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Decarbonising the energy intensive basic materials industry through electrification - implications for future EU electricity demand

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ABSTRACT

The need for low-carbon transitions in the industrial sector is increasingly recognised by governments and industry. However, radical pathways for reaching near-zero emissions in the energy intensive basic materials industry are still relatively unexplored. Most studies focus on mitigation options that lead to marginal emission reductions, e.g., energy and materials efficiency improvements and some fuel switching, or they rely on carbon capture and storage that allows continued use of existing processes and feedstock. In light of the vast future potential for primary renewable electricity we explore as a what-if thought-experiment the implications of electrifying a stable basic materials production in the EU. A quantitative technical scenario analysis of potential future electricity demand in the production of the most energy and carbon intensive basic materials, i.e., steel, cement, glass, lime, olefins, chlorine and ammonia, is presented for EU28. Production of these seven basic materials resulted in directly and indirectly energy related CO_2 emissions of about 457 Mton in 2010, equivalent to almost 13 % of all energy related GHG in EU28. Their production in 2010 required 125 TWh of electricity and 1432 TWh of fossil fuels and feedstock. A complete shift to electricity would result in an electricity demand of 1600 TWh, about 1100 TWh of which would be for producing hydrogen and hydrocarbon feedstock. We assume closed loops for carbon dioxide through recovery from waste incineration and biogenic sources. With increased materials efficiency and some share of bio-based materials and biofuels the electricity demand can be much lower. Our analysis shows that near-zero emissions could in principle be reached without relying on CCS (except for limestone related emissions) and suggests that a circular economy powered by renewable electricity may indeed be possible, at least from an energy resource and technology point of view.

KEYWORDS

INTRODUCTION

The EU objective to reduce greenhouse gas emissions by 80 to 95 per cent by 2050 relative to 1990 according to the Low Carbon Economy Roadmap includes a suggested industry sector ambition of 83 to 87 per cent reduction [1]. To reach such, for practical purposes, near zero emissions require major technical change across all sectors. Most 2050 low carbon scenarios show relatively modest increases in electricity demand as a result of higher efficiency in existing applications, and limited increases through new end-uses, including electrification of transport [2]. For reducing emissions from basic material industry most scenarios revert to carbon capture and storage (CCS) as the main option.

The three main categories of technical options for reducing carbon dioxide emissions from basic materials productions are improved energy efficiency, less carbon intensive energy supply or CCS, and improved materials efficiency [3]. The need for energy intensive primary processing of ores and minerals can be reduced through, e.g., recycling, lighter constructions, extending the life of products, and design of products that are easier to maintain, repair, upgrade, remanufacture or recycle. Such measures are also central to the circular economy [4].

However, even in a circular economy there will still be a need to produce virgin materials to replenish the system and for special applications that require high quality virgin materials,

e.g., food packaging. There will also be a need to produce things that are consumed or that dissipate, e.g., nitrogen fertiliser for agriculture or argon gas for super-insulating windows.

The loop on carbon dioxide must also be closed, e.g., by capturing CO_2 from waste incineration and biogenic sources, or even air-capture. Carbon capture and geological storage is not a long term sustainable option. A relatively new and unexplored option for producing basic organic materials (e.g., plastics) and chemicals is to convert water and carbon dioxide to hydrocarbons through electrolysis. Primary electricity from solar and wind for electrolysis is, in this context, a relatively abundant and renewable resource, and likely to be available at reasonable cost.

The IPCC Fifth Assessment Report [3] provides the most comprehensive recent review of mitigation options in industry. These include materials efficiency, energy efficiency, fuel shifts from coal to gas, CCS, as well as decarbonisation of electricity supply to reduce indirect emissions. Material efficiency and demand is highlighted as important for emissions but the overall mitigation potential is not quantified. It is concluded that the energy intensity of industry may be reduced by up to 25 % through best available technology and by an additional 20 % at maximum through innovation before approaching technological limits in some energy intensive industries. In four key sub-sectors (cement, steel, chemicals and pulp and paper) that are assessed in greater detail, CCS is essentially the only option presented that can reduce CO_2 emissions in the range of 70-90 %.

