeill. 2011. The Anthropocene: Conceptual and historical perspectives. *Philosophical transactions of the royal society* 369: 842-867.

Steffen, Will, Johan Rockström, Katherine Richardson, Timothy M. Lenton, Carl Folke, Diana Liverman, Colin P. Summerhayes, Anthony D. Barnosky, Sarah E. Cornell, et al. 2018. Trajectories of the Earth system in the Anthropocene. *PNAS* 115(33): 8252-8259.

Steffen, Will, Katherine Richardson, Johan Rockström, Sarah E. Cornell, Ingo Fetzer, et al. 2015b. Planetary boundaries: Guiding human development on a changing planet. *Science* 347(6223): 1259855.

Steffen, Will, Wendy Broadgate, Lisa Deutsch, Owen Gaffney, and Cornelia Ludwig. 2015a. The trajectory of the Anthropocene: The great acceleration. *The Anthropocene review* 2(1): 81-98.

Steiner, Dieter, and Markus Nauser, eds. 1993. *Human ecology: Fragments of anti-fragmentary views of the world*. London and New York: Routledge.

Stern, David I. 2004. The rise and fall of the environmental Kuznets curve. *World development* 32(8): 1419-1439.

Stivers, Richard. 1999. *Technology as magic: The triumph of the irrational*. New York: Continuum.

Stock, Ryan, and Trevor Birkenholtz. 2019a. The sun and the scythe: Energy dispossessions and the agrarian question of labor in solar parks. *The journal of peasant studies*: 1-24.

Stock, Ryan, and Trevor Birkenholtz. 2019b. Photons vs. firewood: Female (dis)empowerment by solar power in India. *Gender, place and culture* 27(1): 1628-1651.

Stokes, Kenneth M. 1994. *Man and the biosphere: Toward a coevolutionary political economy*. Armonk and London: M.E. Sharpe.

Strumsky, Deborah, José Lobo, and Joseph Tainter. 2010. Complexity and the productivity of innovation. *Systems research and behavioral science* 27(5): 496-509.

Suess, Eduard. 1875. *Die Entstehung der Alpen*. W. Braumüller.

Sultan, Zafar Ahmad, and Tarek Tawfik Yousfe Alkhateeb. 2019. Energy consumption and economic growth: The evidence from India. *International journal of energy economics and politcy* 9(5): 142-147.

Supran, Geoffrey and Naomi Oreskes. 2020. Assessing ExxonMobil's climate change communications (1977-2014). *Environmental research letters* 12: 084019.

Tainter, Joseph A. 1988. *Collapse of complex societies*. Cambridge University Press.

Tainter, Joseph A. 2006. Social complexity and sustainability. *Ecological complexity* 3: 91-103.

Tainter, Joseph A., and Temis G. Taylor. 2014. Complexity, problem-solving, sustainability and resilience. *Building research and information* 42(2): 168-181.

Takedomi Karlsson, Mariko, and Vasna Ramasar. 2020. Selling women the green dream: The paradox of feminism and sustainability in fashion marketing. *Journal of political ecology* 27(1): 335-359.

Temper, Leah, Sofia Avila, Daniela Del Bene, Jennifer Gobby, Nicholas Kosoy, Philippe Le Billon, Joan Martinez-Alier, Patricia Perkins, Brototi Roy, Arnim Scheidel, and Mariana Walter. Movements shaping climate futures: A systemic mapping of protests against fossil fuel and low-carbon energy projects. *Environmental research letters* 15: 123004.

Terzini, E., A. De Lillo, F. Di Mario, C. Privato, G. Graditi, G. Di Francia, A. Antonaia, A. Mittiga, P. Delli Veneri, and C. Minarini, eds. 2011. Quaderno: Fotovoltaico. Agencia nazionale per le nuove technologie, l'energia e lo sviluppo economic sostenibile.

Thomson, Elspeth. 2003. *The Chinese coal industry: An economic history*. London and New York: Routledge.

Tian, Xu, Rui Wu, Yong Geng, Raimund Bleischwitz, and Yihui Chen. 2017. Environmental and resource footprints between China and EU countries. *Journal of cleaner production* 168: 322-330.

