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A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris agreement?

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Article Title:

Technology and policy options for making heavy industry products consistent with 1.5-2°C compatible deep decarbonization pathways

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Abstract

The production of heavy industry commodities is responsible for 1/3 of annual global GHG emissions. The Paris Agreement goals of +1.5-2°C require global emissions reach net-zero and possibly negative somewhere between 2060 and 2080. Given the normal timetable for retirement or retrofit of industrial facilities (>=20 years) all new equipment must be net-zero or negative carbon by the early 2040s. In this article we demonstrate to policymakers and modellers that industrial decarbonization is technically possible and how it might be achieved. First, we synthesize sectoral lab-bench and near-commercial technology options for reducing emissions to net-zero within 1-2 investment cycles, pathways more or less appropriate given regional resources (i.e. access to biomass, renewable electricity, or geological storage of CO_2) and political circumstances. Second, we synthesize policy options, focussing on those that encourage a managed transition from today's industry to net-zero emissions with a minimum of stranded assets, unemployment and social trauma.

Keywords: industry; decarbonization; pathways; policy; renewables; CCS

1 INTRODUCTION

The production of steel, cement, glass, aluminum, chemicals, plastics, non-ferrous metals, pulp and paper and other GHG intense commodities is responsible for approximately 1/3 of annual global GHG emissions (Allwood et al., 2010). Based on IPCC AR5 (Edenhofer et al., 2014) and the goals of the Paris Agreement, stabilization of the global average surface temperature requires that emissions reach net zero and possibly negative (Fuss et al., 2014; Millar et al., 2017; Pye et al., 2017) somewhere between 2060 and 2080, depending, amongst other things, on the target (i.e. 1.5 or 2°C above preindustrial levels) (Edenhofer et al., 2014) and availability of negative emissions (Fuss et al., 2014; Peters and Geden, 2017). While substantial attention has been paid to decarbonizing electricity production, transport and buildings, firm and government analyst and policymaker knowledge of how to decarbonise heavy industry lags (Fischedick et al., 2014b; Loftus et al., 2015). Substantial reduction of material demand for final products made from GHG intense inputs is possible (e.g. reduced steel and cement content of structures through better design and substitution), but is still limited by various barriers (Allwood and Cullen, 2012; Allwood et al., 2010; Fischedick et al., 2014b). Growing global demand, however, means that ambitious climate targets are at risk unless industrial processes are also decarbonised to the point emissions are net-zero or negative (Allwood et al., 2010; Denis-Ryan et al., 2016). Given the normal timetable retirement of heavy industry production facilities, which can last 20 years or much more with refurbishment, this implies that all new equipment be net-zero or negative carbon by the early 2040s.

Global climate policy to date has not focused on reducing the GHG intensity of industry. It has been repeatedly found that industry will be the hardest sector to decarbonise due to its heterogeneity (i.e. almost every facility worldwide is different, producing a wide array of product qualities and variations), GHG intensity, trade exposure, cost sensitivity, and long lived facilities (Bataille et al., 2016b, 2016c; Fischedick et al., 2014b). Despite the lack of climate policy focus, competitiveness pressure has driven many energy intensive and trade exposed industries to reduce energy consumption and GHG emissions, some below 1990 levels, but deep decarbonization of heavy industry remains a formidable challenge (Fischedick et al., 2014b). Many existing processes are more than 100 years old, have reached their limits of practical efficiency (ABB Ltd. - Enerdata, 2013). Motivated by competitiveness concerns, the potential for carbon leakage, and a lack of compelling co-benefits, industry has been largely exempted from carbon taxes, faced lower rates, given free emissions permits, or otherwise excepted from GHG regulation. The focus of the debate is how to reduce carbon leakage, not how to decarbonize.

The 2014 IPCC WGIII 5th Assessment Report Industry chapter (Fischedick et al., 2014b) is the most synthetic work to date on the technological and policy options for reducing industrial emissions, but due to its mandate and a lack of existing literature, it did not assess the capacity for very deep reductions (80-100+%). We refer to this as **"decarbonization lite",** focussing on efficiency, some fuel switching, energy cascading (where high quality waste heat from one industrial facility is reused by another or for general heating), destructive and non-destructive recycling, reduced demand and dematerialization (Allwood et al., 2010). Modelling studies, be they national or of a global integrated assessment model variety, typically incorporate only moderate (up to 50%) sector mitigation (Nabernegg et al., 2017) and simulate industry in an aggregate way that obscures sectoral complexity and capacities to abate (Edelenbosch et al., 2017). These approaches often lead to results and policy advice reflecting substantial unnecessary residual industrial emissions ("Mission 2020: Industry Milestones," 2017) requiring more reductions at higher costs from other sectors, and leading to the common perception that very deep targets are practically impossible. As a result, the analyst and policymaker knowledge base of technical and policy options to decarbonise industry is low.

While the peer-reviewed climate policy literature considering industrial emission reductions deeper than 50% is nascent (Åhman et al., 2016a; Denis-Ryan et al., 2016; Fischedick et al., 2014a; Lechtenbohmer et al., 2016), in this article we accomplish two objectives to aid policymakers, analysts and modellers. First, to demonstrate that decarbonization of heavy industry is possible, we have surveyed and synthesized by sector key initial conceptual, pre-commercial and commercial technology and process options for reducing emissions to near zero or less within 1-2 investment cycles. The results are included in a supplementary database. Second, to show how development and uptake of these technologies could occur, we have synthesized national, international and sectoral policy options to achieve this, focussing on options that encourage a managed transition from today's fossil fuel orientated industry to net-zero emissions with a minimum of stranded current and future assets, unemployment and social trauma, while overcoming the economic and social barriers (i.e. small co-benefits and intense economic competition) that have limited the incentives to apply new industrial mitigation technologies.

The structure of the article is as follows: 1) the general and sector specific options for industrial deep decarbonization, 2) policy options to develop and trigger investment in decarbonization technologies, and 3) further needed research.

2 SYNTHESIS: INDUSTRIAL DECARBONIZATION TECHNOLOGY REVIEW

Almost all industry uses electricity and diesel motors for various tasks. To make this analysis tractable, we assume all electricity generation has been largely decarbonized by 2040, and that work done by diesel motors is done by electric motors or bio-diesel based on non-food feedstocks (e.g. woody biomass, switchgrass), bio-ethanol, or a synthetic renewable hydrocarbon (see section 4.3). These assumptions also allow for deep decarbonization of mineral mining, forestry, and aluminum production (assuming SF_6 from bauxite electrolysis is eliminated via ongoing work on advanced anodes and cathodes).