Results along the same lines can be found in the IEA Energy Technology Perspective scenario (IEA, 2012 cited in [3]) where most of the 3 $GtCO_2$-eq emission reductions when comparing the 4DS and 2DS low demand scenarios result from energy efficiency and CCS. Fuel and feedstock switching account only for about 10 % (300 $MtCO_2$-eq) of the reduction. A recent roadmap for renewable energy in manufacturing up to 2030 emphasises biomass as an option for process heat demand, purporting that [5] (IRENA, 2014): "Currently, biomass offers the only renewable energy option to provide high-temperature heat." The roadmap includes the option of electrification, e.g., by noting the possibility of relocating primary aluminium smelters next to renewable power supply. However, the mitigation options are limited mainly to biomass and solar thermal (for low and medium temperature heat) and the overall finding is "that the economic realisable potential of different renewable energy resources to generate industrial process heat could be as high as 25 EJ by 2030" [5] (IRENA, 2014).

A recent study by the German Federal Environment Agency explores more radical technology options for 2050 to show how Germany can reduce GHG-emissions by 95 % [6]. For industry, these mitigation options include power-to-gas methane for fuel and feedstock as well as electrification, assuming 100 % renewable electricity production. Such options are noted also in the IPCC report but they are not included in the analysis because IPCC bases its findings on reviews of the existing literature and the options assumed by UBA [6], including the use of electricity/hydrogen and carbon dioxide as a feedstock, are still relatively unknown and unexplored.

Motivated by the knowledge gap identified by the IPCC and inspired by the UBA report we explore, in a what-if thought-experiment, the implications of electrifying the production of seven key basic materials in EU28. The analysis is motivated also by the possible future abundance of solar and wind resources in EU, which means that there could be a vast potential for producing primary renewable electricity. Therefore we carry out a quantitative scenario analysis of potential future electricity demand through electrification for steel, cement, glass, lime, olefins, chlorine and ammonia. Our approach and key technology

assumptions are described in the following sections followed by the scenario results. Economic and policy implications are discussed in the final sections.

METHODOLOGY AND DATA

In this paper we apply a scenario analysis based on a simple model of the core technologies used to produce the most energy intensive basic materials used in European economies such as primary and secondary steel, cement, glass, lime, olefins (the basic product for most plastics), chlorine and ammonia which is mainly used as a platform product to obtain fertilizers for agriculture[2]. Production of these eight basic materials resulted in direct and indirect CO_2 emissions of about 415 Mton in 2010, which was almost 10% of all GHG emissions of the whole EU28.

In our scenario we start with estimating energy input plus all related CO_2 emissions of the production and then estimate the respective values for 2050, assuming a complete switch to the most advanced low carbon technologies described in the literature that could be available by this time (see technology description below). Together with these technologies we also assume a complete conversion of European electricity production to low carbon sources and a supply of industry with electricity or renewables based hydrogen as well as derived methane or syngases for feedstock and some other process uses.

Table 1. Global and European Production and consumption volumes of seven basic materials and projection for the EU for 2050

in million tons	Global Production	EU 28 Consumption	EU 28 Production	
Product	2010	2010	2010	2050
Steel	**1 431**	**161**	**173**	**180**
• Secondary steel from scrap (Electric arc furnace)	420	----	71 / 71	80
• Primary steel (2010: Blast oxygen furnace; 2050: Electrowinning)	994	----	95 / 101	100
• Primary steel (open hearth furnace)	16	---	0.7	---
Minerals			**253**	**250**
• Cement	3 290	185	192	190
• Glass	n.a.	n.a.	34	34
• Lime	313	26	27	17
Basic chemicals			**65**	**62**
• Olefins (HVC)**)	n.a.	43	42	40
• *hereof: ethylene*	*138*)*	*20*	*20*	*20*
• Chlorine	n.a.	9	10	10
• Ammonia	n.a.	13	13	13

*) World capacity in January 2011 of which 24 Mill. tons (17%) are located in the EU28 (Gas and Oil Journal 2012, **) HVC (in the context of steam cracking) includes ethylene, propylene, butadiene and benzene here. http://www.ogj.com/articles/print/vol-110/issue-07/special-report-ethylene-report/global-ethylene-capacity.html)

Sources: Eurostat COMEXT database [8], World Steel (2014) [9], Cefic (2013) [10].

