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Direct and indirect electrification of industry and beyond

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Abstract: Achieving net zero greenhouse gas emissions is very challenging. Given the limitations in the direct use of renewable energy for heat and mobility, electrification of the broad economy seems a must, provided electricity supply is CO_2-free. The recent cost reductions of solar and wind technologies, their immense potential, and the improvement in electric technologies for industry and transport, open new avenues for achieving humankind's climate mitigation goals. However, a large fraction of the best solar and wind resources are situated far away from large consumption centres. Moreover, the variability of solar and wind and the shortcomings of electricity storage limit the scope for direct electrification. Indirect electrification through electrolysis of water and the use of hydrogen and hydrogen-rich feedstock and fuels may in all end-use sectors complement electrification where it appears excessively challenging, serve the power sector itself, and also help harness remote resources and ship them to consumers or industries.

Keywords: climate change, energy, industry, electricity, hydrogen, materials

JEL classification: Q2, Q4, Q5

I. Introduction

The United Nations Framework Convention on Climate Change (UNFCCC) that binds over 195 countries on this planet has for its ultimate objective the stabilization of atmospheric concentrations of greenhouse gas (GHG). Whatever the level to be reached, stabilization implies zero net emissions. The Paris Accords, adopted unanimously at the 21st Conference of the Parties (COP) to the UNFCCC although rejected thereafter by the government of the United States, requires that net zero emissions are achieved as soon as 2050 for limiting global warming to 1.5°C, or by 2075 for limiting warming to 2°C (IPCC, 2018). How could a world of about 10 billion people, in the second half of this century, achieve zero net GHG emissions?

One important part of the response is likely to rest on an extensive electrification of the economy, based on zero carbon electricity. Although there are other options, solar and wind power, whose costs have been and still are plummeting, might play an extensive role—or rather several roles. The first role would be to support the decarbonization of

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the power sector in responding to the usual consumer demand for electricity. A second role would be to help replace direct use of fossil fuels in consuming sectors, thanks to low electricity costs and high efficiency of applications. Third and fourth roles, partly linked but distinct, would be to help harvest abundant solar and wind resources in vast areas where the local consumption is small, and bring that energy to consuming centres; and to complement direct electrification with a sort of indirect electrification based on renewable-based hydrogen-rich synthetic fuels.

The first section of the present paper considers the current trend towards electrification. The second section discusses the expanding role of renewable energy technology in the decarbonization of the power sector. The third section investigates the possibilities for replacing (more) direct fossil fuel use with electricity in industry, buildings, transportation, and again the power sector; special attention is given to the industry sector, often considered the most difficult to decarbonize. A final, fifth section, wraps up and discusses the overall role of electrification in a climate change mitigation perspective. It also attempts to draw some relevant policy considerations.

II. The trend towards electrification

Electrification of the broad energy mix is a long-term trend. Since 1990, global electricity demand has more than doubled, increasing at an average rate of 3 per cent per year. Meanwhile total final energy demand grew at only 1.6 per cent annually. As a result, the share of electricity in final energy demand increased from 13 per cent in 1990 to 19 per cent in 2017 (IEA, 2018*a*). Developing and emerging economies have driven most of this growth. However, even in more mature economies, the demand for electricity grew at around 1 per cent per year because of or despite saturation of 'white goods'—still more than final energy demand, which remained almost flat between 2000 and 2017.

Final energy, however, is only a convention, and may not suffice to describe the role of electricity in the broader energy mix. Another metric would be the primary energy demand. Another possible metric, proposed by Lempérière (2017), is that of 'useful energy'. Exactly like the 'final demand' concept which ignores the large amounts of coal and gas wasted as heat in power plants, the 'useful energy' concept ignores the large losses of heat in motors and vehicles and other poorly efficient devices. Of a global energy consumption rounded at 15m tonnes oil-equivalent (Mtoe) per year, or 175 petawatt hours (PWh), Lempérière estimates the 'useful energy' at about half that amount, 75 PWh (plus 10 PWh as feedstock in the industry). The share of electricity, at about 22 PWh, then represents 30 per cent.

Buildings represent more than half of global electricity demand, which is almost equally split between the residential and services sectors.

In the past 2 years, investment in the electricity sector has overtaken investment in oil, gas, and coal supply. Of the 60 per cent of power sector investment in 2017 that went into generation, the majority was in developing economies. China saw the biggest single contribution with a total investment of $131 billion, $100 billion of which went towards renewables based sources of generation, 30 per cent of the world total.

Three key factors contribute to this continuous growth of electricity demand in emerging economies over the last 25 years: industrialization, middle-class growth, and greater access to electricity.

Industrial production has boomed, and emerging economies now produce around half of all industrial output, compared to less than a quarter in the 1990s.

The share of the services sector in total employment in emerging economies grew from 30 per cent in 1990 to 44 per cent today. The higher income allowed the population to afford more appliances and cooling equipment, although it did not yet reach the level of saturation seen in advanced economies. Worldwide investment in electricity generation, networks, and storage of $750 billion in 2017 was roughly equivalent to the combined investment in oil, gas, and coal supply. Throughout the world, customers spent US$ 2,500 billion on electricity, almost 40 per cent of their total energy expenditures, next to oil that counts for about a half.

Almost 1 billion people have obtained access to electricity since 2000, 60 per cent of them in India alone, even though there are still 1 billion people without such access (mostly in Sub-Saharan Africa).

Electricity demand in China has multiplied by five since 2000, making it the largest electricity market ahead of the United States. India tripled its electricity consumption in the same time, and is now the third market globally. Although *per capita* demand in China is now close to that of some large European economies, that of India is still lagging far behind. Most of the forthcoming growth of electricity demand in the coming decades will take place in these two giant countries. India will add the equivalent of today's European Union to its electricity generation by 2040, while China will add the equivalent of today's United States—or more and almost double its own current consumption level (IEA, 2018*a*). Of particular relevance for the fate of power systems is the rapid increase of air conditioners; they already consume 2,200 TWh (terawatt hours) annually, 10 per cent of total electricity consumption, while only 8 per cent of the 2.8 billion inhabitants of the hottest countries have access to some form of cooling. Hence the electricity consumption of air conditioners may jump to 6,200 TWh by 2050. Furthermore, the share of space cooling in peak electricity load is projected to rise sharply in countries such as India, from just 10 per cent today to 45 per cent in 2050 (IEA, 2018*b*). However, energy efficiency standards have a considerable potential for slowing that increase, while cold storage can further help shaving the peaks to facilitate the matching of demand for cooling with the generation of solar photovoltaic (PV) electricity.

