Sustainability transition in basic industries - the forgotten sector

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Abstract: Emissions of greenhouse gases in all sectors of society must reach near zero, in developed countries preferably by 2050, in order to reach climate policy objectives. Alternatives and strategies for the energy and transport sectors are relatively well understood but the basic industries are often overlooked, not least in sustainability transition and innovation system studies. The policy and technology implications of near zero emissions for industry have not been extensively studied. We explore and review technologies for greenhouse gas reductions in three basic industries: cement, steel and organic chemistry, using a technology innovation system and multilevel perspective approach. Carbon capture and storage (CCS) is often put forward as the key mitigation option for basic industry but our study include a number of other technology options. These technologies may have more synergistic characteristics with emerging technologies in other sectors and therefore, good development prospects.

A better understanding of technologies for transforming basic industries and their development prospects is needed for better informed policy-making. The three basic industries studied are at very early, yet different, stages towards a transition and thus need different policies to succeed. Emissions trade or carbon taxes are important for the market formation of decarbonised production technologies, but not sufficient for their early development and deployment. Technology strategies and roadmaps are important first steps in a process to develop associated policy strategies. More studies are needed on existing regimes and future production and product niches of the basic industries, in order to build a more comprehensive understanding of possible transition pathways.

Keywords: variation analysis, basic industries, low-carbon technologies, sustainability transition

1. Introduction

The EU Kyoto and 2020 targets involve relatively marginal and near term emission reductions, minus 5 and 20 per cent, respectively, compared to 1990. Such targets can be reached without fundamental infrastructure changes or technology shifts (although strong energy and climate policies are needed). Energy efficiency improvements and fuel switching are measures enough for basic industries. The 2-degree target, however, implies a new problem framing and requires new approaches to climate change mitigation strategies, with deeper reductions and longer term perspectives.

The near-zero emissions needed in developed countries by mid-century requires near-zero emissions across all sectors. It implies technology shifts in, for example, power systems and vehicle technologies, but also in the energy intensive basic industries. The latter sector is often overlooked, or treated with rough assumptions, in scenario studies and roadmaps. Whereas mitigation options and transition strategies are fairly well understood for the energy supply, buildings and transport sector, there is much less knowledge about options for the basic industries. Major changes to production routes are dependent on several factors and a systemic approach is thus needed to escape the current carbon lock-in [1].

The primary objective here is to explore and assess technology options that can reduce emissions from key industrial processes to near zero, and their possible transition pathways. We analyse such options for three subsectors: cement, iron and steel, and chemicals. The important option of carbon capture and storage (CCS) is excluded since it has received relatively extensive treatment elsewhere. CCS retrofitted on existing plants will not itself be enough for a radical decarbonisation in industry [2]. However, CCS integrated into future potential greenfield productions sites, e.g. BLG in paper and pulp or new oxy-fuelled cement factories, could have a major potential. Furthermore, we assume that sustainably produced bioenergy will not be available in significant quantities for industrial energy purposes due to resource constraints.

Basic industries are characterized by high capital intensity and low capital turn-over rates. This means that a 40-50 year transition period may be viewed as relatively short. Fundamental changes in feedstock, process technologies or products through the process of R&D, demonstration projects and technology diffusion will be slow. They are also unlikely to occur without government policy and long term strategies. Based on the assessment of technology options and their associated innovation systems we discuss policy options for governing a sustainability transition in these basic industries.

2. The transition and innovation system approach

It has recently been suggested that the multi-level perspective of sustainability transitions and theories on technology innovation systems can be combined to capture the strengths of both frameworks in aiding innovation policy decisions and to make prospective analysis of future innovation systems [3]. The foresight character of our study makes it a suitable test case for such a combined framework. At the core of the method is the variation analysis, an explorative approach to identify plausible options of how the innovation system may develop along different technological trajectories and of how these interacts with organisational variants [4].

Following Markard et al. [4] the analysis is conducted in three parts: basic analysis, context analysis and variation analysis. A rough scenario on how the political and technological context will develop is outlined. Based on the variation analysis, policy options are discussed. The basic analysis concentrates on the emerging technological innovation systems, and is restricted to those actors, networks and institutions that actively support the technology [3]. Although some of the technology options/niches described here cannot strictly be considered to be part of any technological innovation system we have applied the same analysis to them, specifying that they are in an embryonic phase. This is due to the fact that we are studying technologies that may be ready for commercial application 30-40 years from now. The challenge of climate change makes it important to speed up the introduction of new technology on the market.

The context analysis focuses on the current socio-technical regimes that need to change in order to enable decarbonisation. We include technologies developed outside of Europe, but our focus is on how these can be implemented in European industries, and what actors, networks and institutions exist that can enable the transition. International factors that may influence the development and diffusion of the studied technologies in a European context are taken into account.

Although the approach is explorative, our scenario is of a normative character. We have selected technologies that have the potential to substantially abate emissions of carbon dioxide in cement, steel and chemical manufacturing. The analysis is based on written material published by relevant actors and networks and earlier assessments. The study should not be seen as comprehensive, but aims at giving a first insight into the obstacles and possibilities for a full decarbonisation of basic industries during this century.