Tokimatsu, Koji, Henrik Wachtmeister, Benjamin McLellan, Simon Davidsson, Shinsuke Murakami, Mikael Höök, Rieko Yasuoka, and Masahiro Nishio. 2017. Energy modeling approach to the global energy-mineral nexus: A first look at metal requirements and the 2°C target. *Applied energy* 207(1): 494-509.

Trading economics. 2020. India GDP. *Trading economics*. https://tradingeconomics.com/india/gdp. Accessed 09-12-2020.

Trading economics. 2021. China Average Yearly Wages in Manufacturing. *Trading economics*. https://tradingeconomics.com/china/wages-in-manufacturing. Accessed 09-02-2021.

Trainer, Ted, and Samuel Alexander. 2019. The simpler way: Envisioning a sustainable society in an age of limits. *Real-world economics review* 87: 247-260.

Trainer, Ted. 2007. The simpler way. In *Renewable energy cannot sustain a consumer society*, edited by Ted Trainer, 135-157. Dordrecht: Springer.

Trainer, Ted. 2014. Some inconvenient theses. *Energy policy* 64: 168-174.

Trend economy. 2020. https://trendeconomy.com/. Accessed 14-04-2020.

Uddenfeldt, Therese. 2016. *Gratislunchen*. Albert Bonniers Förlag.

UNDP. 2016. *UNDP support to the implementation of sustainable development goal 7: Affordable and clean energy*. New York, NY.

UN-Energy. 2012. *Sustainable energy in a green economy: Policy brief*. Ministerial meeting on energy and green industry. Vienna: UNIDO.

UNEP. 2011. *Decoupling natural resource use and environmental impacts from economic growth*. Villars-sous-Yens: UNEP/Earthprint.

UNEP. 2014. *Decoupling 2: Technologies, Opportunities and Policy Options. A Report of the Working Group on Decoupling to the International Resource Panel*. Nairobi: UNEP.

UNEP. 2016. *Global material flows and resource productivity*. Assessment report for the UNEP international resource panel.

Vakulchuk, Roman, Indra Overland, and Daniel Scholten. 2020. Renewable energy and geopolitics: A review. *Renewable and sustainable energy reviews* 122: 109547.

Vernadsky, Vladimir I. 1945. The biosphere and the noösphere. *American scientist*, 33(1): 1-12.

Vernadsky, Vladimir I. 1998[1929]. *The biosphere*. New York: Springer-Verlag.

Vernadsky, Vladimir I. 2001[1938]. Problems of biogeochemistry II: On the fundamental material-energetic distinction between living and nonliving natural bodies of the biosphere. *21st century science and technology* 13(4): 20-39.

Vogel, Steven. 1996. *Against nature: The concept of nature in critical theory*. Albany: State University of New York Press.

Voosen, Paul. 2018. The realist. *Science* 359(6382): 1320-1324.

Wackernagel Mathis, Niels B. Schulz, Diana Deumling, Alejandro Callejas Linares, martin Jenkins, et al. 2002. Tracking the ecological overshoot of the human economy. *Proceedings of the national academy of sciences* 99 (14): 9266–9271.

Wackernagel, Mathis, and Chad Monfreda. 2004. Ecological footprints and energy. *Encyclopedia of energy* 2: 1-11.

Walker, Jeremy. 2020. *More heat than life: The tangled roots of ecology, energy, and economics*. Singapore: Palgrave Macmillan

Wallerstein, Immanuel. 2004. *World-systems analysis: An introduction*. Durham and London: Duke University Press.

Wallerstein, Immanuel. 2011a. *The modern world system I: Capitalist agriculture and the origins of the European world-economy in the sixteenth century*. Berkley, Los Angeles and London: University of California Press.

Wallerstein, Immanuel. 2011b. *The modern world system II: Mercantilism and the consolidation of the European world-economy, 1600-1750*. Berkley, Los Angeles and London: University of California Press.

Wallerstein, Immanuel. 2011c. *The modern world system III: The second era of great expansion of the capitalist world-economy, 1730-1840*. Berkley, Los Angeles and London: University of California Press.