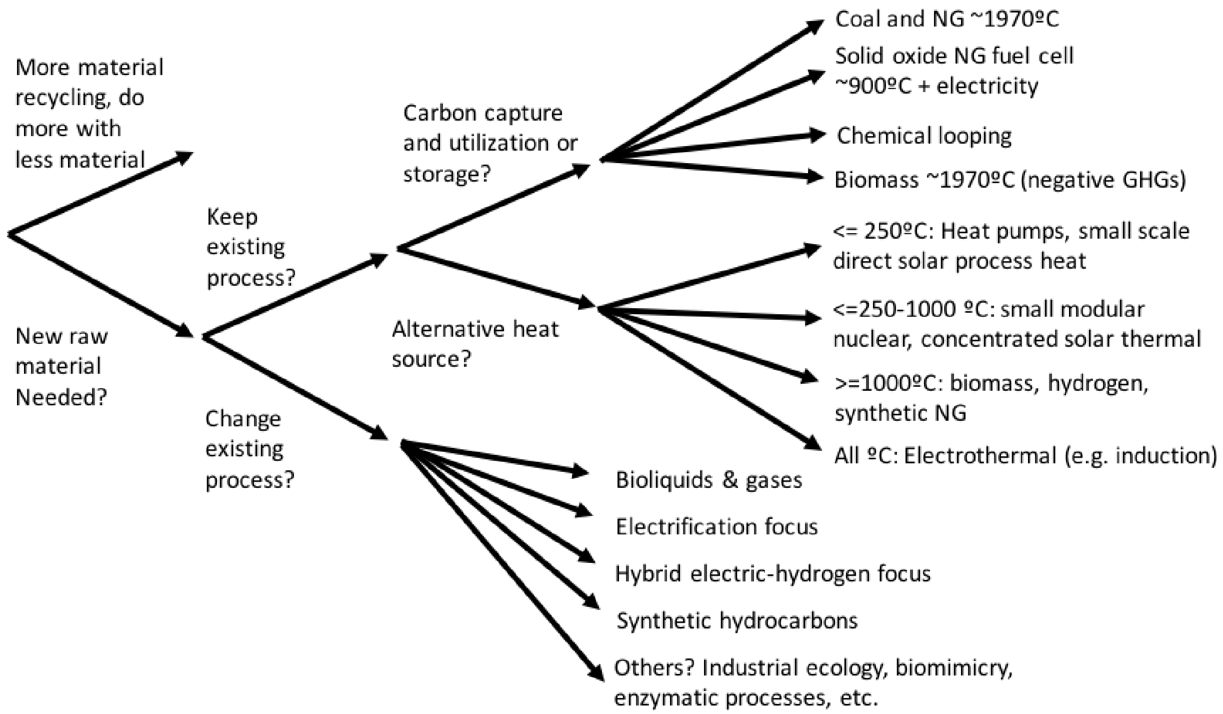
We also here mention the broad categories of industry ecology (McKinley, 2008) or circular economy (Andersen, 2007) (i.e. closed loop utilization of materials driven by energy), and biomimicry (i.e. replication of biological, typically enzymatically driven chemical processes which operate at atmospheric and ocean temperatures). These processes have promise but much research is required to ascertain whether they are commercially scalable. Given their very long run potential we leave detailed discussion for another review while acknowledging their importance in the latter half of this century.

2.1 METHOD AND GENERALIZABLE RESULTS

A database, open source with citation, of sectoral decarbonization technologies has been attached to this article that lists key technology characteristics, energy use, emissions compared to current technology, commercial readiness, relative upfront and operating costs where available and sources. It forms the foundation of the research program that produced this paper. It is disaggregated into a generic options, chemicals (distinguished by type), cement, iron and steel, mining, metal processing, glass, (bio)refineries, and pulp and paper. The database is not meant to be exhaustive but demonstrative of what is technically possible or acceptable in most jurisdictional circumstances, and to be a living document maintained and curated by interested researchers.

Many ways of thinking about industrial decarbonization are possible, but in Figure 1 below we have organized the generalized options as follows: 1) dematerialize or recycle/reuse, 2) keep the core existing process or make fundamental changes, and 3) if the existing process is kept does one go to carbon capture and storage or to GHG free process heating? While it is a financial question incorporating full supply chain and life cycle analysis to what degree it is cheaper to dematerialize, substitute, and recycle versus creating decarbonised raw materials, we assume as a first step that consumers of GHG intense raw materials (Allwood et al., 2010), driven by education and perhaps carbon pricing, will first reduce their raw material demands through more sustainable consumption patterns (e.g. by using products longer or more intensively, perhaps through use sharing), better design and substitution of GHG intense materials (e.g. through light weight design, component reuse without full material recycling, improvement of durability) (Allwood et al., 2012).

Figure 1 Generalized heavy industry decarbonization options



The second choice is does a sector keep a well known existing process designed around fossil fuel combustion heat and services (e.g. BF-BOF steel making) or conduct the financially and temporally more risky transition and commercialization of alternative processes (e.g. hydrogen based steel making) using R&D and pilot plants as first steps? If the existing process is kept then there is choice between using carbon capture and utilization and storage (Bataille et al., 2015; Leeson et al., 2017) with combusted coal, fossil methane, chemical looping, biomass, or solid oxide fossil methane fuel cells (McMillan et al., 2016), or to use an alternative GHG free heat source, for which development must again be done. For the latter, we describe three temperature classes (0-250°C for general steam and food processing needs, 250-1000°C for general purposes (e.g. chemical processing), and 1000+°C for lime, cement and steel making (1200, 1400 and 1600°C (McMillan et al., 2016))) and zero GHG alternatives within those heat classes (heat pumps, facility level solar process heat (McMillan et al., 2016), concentrated solar thermal (McMillan et al., 2016), biomass (IRENA, 2014), hydrogen (Garmsiri et al., 2014), synthetic methane combustion (Garmsiri et al., 2014), and advanced electrothermal technologies (e.g. microwaves)). These processes could also be used in tandem; initial heating with heat pumps or solar could be boosted with more expensive biogas, hydrogen or synthetic methane. If new basic processes are chosen, a suite of other options open up that can be used by themselves or in combination: replacing fossil liquid and gaseous fuels and feedstocks with biomass (IRENA, 2014), decarbonized direct or electrothermal electrification (Lechtenbohmer et al., 2016), a hybrid of electrification and hydrogen (Lechtenbohmer et al., 2016; Palm et al., 2015), and synthetic hydrocarbons (Garmsiri et al., 2014). We describe these in turn.