3. Low energy, low carbon cements

3.1 Basic analysis

3.1.1 Technical and environmental aspects

Emissions of greenhouse gases in cement production is caused by two factors; burning of fossil fuels for heat (40%) and the calcination of limestone to chemically reactive calcium oxide (60%). This calcium oxide is the main constituent of clinker, the binding material in cement. The most widespread type of cement is Portland cement which is made out of mainly clinker [5]. Many alternative materials have been suggested as replacement for Portland cement to reduce the emissions of greenhouse gases from cement production [6], [7]. Only four concepts have the potential to reach near-zero emissions; the use of waste materials, recycling of carbon dioxide, substitution of limestone with magnesium-based silicates, or to apply CCS to the existing process. All suggested alternatives except CCS will also reduce energy use and enable the use of other sources than fossil fuels for heat production. Substitution of fossil fuels in lime-kilns is considered difficult, since high heating values are required to produce the temperature needed for calcination (above 1450°C), although plasma technology may be an option to reduce fuel related emissions.

Readily available materials for cement production, except $CaCO_3$, are SiO_2, Fe_2O_3 and Al_2O_3 [8]. These materials are available in a number of waste streams, such as sewage sludge, drinking water treatment plant sludge, waste from basic oxygen furnaces, and marble sludge [9]. Already used as partial replacements for clinker in pozzolanic cements, another alternative is to produce cement completely from such waste. Such a solution will lead to energy savings, less industrial waste in land-fills and concurrently reduce the need for mining. The main energy savings results from that the materials does not have to be quarried or heated to the same extent as in ordinary cement production based on limestone. If the energy used in manufacturing process is provided by renewable energy sources this cement can be near-carbon neutral.

A related concept is used by the company Calera in California, using CO_2-rich flue gases that reacts with Ca (or Mg) in waste water streams, ponds or seawater to form vaterite, imitating the formation of coral reefs. Vaterite is an unstable form of $CaCO_3$ which stabilise into calcite or aragonite in contact with water (which stable state that forms, depends on the temperature conditions) [10]. Crushed and dry vaterite can be used as cement due to its reactive characteristics. Depending on the carbon dioxide source and the energy used in the process, the Calera cement can be carbon negative.

Magnesium silicates can also be used for cement production. This alternative has been developed at Imperial College in the UK and is manufactured at small scale by the company Novacem. The resulting Novacem cement is a mix of magnesium oxide (MgO) and hydrated magnesium carbonate ($xMgCO_3 \cdot yMg(OH)_2 \cdot zH_2O$). Magnesium silicates is heated to a temperature of 170°C, reacts with carbon dioxide, water, and some additives to form $MgCO_3$. The magnesium carbonate is heated to 700°C to form MgO, releasing CO_2. This CO_2 is recycled to the first part of the process, and reacted with the hydrated magnesium carbonate [11]. This latter product is mixed with the MgO to form cement. Due to the low temperature in the process biomass can be used for energy purposes. If electricity from renewable sources is readily available electro-thermal technologies can also be used.

3.1.2 Market aspects

The main obstacle for gaining market shares with alternative cements is that the durability and quality of these are yet to be proven for construction purposes [11], [8]. The small number of companies that exist on the market only produce cement for small niche-markets.

CeraTech in the US and Cenin in the UK both produce cement from waste materials. Both companies offer products for construction, such as precast concrete and masonry blocks. These products has been commercially available for more than four years and Cenin's cement has been certified according to European cement standards. Scale-up depends on readily available waste streams. CeraTech relies on fly ash which is readily available as long as coal is used for electricity production. No potential studies have been done but waste generation from manufacturing is large in the UK, France, Germany and Poland, who together produce more than 240 million tonnes of industrial waste per annum [12].

Cement based on magnesium-silicates has only been produced at a laboratory pilot plant but Novacem aims at offering commercial products by 2017/2018. The Bindan Company in the USA is also manufacturing magnesium based cement which is already on the market as a niche product, for architectural and artistic purposes, road repair, and fire-resistant coatings. Scale-up production and tests on safety and long-term performance, such as rheological and mechanical properties, which is required for construction purposes, are important steps to be taken for magnesium-based cement [6]. Magnesium silicate minerals are abundant but deposits tend to be located in environmentally sensitive regions why this type of cement production may be limited to a few locations [13].

Only one company has developed cement which actively captures carbon dioxide. No commercial products are available, but one demonstration plant is being operated. The company, Calera, aims at producing 5 million tons of cement by 2030. The availability of the raw materials needed for Calera's cement also determines its manufacturing sites. If waste streams are not available, magnesium or calcium rich waters, such as ponds or seawater could be used. A source of carbon dioxide is also needed, why the demonstration plant is located close to a coal-fired power plant. The out-take of vaterite from seawater may have an impact on aquatic life if implemented on a large scale, why the matter should be researched.

3.1.3 Actors and institutions

Core actors in the development of new cements are the small manufacturers and a few research institutes and universities. Novacem is a spin-out from Imperial College London and Calera is indirectly a product following research on coral reef formation being conducted at the University of California at Santa Cruz. A small number of construction firms and institutes involved in building research is also involved. Funding is largely public in Europe, but in the US some private actors have engaged in investments.

Consumers in the construction sector and green building networks such as the World Green Building Council has a potential role to play, but has not been particularly active in promoting new types of cement. Waste-based cement has been given LEED credits in the US due to its possibilities for relying on local materials and reducing land-fill waste.