Our modelling approach in a first step uses 2010 physical production data of these products, derived from EUROSTAT data and industry association data for steel, cement and chemicals (see Table 1). For the scenario we make the simplified assumption that production levels of the year 2010 will remain about stable until 2050. As the EU28 was more or less net self-

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[2] In Schneider et al. [7] we describe a more detailed modelling approach, that covers the whole of industry and takes into account the most important technologies currently in use as well as several technology developments until 2050. This detailed analysis, however, was limited to the German State of North Rhine Westphalia.

sufficient in all of these basic products (albeit partly very significant imports as well as exports of those basic materials, be it in kind or embedded into manufactured products) and demand only slowly growing or stable for most of these products, we assume that production in Europe will be stabilised at about current levels (see Table 1) with an exemption for lime, for which production will decline due to decreasing demand for fossil power plants and steel making.

In a second step we define the relevant production technologies for these products plus for hydrogen, methane and synfuels which will be used as low carbon energy and feedstock supply by 2050. For 2010 we use an aggregated technology for each of the materials which represents average input values of the various fuels, feedstocks and electricity as well as the CO_2 emissions from the processes itself over all production sites in the EU. Such a simplification is justified as production technologies for those basic materials are more or less uniform compared to the overall process energy and material use and can thus be reflected by average technology characteristics.

For the 2050 scenario we use technical parameters from literature to estimate energy use and emissions for the most advanced low carbon technologies for the basic materials analysed. We discuss the respective core technologies and their technical parameters below.

TECHNOLOGIES FOR DECARBONISING BASIC MATERIALS PRODUCTION

Processing metal ores and minerals to basic materials requires high temperature heating which today is supplied by fossil energy, notably natural gas and coal/coke. Fossil energy carriers are also used as feedstock for the petrochemical and fuel industry. Almost 12 % of all oil is used as feedstock for basic petrochemicals, including losses for conversion [11].

Replacing both the fossil used as energy and as feedstock by utilising renewable electricity is at the core of the scenario sketched in this paper. Electricity is a very versatile form of energy and can be used for heating in industry either directly with various electro-thermal processes or indirectly with hydrogen as an energy carrier. Electricity can also, together with CO or CO_2, be used to manufacture both carbon based feedstock used for plastics. Several key technologies and technical systems assumed in our scenario need to be further developed in order to be technically available by 2050 with the efficiencies we have assumed in our scenario.

Electro-thermal processes for heating

Industrial processes need heating at low (below 100 degrees), medium (between 100 to 400 degrees) and high temperatures (400 to >2000 degrees). Supplying this heat by electricity instead of carbon fuels can be done in several ways.

Electric furnaces can supply heat with normal convection heating (same as heating with fuels) in all temperature ranges. Heat pumps can supply low- to medium-temperatures by using electricity and a low temperatures reserve (e.g. excess heat in a paper and pulp factory).

Advanced electro-thermal technologies include electromagnetic radiation, heating via microwaves, infrared radiation, radio waves, ultra violet light, induction, electron beams and plasma technologies and can potentially supply heat in all temperatures (see EPRI [12] for an overview). Electro-thermal technologies have the potential of being efficient as they promise a more controlled heating process and can thus heat a very specific area without heating the surrounding material as is the case with conventional convection heating. Electro-thermal technologies usually also offer a better controllability of temperature gradients compared to traditional and fuel based heating.

Infrared radiation heats only the surface, microwave and radio frequencies penetrate the material and heat the volume whereas induction heating limits the heat to the connected material. Electric arc heating is another electro thermal technology that has since long been used for steel production from scrap (electric arc furnaces). Plasma technology (supplying heat via an electric arc heated ionised gas) has the advantage of extremely high temperatures above 2000 degrees and is today used for waste management and in several niches within the steel industry [13]. Paper drying is also an area where the use of electricity in infrared dryers could increase and replace gas fired dryers and electric impulse drying could increase overall efficiency [12].