Carbon capture and utilization or storage (CCUS) is a technically viable option for most large combustion industrial facilities to keep their existing production processes (Bataille et al., 2015; International Energy Agency (IEA), 2014; Leeson et al., 2017), but could be very expensive due to a smaller flue gas volume than electricity generation plants and the need to transport the CO_2 to a disposal site. Work is underway to reduce the cost of capturing CO_2 from the flue gas stream, the most expensive part of CCUS, e.g. through advanced membrane separation technology (Khalilpour et al., 2015). Another path to reducing the cost of CCUS is to avoid having nitrogen in the flue gas and produce a relatively pure stream of CO_2, e.g. through chemical looping or direct oxy-combustion, where fuels are combustion with just oxygen (or even within the energy transfer fluid (Allam et al., 2013)), the challenge being the cost of oxygen. Whatever the method, the resulting CO_2 can be compressed, stored underground or be used for other processes (e.g. making renewable methanol, ethanol or other compounds; discussion following). Solid oxide fuel cells provide the promise of being able to consume abundant fossil methane and produce electricity while operating at a temperature (600-900°C) useful for industrial process heat and while also producing a pure stream of CO_2. There are limits to the tonnage that can be accommodated through utilization, however, and eventually storage will be required, limiting large scale CCS to those areas in economic transport distance of secure geological storage (e.g. the North Sea, or the Western Canadian Sedimentary Basin). A key long term advantage of CCUS is that when combined with biomass combustion it allows net negative emissions, permitting really deep and eventually negative targets if climate sensitivity proves them necessary. There are also substantial social acceptance barriers to geological CO_2 storage in some countries as well.

Solar thermal, biomass, synthetic methane, hydrogen or renewable electricity can all be used as GHG free alternative process heat sources, where the heat is transferred directly or with steam or other transfer fluids. All are at various stage of development, with biomass closest to commercial usability. While small modular nuclear reactors are also considered in the literature (McMillan et al., 2016), beyond the economic context there are substantial concerns with security, waste handling and proliferation, eliminating its consideration in many regions, especially if other options are available.

2.2 THE PULP AND PAPER INDUSTRY: KEY TO A BIOMASS PATHWAY?

Raw pulp, the precursor to paper, is made in a mixture of two ways, mechanical or chemical pulping; the need for raw pulp can be reduced using more recycled fibre. In mechanical pulping machinery tears up the cellulose wood fibre in preparation for paper making, while in chemical pulping the lignin that holds the cellulose together is dissolved. In the latter case the dissolved lignin can be used as a biofuel to heat and power the plant using recovery boilers (a net surplus of electricity to the grid is also common). This has become standard practice in new and rebuilt mills with chemical pulping in some regions, e.g. Canada. For mechanical pulping decarbonised electricity is necessary to power the motors. There is substantial methane intense waste sludge from chemical pulping that can be reduced via drying and using anaerobic digestion to transform it into combustible bio-gases.

The pulp and paper sector is important from a decarbonization perspective in that it sits at the nexus of bulk natural CO_2 absorption processes by forests and potentially grasslands, and thus potential bulk feedstocks for CO_2 absorptive building materials and net-zero chemical feedstocks and transport liquid fuels (next section, 4.3). Production of wood pellets from waste and biomass already allows other sectors to more easily convert to biofuel (e.g. home or district energy systems).

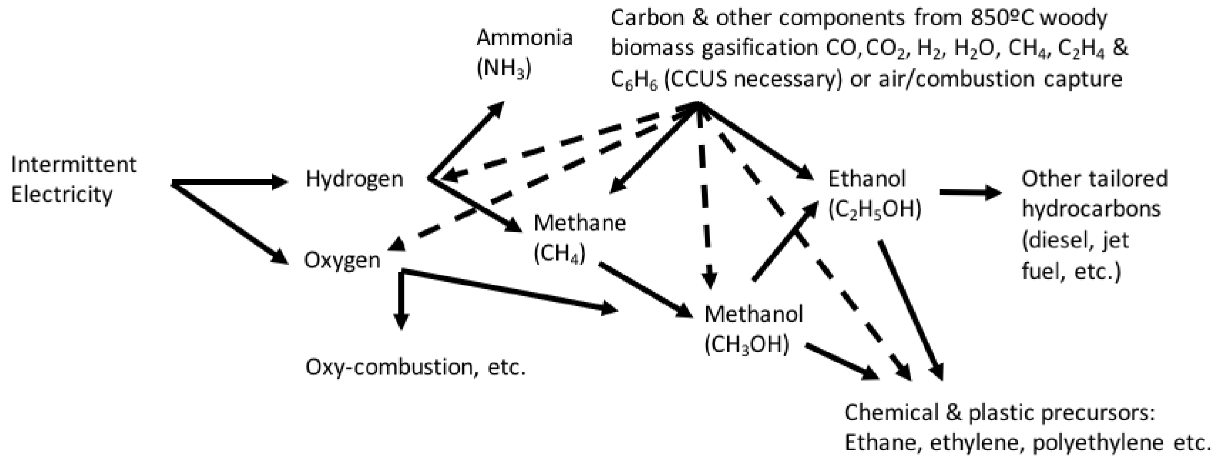
2.3 KEYSTONE CHEMICALS & RENEWABLE FUELS: DECARBONISED ELECTRICITY AND BIOMASS

Because of their carbon neutrality, **bioliquids (bioethanol, biodiesel), gases (biomethane), and solids (biocharcoal)** are often discussed as a near term replacement for fossil fuels (IRENA, 2014). There are three key pathways to turn biomass into usable gaseous and liquid fuels: low temperature fermentation and anaerobic biochemical digestion, which can transform most food waste into gaseous or liquid fuels, and medium temperature (850°C) thermochemical gasification, of which there has been less development but it can also transform wood or switchgrass biomass, of which there is a magnitude larger supply with less food growing land conflicts (Meijden et al., 2011). Charcoal is byproduct of lower temperature biomass combustion, leaving most of the carbon intact. The main issues with biomass are the competition for land use and the biomass it can supply across sectors (i.e. the available land and biomass will go to the highest value economic activities, which may not be industry), protection of biodiversity, life cycle emissions, reliability of locally sourced feedstock (security of supply) and air quality (Kypreos et al., 2017).