No networks or any institutions favouring new types of cement exist today. One aim of Novacem is the build-up of such a network in Europe, promoting low-carbon cements and knowledge sharing. The Cement sustainability initiative, incorporating some of the largest cement producers in the world, recognise alternative cements but only pursues CCS as a long-term option [14]. Research on CCS is also the only one conducted by European cement research academy (ECRA) on greenhouse gas abatement.

3.2 Context analysis

The main sector that novel cements will have an impact on is the construction sector. The diffusion of low-carbon cement will be slowed down by the rigid set of standards and building codes that are adapted to the specific characteristics of currently used Portland cement. These standards is a result of risk minimization of structural failure, mainly for safety reasons and will not be easy to challenge. Even after validation of the new technologies and new, specific standards in place, the diffusion of alternative cements may be slow, due to safety considerations and inertia among construction agencies, architects and design engineers. Cement industry has a well established production and supply chain, and can, due to economies of scale, offer products of low prices. It is tightly linked to the users in building industry and several decades of development has built up networks that largely rely on trust. Alternative cements will most likely have to start in niche applications to prove economic viability and to gain experiences on the long term durability and strength.

There is very little pressure from the landscape level on the construction sector to implement new types of cement. The cement manufacturing industries has been affected by increased production costs because of rising electricity price since the introduction of EU-ETS but this has so far had little impact on business. The cement production in Europe was not largely affected by the economic crisis and it is likely to be a stable market in the future. Cement is a bulk product which is not easily transported long distances why the market for cement and clinker is typically regional or national. The industrial structure and the quality requirements of the buyers also plays a crucial role in determining geographical boundaries of the market. Manufacture plants tend to be close to raw-material sources to minimize the costs of transportation [15].

The promotion of recycling and the European programmes on material scarcity can affect the future of cement and concrete production. Other waste streams than the ones utilised for cement production today can come into consideration, such as scrapped solar cells or electronic waste, which are both rich in silicon [6].

3.3 Variation analysis

3.3.1 Technological variations

The *type of material* used will determine how the new cement will be used and to what extent it can diffuse into the market. Type of raw material needed and found locally is a precondition for manufacture of new cement types. The *environmental benefits* are large irrespective of material and technology but the largest gains can be found in using waste as raw material since it also lowers the use of raw material. The reduction of greenhouse gas emissions are however larger for magnesium-based cement and Calera's technology, since both processes stores carbon dioxide and therefore has the potential of being carbon negative. Environmental assessments, such as LCA could be done to compare the relative benefits of each technology.

To what extent it would be easy to *substitute* ordinary cement differs between the alternatives studied. Waste based cement has the greatest potential of rapid up-scaling, due to the fact that it has been used for a while and that standards in Europe already allows for partial substitution of clinker in cement. It is also the technology that fits best within current regime. Characteristics have been contested and partial substitution is possible. Magnesium-based cement is will more likely substitute niche applications in a first step.

3.3.2 Organisational variations in relation to technological

Due to the embryonic character of the socio-technological systems of low-carbon cements, any organizational variations is hard to distinguish. However, Calera's cement and waste-based cement offers solutions to other industries' environmental issues why these processes might have a larger probability of gaining momentum. CCS is promoted on European level, and the option of storing carbon dioxide in construction could be an economical alternative to aquifer storage. The Calera cement could even be an option for co-production with existing cement manufacturing, capturing the process emissions from clinker production to produce the second type of cement. Up-scaling of niches may also be driven by consumer related institutions such as eco-labelling, but it this will likely take longer time if low-carbon cements are not recognised on national or EU-level.

Knowledge building and testing to confirm safety issues is most crucial for further development. All three cement types can co-exist and co-evolve and will most probably benefit from the same legislation and knowledge building about new possibilities in cement-production.

4. Electricity-based steel production

4.1. Basic analysis

4.1.1 Technical and environmental aspects

The most important process to change when abating greenhouse gases in steel manufacturing is the iron production in the blast furnace. About 82% of the emissions of greenhouse gases in steel production is caused by the use of coke in the reduction process where oxygen is removed from the iron ore [16]. As long as steel production exceeds the amount of available steel scrap, reduction agents are needed, and to find a replacement for the coke used today is a crucial step towards decarbonising the steel industry. Two alternatives exist that fit this purpose; hydrogen as a reduction agent or reduction through electrolysis.

Using hydrogen as a reduction agent is not a new idea but has not been implemented due to the higher cost compared to coke [17]. In the context of climate change mitigation, reduction with hydrogen has now been tested at lab-scale. One technology that seems prominent has been developed at the University of Utah; so-called suspension reduction [18]. This technology will use 38% less energy than current steel production since the iron ore does not have to be sintered or pelleted and no energy is needed for coking. The total energy savings will be less, about 15%, since the hydrogen, to be sustainable, must be produced from electricity through electrolysis. Reduction with hydrogen is an endothermic process (as opposed to reduction with coke) and thus needs a heat source. The extra heat required could be provided by electricity (e.g. microwave technology) or by burning excess hydrogen, the latter being a less energy efficient alternative. About 60% of the hydrogen can be utilised in the process, so the gas must be recirculated. The amount needed depends largely on temperature and required speed of the reduction, why lower amounts of excess hydrogen can be expected to be needed in a mature technology. The flue gas from reduction with hydrogen will be mainly water vapour, which should be used for new hydrogen production since the high temperature can be used to increase efficiency in water electrolysis [19].