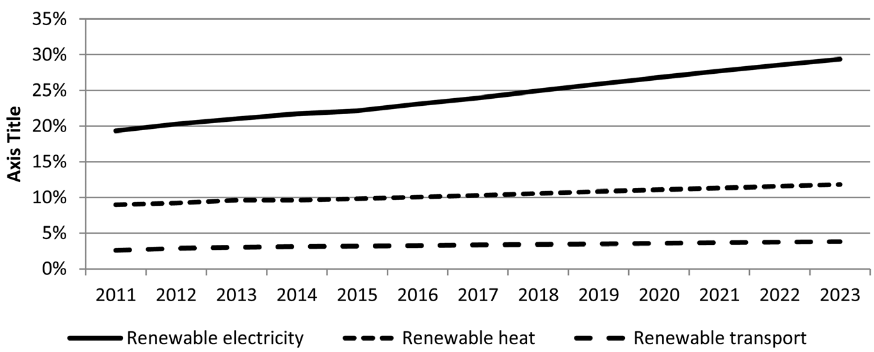
III. Trends in the deployment of renewables

Global power generation capacity additions were 294 GW in 2017, of which 178 GW were renewable. Wind and solar additions outpaced those of fossil fuels for the second year in a row, driven by policy support and falling costs. The global solar PV market had a record-setting year in 2017, with 97 GW of new additions, more than one-quarter higher than the previous year. Cumulative PV capacity will further expand by about 600 GW in the next 5 years and reach 1 TW globally (IEA, 2018*c*).

Clearly the decarbonization of the power sector leads the way before that of heat and transport. The penetration of renewables in the broader energy mix remains low. Even excluding the traditional uses of biomass, which are not always sustainable or healthy, bioenergy in its current modern forms represents in 2017 half the contribution of all renewables to the global energy balances, as it is the only renewable energy that can contribute to electricity generation, transport, and heat, especially in industry. In absolute terms, its progression remains faster than all others combined, while in shares of total energy the progression of electric renewable technologies is fastest, gaining 1 percentage point per year, as can be seen in Figure 1.

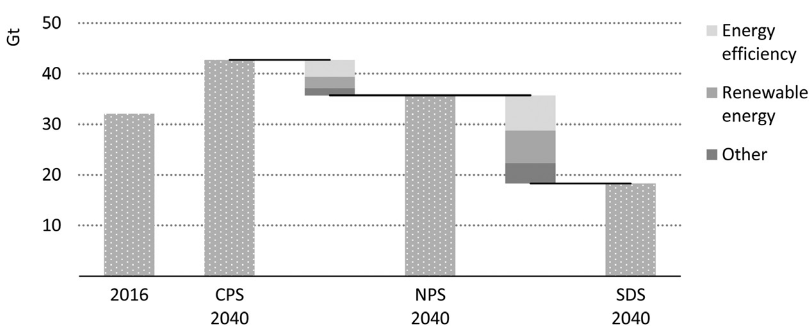
Most energy scenarios for the coming decades that are roughly compatible with the objectives of the UNFCCC and its Paris Accords reveal the primary roles of energy efficiency improvements and renewable energy deployment. Each area would be responsible for about a third of global emissions reductions compared to trend scenarios. The remainder would come from some extension of nuclear power generation, and carbon-dioxide (CO_2) capture and storage or re-use. This is, for example, the case of the Sustainable Development Scenario (SDS) of the International Energy Agency's (IEA's) *World Energy Outlook* (WEO) series, as can be seen by comparison with both the Current Policy Scenario (CPS) and the New Policies Scenario (NPS).

Figure 1: Shares of renewables in the energy mix of the power sector, the transport sector, and heat



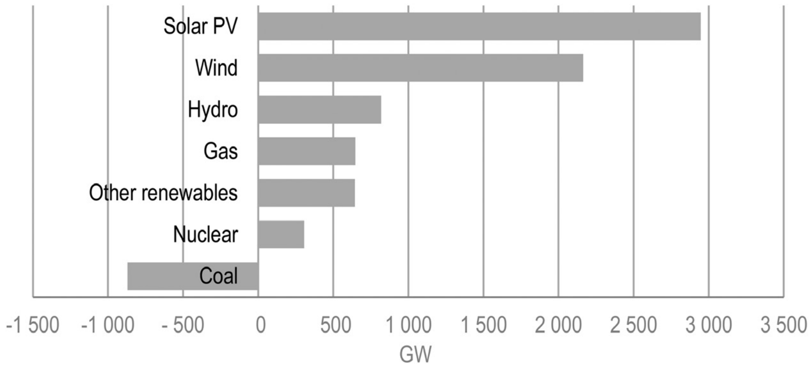
Source: IEA, 2018*c*.

Figure 2: Contribution of energy efficiency and renewables to global reductions in energy-related CO_2 emissions by scenario



Source: IEA, 2017*a*.

Figure 3: Global net capacity additions 2016–40 in the WEO Sustainable Development Scenario



Source: IEA, 2017*a*.

Most of the growth of renewable energy technologies in the SDS is that of solar and wind power capacities, as can be seen in Figure 3. However, these energies are variable, and cannot be made fully dispatchable. Hence the integration of a large share of variable renewables can create a series of issues, and requires greater flexibility from the rest of the system, including dispatchable generation technologies.

In many cases, there will remain a need for some thermal power plants being used as peaking plants and especially during the infrequent but always possible 'week without wind' in winter in temperate countries—unless they have large hydropower and/or pumped storage capacities and reservoirs. One issue of any deep decarbonization scenario consists in providing this 'final' (e.g. before 100 per cent of renewable power) 5–15 per cent of electricity generation with minimal CO_2 emissions, an issue that is considered further in the next section.

These limits will be reached earlier for small, islanded electricity networks, often run on diesel fuels at the moment. These networks provide enormous opportunities for early deployment of the new technologies and fuels considered in this paper.

IV. Replacing more fossil fuels with electricity

The industry and transports sectors are often considered 'harder to decarbonize' sectors compared to the power sector, and the buildings (residential and services) sectors. We start our investigation with industry, indeed a complex sector, because there might be important synergies between the greening of various industrial products, and the production of green chemicals and fuels that could prove useful for a deep decarbonization of both the building and transport sectors.

(i) Industry

Industry is the largest energy-consuming sector, especially if non-energy uses of fossil fuels (as feedstocks and process agents) are included. Three-quarters of energy use is in the form of heat. Carbon dioxide emissions from cement, chemicals, and iron and steel provide three-quarters of total industrial emissions. They are particularly difficult to tackle as they mix emissions arising from the combustion of fossil fuels for energy use, and emissions arising from various processes, notably extraction of hydrogen from fossil fuels for producing ammonia and other chemicals, reduction of iron ore with carbon that gets oxidized in the process, and calcination of limestone for cement-making unavoidably generating CO_2.

However, the recent rapid cost reductions in solar and wind power may enable new options for greening the industry and transport sectors, either directly from electricity or through the production of hydrogen-rich chemicals and fuels.

The greater efficiency of electric industrial processes can often close the cost gap with fossil fuels. EPRI (2018) and BZE (2018) both provide numerous examples relying on infrared heating, ultraviolet curing, microwave and radio frequency heating, induction heating, melting or hardening, and electric arc furnaces, in sectors as diverse as chemicals and petrochemicals, iron and steel, food, drink and tobacco, glass, pottery, and building materials, machinery, and paper and printing. EPRI (2018) sees a technical potential of 250 TWh in Europe (EU+5), and a smaller economic potential (with payback time less than 3 years, not accounting for CO_2 reduction or any process quality improvement) of 178 TWh, which would substitute to 43 Mtoe of natural gas, equivalent to 500 TWh. These figures clearly reveal the (final) energy efficiency improvement involved. In total, electro-magnetic technology would substitute 11.5 per cent of the overall fossil fuel consumption of the EU's industry.