Hydrogen can potentially be used in place of fossil methane for process heat and feedstock, but it must be made cost effectively, distributed, and handled carefully; it is explosive and corrosive. There are several ways to make hydrogen: steam methane reforming of fossil methane (with byproduct CO_2 to dispose of via utilization or geological storage), gasification of biomass, electrolysis of water, or potentially through photocatalytic processes (International Energy Agency (IEA), 2017a). No more than 10% hydrogen can be mixed in with methane and transported directly in traditional iron based methane pipes, but it can be used in appropriately chosen plastic pipes. In some areas hydrogen pipeline networks already exist (e.g. the Rhine-Ruhr area in Germany) that collect excess hydrogen from industrial processes and distribute it to potential end-users.

Once system scale and economics reach the point that bulk excess intermittent wind and solar electricity is available there is the possibility of using electrolysis or direct hydrogen production (International Energy Agency (IEA), 2017a) and captured CO_2 to make synthetic renewable hydrocarbons and other keystone chemicals that underpin the global economy (e.g. ammonia, methane, methanol, ethanol, ethylene, polyethylene; Figure 2)(International Energy Agency (IEA), 2017a; Lechtenbohmer et al., 2016). Biobased processes generally have an excess of carbon and the usable product yields from gasification and anaerobic digestion can be increased through adding hydrogen, depending on the C_xH_y balance of the feedstock and product.

Figure 2 Production of ammonia and synthetic hydrocarbons using intermittent electricity and/or gasified biomass



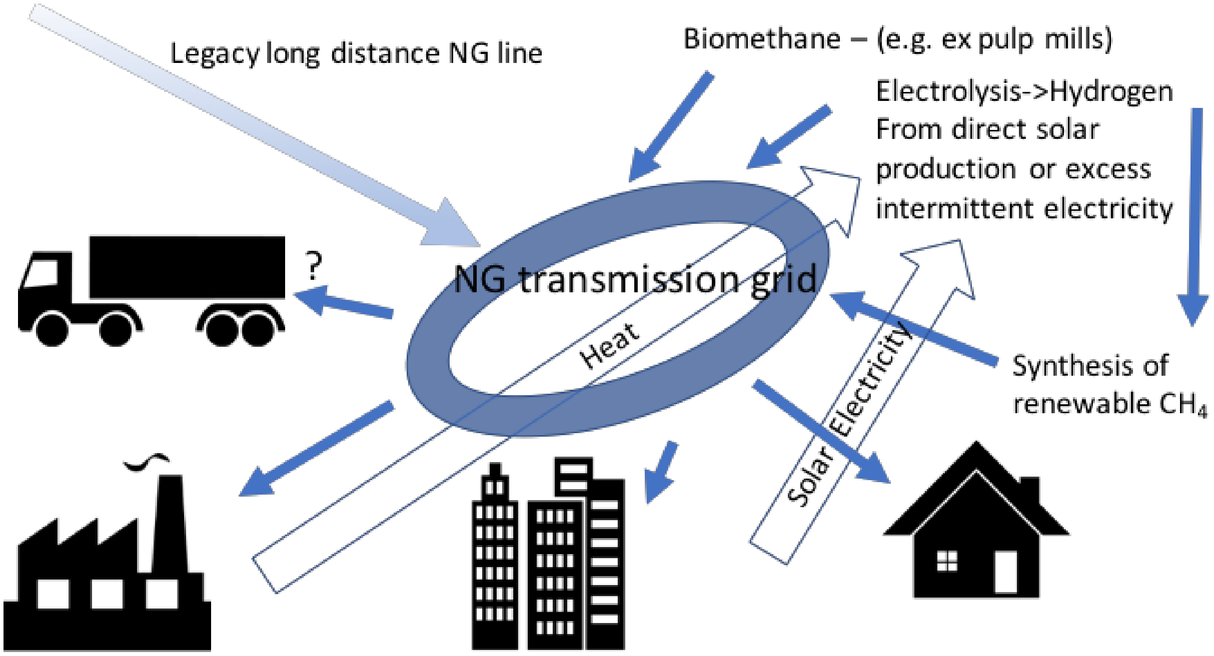
Ammonia is a keystone chemical in that it is used for making fertilizers, other chemicals and can be a safe way to ship bulk hydrogen. The process heating needs of **ammonia** synthesis (350-400°C for feedstock preheat, 780-830°C for reformation, and 350-550°C for ammonia synthesis) can all potentially be met with renewable sources as per Figure 1. If fossil fuel methane feedstock is used, via steam methane reforming, the CO_2 waste stream is relatively pure and amenable to CCUS. The need for CCUS can be eliminated by replacing fossil natural gas as the hydrogen feedstock with gasified woody biomass with some CCUS necessary for net zero GHGs (Meijden et al., 2011) or net zero GHG hydrogen made from electrolyzed water. All the above technologies are commercial but not competitive without carbon pricing or other market interventions.

Renewable **methane, methanol** and **ethanol** can be made from biomass via anaerobic digestion or gasification (Meijden et al., 2011), or synthetically from renewable electricity (Fasihi et al., 2017; Gulagi et al., 2017) by adding carbon to renewable hydrogen, the carbon coming either from biomass gasification/combustion, fermentation, digestion, fossil fuel CCS facilities or via direct air capture (pilot stage) (Carbon Engineering, 2017).

Olefins and other precursors to most plastics (e.g. ethane, ethylene, polyethylene) can be produced directly via biomass gasification or via renewable electricity; electricity based plastics are more expensive that biomass plastics to a point, but the feedstock is not scarce (Palm et al., 2015). Related processes can be used to make almost any desired hydrocarbon (Fasihi et al., 2017; Gulagi et al., 2017).