Wallerstein, Immanuel. 2011d. *The modern world system IV: Centrist liberalism triumphant, 1789-1914*. Berkley, Los Angeles and London: University of California Press.

Wang, Qunwei, D.Q. Zhou, Peng Zhou, and Q.W. Wang. 2011. CO_2 emissions, energy consumption and economic growth in China: A panel data analysis. *Energy policy* 39: 4870-4875.

Wang, Zhaohua, and Chao Feng. 2014. The impact and economic cost of environmental regulation on energy utilization in China. *Applied economics* 46(27): 3362-3376.

Warlenius, Rikard. 2016. Linking ecological debt and ecologically unequal exchange: Stocks, flows, and unequal sink appropriation. *Journal of political ecology* 23(1): 364-380.

Warr, Benjamin, and Robert Ayres. 2010. Evidence of causality between the quantity and quality of energy consumption and economic growth. *Energy* 35(4): 1688-1693.

Watt, Jarrod, Naomi Ng, and Finbarr Bermingham. 2019. Behind the tariffs: Solar cells and the exodus of Chinese companies from China. *South China morning post*. https://www.scmp.com/podcasts/article/3015831/behind-tariffs-solar-cells-and-exodus-chinese-companies-china. Accessed 20-02-2020

WB. 2017. *The growing role of minerals and metals for a low carbon future*. World Bank Group and EGPS. June 2017.

Wealer, Ben, Simon Bauer, Leonard Göke, Christian R. von Hirschhausen, and Claudia Kemfert. 2019. High-priced and dangerous: Nuclear power is not an option for the climate-friendly energy mix. *DIW weekly report* 9(30): 253-243.

Weart, Spencer. 2003. *The discovery of global warming*. Cambridge and London: Harvard University Press.

Weisdorf, Jacob L. 2005. From foraging to farming: Explaining the Neolithic Revolution. *Journal of economic surveys* 19(4): 561-586

Weißbach, D., G. Ruprecht, A. Huke, K. Czerski, S. Gottlieb and A. Hussein. 2013. Energy intensities, EROIs, and energy payback times of electricity generating power plants. *Energy* 52: 2010-221.

Weisz, Helga, Marina Fischer-Kowalski, Clemens M. Grünbühel, Helmut Haberl, Fridolin Krausmann, and Verena Winiwarter. 2001 Global environmental change and historical transitions. *The European journal of social science research* 14(2): 117-142.

Wettengel, Julian. 2020. Spelling out the coal exit – Germany’s phase-out plan. *Clean energy wire*. Published 03-07-2020. https://www.cleanenergywire.org/factsheets/spelling-out-coal-phase-out-germanys-exit-law-draft. Accessed 20-09-2020.

Wiedenhofer, Dominik, Doris Virág, Gerald Kalt, Barbara Plank, Jan Streeck, Melanie Pichler, Andreas Mayer, Fridolin Krausmann, Paul Brockway, and Anke Schaffartzik. 2020. A systematic review of the evidence on decoupling of FDP, resource use and GHG emissions, part I: Bibliometric and conceptual mapping. *Environmental research letters* 15(6): 063002.

Wiedmann, Thomas O., Heinz Schandl, Manfred Lenzen, Daniel Moran, Sangwon Suh, James West, and Keiichiro Kanemoto. 2015. The material footprint of nations. *PNAS* 112(20): 6271-6276.

Wiedmann, Thomas, Manfred Lenzen, Lorenz T. Keyßer, and Julia K. Steinberger. 2020. Scientists’ warning on affluence. *Nature Communications* 11: 3107.

Wilkinson, Richard G. 1973. *Poverty and progress: An ecological model of economic development*. London: Methuen.

Wilson, Sheena, Adam Carlson, and Imre Szeman, eds. 2017. *Petrocultures: Oil, politics, culture*. Montreal and Kingston: McGill-Queen’s University press.

Winner, Langdon. 1978. *Autonomous technology: Technics-out-of-control as a theme in political thought*. Cambridge: The MIT Press.

Winner, Langdon. 1979. The political philosophy of alternative technology: Historical roots and present prospects. *Technology in society* 1(1): 75-86.