Another area could be that of equipment with high coefficient of performance (COP) recycling energy waste fluxes, such as heat pumps with COP from 2 to 4, depending on the temperature lift that is necessary, or mechanical vapour recompression machines, with COP ranging from 5 to 10 as they avoid the condensation losses of low-temperature low-pressure steam. Voltachem assumes a potential for these technologies to halve energy for the heat demand of the EU's chemical industry below 200°C and save 15–20 per cent in total (van Kranenburg *et al.*, 2016).

One may also consider cheap equipment called to work only when market electricity prices are lower than average (at times of 'excess' supply), such as electric resistances immerged in fossil-fuelled boilers. Some large industries already operate steam generation in electric boilers replacing natural-gas (NG) fired boilers as a demand-side management tool using low-cost variable renewable power.

Another dimension to consider is that electrification of industry can provide flexibility services to power grids confronted with the challenge of integrating large shares of variable. For example, Trimet Aluminium SE retrofitted its factory in Essen to allow managing of the heat and keeping the temperature of smelters in a safe range despite fluctuating amounts of electricity (Philibert, 2017).

A fuller replacement of fossil fuels with renewable electricity may however require carbon prices reaching high levels of about €120–150/tCO_2_somewhat more than assumed by 2040 in IEA's Sustainable Development Scenario (IEA, 2017*a*). But is it technically possible in all industrial sectors? Chemicals, iron and steel, and cement, characterized by large process emissions, need closer examination.

The production of chemicals may offer a considerable potential for electrification. The DECHEMA study (Bazzanella and Ausfelder, 2017) for the European Council of Chemical Industry shows that an ambitious scenario could save 101 Mt CO_2, or 84 per cent of the anticipated emissions of the European chemical industry. The main share of emission cuts would come from using hydrogen from low-carbon electricity to produce ammonia and methanol, olefins (ethylene and propylene), and benzene, toluene, and xylene (BTX). This would require 1,900 TWh of green power according to the 'ambitious scenario' of the study, and up to 4,900 TWh in a 'maximum scenario'.

Hydrogen, ammonia, and methanol

The total on-purpose production of *hydrogen* today is over 70m tonnes per year (Mt/y) globally. Of this, 33 Mt goes to ammonia production, 23 Mt is used in refineries (together with 10 Mt hydrogen (H_2) by-product) for upgrading and hydro treating (i.e. reducing the sulphur content) of fuels, 12 Mt goes to methanol production, and the rest is used for other chemicals, and metallurgy. Currently about 40 per cent of the global methanol production has energy uses, either directly in blends or indirectly as feedstock for dimethyl ether and other additives. As both ammonia and methanol can serve as hydrogen carriers and storage, these energy uses would likely become much larger, and even exceed their current industrial uses.

Fossil fuels currently provide over 95 per cent of hydrogen: steam methane reforming (SMR), naphtha partial oxidation, and coal gasification. This production entails important CO_2 emissions, from 9 to 20 tCO_2/tH_2. Assuming NG price of €5.7/MBtu in Europe, the cost of producing hydrogen can be assessed at €1.37/kg. Capturing and storing 90 per cent of the CO_2 in the flue gas of SMR plants non-integrated in a broader industrial complex ('merchant' plants) would requires an increase of almost 80 per cent of the total plant costs, and present a CO_2 avoidance cost of €60–70/tCO_2.[1] The levelized cost of hydrogen would increase to €2/kg.

These costs are particularly contingent on the cost of natural gas, set to progressively increase over time (IEA, 2017*a*). Hydrogen from an SMR merchant plant with carbon capture and storage (CCS) would thus cost about €2.3/kg in 2025 and €2.6/kg in Europe in 2040. Figure 4 presents a wider set of natural gas prices and resulting hydrogen costs from steam methane reforming. (Figures 4–8 are all drawn from the author's own analysis.)

Figure 5 shows the cost of hydrogen from water electrolysis with respect to the load factor of electrolysers, in comparison with that of NG-based hydrogen. Two electricity prices are figured: US\$70/MWh, and US\$30/MWh. The former could be the cost of offshore wind power in North Europe, whose resource is large, the latter could represent the cost for hybrid solar PV and onshore wind power in the world's best resource areas, such as the Horn of Africa, Australia, North Africa, northern Chile, southern Peru, Patagonia, and South Africa, as well as several regions in China and the United States.

At the 47 per cent load factor considered for offshore wind power, the cost of large-scale electric hydrogen production would be €3.16/kg, over twice the current cost of producing hydrogen from SMR without carbon capture. As NG prices progressively increase in Europe, and carbon emission reductions across the entire economy become necessary to comply with the EU commitments, the cost gap with offshore wind-based

[1] The cost of CO_2 transport and storage is assumed to be €10/t CO_2, the difference is the cost of capture according to IEA GHG (2017*a*).

Figure 4: Cost of hydrogen from natural gas

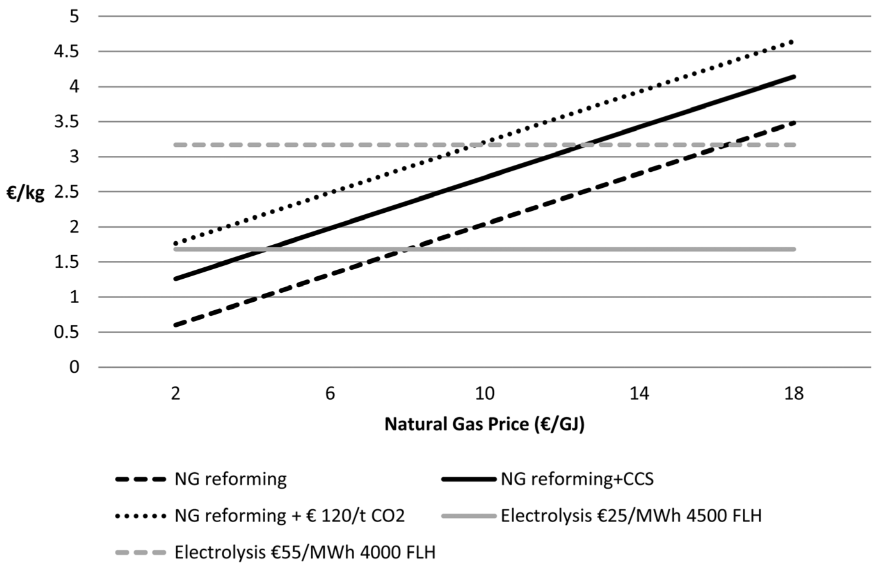
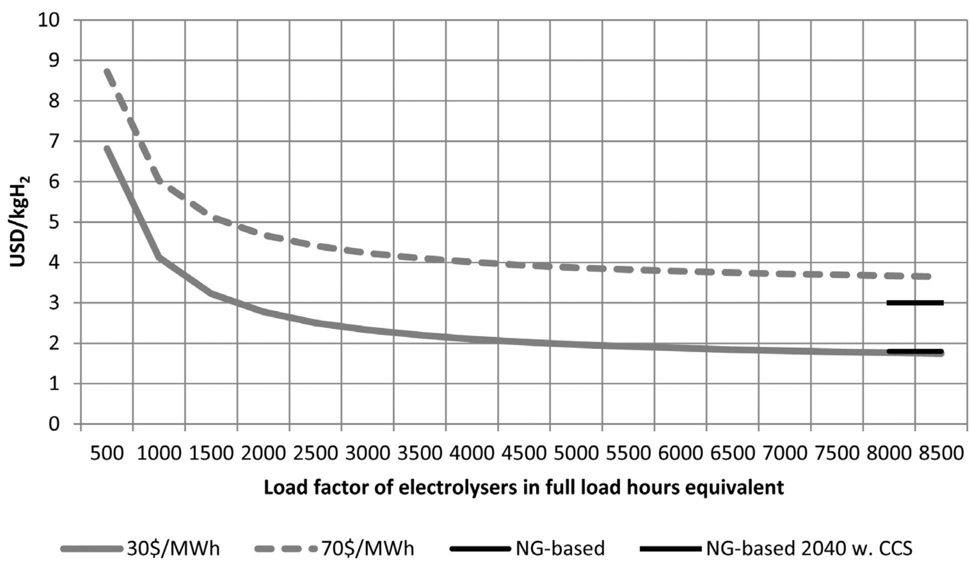