Electrolysis of iron ore to produce iron is also possible. This process is known as electrowinning. The iron ore can solved or suspended in an acid or alkaline solution to enable the process. It can also be melted in a saline solution for high temperature electrolysis (above 1600 °C). If the iron is not melted the electrolysis can be performed at 110 °C. The studies show that 2.8-3.2 MWH/ton sponge iron is needed for the electrowinning process [20], [21]. The low-temperature process is at a more technologically mature stage.

Both technologies rely on electricity production from renewable energy sources to be sustainable. If the whole steelmaking process would be electrified, including melting before casting, the electricity use of either technology would be around 4 Mwh/ton steel.

New reduction methods offers some advantages to current production apart from lowering emissions of carbon dioxide. Hydrogen reduction is faster than reduction with coke and could shorten manufacturing time [22], [18]. Coke contains sulphur which must be removed from the steel, and about 100 Nm^3 of oxygen is needed in order to reduce the concentration of carbon in steel production today. As requirements on low sulphur and carbon content in some speciality steels grows, using reduction methods free from carbon may reduce costs. To get a breakthrough in the use of new reduction methods in steel industry this must however be recognised as a long-term strategy since the plant life times are long and infrastructural investments large. The use of hydrogen as a reduction agent could also be utilised as a means of energy storage or load smoothing in the electricity grid if implemented in a smart way.

4.1.2 Market aspects, actors and institutions

The research done on zero-carbon solutions to the reduction of iron ores is conducted in public-private projects. In Europe the research has been done within ULCOS, a project coordinated by ArcelorMittal, incorporating the major steelmaking firms of Europa. Funding has been provided by the steel industries and by the European Commission through the 6^{th} Framework programme and the Research Fund Coal Steel programme. The project aims at identifying technologies that can reduce emissions from steelmaking by at least 50% to 2050. It is now in its second phase, where some of the identified technologies are to be demonstrated. Three technologies utilising CCS are chosen from the first phase, together with alkaline electrolysis. Not much has been reported from the second phase of the project. In March 2011, Jean-Pierre Birat, the coordinator of the programme gave an update to the European Commission, where he concluded that “ULCOS was a research initiative, has turned into a demonstration initiative but it IS NOT a plan for reducing the emissions of the steel sector!”.

At the time being no market exists for low-carbon steelmaking and no actors or networks actively pursue the development. No institutions are in place to promote alternatives others than CCS for reducing greenhouse gas emissions from steel production.

4.2 Context analysis

The steel industry in Europe is well established and generally considered to be an important part of society, historically being considered as a measure of wealth of a nation. Existing plants are generally old, but continuous refurbishment can substantially enhance their lifetimes. Research on adoption of innovative technologies in the steel industry has shown that diffusion has been slow, even under favourable economic conditions, and that government intervention has been important when research and development does not concern the core business of the firm [23], [24]. The European steelmakers are increasingly being challenged by international competition and material substitution in products traditionally consisting mainly of steel, such as cars (where plastics now is a large constituent). China and India are today the leading producers of steel and to meet this increasing competition, European steel industries are increasingly producing higher-value products, such as lightweight steel. Alloying materials make up a large share of these steels, which may put a cap on the growing production, since alloying feedstock have a risk of becoming depleted [25]. With the falling demand due to the economic crisis and the cooling of the market in the Chinese building sector, new investment in steel industry in Europe is hard to picture.

EU-ETS and the IPPC Directive, now replaced by Directive 2010/75/EU, are the main policies affecting the existing primary steel manufacturing industry in the environmental field. These policies will most probably not be strong enough to enable the development of hydrogen as a reduction agent or electrowinning processes. Steel often deemed the sector most vulnerable to leakage due to the international character of the market, but some studies has shown that the losses is probably small 26]. The perceived risk of leakage, however, weakens the stringency of current measures. Institutions supporting reduction of greenhouse gases in steel industry are all focused on implementing CCS and to some extent increased recycling. Directive 2010/75/EU directly supports CCS, in that all member states must ensure that suitable storage sites are available, transport facilities are technically and economically feasible and that it is feasible to retrofit for carbon dioxide capture. Due to issues of security of energy supply, the European Commission has stated that “coal is, and will remain, a key element” in the future fuel mix. The Research fund for coal and steel is aimed at promoting “clean-coal” technologies and support research projects from production processes, to the impact on climate and environment. Long-term strategy of the programme is based on the priorities by the European Commission in collaboration with Coal Advisory Group, and the Steel Advisory Group.

A sustainable steel industry would most probably rely more on scrap than it currently does. This development path is supported by a number of European strategies (e.g. [27], [28]). About 85% of the steel is recycled today, but a large part is accumulated in the user phase. To enhance the recycling rate, better steel classification and assortment is needed. Less than 40% of steel production today is from recycled steel and to reach near 100% production from scrap steel would take at least 40 years if steel production remained at present levels. The secondary steel production route reduces emissions by almost 80%, depending on electricity mix used in the electric arc furnace. To reach near-zero emissions, other melting ovens is needed and the small amount of coal added for reduction should be substituted by hydrogen. The development of new melting ovens, such as plasma or induction ovens would benefit also the electrowinning process or the route in which hydrogen is used as reduction agent. The key benefits besides lower emissions will be higher thermal efficiency than with the use of electric arc furnaces and fewer waste products [29].