Most of electro-thermal technologies are proven as basic concepts or as niche applications but need development in order to be aligned with the specific process needs in respective industries, particulary for the low-cost mass production of materials. Examples of current use of electro thermal technologies for heating are in the food industry for drying and in the automotive industry for coating, curing paints, etc. where there is a specific need for exact and well controlled temperatures and temperature gradients. The main barrier today for further expansion is the price of electricity compared to the price of carbon based fuels.

Electrolysis of water to produce hydrogen

Electrolysis is used for separating chemical elements by deploying a direct current to a material placed in an electrochemical cell. Electrolysis is currently used when transforming aluminium oxide to aluminium, for separating saline solution (sodium chloride and water) into chlorine, NaOH and hydrogen as well as for separating water into hydrogen and CO_2. In the future electrolysis could also be used for steel making from iron ore.

Using electrolysis to produce hydrogen from water is a key technology in our scenarios. Renewable hydrogen is used in our scenarios to replace fossil derived hydrogen in the ammonia industry and to, together with CO_2 or CO, produce methane/methanol/F-T naptha for replacing the fossil feedstock (mainly naphta or ethane) in the petrochemical industry.

Commercial electrolysis technology today is based on alkaline electrolysers with efficiencies around 48 to 83 % [14]. Two future concepts being developed for electrolysis is polymer electrolyte membrane (PEM) electrolysers and solid-oxid electrolyser cells (SOEC). SOEC seems to have the highest potential for efficiency (above 75% power-to-hydrogen), investment costs, production capacity and also the potential ability to maintain efficiency at lower loads (thus being suitable for power-to-gas concepts) [14]. SOEC is a high temperature electrolyser and thus needs steam but this heat demand can be integrated into most processes using surplus heat from e.g. the methanisation step. SOEC could need another 10 years of development according to [14]. In our scenarios we have assumed an average efficiency of 71% for hydrogen production based on a meta-analysis by Fischedick et al. [15].

Producing hydro-carbons from hydrogen, CO_2 and syngas

For replacing the fossil feedstock currently used for olefin production we need renewable energy and renewable (or recirculated) carbon. The carbon is derived either from captured CO_2 or as the CO part of syngas (CO + H_2). The energy is supplied either from renewable electricity or from the hydrogen in syngas produced from biomass (e.g. waste or woody biomass). From this we manufacture either methane and/or Fisher-Tropsch naphta. Methane can be converted into olefins in several processes and F-T naptha replaces current petroleum naptha conversion routes to olefins

Both methane and F-T naptha can be produced in well-known processes from syngas that carries both the energy and the carbon we need [16, 17]. The syngas can be produce by gasification or pyrolysis of woody biomass or biogenic waste [18] Future development of supercritical gasification could produce syngas efficiently from wet biomass such as household waste streams [19]. Indirect gasification in smaller to medium size scales can also convert a major share of the biomass to methane directly [20].

Methane can also be produced using hydrogen produced from electrolysis of water and captured CO_2 from e.g. flue gases in cement production in a Sabatier process. Today, this process is normally divided in two steps, first a RWGS (reversed water gas shift reaction) for producing CO and hydrogen (syngas) from water followed by a methanisation process of the syngas [21]. With suitable catalysts the Sabatier process can however also be done in one step (directly from hydrogen and CO_2 to methane). The Sabatier process is exothermic producing surplus heat that can be used for e.g. heating the electrolyser used for producing the hydrogen. Producing methane from renewable electricity, water and CO_2 will require integration of processes and co-production in order to more efficiently use surplus heat, methane, hydrogen and oxygen in various steps to maximise both total energy efficiency and utilisation of resources [22].

The carbon used for manufacturing renewable hydro carbons comes either from captured CO_2 or from biomass streams (via gasification producing a syngas). CO_2 can be captured and recycled either from flue gases, from air capture or even from sea capture in a future scenario [23]. The syngas route uses the energy embedded in the waste/biomass streams and thus reduces the electricity need as less hydrogen needs to be produced via electrolysis. The production routes stemming from syngas and electrolysis of water can be integrated for higher efficiency. Biomass gasification has a hydrogen deficit resulting in carbon leaving the process as CO_2 and not as usable chemical/fuel. Adding hydrogen produced from e.g. low priced ("surplus") electricity in an intermittent 100 % renewable electricity future can be used to boost syngas production [24].