Figure 3 describes how the existing retail fossil methane grid could be used for one potential transition pathway from today's fossil methane end-uses to a fully decarbonised economy (Garmsiri et al., 2014), running on a varying mix of sources. It would start with woody biomass derived biogas, then hydrogen from excess intermittent electrolyzed electricity, and finally, synthetic methane constructed from renewable hydrogen and carbon derived from biomass or CCUS. The advantage of this transition pathway is that it allows legacy buildings and industry to decrease their GHG intensity as renewable hydrogen and methane fill the grid, minimizing stranded assets, while also potentially allowing them to contribute PV electricity and heat to the electrolysis process if the electrolyzers were appropriately located.

Figure 3 Reuse of the fossil methane retail distribution grid for legacy industry and buildings



2.4 IRON & STEEL, METAL PROCESSING & GLASS: DECARBONISED ELECTRICITY OR CCUS

2.4.1 IRON AND STEEL

There are currently three main technologies to make steel: the blast furnace-basic oxygen furnace (BF-BOF) route, electric arc furnaces (EAFs), and direct reduced iron followed by an EAF

(Denis-Ryan et al., 2016). There are several sector specific reviews (Hasanbeigi et al., 2014; Morfeldt et al., 2015; Quader et al., 2015) and programs (Neuhoff et al., 2014a) (e.g. UCLOS) that assess the options and work on piloting for 20-50% emissions reductions, but the treatment of net zero options is nascent. Raw (i.e. from iron ore) steel is typically made via the blast furnace to basic oxygen furnace (BF-BOF) route. The raw oxidized iron (Fe_2O_3) is "reduced" (i.e. the oxygen is removed) in a blast furnace using coking coal. Almost pure carbon coal is reacted with the oxygen to remove it, producing CO process emissions that can be further combusted for heat to CO_2. The resulting pure iron is melted and combined with carbon, zinc, chromium and other elements to adjust the character of the final steel. This is the most GHG intensive way to make steel and there are limited opportunities to improve GHG intensity. One possible avenue is to replace coking coal with biocharcoal for reduction, combined with CCS for process heating (IRENA, 2014; Leeson et al., 2017).

EAFs are typically used to melt recycled steel for reuse. Because of the way it is found and gathered, however, the scrap from which recycled steel is made typically has too many impurities (mainly tin, copper, nickel, molybdenum, chromium, and lead) to be used for high performance applications, such as tinplated food cans or automotive "exposed" surfaces (e.g. door skins) (Allwood, 2016). While attempts have been made to improve scrap sorting, it is not yet economical to remove all sources of undesirable residuals. If recycling systems or EAF processors could be set up to sort out these impurities and products designed so that they are easy to disassemble, the literature indicates recycled steel could be used in up to 50-75% of applications globally by 2050 (Allwood et al., 2012, 2010; International Energy Agency (IEA), 2009; Morfeldt et al., 2015; Pauliuk et al., 2013). Regional applicability would vary.

EAFs, however, can also be used to make raw steel by direct reduced iron (DRI) methods, which normally use fossil methane as the reductant and heat source. The first of two key routes besides recycling to decarbonizing steel production is to use renewable hydrogen in a DRI as the reductant (Åhman et al., 2012; Fischedick et al., 2014a; McMillan et al., 2016) with solid state iron ore, followed by melting and alloying in an EAF; SSAB, LKAB and Vattenfall are working with the Swedish Energy Agency in a joint venture to pilot this system (Vattenfall AB, 2017). There is a side benefit that reduction is 10 times faster than the conventional CO method. This route could also be utilized to maximize the value of off peak renewable electricity and smooth the electricity load curve, as the hydrogen can be made off peak demand, while its alternative for decarbonised steel making, electrowinning (below), requires electricity when the process is being run (Fischedick et al., 2014a; Lechtenbohmer et al., 2016).

There is one other main path for making decarbonised steel, electrowinning (Åhman et al., 2012; Allanore, 2014; Fischedick et al., 2014a). Based on decarbonised electricity and electrolysis (i.e. oxygen is directly separated from iron ore by adding electrons to Fe_2O_3), iron ore is either solved or suspended in a solid state in an acid or alkaline solution, where electrolysis of the oxide can occur at 110°C (which allows a wide range of cathodes and anodes) followed by melting in an EAF (Lechtenbohmer et al., 2016), or directly through molten oxide electrolysis at 1600°C (Allanore, 2014; Allanore et al., 2013). Substantial R&D and commercialization is needed, however, to produce cathodes and anodes that will cost effectively survive the direct process (Allanore, 2014).

2.4.2 METAL SMELTING

Much metal processing to date, with some exceptions, has been done by crushing and melting of source ores. The crushing may be unavoidable, but it can be done with decarbonised electricity, while the pyrolytic melting (e.g. smelting, roasting) can be replaced with leaching of the desired metal using various tailored solutions (e.g. acids or alkaline solutions), followed by electrolysis (a.k.a. electrowinning) or precipitation of the metal ores from the solution. Electrowinning had been used commercially for lead, copper, gold, silver, zinc, aluminum, chromium, cobalt, manganese, and rare-earth and alkali metals; nickel needs to be post processed.

2.4.3 GLASS

Two potential decarbonization technologies were found for glass production, oxy-fuel firing with CCUS and direct electric melting.

2.5 CEMENT: INCREASING CEMENTIOUS MATERIALS, CCUS AND FUTURE CHEMISTRIES

Cement is the mineral glue that holds concrete aggregate together, and its production is the source of most concrete related emissions; there are several existing reviews (D'Alessandro et al., 2016; Imbabi et al., 2012; Neuhoff et al., 2014b; WBCSD and IEA, 2009). Ordinary Portland Cement (OPC) is 95% clinker (EU CEM I (WBCSD and IEA, 2009)), composed of calcium carbonate from which CO_2 is removed plus a widely varying mixture of silicon, aluminum and iron oxides and gypsum, with the remainder being cementious materials composed of the aforesaid oxides (blast furnace slag (up to 75%, CEM III), coal plant or incinerator fly ash (up to 35%, CEM II), volcanic ash, silica fume, amongst others). Sources differ on the global average clinker composition of cement, with estimates between 65-78% clinker. Besides design and material substitution (sources indicate cement use can be reduced 20-60%), the most commonly cited way to reduce emissions in the sector is to use less clinker in ratio with cementious materials (typically by 25%, but up to 95% in the case of blast furnace slag for some end uses). Clinker/cementious material ratios are governed by local construction regulations, and depend on the final application.