Winner, Langdon. 1980. Do artifacts have politics? *Daedalus* 109(1): 121-136.

Winner, Langdon. 2020[1986]. *The whale and the reactor: A search for limits in an age of high technology*. Chicago and London: The University of Chicago Press.

Wolf, Eric R. 2010[1982]. *Europe and the people without history*. Berkeley, Los Angeles and London: University of California Press.

Wong, J.H., Mohammad Royapoor and C.W. Chan. 2016. Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic systems. *Renewable and sustainable energy reviews* 58: 608-618.

Worldometer. 2020a. German energy. https://www.worldometers.info/energy/germany-energy/. Accessed 15-03-2020.

Worldometer. 2020b. China GDP. https://www.worldometers.info/gdp/china-gdp/. Accessed 09-12-2020.

Worldometer. 2020c. Germany GDP. https://www.worldometers.info/gdp/germany-gdp/. Accessed 09-12-2020.

Worldometer. 2020d. Italy GDP. https://www.worldometers.info/gdp/italy-gdp/. Accessed 09-12-2020.

Wrigley, Edward A. 1988. *Continuity, change and chance: The character of the Industrial Revolution in England*. Cambridge: Cambridge University Press.

Wullenkord, Marlis, and Gerhard Reese. 2021. Avoidance, rationalization, and denial: Defensive self-protection in the face of climate change negatively predicts pre-environmental behavior. *PsyArXiv*. https://doi.org/10.31234/osf.io/uwmcx.

WWF, 2018. *Living Planet Report 2018: Aiming Higher*. WWF, Gland, Switzerland.

WWF. 2020. *Living planet report 2020: Bending the curve of biodiversity loss*. WWF, Gland, Switzerland.

Yang, Dennis T., Vivian W. Chen, and Ryan Monarch. 2010. Rising wages: Has china lost its global labor advantage? *Pacific economic review* 15(4): 482-504.

Yang, Hong, Zianjin Huang, and Julian R. Thompson. 2014. Tackle pollution from solar panels. *Nature* 509, 563.

Yenneti, Komali, Rosie Day, and Oleg Golubchikov. 2016. Spatial justice and the land politics of renewables: Dispossessing vulnerable communities through solar energy mega-projects. *Geoforum* 76: 90-99.

York, Richard, and Philip Mancus. 2009. Critical human ecology: Historical materialism and natural laws. *Sociological theory* 27(2): 122-149.

York, Richard, and Shannon Elizabeth Bell. 2019. Energy transitions or additions?: Why a transition from fossil fuels requires more than the growth of renewable energy. *Energy research and social science* 51: 40-43.

York, Richard. 2012. Do alternative energy sources displace fossil fuels? *Nature climate change* 2(6): 441-443.

Yu, Hyun Jin Julie, Nathalie Popiolek, and Patrice Geoffron. 2016. Solar photovoltaic energy policy and globalization: A multiperspective approach with case studies of Germany, Japan, and China. *Progress in photovoltaics: Research and applications* 24: 458-476.

Yue, Dajun, Fengqi You, and Seth B. Darling. 2014. Domestic and overseas manufacturing scenarios of silicon-based photovoltaics: Life cycle energy and environmental comparative analysis. *Solar energy* 105: 669-678.

Zehner, Ozzie. 2012. *Green illusions: The dirty secret of clean energy and the future of environmentalism*. Lincoln and London: University of Nebraska Press.

Zhang, Sufang, and Yongxiu He. 2013. Analysis on the development and policy of solar PV power in China. *Renewable and sustainable energy review* 21: 393-401.

Zinn, Howard. 1995. *A people's history of the United States 1492—present.* New York: Harper.

Appendix A – Glossary

Aspiration – The articulated and pursued target of a specific social group. I use the term mostly to denote solar PV aspirations, i.e., the socially articulated targets to install solar PV technology.

Asymmetry – Denotes the condition in which two categories are not the same, i.e., an imbalance of proportion. I use the word primarily to describe 'global asymmetries,' i.e., the uneven distribution of matter-energy determined by differences in wages and prices in the *world economy*.