Figure 5: Cost of hydrogen from water electrolysis for various electricity prices and electrolysers load factors



Notes: Assumptions: Electrolysers Capex US$ 450/kW_{input} (Simonsen, 2017), + installation 30 per cent, + maintenance 20 per cent, efficiency 70 per cent, WACC 7 per cent, lifetime 30 years. Gas prices in Europe: Sustainable Development Scenario, IEA (2017*a*).

hydrogen would progressively reduce but probably not enough to fill the cost gap with CCS if widely available.

Ammonia (NH_3) is at the heart of the fertilizer industry, bringing nitrogen to plants. It is also used to manufacture explosive, cleansers, dyes, fibres, plastics, nylon and acrylics, or as a refrigerant. Ammonia can be produced from water electrolysis and nitrogen taken from the air with the well-established Haber–Bosch (H–B) process at costs that largely depend on the cost of electricity, provided the electrolysers have load factors above one-third, and the ammonia synthesis loop is run continuously at a capacity greater than 50 per cent of its maximum capacity.

In the case of hydrogen production in integrated ammonia/urea plant or a methanol plant, where the CO_2 generated from the process is often captured and reused, the cost of capturing the remaining, more diluted, CO_2 emissions is higher than in the case of merchant plants and reaches €80 to €100/tCO_2 (IEA GHG, 2017*b*). This, and the simplifications of the H–B process permitted by the greater purity of renewable-electricity-based relative to NG-based hydrogen, can slightly improve the competitive position of electric ammonia produced from offshore wind in Europe *vis-à-vis* natural gas, but still does not fill the gap, as shown in Figure 6 (based on natural gas cost expectations in the SDS, of €6.66/Mbtu in Europe by 2040).

More importantly, perhaps, ammonia production does not require material inputs other than air and water, and transport of ammonia in ocean-going tankers and pipelines is already routine, at a cost of about €40/t over long distances. Therefore, as shown in Figure 7, an even more serious competitor for offshore-wind-based ammonia production might be solar- and wind-based ammonia imported from areas with much better resources, such as North Africa (Philibert, 2018).

Methanol, the simplest alcohol, is widely used as a precursor of plastics (through both propylene and formaldehyde), plywood, paints, explosives, and permanent-press textiles. Methanol also forms gasoline additives in some countries, enters the production of fatty acid methyl ester biodiesel, and forms the basis of dimethyl ether (DME), an aerosol spray propellant and a transportation diesel fuel. DME can also be used in

Figure 6: Costs of ammonia from natural gas in Europe, vs from electrolysis

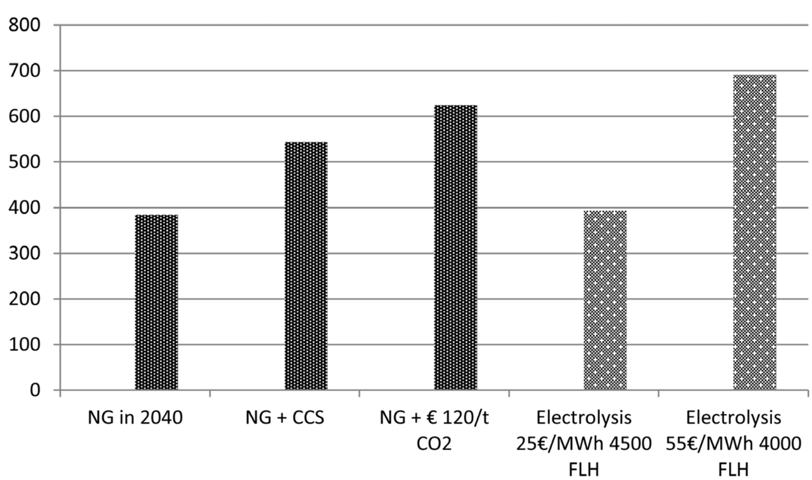
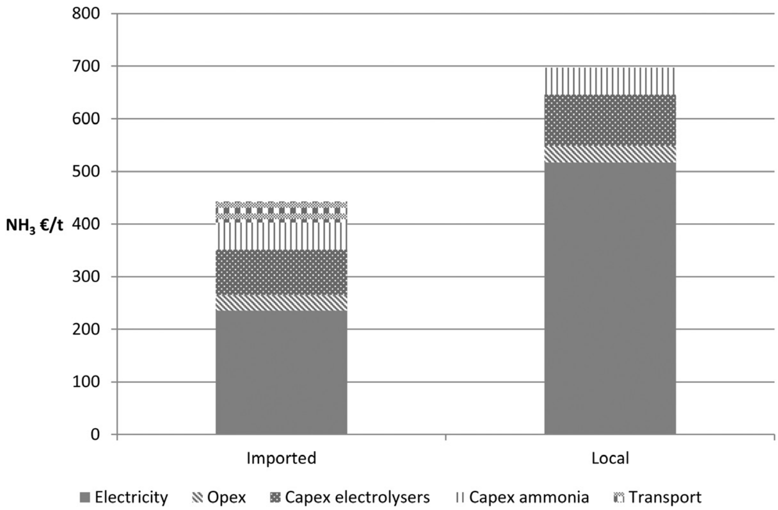


Figure 7: Costs of European electric ammonia production vs imports from best resource areas



combination with liquefied petroleum gas for home heating and cooking. Sixty per cent of methanol is used as a feedstock, while 40 per cent enters into energy fuels. The global production of methanol reaches around 80 Mt/y, and its European demand accounts for about 9 Mt/y.