A SCENARIO ON DECARBONISING BASIC MATERIAL PRODUCTION

In 2010 the EU28 produced 491 Mtons of the eight basic materials discussed here with the bulk being cement and steel, followed by olefins and glass (see Table 1). That was more than one ton per capita and is assumed to remain stable over the next decades, vs. a still significant increase of physical production in other world regions. This means that European production share which stood for e.g. 11% of global steel production, 6% of cement production and 17% of global ethylene production capacities will constantly decline in the future.

In 2010 fossil fuels were mainly used for olefin production; 551 TWh of oil products as feedstocks plus 198 TWh used energetically during the steam cracking process. Coal was used in oxygen steel making and in cement production. For the remaining processes natural gas for energetic purposes or for steam reforming to hydrogen used as feedstock for ammonia was the main energy supply. The use of fossil energy plus significant amounts of non energy related CO_2 emissions from cement, steel and glass making generated 374 Mton of CO_2 in 2010. Electricity consumption stood for another 41 Mtons (see Table 2).

Next to the situation in 2010 Table 2 gives the main scenario results. For 2050 it is assumed that the analysed energy intensive productions will be based completely on electricity, hydrogen and/or synthetic gases. The respective technologies and technological data are given in the section below.

Table 2. Fuel, electricity and hydrocarbon feedstock demand of seven basic industrial products in 2010 and projection for 2050

Product	energy demand 2010 (TWh)		Direct CO$_2$-Emissions (Mt) *)	CO$_2$ Em. from electricity **)	energy demand 2050 (TWh) ***)			Direct CO$_2$-Emissions (Mt) *)
	electricity	other	2010	2010	electricity	H2	Syngas / FT naphta	2050
Steel	**52**	**367**	**147**	**17**	**296**	**0**	**0**	**0**
Secondary steel from crap (electric arc furnace)	37	14	3	12	38	0	0	0
Blast oxygen furnace	14	354	144	5	0	0	0	0
Electrowinning	0	0	0	0	258	0	0	0
Minerals	**39**	**210**	**164**	**13**	**169**	**0**	**0**	**85**
Cement	22	122	117	7	122	0	0	67
Glass	15	55	30	5	29	0	0	4
Lime	2	33	16	1	19	0	0	14
Basic chemicals	**35**	**875**	**64**	**12**	**43**	**66**	**617**	**0**
Olefins (HVC)	0	198	38	0	0	0	66	0
Chlorine	35	0	0	12	29	0	0	0
Ammonia	0	59	26	0	13	0	0	0
Fuel use as raw material								
Olefins (HVC)	*0*	*551*	*--*	*--*	*0*	*0*	*551*	*--*
Ammonia	*0*	*66*	*--*	*--*	*0*	*66*	*0*	*--*
Total (including feedstock)	**125**	**1 452**	**374**	**41**	**508**	**66**	**617**	**85**
Energy total (incl. feedstock)	**1 577**		**---**		**1 192**			**---**

*) Includes process related emissions, CO$_2$ from feedstocks that is temporarily bound in products (base chemicals) amounts to additional 160 Mton of potential CO$_2$ emissions. **) 331g/kWh [25]; ***) by 2050 all fuels are assumed to be zero carbon electricity or derived from zero carbon electricity.

Source: own calculations

Iron and Steel

By shifting primary **steel** production from oxygen to electrowinning, steel production is assumed to be completely electrified, apart from thermal energy in secondary steel production which is partly converted to hydrogen. By this final energy demand for steel making can be reduced by almost 30% vs. 2010 levels.

Over 90% of the carbon dioxide emissions of steel production result from the primary steel route. Here the reduction of iron ore into iron accounts for about 80% of the emissions. Apart from increasing the percentage of scrap-based production (which is not assumed here), finding new reduction agents is therefore the most important step towards decarbonising the steel industry. Three alternatives exist; to use hydrogen, to reduce iron ore in electrolysis or to use bio-char instead of coke.