Complexity – Following Tainter (1988: 23), I use the term complexity to refer to "the size of a society, the number and distinctiveness of its parts, the variety of specialized social roles that it incorporates … and the variety of mechanisms for organizing these into a coherent functioning whole." For Tainter (1988: 37-38), an increase in complexity, understood as an increase in "different kinds of parts, more social differentiation, more inequality, and more kinds of centralization and control," is a type of social response to problems. A substantial decline in level of complexity is a social collapse.

Conception – An abstract idea or categorization constructed by a social group to survive in – and/or to make sense of – the world. Following Bateson (2000 [1973]), human conceptions are continually developed in relation to the contexts (i.e., the natural environments and social networks) in which they are applied.

Dissipative structure – A dissipative structure is a type of system – e.g., an organism, a hurricane, or an economy – which exists far from thermodynamic equilibrium. It maintains this state by drawing highly ordered (low-entropy) matter-energy from its environment and dissipating it in a manner that reproduces its form. A dissipative structure is an integral part of its environment since it depends upon it for this necessary exchange of *matter-energy*.

Ecologically unequal exchange – The theory of ecologically unequal exchange explains how wealthier nations rely on net imports of resources to sustain their levels of consumption and technological development, while displacing much of their work and environmental loads to poorer nations. Ecologically unequal exchange occurs in international trade when prices of commodities are not proportional to the inputs of resources in their production. In such a scenario, commodities traded at an equal exchange value (say $100 for $100) may imply an unequal exchange in terms of biophysical measures – such as embodied land, labor, energy, or materials – spent in the production of the commodities.

Embodied – The biophysical resources dissipated (or, "invested") in the production of a given commodity. Embodied emissions, for instance, denotes the amount of greenhouse gas emissions (e.g., kg of CO_2-eq.) associated with the production of a given commodity (e.g., a solar PV module). The term 'embodied land' denotes the land necessary for the production of a particular commodity. Throughout this thesis, I use the terms 'embodied labor,' 'embodied energy,' and 'embodied resources' in a similar way.

Energy carrier – A substance or device that "contains" or "carries" energy potential for human end transformation. These include petroleum, batteries, electricity, mechanical springs, dammed water, ethanol, wood, and so on. Energy carriers are distinguished from 'primary energy sources,' which are the unprocessed stocks and flows of energy in nature, including direct sunshine, coal, crude oil, wind, and biomass.

Energy density – A measure of the amount of energy per unit of mass (e.g. measured as MJ/kg).

Entropy – According to the second law of thermodynamics, energy always tends towards a state of thermal equilibrium, i.e., towards less ordered states. For example, if a cup of hot tea is left alone, the tea will cool off until it reaches the temperature of its surrounding environment. Entropy is the physical tendency whereby highly ordered states (e.g., a hot liquid) naturally tend toward less ordered states (e.g., cold liquid). When energy is converted (e.g., from coal to electricity), there is always a loss of useful energy, which typically dissipates from the system in the form of heat. To regather the dissipated energy is theoretically possible, but the act of doing so requires more energy than is gathered and is therefore energetically futile. This means that no *dissipative structure* can sustain itself from the same energy indefinitely and is therefore inescapably dependent upon its environment for a continual supply of highly ordered (low-entropy) energy. Georgescu-Roegen (1975) famously suggested that not only energy, but also matter, is subjected to entropy.

Environmental load displacement – A situation wherein typically wealthier nations displace the environmental burdens resulting from their high levels of consumption and technological development to poorer nations in the world economy. Environmental load displacement generally occurs through *ecologically unequal exchange*, but it can also occur through waste dumping.

Exergy – According to the first law of thermodynamics, energy cannot be created or destroyed. It is therefore incorrect to talk of 'energy consumption.' What is consumed, strictly speaking, is 'exergy,' which refers to a thermodynamic system's total amount of usable energy. For readability, I have chosen to use the term 'energy consumption' in this thesis, even if I actually mean 'exergy consumption.'