Methanol (MeOH) is usually produced from fossil fuels through catalytic reactions to associate carbon monoxide and hydrogen. Alternatives include biomethanol, and the hydrogenation of CO_2 with renewables-based hydrogen, demonstrated in particular by Carbon Recycling International (Stefansson, 2017). Even if the CO_2 is of fossil origin, there will be benefits of capturing and recycling it to replace additional fossil fuel or feedstock. Bazzanella and Ausfelder (2017) assess them at over 1.5 tCO_2 /tMeOH. In the long run, however, as the global economy nears net zero emissions level, carbon recycled in synthetic fuels and goods will have to come from the air, via photosynthesis or direct air capture

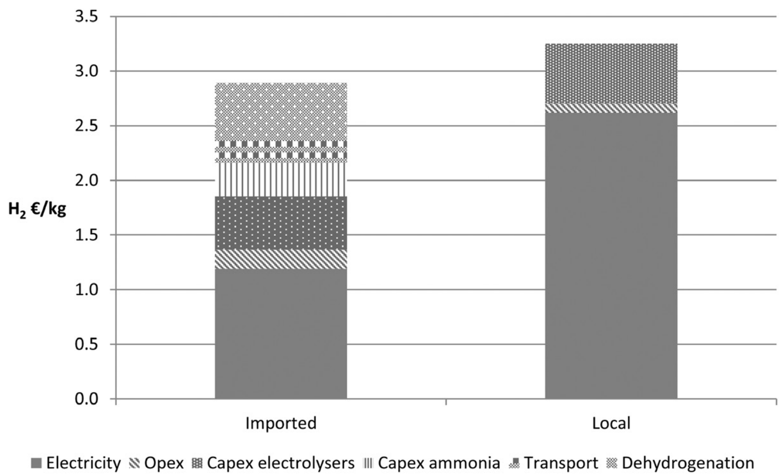
For green methanol, like for green ammonia, the competition to offshore wind power in Northern Europe may come from areas with better and cheaper renewable potential, with reduced shipping costs as methanol is liquid at normal temperature and pressure, provided CO_2 can be procured.

However, for applications requiring pure hydrogen, the total cost of turning hydrogen to ammonia, transporting it and extracting pure hydrogen from ammonia would considerably reduce the competitive edge of producing ammonia in remote regions with better resources, as shown in Figure 8.

Other chemicals

While the efficiency in the electric production of ammonia and methanol is roughly comparable with the efficiency of producing them from fossil fuels, the electric production of olefins is 40 per cent more energy intensive than naphtha cracking, according to Bazzanella and Ausfelder (2017). The electrification of olefins and BTX production thus largely explain the high electricity demand of a complete transformation of the

Figure 8: Costs of European hydrogen production from renewables vs imports of hydrogen as ammonia from best resources areas



European chemical industry. Nevertheless, such electric paths could be carbon sinks for other industrial sectors, requiring large amounts of CO_2 captured from power or industrial plants or directly from the air, as a source of carbon feedstock.

Iron and steel

Steelmaking is a considerable challenge as it represents 4 per cent of Europe's total CO_2 emissions. Emissions originate from both energy use and the reduction of iron ores. Among other options for decarbonization of steelmaking such as HIsarna (IEA, 2017*b*), renewable electricity could be used directly through electrolysis of iron ore, also known as electro-winning. Two processes at various temperature levels, Ulcowin and Ulcolysis, have been developed at laboratory scale, as part of the European research programme ultra-low carbon dioxide steelmaking (Ulcos). The Siderwin project of Arcelor Mittal is a continuation that includes demand-side management of variable renewables (Birat, 2017). Meanwhile, start-ups attempt to develop innovative processes and materials for molten iron-oxide electrolysis (Sadoway, 2017).

Another option for a greater uptake of electricity in steelmaking is to use hydrogen to reduce iron ore in the direct reduction path. Under this 'electric' road, iron ores are reduced with 'syngas', a mix of carbon monoxide and hydrogen extracted from natural gas; direct-reduced iron is then melted with scrap in electric arc furnaces. In the project Hybrit, a joint-venture of Swedish iron and steel producers with the electric utility Vattenfall, is developing, hydrogen from renewables would replace NG-based syngas (Görnerup, 2017). Other European steelmakers in Austria and Germany follow suit (Birat, 2017). This option seems to present a higher technical readiness level, and allows for the progressive introduction of renewable-based hydrogen in existing direct iron reduction facilities. However, it is less efficient than direct electrification. If regional offshore wind power is to be the main source of electricity for steelmaking, direct electrification may thus become the best choice. At 2.6 MWh of electricity per tonne of crude steel (Weigel *et al.*, 2016), conversion of the European steelmaking industry would require some 416 TWh for 160 Mt steel per year.

(ii) Cement

The calcination of limestone ($CaCO_3$) to produce lime (CaO), the first step of cement-making, based on burning fossil fuels, as well as biomass and waste, is an energy-intensive process. As the reaction progresses, the material cools itself, making heat transfers to unreacted limestone increasingly difficult. New microwave-assist technology (MAT) combines radiant heat and microwave activation in the same electric kiln to dissociate $CaCO_3$ to CaO simultaneously at the centre and the surface of the material, increasing the rate and uniformity of calcination (Fall *et al.*, 2011).

For the cement industry, besides such options for efficient partial electrification, options for also reducing process emissions are still under laboratory development and not further examined in this note (see Philibert, 2017; IEA/CSI, 2018). However, CO_2 captured from cement production could be recycled into chemicals and fuels with renewables-based hydrogen, as considered above. Siting electrolysers on cement plant sites could be an interesting option, as it would also ease oxy-combustion, which may in turn ease CO_2 capture.