One direct way to net zero cement is the use of CCUS for process emissions, perhaps via carbonate looping given the ready presence of limestone, combined with CCUS or one of the alternative process heat sources (e.g. biomass, hydrogen, synthetic methane) for process heat needs (900-1400°C).

Several alternative chemistries for cement (e.g. magnesium oxide, alkali-activated aluminum silicon cements (geopolymers), and calera) have been or are being piloted that could potentially reach net zero, or even negative emissions in the case of magnesium oxide, while being as strong or stronger than OPC. Most would likely require at least 10-15 years lag time from serious initiation to full commercialization, and would require substantial testing to ascertain their end use suitability, as well as market education to convince both regulators and market participants of their safety and usability.

3 POLICY PACKAGE DESIGN FOR INDUSTRIAL DECARBONIZATION

As shown, deep decarbonization of currently GHG intense materials is technically possible but will, for the foreseeable future, likely incur substantially higher production costs with few tangible co-benefits where profit margins are thin, competition is fierce, and retrofits and new build investments are very lumpy and few and far between. Given these limitations and tightness of the carbon budget associated with +1.5-2°C, how do we “jump” to zero or negative carbon industrial technologies in a politically acceptable way with a minimum of damage to existing assets, firms and workforces?

A primary requirement is making development of decarbonised heavy industry an explicit international, national, regional and sectoral priority. Once this is communicated as policy, each region needs a heavy industry decarbonization pathway/visioning/roadmapping effort (Åhman et al., 2012; Argyriou et al., 2016; Bataille et al., 2016a, 2016b, 2016c; McMillan et al., 2016; Neuhoff et al., 2014a, 2014b; Williams et al., 2012; WSP Parson Brinkerhoff and DNV GL, 2015) focussed on its particular competitive (dis)advantages and potential markets (e.g. reflecting access to biomass, decarbonised electricity, and geological storage for carbon dioxide). Stakeholder-oriented pathway processes are important tools to learn, strategize, communicate, coordinate, direct and legitimize transitions (Weber and Rohracher, 2012), and can help create a common vision between government, industry and civil society. While typically done as one-off exercises, to be maximally effective these processes need to be ongoing through the life of the transition as new information is generated (Mathy et al., 2016), and to support short and long run planning, policy and decision making, especially in the case of infrastructure. Fully developed pathways will require long-term dynamic strategies that include the whole innovation chain, from basic research to partial and full piloting, to long-term market policies to support demand for zero-emission materials (Åhman et al., 2016a; Wesseling et al., 2017). In the transport, building and electricity sectors this could be managed mainly within national borders; for highly traded industry a global strategy is required.

At the same time as the research, development, commercialization and market uptake processes, several other “public good”, market supporting aspects of industrial decarbonization, each worthy of a review, need to be created. Institutions are required to coordinate public research and technology diffusion, investigate and plan for industrial parks that would physically allow for more energy cascading, the labour force needs to be adapted to build, oiperate and maintain the new technologies, and investments need to be planned and made in necessary infrastructure (e.g. electricity transmission, CO_2 transmission) (Åhman et al., 2016b).

3.1 MARKET DIFFUSION OF PROVEN NET-ZERO INDUSTRIAL TECHNOLOGIES

A low-carbon transformation in the industry sector can only succeed if some firms dedicate their strategy to the transition. For this to occur the standard approach must be clearly linked to a combination of large risks (e.g. becoming financially or operationally stranded due to increasing carbon prices or regulations during the life of the asset), and large rewards (e.g. competitive advantage from producing a lower carbon commodity, higher market share and preferential access to markets if a facility meets or exceeds carbon content standard). There must be credible and commercializable technical, material and process pathways, as well as internationally accepted and used standards and certification processes for carbon content. To proceed firms need: (i) a clear regulatory framework covering all components (e.g. bulk handling of hydrogen, long term CCS storage and liability); (ii) clarity on the allocation of incremental costs of low carbon processes; and (iii) financing provisions that address regulatory risks and facilitate investment in capital intensive activities.

Carbon pricing is typically discussed as the key policy tool both to facilitate the use of new technologies and to discourage carbon intensive activities (Baranzini et al., 2017; Carbon Pricing Leadership Coalition, 2017) partly because of its potential role in induced low GHG innovation (Aghion et al., 2016; Calel and Dechezleprêtre, 2016; Newell, 2010; Weber and Neuhoff, 2010). The complexity and heterogeneity of production processes, value chains, and end-uses argues for a strong role for carbon pricing to facilitate a transition in the materials sector (i.e. through CO_2 efficient material production, substitution, recycling, and end use efficiency).