To enable implementation of hydrogen as a reduction agent in steel industry, development is needed on electrolyser technology to lower the cost and increase efficiency of producing hydrogen from water. This innovation system is recognised by the European Commission as a European Technology Platform under the Joint Technology Initiatives but the focus is currently on use in transport and stationary fuel cells.

One alternative to the suggested technologies for reduction would be to use biomass instead of coke as a reduction agent. Charcoal could be used in existing blast furnaces, but due to the lower mechanical strength of charcoal compared to coke this is not a viable option. The utilisation of biomass would probably only be favourable if the biomass is gasified and used in direct reduction. Since competition for biomass will most probably increase in the future, this might be an expensive option, especially if biomass is increasingly being used to produce high-value materials (see section 5 below).

4.3 Variation analysis

4.3.1 Technological variations

Two groups of technological variants exist for electricity-based steel production. Both routes shows good technical performance at lab-scale but none has been proven in up-scaled situations. Further research is needed to determine if the resulting steel products will have different characteristics depending on technology. The high price of hydrogen is currently favouring electrowinning, but this may change if hydrogen becomes a more important energy carrier in the future. Hydrogen as a reduction agent could be used in existing shaft or fluidized bed furnaces, but those constitute only about 6% of current steel production in the world.

For both technology options the use of electricity in Europe would increase by roughly 450 TWh/year if those technologies were applied today, increasing final industrial electricity use by 45% [30].

4.3.2 Organisational variations

More than half of steel is today produced in integrated steel mills where reduction is made in blast furnaces. In mini-mills scrap is melted in electric arc furnaces, and sometimes blended with direct reduced iron. Relying on this organisational structure it could be more likely that new reduction methods are first implemented in mini-mills, where up-scaling is not as crucial. A shift towards more recycling will favour steelmaking in mini-mills. The other alternative is that the non-environmental benefits of utilising electricity for steelmaking (lower carbon and sulphur content) are perceived as a business opportunity by companies engaged in producing speciality steel, which is today mostly being done in integrated steel mills.

With larger dependence on electricity for industrial processes there may be an organisational shift towards more in-house electricity generation. In Sweden the pulp and paper industry has already made a reorientation, investing in wind power for securing low electricity costs [31]. With variable electricity production the use of hydrogen for reduction can be favourable since the hydrogen also serves as energy storage, which enables continuous steel production. If hydrogen is not produced in-house a transportation infrastructure and centralized production of hydrogen is needed, why this route is more dependent on development in other sectors, such as transport and energy storage.

4.3.3 Technological and organisational coherence

The organisational variants of future low-carbon steelmaking sketched above are highly speculative, due to the low participation of actors. At this point more research and up-scaling of the technologies is needed in demonstrations. Since using electricity for steelmaking is today most compatible with mini-mills, demonstration projects engaging actors at those plants seems most plausible.

5. Green chemicals and biorefineries

5.1. Basic analysis

5.1.1 Technical and environmental aspects

Most of our chemicals contain fossil carbon that will eventually leak into the atmospehere in the form of CO_2 or CH_4 thus augmenting climate change. Approximately 5% of all fossil petroleum is used as feedstock for chemicals. The rest becomes transportation fuels. Carbon from biomass is the only near term renewable source available for the production of chemicals to substitute current petrochemicals. Today only 2% of all chemicals is derived from biomass.

To replace the petro-chemistry the concept of biorefineries has been proposed. It can be defined as an industry that, based on input of biomass, produces a large number of output products: power, heat, chemicals, materials and fuels. The basic idea is similar to a petroleum refinery, to use the inflowing carbon (in this case biomass) efficiently and to produce as much high value products as possible. The variety in designs of biorefineries is huge.

Biomass can be converted to useful chemicals in a biorefineries in two principal ways. The first principal way is to produce base chemicals (e.g olefins such as ethylene) similar to those produced by petroleum refineries today. This will enable to use the existing stock of down stream processing equipment. The other principal way is to take advantage of the specific structures and e.g the excess of oxygene that exists in biomass compared to petroleum products. This will require specifically developed down streams chemical factories but enables a more efficient utilisation of the biomass. The suitable route depends partly on which feedstock is available [32].

However, the main biomass resources available for large scale chemicals production in the future will be woody biomass, e.g. lignocelluloses. Lignocelluloses can be transformed to usable products in two ways: either as a syngas (H_2 and CO) is produced through pyrolysis, steam reforming or gasification. This is the thermochemical route and will split the whole biomass into minimal building blocks in the form of syngas (H_2 and CO) which later can be transferred into methanol, hydrogen or ethanol, all usable basic chemicals. The other route for transforming lignocellulosic material is the biochemical route where the existing properties of the biomass is preserved as much as possible to generate appropriate chemicals [33]-[35]. However, most of the output will be ethylene which is totally compatible with current down stream processing equipment. Approximately a third of the output will be lignin which can be converted to aromatics.