For a complete decarbonisation that would make iron-ore based steel production inherently carbon free the introduction of electrowinning (electrolysis of iron ore) is assumed in this paper. This means two major technical steps for primary steel production: First, iron ore is

either solved or suspended in an acid or alkaline solution or it is 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. Available studies show that 2.8-3.2 MWh of electricity per ton of sponge iron is needed for the electrowinning process [26, 27]. If electrowinning in an acid or alkaline solution or hydrogen reduction is used, the iron ore is reduced in solid state, creating sponge iron which must be melted afterwards for alloying purposes. EPRI [12] suggests using plasma or induction ovens for smelting. The key benefits besides lower emissions will be higher thermal efficiency than with the use of electric arc furnaces and fewer waste products. With electricity for melting included this would be approximately between 2,6 to 3,7 MWh/ton steel depending on technical development [28, 29].

Electrowinning offers some advantages to current production apart from lowering emissions of carbon dioxide, e.g. significantly lower costs of the equipment [28] and a reduced need to remove sulphur stemming from coal. As requirements on low sulphur and carbon content in some speciality steels grow, using reduction methods free from carbon may reduce costs.

Secondary steel making already today uses electric arc furnace for melting scrap steel to produce sponge iron and also some carbon fuel based heating for further processing to steel. The last part of the production chain can also change to direct electric heating which is assumed in our scenario.

An indirect route to electrification would be the use of hydrogen in a DRI process which is currently used with natural gas as a reduction agent. This route could also be utilised as a means of energy storage or load smoothing in the electricity grid if implemented in a smart way.

In our scenario we assume that 2.6 MWh electricity per ton of steel is needed in the primary route and that 0.5 MWh/ton is needed in the secondary route.

Minerals, Cement, Glass and Lime

The most relevant products of mineral industry with regards to GHG emissions are cement, glass and lime manufacturing. These industries have in common that they need high temperatures, usually above 1400 °C for processing mineral feedstock such as limestone and sand into useful materials such as clinker, glass or lime. Recycling is an option for glass industry (apart from flat glass production) common already today for economic reasons. Cement products (concrete) can be reused as building material, road filling etc. but are seldom reprocessed to new clinker and lime.

Cement: Emissions of greenhouse gases in cement production are caused by two factors; burning of fossil fuels for heat (40%) and in the calcination of limestone to chemically reactive calcium oxide (60%). For cement manufacturing it is theoretically possible to replace current clinker with other materials. The options of reducing the share of limestone as feedstock and thus avoiding process-emissions look promising but are not yet commercial. Options include magnesium based cement or cement made from sewage sludge [30, 31, 32]. In our scenario we have assumed that new, low clinker cements achieve a market share of 50%. At the same time, some clinker substitutes such as fly ash and slag from blast furnaces for conventional oxygen steel production will be reduced in a future low carbon scenario. So we assume that the rest of cement production is supplied by cement clinker (85%) and other substitutes like limestone and gypsum. High temperature heat production can be converted from using carbon fuels to using electricity by e.g. future adaption of plasma technologies to cement production.

In the scenario we have assumed electric heating using plasma or another high temperature electro-thermal process. The basic heating demand stays the same apart from normally assumed better integration of heat use all along the production chain with new and modern facilities that will be built. In our scenario, we assume that 0.9 MWh electricity per ton of clinker is needed which includes a 12% efficiency improvement in thermal demand compared to today.

Melting of glass currently uses mainly natural gas for heating. This can be replaced either by methane of renewable origin or by electric furnaces as assumed in our scenario in combination with the use of scrap glass as input (60% in UBA [6] by 2050). For glass production electric melters are already in use in certain productions on a smaller scale but need to be up-scaled and proven for all qualities of glass. Current fuel based heating is quite inefficient compared to what potentially could be achieved with electric heating. Due to the conversion to electric ovens we assume an overall increase in final energy efficiency of glass production by about 68% from approximately current 2.1 MWh/ton down to 0.85 MWh/ton assumed in our scenario, slightly more conservative than the 0.65 MWh/ton used by UBA [6] because we think their assumption on 100% waste heat recovery is probably too optimistic.