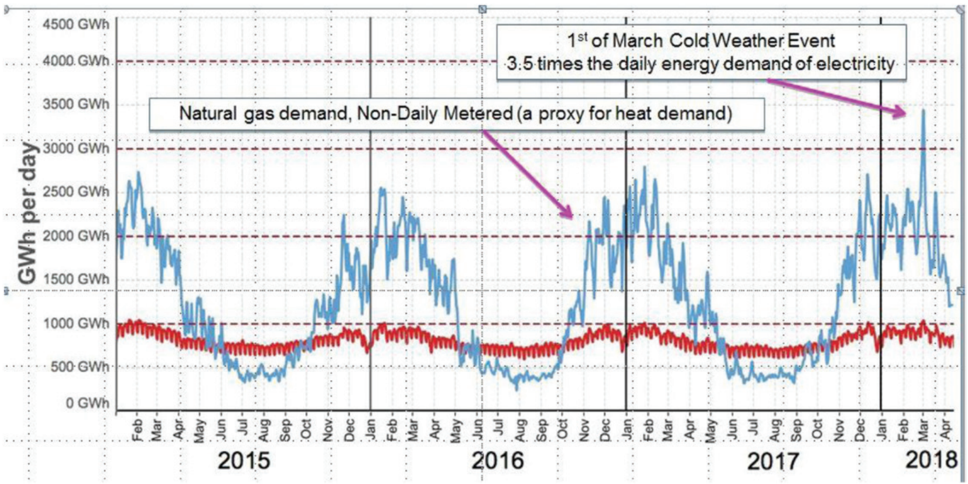
(iii) Buildings

Heat pumps are probably the best technology to replace the direct use of fossil fuels in buildings, thanks to their excellent efficiency. Drawing heat from the ambient air, water bodies, or the ground, they introduce more kilowatt hour (kWh) heat in buildings than they consume of electricity (or more rarely natural gas). There are several barriers, however, to their deployment. The large up-front expenditure is an obvious one. Another difficulty is that the coefficient of performance is highest when the temperature lift is minimal. As a consequence, air heat pumps are less effective when the outside air gets really cooled. Ground-based heat pumps are much more efficient, but it may not be easy to install them in dense cities. Underground water bodies sometimes offer a good option. Another option under development consists in coupling solar thermal panels with heat pumps. To preserve performance it is best to keep the temperature of the water circulating in the radiators relatively low. Reaching comfort temperatures in buildings then requires large exchange surfaces, which may cost more, especially in retrofitting. In some cases, however, a strengthening of the insulation of the building can be coupled with a change of heating technology and compensate for a lower temperature in unmodified radiators.

About 10m heat pumps had been installed in Europe by 2017, and 25m globally. Most of them being reversible air–air systems (blowing air in the building), they are also able to provide cooling. The remainder are air–water systems and ground-source heat pumps. Nordic countries are the most equipped.

Using electricity to provide heat is often presented as a key component of so-called 'sector coupling' and a way to facilitate the integration of large shares of variable renewable energy technologies—solar photovoltaics (PV) and wind power—into the power grids. Indeed, the accumulation of heat, especially in well-insulated buildings and in

Figure 9: Fluctuations of electricity and gas demand for heat in the UK



Notes: The line with small seasonal variations, almost always below the 1,000 GWh/d line, represents the electricity demand. The line with ample variations represents a good proxy for heat demand satisfied with natural gas.
Source: Dr Grant Wilson, University of Sheffield, UK. Data from National Grid, Elexon, and BEIS.

hot water tanks, allows drawing electricity from the grid at times of lower demand—or higher supply from variable sources. Indeed, the thermal inertia of hot water tanks has already long been exploited in countries such as France to add more flexibility to the power systems—in the case of France initially characterized by a large share of relatively un-flexible nuclear power generation (at least from an economic standpoint).

Thus the development of electric heating can help smooth out the variability of renewable power and of demand—and the gaps between them—on an hourly or daily basis. However, it also runs the risks of increasing the seasonal imbalance of the demand, as can be seen from the case of the UK in Figure 9.

Production of hydrogen-rich fuels may thus have a role to play in complementing direct electrification, taking advantage of existing gas transport, storage, and distribution networks. There are three options: blending hydrogen within natural gas or biogas (limited to about 20 per cent in volume, less than 10 per cent in energy); converting the gas grids to pure hydrogen; and synthesizing methane from recycled carbon and green hydrogen. In November 2018, the UK's Committee on Climate Change (2018) came to the view that a hybrid approach would be more realistic than either a 'full hydrogen' pathway or a 'full electrification pathway'.

(iv) Transports

The IEA publication the *Global EV Outlook 2018* (IEA, 2018*d*) has an EV30@30 scenario that is consistent with the ambitions pledged by Electric Vehicles Initiative member countries under the EV30@30 campaign. The EV30@30 target is a 30 per cent market share of EVs for light duty vehicles, buses, and trucks collectively. In this scenario, there are 220m electric light-duty vehicles on the road in 2030, of which about

90m are plug-in hybrid electric vehicles. While this scenario focuses on the EV30@30 target only, it is clear that achievement of this target must be accompanied by a reduction of the carbon intensity of power generation (exceeding 50 per cent by 2030) and continued growth of EVs after 2030, to be fully compatible with the well-below 2°C target of the Paris Agreement. Meanwhile, electric transportation is making remarkable progress for light-duty vehicles, but some transport modes seem difficult to electrify in full, in particular long-haul trucking, marine transport, and aviation. In this respect, one should consider possible use of green electricity to manufacture transport fuels. These could be diatomic hydrogen, ammonia, methanol, or various hydrocarbons.

A 'chicken and egg' problem has so far hampered the deployment of hydrogen vehicles: owners of hydrogen vehicles have access to few refuelling stations, while the building of refuelling stations is not profitable due to the scarcity of hydrogen vehicles. The high cost of fuel cells, and the logistical challenge of distributing hydrogen to refuelling stations, represent other challenges.

Japan, probably the country whose industry is most engaged in developing fuel cell vehicles (FCVs), targets 800,000 FCVs by 2030, requiring about 80,000 tonnes of hydrogen per year. Even if Europe were to set up similarly ambitious targets for itself, weighted by population, this would require about 15 TWh and not form a very large outlet for offshore wind power.

Ammonia seems well fitted for long-haul maritime transportation, as recently acknowledged by Lloyd's Register and the University of Maritime Advisory Services (2017), but more difficult to generalize on land or in the sky. Combining recycled carbon and green hydrogen would allow the production of synthetic, renewable, and carbon-neutral hydrocarbons of any type—now tagged as 'electro fuels'—either from methanol or more directly from carbon monoxide and hydrogen through Fischer–Tropsch fuel synthesis, as Sunfire in Dresden proves—on the small scale of one barrel of synthetic diesel per day (Bazzanella and Ausfelder, 2017).

As is discussed in Box 1, in a world of many fossil CO_2-emitting sources, recycling carbon dioxide from fossil origin may help reduce emissions; however, carbon used to manufacture synthetic hydrocarbons will need to be taken out of the atmosphere in the longer run, or compensated in full with negative emissions.

The overall efficiency from electricity to hydrogen-rich liquid fuels used in transport would be small, assessed as 13 per cent overall (including the efficiency of internal combustion engines) versus 73 per cent for electric traction (Malins, 2017). Costs would likely be high, but estimates diverge, from twice the cost of conventional fuels according to Sunfire, to six times that of diesel or jet fuel according to Malins, although based on a cost of €50/MWh. However, the cost of synthetic fuels may decline considerably over time and, according to Frontier Economics (2018), approach that of fossil fuels.

In any case, the cost of electricity dominates the cost of electro fuels, so that procurement from regions with significantly lower renewable electricity costs would likely be a must, as these 'oil products' are routinely shipped long distances.

On top of a closed CO_2 cycle, Frontier Economics (2018) underlines several other sustainability criteria for importing synthetic fuels into Germany: the additionality of renewable electricity generation, sustainable use of space, the sustainable economic development in the production countries, and, in dry climate zones, the need to source water from seawater desalination.