For the thermochemical route, breaking down carbonaceous material to syngas via gasification is a proven technology for coal and oil and oil residuals. However, for woody biomass, the ability to produce a clean syngas (free from tars) suitable for down stream synthesis is still a difficult issue and needs further development. For the biochemicals route, breaking down cellulose and hemicelluloses (approximaltey 2/3rds of the woody biomass) to fermentable sugars is technically available today (e.g via acid hydrolysis) but needs more basic development for enabling promising future technologies such as enzymatic hydrolysis that would make this route cost competitive. The technical ability to transform the remaining lignin (1/3 rd of woody biomass) to different aromatics is currently developing fast.

Whatever route, the benefits of a biorefinery is that a broad range of biomass feedstock can be used. Ligno-cellulosic biomass, such as wood, agricultural residues or grass, is more readily available than dedicated crops and has less seasonal dependency [32]. The environmental impact of ligno-cellulosic feedstock is generally lower than for dedicated crops, most studies show they have less impact on land-use changes and emit less greenhouse gases [34]. Life-cycle analysis of the potential products from a biorefinery should however be a guiding principle when to decide which chemicals to manufacture. The difference between the thermochemical and the biochemical route in environmental performance does not give any clear winner. Local availability to feedstock, local technical know-how, and the market for the main output from a future biorefinery (mainly which types of biofuels) will eventually determine the technology choice.

A main long-term challenge for the biorefinery concept is to secure and develop a large and sustainably produced flow of biomass. Here, the last years debate and resulting build up of knowledge on sustainable supply of bioenergy will be crucial, see e.g. [36].

5.1.2 Market aspects

Production of chemicals from biomass is already established. More than 90% of the world's ethanol production is from biomass [34] and the number of specific chemicals developed from certain biomass types is rapidly growing.

The European project BIOPOL which was launched to map activities on biorefineries in Europe concluded that 34 existing or planned biorefineries could be identified in 2009, together with 45 research and demonstration projects. The projects were located in areas with access to suitable feedstock and intensive petrochemicals production. There is a strong push for demonstrating both the gasification and the hydrolisys route for enabling so called 2^{nd} generation of biofuels. Furthermore the use and interest for biogas and biomethane which could replace natural gas have been increasing the last years and share many of the technical components of especially the thermochemical route, see e.g. [37].

The driver for investing in biorefineries depends on actors involved. Biofuels that reduce greenhouse gas emissions are supported for environmental goals from policies while chemicals and materials must be produced for economic reasons [38]. The current growth of biochemicals is happening in context where the specifics features of biomass have specific advantages for the chemicals produced. However, with the current rush for producing biofuels and the concurrent technical development, the interest for introducing biomass as a feedstock for replacing basic petro-chemicals is increasing.

5.1.3 Actors

A broad range of actors is involved in the development of biorefineries. Small speciality chemical producers along with a small number of large chemical firms can be seen as core actors for down stream processing. For upstream processing (e.g the production of basic chemicals), the emerging biofuel industry and e.g. the forest industry has started to play a role in promoting biorefineries. Research and development projects are funded by the European Commission through the 6^{th} and 7^{th} framework programmes and nationally funded projects has also been launched. The European association EuropaBio was established in 1996 to promote bio-technology in the European Union. The association represents 62 corporate and 7 associate members, which comprise 1800 small and medium sized enterprises. Although EuropaBio does not exclusively enact biorefineries, the association and some of its members are engaged in a number of biorefinery projects.

The consumer market for biobased chemicals is still small but emerging. The major market push for core technological development is today driven by the varying legislation on biofuels.

5.1.4 Institutions

The EU has recognised the benefits of biorefineries and pushes this along with the strong push for replacing petroleum derived fuels in the transport sector. The EU and national governments has also initiated several research efforts into developing the use of biobased chemicals into usable products (so called white chemistry and green chemistry). However, the link between the climate policy agenda and the development of lignocellulosic biochemicals is weak and not recognised (e.g the embodied climate neutrality of biomass in products cannot not be accounted for in the UNFCCC framework). As stated before, the current interest and development of biobased chemicals comes in situations where there is a specific features in the biomass that is good and from a general notion among the chemical industry that their reliance on products form petroleum refineries needs to change in light of peak oil and climate policy.

5.2 Context analysis

The biorefinery concept will challenge the current practice in many sectors: chemical industry, the pulp and paper industry, starch and sugar industry and the biofuels industry together with agriculture and domestic and industrial waste handling. However, an external change in regime which favours biorefineries is ongoing and could be the main driver for biorefineries in the long-term. Climate policies are making the domestic demand for petroleum based fuels declining and replaced by biofuels. As large share of the chemical industry is linked to the petroleum industry, this climate policy induced change will automatically also drive the development of biomass based chemicals in Europe. However, the competition for biomass will be fierce in a future climate restricted world. However, generally chemicals have a much higher market value compared to fuels and energy.

The forest industry and its ability to supply large amounts of sustainably grown biomass for other purposes than timber and paper and pulp is of course of great importance: Landscape factors affects the forest industry (including paper and pulp) is a driving force in developing biorefineries and a more diverged output of materials from forest biomass. Pulp and paper industry must diversify to get higher value out of their processes [38]. As an example, the forest products association of Canada has plans on transforming Canada's forest products industry. The forest industry is one actor that has entered the scene in promoting biorefineries. Already in the 1930s pulp and paper companies in Sweden established chemical production from biomass due to shortage of chemicals in Sweden caused by the WWII [38].