Lime: The demand for lime will decrease substantially if we phase out fossil fuels containing sulphur due to less demand in steel, cement and environmental sectors. For the burning of limestone we anticipate the same process with some efficiency improvement leading to a reduction of final energy demand by 20% but no major technical breakthroughs. The currently preferred fuels, natural gas and coal, will be changed upstream to high temperature electro-thermal processes.

Basic Chemicals, Chlorine, Ammonia and Olefins

The production of chlorine and ammonia is a major consumer of electricity and natural gas today.

Chlorine is produced by electrolysis of sodium chloride solutions (brine). It is a very energy intensive process consuming large amounts of electricity. An average EU Chlorine production uses 3,6MWh /ton Chlorine. We have assumed that this be reduced to 3 MWh/ton in 2050 by advanced membrane technology and partly oxygen consuming cathodes and supplied fully by renewable electricity.

Ammonia is the basic building block for producing fertilizers. It is manufactured in the Haber-Bosch process by combining nitrogen and hydrogen to form ammonia. Today the hydrogen is derived from reforming natural gas but this can be changed to hydrogen from electrolysis of water. In our scenario we assume the hydrogen is produced from electrolysis instead of natural gas reforming which enables final energy demand reduction of ammonia production by 36%. CO_2 needed to process ammonia further to urea is not taken from fossil energy sources such as gas or petroleum but from capture from combustion or air capture and thereby closing the carbon loop here.

Olefin production will be fed by synthetic gases derived from zero carbon electricity via hydrogen and carbon sources using Fischer-Tropsch synthesis. While feedstock use remains stable due to the assumption of constant production volume process energy demand will be decreased by two third among others by modernisation of crackers etc.

In our scenario we have assumed that 25 MWh/ton of olefins (HVC) are needed and that the roughly 3.1 tons of CO_2 needed for the production of each ton of olefins are captured from e.g. flue gases and readily available based on [22].

Scenario result

In total the above mentioned changes in processes make for a complete conversion of the energy mix for production of the eight basic materials from 86% fossil fuels in 2010 to 89% electricity in 2050, with the rest supplied by electricity based syngas and hydrogen in the scenario. At the same time total energy demand can be reduced by 24%, or 386 TWh to 1192 TWh with energy content of feedstock included.

These savings, however are compensated for by conversion losses of about 29% and 36% from producing hydrogen and syngas. In total hydrogen and syngas production for the use in the eight basic materials needs 996 TWh of zero carbon electricity with an output of 617 TWh of hydrogen and syngas and resulting energetic losses of 374 TWh[3].

Table 3. Conversion balance of electricity to hydrogen and synthetic fuels for feedstock and energetic use in basic material production, Scenario for 2050

in TWh	Fuel demand 2050		Efficiency	Electricity demand
	Energy	feedstock		
Hydrogen	0	66	71%	93
Syngas / Fischer-Tropsch naphta	66	551	64%	965
Total	66	617		1 057

Source: own calculations based on a conversion efficiency of 71% for hydrogen generation [15, s. above] and assuming high temperature electrolysis (SOEC) with excess heat integration of the FT process [33].

Brief discussion of scenario results:

Our rough scenario of a radically decarbonised production of eight basic materials shows that such a strategy would mean a complete direct and indirect conversion of industry production from fossil towards electric supply. For the electricity demand this would mean an increase by a factor of four (to 504 TWh), for direct use only and by a factor of 12.8 if electricity for conversion to hydrogen and synfuels is included. Particularly the conversion of feedstock for basic chemicals would need high amount of electricity to be converted. While in 2010 about 60% of the energy input for the eight basic products is used energetically and 40% as feedstock, these shares will be 39 to 61% in 2050.