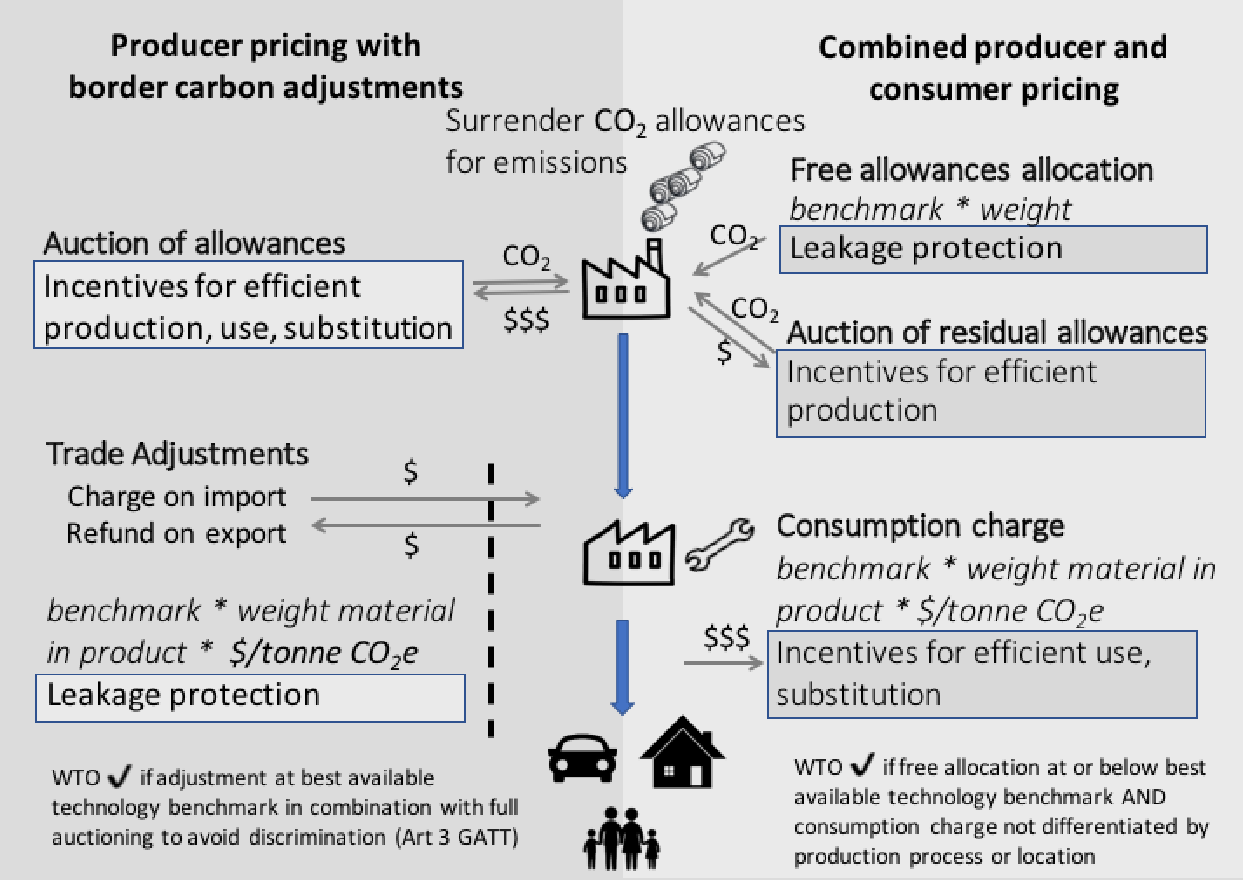
Several methods exist to internalize carbon costs in decision making with respect to materials (e.g. direct carbon pricing through taxation or cap and trade, or tradeable regulations that simulate pricing) (Carbon Pricing Leadership Coalition, 2017). So far, all have in common that they directly apply to the producing firms of materials like steel or cement, with the expectation the firms can and will pass-through incremental costs along the value chain through to final consumers. However, given the current carbon intensity of basic material production and their highly-traded nature, all carbon pricing schemes also include special trade provisions (e.g. free allowances or tax exemptions). Hence, in practice, carbon price pass-through in industry is largely muted. The primary envisaged strategy to increase the carbon costs passed down to consumers is a gradual phasing out of free allowances. As carbon pricing is a jurisdiction by jurisdiction process, however, phasing out of free allowance allocation can only be a slowly snowballing process with each jurisdiction responding to levels of carbon prices and free allocation in other jurisdictions to maintain protection for domestic industry.

Instead of gradual phasing out of free allowance allocation, jurisdictions can fully phase out free allowance allocation if they instead secure carbon leakage protection, such as through the use of border-tax adjustments (Figure 4) (Fischer and Fox, 2012; Monjon and Quirion, 2011; OECD, 2015; Quirion et al., 2011)**.** BTAs are a key means to achieve equalizing emissions pricing for imports and domestic production (Böhringer et al., 2012a, 2012b; Ismer and Neuhoff, 2007; G. Peters and Hertwich, 2008). BTAs face some practical difficulties, however, around determination of emissions content of imported products: accounting for intermediate inputs, varying production processes, and production orientated emission accounting (Droege, 2011). BTAs must also be compliant with WTO rules, i.e. foreign producers must face the same rules as domestic producers, and that measures have been applied in the least trade restrictive manner (Dröge, 2009; Ismer and Neuhoff, 2007; Trachtman, 2016).

End-use (instead of production) based consumption carbon pricing (Figure 4) would provide a method of internalizing carbon content in decision making at all stages of a material's life cycle, from initial demand, through end use design, material choice, and material production. If achievable, this would eliminate all distortions that regional carbon price differences may create between different locations and respective production methods. It works relatively easily for emissions linked to use of fossil fuels (e.g. California's Low Carbon Fuel Standard (California Air Resources Board, 2017), copied by several other jurisdictions), but it is more difficult to implement for materials, as it requires a tracing of the GHG content of all materials embodied in a product (Davis and Caldeira, 2010; Neuhoff et al., 2014a, 2014b; G. P. Peters and Hertwich, 2008; Steininger et al., 2014).

There is also the possibility of **combining production and consumption pricing,** (Figure 4, based on author synthesis of Neuhoff (2017)). Carbon leakage protection is maintained by free allowance allocation based on a best available technology (BAT) intensity benchmarks. Producers with break-through low-carbon technologies can reduce their incremental costs by selling allowances they receive at the conventional BAT benchmark, which is above their emission level. This upstream approach is combined with a consumption charge at the same benchmark level applied to all regional sales of the material, regardless of origin. This consumption charge re-instates consumers' incentives for efficient material use and substitution for lower-carbon materials, incentives muted by the initial producer free allowance allocation. Eithor or both the production and consumption charges may also be used to fund net zero technology R&D and piloting.

Figure 4 Producer pricing with BTA/BCAs vs. hybrid production & consumption pricing



Governments can also lead by example and use their own considerable purchasing power to create a market pull for low carbon products and commodities. Governments can adopt low carbon government procurement practices faster than they can design and introduce regulations, and since low carbon content stipulations can be designed to not violate existing international trade agreements (i.e. they treat all suppliers equally) they can be implemented without fear of carbon leakage. More importantly it provides a test case for the efficacy of the adopted strategy, revealing unintended consequences with flexibility to course correct before adopting economy wide international procurement standards that are more rigid and difficult to amend. Green public procurement can create early markets for climate friendly materials without recourse to international negotiations, and building and material efficiency codes (Scott et al., 2017) can help transform markets where these choices are economically viable but not pursued without a firm market pull because of perceived risks. Finally, cartels of private producers can combine their purchasing power to drive the supply and economies of scale for green procurement, e.g. the Sustainable Purchasing Leadership Council ("Sustainable

Purchasing Leadership Council," 2017) or aluminum users in search of low carbon aluminum (Hobson, 2017).