Box 1: Sourcing carbon for synthetic hydrogen-rich fuels

Apart from diatomic hydrogen and ammonia, which contain no carbon, other hydrogen-rich fuels would contain carbon atoms. Recycling carbon from industrial CO_2 fluxes otherwise emitted to the atmosphere, so-called carbon capture and use (CCU), may help reduce CO_2 emissions, but would not allow net zero emissions. Both carbon providers and users may claim carbon reductions, and the risk of double counting exists. Moreover, if governments were to incentivize all steps in the process there is a risk of creating significant inefficiencies. For example, CO_2 from natural gas-based production of ammonia could be captured then combined with renewables-based hydrogen to produce synthetic methane for combustion. Such a scheme would offer no climate benefit over simply using renewable-based hydrogen to produce ammonia, and directly combust natural gas—and entail significantly higher capital expenditures and energy losses. To reduce such a risk, it seems preferable that only 'unavoidable emissions' should be captured for re-use.

As the global economy nears full decarbonization, however, this carbon will have to come from the atmosphere. Direct air capture is a reality today, but it is expected to require significant amounts of energy; it is arguably more difficult to extract carbon dioxide from air at a concentration of 400 ppm (albeit increasing rapidly) than nitrogen for ammonia making, at a concentration of 78 per cent in the air. However, most of the required energy may be delivered as low temperature heat, and synergies with some conversion processes can alleviate the energy costs. Another option is to capture CO_2 from industrial plants initially consuming bioenergy. The most intriguing option, however, might be to co-produce biogas and biofuels with synthetic methane or Fischer–Tropsch liquid hydrocarbons, by adding hydrogen from renewables in the manufacturing of biogas or biofuels, where there is always an excess of carbon that is turned into CO_2. From both ends, the sustainability would be greatly enhanced: from a given amount of biomass, up to twice as much usable fuels could be produced thanks to the addition of the energy from hydrogen, while synthetic fuels would be 'carbon-neutral' thanks to the atmospheric origin or the carbon in biomass.

The necessity of a closed CO_2 cycle in the long run gives significant interest to the hydrogen enhancement of biofuels proposed by Ilkka Hannula (2016) and his colleagues at the Finnish technical research centre VTT. Renewables-based hydrogen could roughly double the potential of biomass feedstock to produce biofuels, hence alleviating the 'fuel vs food' and 'fuel vs biodiversity' concerns. However, while biomass is a precious and relatively scarce resource globally that needs to be mobilized sustainably (IEA, 2017c), it still represents an important resource in Northern Europe, which offshore wind power could help use in an optimal manner.

(v) The power sector

The analysis of the production of hydrogen from renewables presented in the previous section provides various insights. Most of the required storable energy fuels that could be used in thermal plant to ensure electricity security in the context of very high penetration of variable renewables may come from 'stranded' renewable potential in remote regions with excellent resources and low local demand. Production of such fuels from otherwise curtailed electricity in those regions with lower quality resources may be limited. As the IEA (2017*a*) puts it,

> in the SDS, one-third of the world's electricity is supplied by wind and solar PV in 2040, and as much as 8 per cent of variable electricity generation could be lost because of curtailment in the United States, European Union and India, unless there is scope to store it or to make use of it. The curtailed electricity in these three regions could provide around 20 Mtoe of hydrogen, roughly 2 per cent of their natural gas demand in 2040 in the SDS. However, this may be prohibitively expensive. While the costs of the electricity would be very low (since it would otherwise be lost), the capital costs of hydrogen-production facilities are high and facilities are unlikely to be economic if they can only operate intermittently. It may well be that it makes more sense to produce hydrogen using dedicated generation facilities (solar, wind, hydropower or nuclear).

The Japanese cross-ministerial strategic innovation promotion programme (SIP) 'energy carriers' has examined three different ways to transport green (from renewables) or blue (from fossil fuels with CCS) hydrogen from Australia or the Middle East to Japan: cryogenic hydrogen, liquid organic hydrides, and ammonia. However, its leadership now shows a clear preference for ammonia due to its versatility, as it can be combusted as such, or only after partial cracking with heat (which can come from the combustion), while the two other options require re-gasification or de-hydrogenation, both of which representing an energy penalty. Japan thus envisages co-combusting ammonia in existing coal plants, then turning natural gas plants to ammonia (Muraki, 2018). In a recent analysis of a 100 per cent renewable power and heat system in Northern Europe, Ikäheimo *et al.* (2018) see a major role for ammonia as it allows transferring energy from renewables in both time (i.e. storage) and space (e.g. from Norway to Germany).

Furthermore, such fuels for the power sector would need to be easily storable. Although hydrogen gas or synthetic methane could possibly be stored in the existing gas transport, storage, and distribution networks, there could be a strong argument to preserve this option largely to respond to the seasonal demand for heat in buildings (see below). Another affordable option is that of underground storage in various types of caverns, where available. However, if hydrogen is to be transferred from production to consumption regions in a chemical form, presumably ammonia, it would be simpler to just store some ammonia next to power plants.

In islanded systems of small to medium sizes, where the delivery of diesel fuel can increase its costs significantly, the rationale for hydrogen storage may appear shortly to help balance out the variations of solar and wind generation of electricity.

V. Wrapping-up and policy implications

The largest contribution of renewables to our energy today comes from biomass, and its growth still exceeds the growth of the contribution of all other renewable energy combined (IEA, 2018*c*). This is due in part to the ability of bioenergy to contribute directly to our heat needs, especially in industry. Even considerable improvement and new deployment of other direct renewable heat technologies seem unlikely to scale up to the challenge of decarbonizing the global economy. Only renewable electricity technologies may be apt to respond to the challenge. In 2011, the International Energy Agency published a book, *Solar Energy Perspectives* (IEA, 2011), with a chapter titled 'Testing the limits'. In this chapter, the author suggested that by 2060 in a climate mitigation scenario the share of electricity in the final energy demand could 'increase from slightly less than one fifth currently to at least half, perhaps even two-thirds, by 2060–65'. He noted that a round figure of 90,000 TWh could result from a mere continuation of the current 3 per cent per year growth trend.

This view was echoed in November 2018 by the Energy Transition Commission in its report, *Mission Possible* (ETC, 2018):

> Electricity's share of total final energy demand will rise from today's 20% to over 60% by 2060. As a result, total global electricity generation must grow from about 20,000 TWh today to 85–115,000 TWh by mid-century while switching for high-carbon to zero carbon power sources.

But electrification may have two faces: direct electrification (the most important), and 'indirect electrification' through the production of hydrogen and hydrogen-rich fuels and feedstocks from electrolysis, where direct electrification seems impossible or too difficult. Such situations are characterized by either long duration storage, and/or long haul transportation—and this includes the transport of energy itself from resource-rich areas to less-favoured consuming centres.

Energy- and GHG-intensive industries, whose products are traded internationally, may not be in a position to support additional costs for process modification to reduce CO_2 emissions. Furthermore, imposing carbon prices or directly regulating emissions potentially puts carbon-constrained industries at a competitive disadvantage relative to their unconstrained competitors. Governments thus fear that uneven carbon constraints could enhance the competitiveness of non-carbon-constrained producers.