Discussion and Conclusion

Our analysis shows that a hypothetical complete electrification of basic materials industry processes could result in a 1 440 TWh increase in demand for renewable electricity. This can be compared to the current total electricity use in the EU of 2 780 TWh (the industry share of which is about 1 000 TWh). Our thought-experiment, however, was "what-if" everything in industry is electrified. In the real world, and in a circular economy with increased focus on material efficiency and the concurrent development of bio-based materials, electricity demand is likely to be lower, even in a low carbon future. But, even if it would be only half or a third of what has been calculated here, it is still substantial. On the other hand, the perception of the potential for renewable electricity production in Europe has changed dramatically the last years and is orders of magnitude greater than this. Hoefnagels et al. [34] calculated an EU27-

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[3] The fact that the losses for hydrogen and synfuel production overcompensate energy efficiency gains do not lead to higher primary energy use for industry, as the losses for fossil electricity generation in 2010 (which can roughly be estimated to about 200 TWh) have not been accounted for in this paper.

potential of 2 000 TWh only for onshore wind, realisable in 2050. For Europe and North Africa a potential of 47 000 TWh available at 5 euro-cents per kWh in 2050 was modelled and the technical potential amounts to 105 000 TWh [35].

Our analysis does not include an economic analysis but Åhman et al [36] indicates that production cost of basic materials such as steel and cement may typically increase between 20 and 100% assuming a carbon price of 100 EUR/ton CO_2. Such production cost increases, with rather small or sometimes no co-benefits, makes decarbonisation a challenge from an implementation point of view, especially in a world without universal climate policies. It is, however, not likely to be a problem for the economy as a whole since the basic material cost share of most products is very small. For example, a doubling of cement prices will only increase the cost of a normal residential building with <1 **%** [37]. The basic materials cost for a car is about 5 % of the final price and the cost of steel beams accounts for about 4 % of the cost of a steel-frame commercial building [38]. From a macro-perspective one study found that basic materials account for about 4 % of all consumption and investment in some EU member states [39].

An economy based on renewable electricity as the "primary fuel" will have a different energy price logic compared to the current fossil fuel based economy. Today, we use two or three units of fuel to produce one unit of electricity, which is reflected in relative prices between energy carriers. With renewable electricity as the primary energy source it will take two units of electricity to produce one unit of fuel (and three or four units of primary electricity to produce one unit of secondary electricity if power-to-gas storage is used). Thus, relative prices between electricity and hydrogen or hydrocarbon fuels will change.

With renewable electricity which could become the least cost primary energy source in the future, it would be plausible that energy intensive process industries could become flexible "swing consumers" that convert electricity into materials rather than spilling primary solar and wind electricity production. Apart from a massive expansion of renewable supply, electrolysers capable of running on part load with reasonable ramp-rates would be a key technology for this development. Swing production of hydrogen for nitrogen fertiliser, plastics, and steel production, or for increasing yields in bio-based processes, could be a very large flexible load in the future power system.

Historically the basic material industries have located close to raw material feedstock or energy (e.g., the Ruhr area, Iceland and Qatar). In the hypothetical future as sketched here, industry might move closer to renewable electricity sources but it is uncertain whether this rather would mean a shift towards hydro/wind-production at northern latitudes or a much more geographically dispersed location around PV-based electricity production in sun-rich regions.

Electrothermal processes were perceived as an important technology in the 1980's post oil-crisis when nuclear optimism was high. We may now have a situation where they become crucial again as renewable electricity is increasingly replacing fossil fuels and at least theoretically capable of supplying huge amounts of additional electricity. Electrothermal technologies are already extensively used in applications where they offer advantages (e.g., process control, product quality and lower energy cost) e.g., in induction heating, UV-curing and microwave drying. In the hypothetical scenario we sketch here these would need to expand to further applications, particularly high temperature heat generation, e.g. via plasma technology. Electrolysis is another key technology in our scenario. It is needed for hydrogen production but also for electric primary steel making and would have to be developed further for increasing overall system efficiency and reducing costs.

Closing the loop on carbon dioxide would be another important component of a potential electricity based economy for producing basic hydrocarbon materials, chemicals and fuels.

Our analysis shows that the renewable electricity based economy that we sketch here as a what-if thought-experiment could be possible in principle from an energy resource and technology point of view, if the vast potentials of renewable electricity become exploited and in combination with a circular economy as well as closed CO_2 loops. However, much more knowledge concerning various technology and system options and their potential barriers is needed, as well as considerable technology RD&D for electrification and demand flexibility. Further, it is an open question if and how suitable economic conditions can be created to make these developments happen.

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