There is a risk that the emerging biochemicals industry will be negatively affected by the food versus fuel debate. This risk depends strongly on the feedstock chosen and on how agricultural policies develop, not the least in the developing world. There is nothing that hinders a growing biofuels/biochemiclas market in terms of sustainability. However, the development depends on the existence of a comprehensive climate and sustainability policy spanning over the whole use of bioresources.

The possibility of recycling carbon dioxide into hydrocarbons through co-electrolysis with water is an alternative to produce carbon-based chemicals and plastics with low emissions, which exist at a research stage [39]. The development of co-electrolysis into methanol or syngas would most probably complement technologies that are to be used in biorefineries.

5.3 Variation analysis

5.3.1 Technological variations

Two main routes exist for the production of large amounts basic chemicals from lignocellulosic biomass, the thermochemicals and the biochemicals. Basic chemicals with a resemblence of current petroleum derived chemicals can be produced from both routes but current focus is on utilising the inherent structure in various sources of biomass (mostly sugars) to create specific chemicals. The main growth potential lies in utilising lingocellulosic biomass but ensuring efficient utilisation of the biomass is a key requirement. Cherubini and Strømman [34] gives a theoretical example by replacing all bas petrochemicals with biochemicals. Their theoretical calculation shows that this could increase the global demand for woody biomass by 27 to 68 % depending on efficiency in the process [34].

5.3.2 Organisational variations

Production sites of basic biochemicals could both be stand-alone plants but more likely is that integrated biorefineries will evolve producing foremost biofuels and a limited share of the biomass output being e.g. ethylene, lignin etc. Integrated biorefineries located close to existing chemicals and petroleum refineries are gaining ground. One example in Sweden is the announcement made by the chemical cluster in Stenungsund to become completely biomass based by 2030 (currently importing ethene from a nearby refinery and from abroad).

The above mentioned development will evolve concurrently as the industries developing agricultural biomass (e.g. sugars or wheat etc) will continue to develop small niches for finding new high value markets for their products. The forestry industry is also looking to augment their added value and, for example the paper and pulp industry will in the future have the ability, via black liquor gasification, to produce large amounts of syngas for further processing..

5.3.3 Technological and organisational coherence

The single, thermochemical route built on gasification is the most compatible route with existing infrastructure. However, the biochemicals route offers a close to similar compatibility and is probably closer to market in large parts of the world (e.g. already producing ethylene in Brazil). As this development is mainly driven by the policy induced increasing demand for biofuels, the development for biochemicals will most likely be strongly linked to this development.

6 . The broader system and policy context

The analysis of technology options and innovation systems shows that there are considerable differences between the three subsectors in terms of, for example, the character of technological opportunities and maturity of options, as well as markets and actors. If the EU, or the world, is serious about making the transition to a low carbon future, such differences need to be taken into account in the process of policy development. Furthermore, it is important to consider the implications of broader energy system and technology development, as well as the development of international climate and other policy.

In a situation where there is political agreement on action it would be easier to make a transition through the basic demand pull that high carbon prices would create. However, there is little hope that the world will see sufficiently high international carbon prices to initiate technology shifts in the next 10 or 20 years (we do not include engineering-economic analyses in our assessment but 'sufficiently high' is often taken to mean *at least* 40-50 EUR/ton CO_2 in order to motivate CCS). Although many governments prefer ostensibly technology neutral policy instruments such as taxes and emissions trading, in this situation it is necessary to use other types of instruments, e.g., regulation and support schemes, in order to initiate a transition and overcome the risks associated with systemic change.

Even in a hypothetical situation where industry would face relatively high carbon prices it is unlikely that this alone would be enough, or the most effective way, to drive a transition. Considerable R&D efforts and full scale demonstrations that require public financing may be needed to develop various options. Risk averse and asset intensive industries, on their own, are unlikely to take the technical, commercial and political risks involved in substantially changing its often large-scale core process technologies. Ties between basic industries and governments are traditionally strong – historically often characterised by direct or indirect subsidies that have tended to shelter industry from technical and structural changes. Conversely, in a transition to near-zero emissions it seems inevitable that the government has a strong role in facilitating and promoting change.

Transition strategies for industry are highly dependent on the development of energy supply systems at large. Will decarbonised power systems with high shares of variable renewable power be the backbone of energy supply as often envisioned [40]? Is it likely that hydrogen or synthetic hydrocarbon production becomes part of the future system? Will CCS-technologies develop successfully and be applied also to, for example, cement plants in geographical locations that are favourable to CCS transport and storage? In many cases we do not think it will be a matter of "either-or" but rather "both-and" in terms of energy carriers and technologies, since suitable options may vary widely between plants and geographical locations. Transition pathways will also depend on technology R&D that is not necessarily motivated by basic industry needs, but perhaps by applications in other sectors. Bio-catalysis, electrolysis, membranes, and electro-thermal processes are examples of technologies and processes that have a wide range of applications.

The development of markets for basic materials is also uncertain. Although a change into a service-based economy is often proposed as necessary for reducing emissions in the long run, this need not mean that energy intensive activities are reduced in absolute terms [41]. A sustained, but preferably sustainable, basic industry is therefore a more probable scenario. Making the transition in, for example, energy and transport systems, or buildings, requires construction and insulation materials, metals, polymers, etc. In this sense, the basic industry is part of the solution – there can be no system wide transition without it.

