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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 deep decarbonisation in the energy intensive basic materials industry is increasingly recognised. In light of the vast future potential for renewable electricity the implications of electrifying the production of basic materials in the European Union is explored in a what-if thought-experiment. Production of steel, cement, glass, lime, petrochemicals, chlorine and ammonia required 125 TW-hours of electricity and 851 TW-hours of fossil fuels for energetic purposes and 671 TW-hours of fossil fuels as feedstock in 2010. The resulting carbon dioxide emissions were equivalent to 9% of total greenhouse gas emissions in EU28. A complete shift of the energy demand as well as the resource base of feedstocks to electricity would result in an electricity demand of 1713 TW-hours about 1200 TW-hours of which would be for producing hydrogen and hydrocarbons for feedstock and energy purposes. With increased material efficiency and some share of bio-based materials and biofuels the electricity demand can be much lower. Our analysis suggest that electrification of basic materials production is technically possible but could have major implications on how the industry and the electric systems interact. It also entails substantial changes in relative prices for electricity and hydrocarbon fuels.

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1. Introduction

The EU objective to reduce greenhouse gas emissions by 80–95% by 2050 relative to 1990 includes a suggested industry sector ambition of 83–87% reduction [1]. The reduction of greenhouse gases (GHGs) needs to continue down to zero emission in 2060–2070 if EU is to take its responsibility in meeting the <2 °C target agreed in Paris [2].

The three main categories of technical options for reducing carbon dioxide emissions from materials production are (i) improved material efficiency (ii) improved energy efficiency, and (iii) less carbon intensive energy supply or carbon capture and storage (CCS) [3].

The need for energy intensive processing of ores and minerals to usable materials can be reduced through increased use of recycled materials and increased material efficiency via e.g., lighter constructions, extending the life of products, and design of products that are easier to maintain, repair, upgrade, remanufacture. Such measures are central to the circular economy [4] and they are highlighted as important in the Fifth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC AR5) but the resulting mitigation potential is not quantified [3]. However, even in a resource efficient circular economy there would 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 new materials as some are consumed or dissipate (e.g., nitrogen fertiliser for agriculture or argon gas for super-insulating windows) and to close the loop on carbon dioxide through carbon capture and use (CCU).

Energy efficiency through applying best available technology in industry can reduce the energy intensity by an estimated 25% and by an additional 20% at the most through innovation before approaching technological limits in some energy intensive industries [3]. Ahashi et al. [5] simulate a savings potential of 35% for industry globally by 2030 vs. frozen 2005 efficiency, a result which they note is in line with other studies.

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For a deep decarbonisation, material- and energy efficiency will help but will not be able to deliver the reductions needed. For deep decarbonisation it is also necessary to focus on the processing of feedstock to usable materials which includes the reduction of process related emissions (e.g. from calcination of limestone to clinker or reduction of iron ore to iron). The main options for deep decarbonisation of the processing step in materials production are shifting to low carbon energy supply via either biomass, nuclear energy, or renewable electricity and/or to use CCS [53].

CCS and bioenergy are the main options that have been assessed so far for deep decarbonisation of energy intensive industries. In the four key sub-sectors (cement, steel, chemicals and pulp and paper) that are assessed in greater detail in IPCC AR5, CCS is essentially the only option presented that can reduce carbon dioxide (CO_2) emissions in the range of 70–90% [3]. Results along the same lines can be found in the IEA Energy Technology Perspective scenario [6] where most of the 3 $GtCO_2$ equivalent emission reductions when comparing the 4DS and 2DS low demand scenarios result from increased energy efficiency and CCS. Fuel and feedstock switching account only for about 10% (300 MtCO2-eq) of the reduction. Similar assumptions are made in scenario studies for the EU [1] Italy [8] and the UK [9]. The electrification option is also largely overlooked in a recent roadmap for renewable energy in manufacturing up to 2030 [10] which emphasises that "currently, biomass offers the only renewable energy option to provide high-temperature heat" needed for industrial processes.

One exception to the reliance on CCS and biomass is a study by the German Federal Environment Agency (UBA) [11] which explores more radical technology options. For industry, these mitigation options include power-to-gas methane for fuel and feedstock as well as electrification, assuming 100% renewable electricity production. Although such options are noted in IPCC AR5 they are not fully included in their analysis since IPCC bases its findings on reviews of the existing literature, where hydrogen/electricity-based chemicals and fuels, and using carbon dioxide as a feedstock, are still relatively unexplored options.