Fetishism – A cultural attribution of agency or inherent powers to inanimate objects. The word comes from the Portuguese idiom *feitiço*, meaning 'spell' or 'charm.' Historically, Portuguese merchants used the word to describe religious practices among peoples with whom they traded along the west coast of Africa in the 15th century. Karl Marx later applied the concept to the modern understanding of commodities under capitalist relations of production (Marx 1990[1867]:163-177). Marx argued that the human labor invested in commodities tends to be ignored once they start to circulate on the market. In effect, people tend to ascribe autonomous properties or powers to commodified objects, rather than acknowledging the human labor and social relations necessary for their production. Alf Hornborg (1992, 2001, 2016) later developed the concept by applying it to the modern conception of the machine, i.e., "machine fetishism."

Industrialism – A social commitment to mass production of commodities (see chapter three). I use the term 'advanced industrial societies' to describe industrial societies with high levels of *complexity*.

Inherently political – Following Winner (1980), this phrase is used to characterize artifacts that either necessitate or strongly encourage social relations of power.

Machine fetishism – See *fetishism*.

Materialism – A set of philosophical assertions concerning the constitution of reality as ultimately composed of matter (for an extensive explanation, see chapter two). This should not be confused with the common phrase "to be materialistic," which describes an attitude or set of values regarding our relation to commodities.

Matter-energy – A phrase integrating the two physical constituents of matter and energy. I often use the phrase 'matter-energy throughput,' which describes the quantity of matter and energy transformed by a *dissipative structure* (e.g., an economy) over time.

Metabolism – Derived from the Greek word metabolē (exchange). Denotes the material process through which organisms exchange *matter-energy* with their environment. The term was originally used by German biologists in the 1800s to explain how cells in the human body could maintain their material form over time. The term *social metabolism* denotes a socially organized material relation to the environment.

Modern/modernity – In this thesis, modernity refers to the social-cultural norms emerging from the Enlightenment and from the material conditions of the industrial regime (see chapter three).

Power density – A measure designating the horizontal land area needed per watt of energy capacity (expressed as W/m2).

Prime mover – A device or organism transforming energy carriers into motive power that can be directed by humans to perform specific tasks.

Social metabolism – See *metabolism*.

Social-ecological – Including or referring to both social and ecological relations and processes. The term is interchangeable with 'socio-ecological,' 'socio-environmental,' and 'social-environmental.'

Social-ecological regime – A historically developed social-metabolic pattern of interaction between human societies and natural systems. Whereas social metabolism denotes a socially organized exchange of matter-energy with the environment, a social-ecological regime denotes the social metabolism as well as the *conceptions* necessary to support it.

Technological continuum – A concept developed in this thesis to analyze the social-ecological conditions of modern technologies (see chapter two).

Throughput – See *matter-energy*.

World economy – The current world economy is a historically developed world-system. Following Wallerstein (2011a: 15), a world economy is distinguished by the economic (rather than political) linkages between its parts. This contrasts to world empires in which the system's parts share the same political unit. Many world economies have existed in history, but these have typically developed into world empires. According to Wallerstein (2004), the capitalist world-system is necessarily a world economy, since a global political unit would be likely to override the economic actors' pursuit of capital accumulation.

Appendix B – Information sign

TUNNFILM VAR FRAMTIDENS MELODI

För några år sen var tunnfilm det man trodde skulle bli den dominerande solcellstekniken. Dessa 7 kW tyska tunnfilmspaneler är typiska. Glaspaneler med en microtunn film inuti som gör el. Den "gamla tekniken" – kiselsolceller – trodde många skulle ersättas av denna typ.

Men istället är det kiselsolceller som idag dominerar världsmarknaden. De här helt enkelt blivit billigare. Och nu görs de med helsvarta bakgrunder så de kan likna tunnfilm till utseendet. Tunnfilm behöver cirka 25–30 procent större yta än kiselsolceller för att producera lika mycket.

Många tunnfilmsproducenter säger förstås att det är en bättre produkt då den klarar moln bättre än kisel. Vi har provat det här på kullen och verkligheten är vår domare.

Vi här inte kunnat se någon som helst skillnad mellan tunnfilm och kiselsolceller på helåret. Alla är lika bra.