3.2 TECHNOLOGICAL DEVELOPMENT, AND PARTIAL AND FULL SCALE PILOTING

Establishing any sort of carbon pricing has been politically challenging globally, to the point where it is likely to be increased only slowly where it is established (Carbon Pricing Leadership Coalition, 2017). Despite this firms and sectors need to start developing and deploying breakthrough net zero emission technologies for which carbon prices are going to be far too weak and uncertain in the short to medium term to justify the private risks those investments entail. What other policies are available to stimulate technology R&D and commercialization, so that we can *then* raise carbon prices or implement performance standards sufficiently to generalize these technologies, setting up a virtuous cycle of risk friendly technological innovation and regulatory reinforcement?

A variety of complementary polices, such as the already mentioned green public and private procurement, can support or to some extent substitute for carbon pricing. These kinds of policies on their own are unlikely to be sufficient, however, to drive enough innovation in breakthrough technologies. Perhaps the most important problem is the difficulty of capturing the benefits of innovation. There will always be technology "spill overs", where others capture the benefits of a new technology without paying the development costs, particularly in engineering applications with limited intellectual property protection. An associated problem is that industrial decarbonization is only likely to succeed with solutions involving multiple actors (government, basic materials producers, manufacturers, and retailers; e.g. how do steel producers with zero GHG production capture benefits in niche markets that may pay a large mark-up for low-carbon steel when the commodity is globalized?). The Swedish HYBRIT hydrogen DRI joint venture is one attempt to address this question, setting up its own mine-to-fabrication supply chain (Vattenfall AB, 2017).

Deep decarbonization of heavy industry, in the absence of a well-thought through transition plan, could be highly disruptive to existing firms, which face numerous barriers to implementing entirely new processes: expensive and immobile capital structures, unhedgable price volatility, risk and uncertainty, and limited capacity to finance innovation investment. Industrial R&D, piloting and investment is especially risky and expensive and may be very difficult to justify to shareholders. They also do not share the advantage of wind and solar PV, of building many iterations of smaller units (Sovacool et al., 2014), i.e. it is "lumpy". For some technologies, it may take a decade or more until they are applied at scale and benefits begin to flow; funding support is therefore essential. Finally, a unique challenge of innovation in heavy industry is that small prototype plants are not competitive with big incumbent players; to be remotely competitive they must be full scale. The pathway process, if done well, can help to prioritize funding for research and development programs and eventually piloting, while near term carbon pricing, insufficient to generate the technology on its own, can aid with funding research and piloting.

Industry sector structure also matters; many sectors are dominated by a few very large regional or multinational players, and additional research is required to best understand how they may be motivated to adopt new technologies while operating at a global scale. Are firms likely to conduct R&D and develop their own technologies, or are they more likely to leave this risk to others and be 3rd party purchasers of technology? What level of disruption to established firms is likely if low-carbon technologies are developed by new competitors, and what transition policies are necessary?

Given all the above, industrial R&D and piloting of net-zero technologies would ideally be pooled across producing and consuming stakeholders through global collective learning and risk diversification across technology/project portfolios and amongst firms and government entities**.** A key recommendation of this paper is research is needed into policy and institutional structures or mechanisms that can bridge the gap between the focused costs and risks, diffuse spillovers, and the lumpiness of industrial technology experimentation. A key example is the Carbon Trust Offshore Wind Accelerator Program (Carbon Trust, 2017), which targeted key elements of the offshore wind supply chain (e.g. servicing in high seas) for joint work, while leaving other components competitive. Another possibility could be a purpose built multinational institution, funded and owned by industry associations and interested nations, whose purpose is to help fund a portfolio of decarbonization pilot projects. The participating nations could require domestic commodity retailers, whether the commodity was sourced domestically or from foreign sources, to hold a small but steadily increasing proportion of credits generated via verified pilot projects from this institution.

Finally, in our discussion of policy we have followed a logic that proven technologies are best dealt with by carbon pricing while immature technologies need specific support. This is a simplification of a very complicated “push-pull” process on a complex continuum (Åhman et al., 2016a). Carbon pricing has many challenges (Carbon Pricing Leadership Coalition, 2017), especially in a developing country context, perhaps necessitating a more regulatory approach (e.g. ratcheting GHG content standards for domestic and imported materials protected by trade measures or consumption pricing).

4 DISCUSSION AND FUTURE RESEARCH

Our analysis suggests that in a global low carbon economy there will be incentives to move production where it is cheapest, e.g. where the necessary biomass, intermittent renewables, geological storage for CCS, or shared process heat sources (e.g. concentrated solar power) are located, with an associated shift in trade routes in terms of direction, volume and type (e.g. from fossil fuels to ammonia, bioliquids and gases, and synthetic hydrocarbons). This suggests very focused regional and sectoral costs and benefits, and a pressing research, technology development, and policy agenda for every region as to which industrial decarbonization path suits it best, as this will depend on local resources and political circumstances.

To understand these shifts better, energy and climate models need to be improved to explore varying decarbonization pathways for heavy industry, i.e. hybridization techniques (Hourcade et al., 2006; Pye and Bataille, 2016) should be used to include transformative, deep decarbonization industrial detail in all modelling types used for <=2°C studies, be it directly as technologies in IAMs or bottom up stock turnover models, via production functions and elasticities in CGE models, or combinations thereof. Nabernegg et al (2017), which addressed a 50% reduction, and the 2017 IEA ETP (International Energy Agency (IEA), 2017b), are steps in this direction. A related recommendation is that better methods are required for including dynamic trade in global and national models, be it endogenously or through scenarios.

Key areas to investigate with technologically enhanced global models would be the temporal and overall role of relatively known (e.g. biomass), on-the-horizon (e.g. CCUS), and over-the-horizon (e.g. electrification-hydrogen, synthetic and bio-based chemicals and materials) technologies. Given the geographically limited reservoirs for CCUS, the land use constraints for biomass, and demands of negative emissions from both, the 1.5-2°C carbon budgets may eventually force us from these technologically familiar pathways onto the more exotic electric-hydrogen pathways, which are relatively more costly. Can we treat these pathways as seperable in R&D and commercialization, or are there positive and negative path dependencies, i.e. potential "lock-ins" we need to understand and avoid?

In summary, while there are many technologies in the development pipe-line to decarbonise heavy industry, they are poorly represented in existing modelling frameworks and policy discussion. To transition these technologies to commercial usability in time for the Paris Agreement goals we need a broad range of policies from production to end-use.

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