7. First steps towards basic industry transition policy

The assessments undertaken here represent a first attempt of mapping a set of technologies and associated pathways to a sustainable basic industry. More comprehensive and in-depth assessments of technologies and different subsectors in the basic industry are needed in order to arrive at a clearer picture of potential transition policy strategies. Some preliminary observations and suggestions on the way forward can nevertheless be made, based on our analysis.

In contrast to other sectors, one observation is that there are yet no shared visions of how innovative technological solutions can contribute to a transition in basic industries [42]. A first step towards unfolding an industrial transition policy is to develop roadmaps for each subsector, engaging the actors identified above in this process. Such a roadmap is one mechanism for building a shared vision. It may also give input for long-term investment strategies as well as identifying short term R&D priorities and other joint undertakings that can be shared by public and private funding. Studies on the power sector have shown that long-term emission reduction target may have a more important role in spurring innovation than market-based policies although a carbon price may function as a basic demand-pull [43], [44].

The overall purpose of a roadmap may be to establish priorities on RD&D, create networks and institutions for knowledge sharing, and map out possible technology and policy pathways. Our analysis shows that roadmaps need to be developed for each subsector due to the differences in technology characteristics as well as the structure of the socio-technical systems at large. Such differences imply a need for R&D, innovation and industrial policies that are adapted to the different technology characteristics, as well as the specific conditions of the subsectors. Due to uncertainty, changing conditions and the unpredictable nature of technology development, the roadmap should not be a static document but rather an on-going process, and a process open to new actors.

An important observation from this study, and others, is that the actors driving a transition are often not the core incumbent actors of the system that is to be changed. For the steel industry, we make the observation that there are yet no external actors, representing radical technical change, that are driving the transition. Hence, this subsector may be slower to change. The incumbent actors are specialists on their existing core process technologies and it comes as no surprise that CCS, an end-of-pipe solution, has been *the* option for abatement. However, CCS may be more difficult than envisioned to add-on to existing plants, and other technological and organisational variants should also be explored and pursued.

Investments in new technologies that change the core process of manufacturing basic materials is capital intensive and involve considerable risks for industry. Extensive public-private collaboration on research, development and demonstration is therefore needed. Due to the scale of investments in basic industry, such a system may be modelled on the European Union NER300 scheme where revenues from the EU ETS will be used to fund, for example, CCS and large scale renewable energy demonstration projects. Intensified R&D efforts, perhaps including such efforts undertaken through the EU EIT KIC (Knowledge and Innovation Community) scheme in other areas, are also important.

Some specific characteristics of the emerging technological innovation systems that challenge current regimes in each subsector should be noted. For new cements to gain ground, new standards are needed to ascertain users in the construction sector that they are safe to use. Networks build-up and knowledge sharing is of crucial importance in this subsector, due to the tight link between users and producers in the existing regime. In the steel industry, actors that can gain from the non-environmental benefits of low-carbon technologies must be identified. The low carbon and sulphur content of electricity-based steelmaking can provide new ways of making specialty steels, which could be a way of bearing higher production costs. The process of transition in chemicals industry has already gained some momentum. A wide range of actors are involved in developing the biorefinery concept. Lacking, however, are institutions that directly support biomass-based chemicals other than fuels.

8. Concluding summary and outlook

The primary objective in this paper has been to explore and assess technology options that can reduce emissions from key industrial processes to near zero, and the possible transition pathways. The assessment has given a first insight into the obstacles and possibilities for a full decarbonisation of basic industries, which can be used to inform better policy making for governing a sustainability transition.

We have used variation analysis as an explorative method to distinguish coherency between technological and societal components. The concept proved to be useful in this aspect. Together with environmental and economical assessments of future technologies a variation analysis can provide a more comprehensive guiding to policy making.

The assessment has shown that raw materials available for cement and chemicals production will not only determine end-product, but also technological and organisational variants to some extent. The possibility of diffusion and adoption into current infrastructure and incumbent industrial practices differs a lot between the studied technological variants why one plausible scenario is that radical innovation is performed both in niches and within current regime. Only in the case of biomass-based chemicals does favourable institutions exist, these are implemented to support biofuels for reducing greenhouse gas emissions in the transport sector and only indirectly support chemicals production. No institutions exist to support sustainable cement or steel production. For cement there are possibilities that normative institutions may be established among associations promoting low-energy (or 'green') buildings.

Sustainable innovation systems seem to have been somewhat more successful in cases where there are synergies with other environmental benefits, as in the case of biorefineries. A similar possibility can be observed in new cement productions, where industrial waste can be used to create a valuable by-product and at the same time contribute to reduced emissions. The idea of treating carbon dioxide not only as a gas with large environmental impact, but as a possible building block for new materials is a compelling idea which has the possibility to gain large ground if the concept can be proven. The subsector with least potential to be driven by such synergistic effects is the steel industry. This may however change if recycling is more heavily pursued, as is implied by the European strategies to become resource efficient.

The discussion above reveals that the assessment covered in this paper has not been extensive enough to comprehensively guide policy making in either subsector. In-depth studies on all basic industries and their interplay with the energy and societal system they are embedded in will hopefully provide better understanding of the driving and counteracting mechanisms of sustainability transitions in basic industries.

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