Motivated by this knowledge gap and inspired by the UBA report the implications of electrifying the energy and feedstock supply for the production of seven key basic materials in EU28 are explored assuming a fossil- and nuclear-free future. The analysis is motivated also by the abundance of solar and wind resource potentials in EU. Therefore, a quantitative scenario analysis is done of the potential future electricity demand that would result from a complete electrification of steel, cement, glass, lime, petrochemicals, chlorine and ammonia (including an electricity-based supply of hydrocarbon and hydrogen feedstocks for petrochemicals and ammonia production) and assuming constant production levels in 2050 compared to 2010. The future technologies needed are described and motivated and from this scenario, implications on economy, integration, technology strategy and other barriers are derived.

The approach and key technology assumptions are described in the following sections followed by the scenario results.

2. Method and data

The unique timeframe set by climate policy (>2050) is not well suited for formal energy economic modelling, see e.g. Ref. [46]. Energy economic models build on known and reasonably predictable costs and relationships within the economy that change only marginally in the analyzed timeframe. It is thus easy to understand that CCS is the favoured and only option for the materials sector in the few long-term models assessing deep decarbonisation to 2050 as it assumes no systemic changes to the energy system (being an "end of pipe" solution). However, both the long time frame and the changes required in society for attaining deep decarbonisation targets to 2050 could well be systemic and thus go beyond what conventional models can assess. Here, a simple but transparent scenario analysis based on technology assumptions is used instead. The aim of using such an approach is not to predict what will happen in 2050 but to explore what the assumed goal (deep decarbonisation via electrification of industry) would mean for the energy system and the economy.

The scenario is calculated based on three steps: (i) future physical production level assumptions, (ii) current and future technology assumptions, and (iii) calculation of resulting energy demand and CO_2-emissions for producing primary and secondary steel, cement, glass, lime, petrochemicals (the basic products for most plastics), chlorine and ammonia[2].

In the *first step physical production data* for these products are derived from most recent production statistics (EUROSTAT [13]) and industry association data for steel, cement and chemicals [14,15]. 2010 was the last year that had consistent production data for all sectors. Production and consumption in the EU28 shows a moderate decline, is stable or is growing slowly for these products. Production is roughly equal to consumption although there are considerable exports and imports of some materials. For the purposes of this scenario a simplified assumption that production in EU28 will be stabilised at about current levels (Table 1) is made. The exception is lime for which consumption and production will decrease due to less demand from coal power plants and conventional primary steel production. These assumptions are in line with recent projections by the International Energy Agency for OECD Europe in 2050 (including Turkey, Norway and some others) [6] which assume a moderate growth over the whole 40 years of 12–25% for steel, a stabilisation for cement in the lower scenario and for feedstocks in the high and the low scenario.

In a *second step* the *energy input* in total and per physical unit plus all related CO_2 emissions for the production of each product was estimated. For 2010 an aggregated technology assumption for each of the materials was used. These assumptions represent 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 2050, the energy intensities used for calculating energy were derived from literature, assuming a complete switch to the most advanced break-through technologies described below. Together with these technologies a complete conversion of European electricity production to low carbon sources was assumed in line with the targets for the EU [1].

For *calculating emissions in the third step* the energy demand is converted to CO_2 emissions by applying fuel specific emission factors (see note to Table 2). For the minerals, CO_2 emissions from limestone have been taken into account based on IPCC guidelines [17] [3]. For 2050 it is assumed that methane and hydrogen are produced from renewable electricity with typical efficiencies as

[2] In Lechtenböhmer et al. [12] two of the authors present 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.

[3] IPCC's 2006 [17] default emission factor for clinker making (tier 1 method) is 0.52 t CO_2/t clinker. We assume cement production in 2050 to be 50% "low carbon cements" with a 50% reduction in CO_2 emission factor compared to clinker (based on [18]). The other half of cement production consists of 85% clinker and 15% other composites (cp. Section 4.2). The average emission factor for glass production is 0,1 t CO_2/t glass, accounting for a mix of flat and container glass. For lime IPCC's default emission factor according to the tier 1 method is used (0.785 t CO_2/t lime).

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