This is why the transport sector is often considered as more apt to shift to electricity and, even more so, hydrogen, than the industry sector, even though industry today is a much larger consumer of both, and its decarbonization might be in fact cheaper than that of the transport sector. Arguably, however, the competition with heavily-taxed oil products—in some countries—could prove easier for electricity and hydrogen in transport than in industry.

However, industry should not be considered as an impossible-to-decarbonize sector. There are not only technical options available, but also some policy options.

Of the three main industry subsectors considered in this report, cement is less at risk, as it is much less traded than ammonia and steel. With respect to chemicals, the situation varies according to the cost of shifting to renewables. If it is low, as for ammonia used as an industry feedstock, the risk of carbon leakage is low, while it cannot be ignored for methanol and high-value chemicals; the current shift in production and relocation of investment in this subsector towards the United States and its low-cost natural gas illustrates the cost sensitivity of this industry. Finally, international competition and trading are intense in the iron and steel subsector.

Furthermore, having renewables-based, hydrogen-rich chemicals or basic materials manufactured in areas that have excellent resources but—in some cases—relatively little local demand, may entail challenges that fall outside the conventional wisdom about environment and trade. For potential exporting countries, the challenge is to ensure that there will be a large enough market for these materials, whereas potential importing countries must benefit from the differential in renewable resource quality and abundance in meeting their emissions-reduction objectives while still protecting low-carbon production, either local or imported, in relation to inexpensive, carbon-intensive imports. Renewed forms of international cooperation could presumably help meet these challenges.

A global agreement to create a state of equality with respect to GHG emissions, for example with a globally coordinated 'single' carbon pricing system, would in principle solve this issue. While some economists consider it to be the 'first-best' option, others point out that its adoption is very unlikely from a political standpoint, for it does not take inequalities in economic development into account: a single world price would be too high for some countries and too low for others. Also, the system could be economically efficient only if energy taxation were similar in all countries (Godard, 2015).

The industry sector itself implemented such agreements long ago, under the aegis of the International Aluminium Institute, the World Business Council on Sustainable Development, the International Iron and Steel Institute, and others (Baron *et al.*, 2007). However, sector-wide agreements cannot initiate the process. Substituting water electrolysis for steam methane reforming (SMR) in ammonia production, or hydrogen-based direct reduction (H-DR) for blast furnace-basic oxygen furnace (BF-BOF) and natural gas-based direct reduction (NG-DR) in steelmaking—not to mention cement—will require considerable changes in these sectors. As most radically different technologies have not been demonstrated on a large scale, initiating negotiations to force them through global markets would likely not succeed and could even prove counter-productive.

Another possibility would be for governments to restrict international trade of materials based on upstream emissions, and introduce a border tax or 'border carbon adjustment' (BCA) mechanisms. This seems to be compatible with the current rules of the World Trade Organization (WTO) and the various rules of numerous bilateral and multilateral trade agreements. Specific WTO rules allow members to adopt trade-related measures for the protection of the environment. The General Agreement on Tariffs and Trade (GATT), Article XX, recognizes the need to adopt and enforce measures necessary to protect human, animal, and plant life or health, and the conservation of exhaustible natural resources. However, for a measure to fall under Article XX it must not be applied in a manner constituting a means of arbitrary or unjustifiable discrimination between countries where the same conditions prevail, or be a disguised restriction on international trade.

Contrary to a widely held belief, the WTO does not forbid discrimination among products on the basis of the processes or production methods (PPMs) used for their elaboration, provided criteria are fully consistent with domestic regulations. For example, in the 'Shrimp–Turtle' dispute that opposed four Asian countries to the United States over shrimp-catching methods dangerous to turtles, the plaintiffs won because the United States had given more flexibility and assistance to some other foreign countries, while the Appellate Body of the WTO's dispute-resolution mechanism confirmed that WTO members can and should adopt effective measures to protect the environment. Moreover, several countries have introduced measures, such as biofuel sustainability standards, that do distinguish products based on their PPMs.

Baron and Garrett (2017) explore in more detail how BCAs may be applied to create equality. Governments could usefully clarify this issue further with more explicit endorsement, and could elaborate common methods for calculating the amount of carbon used in product manufacturing based on the work of the International Organization for Standardization (ISO).

Another, even stronger, alternative would be for jurisdictions to adopt, in the context of a regional trade agreement or otherwise, a set of standards for the embedded carbon of heavy materials used in their economy, in line with their efforts towards becoming zero-carbon. Non-conforming products would simply be denied entry.

BCAs and standards, however, only work to avoid carbon leakage when the countries willing to protect their industry sectors implement primarily domestic measures. They would not allow initiating the process of implementing constraints based on radical, rather than incremental, process improvements or modifications.

To ensure prompt deployment of innovative clean technologies based on renewables, public and private procurement of clean, carbon-free materials may be the most realistic short-term option. For example, the cost of steel represents only a small fraction of the overall cost of a vehicle. Manufacturers of brand products—carmakers in this case—may want to bolster the green performance image they project to their customers and the general public, including their own stakeholders, whether out of personal conviction or wary of possible backlash—or both. Electric cars and plug-in hybrids could lead the transition towards 'green steel', and renewable energy developers could pay attention to the life-cycle emissions of wind turbines, for example—massive steel objects implanted in the ground in a large concrete structure.

Many developers have done this already, procuring green power and now turning their attention to the 'grey energy' embodied in their products and to procuring preferably cleaner materials. For example, Walmart launched a major supply chain initiative that seeks to remove 1 billion tonnes of global external supply (GES) (cumulative) from its supply chain by 2030. It identified six areas in which suppliers can focus their clean-energy efforts: agriculture, waste, packaging, deforestation, and product use and design. Sustainable procurement of wood and paper-based products is not only a project of the World Resources Institute, it is also becoming a mandatory reference in industry and commerce, and for sustainable fisheries.

Public procurement may play a similar role. Public procurement accounted for 13 per cent of the gross domestic product of Organization for Economic Cooperation and Development (OECD) countries in 2013, and even more in some emerging and developing economies (Baron, 2016). All jurisdictions, public services, and companies have buildings constructed for their own operations or for the public—schools, hospitals, social housing, etc. They procure vehicles of all sorts, railways, bridges, roads, and other infrastructure, and therefore manage concrete, cement, and steel in massive quantities.

The primary objective of procurement is obviously to find and buy products and services that offer good value for taxpayers' money. However, as a government-operated instrument, public procurement should also be aligned with a country's broad policy objectives, balancing these objectives with its primary purpose of finding the best value for public money.

Low-carbon procurement, both public and by large firms, could have domestic and international repercussions. It would create equality for domestic companies facing unfair competition from abroad, and would also provide a strong incentive to competitors to adopt new, low-emitting processes to get or keep access to important foreign markets. For example, this is the dual aim of the Buy Clean California Act signed by the Governor on 15 October 2017. This law requires the Department of General Services to establish and publish in the State Contracting Manual, a maximum acceptable global warming potential for each category of eligible materials by 1 January 2019, in accordance with requirements set out in the law. Four categories of materials are concerned: carbon steel rebar, flat glass, mineral wool board insulation, and structural steel.

The determination of some companies to develop radically new industrial behaviours and technologies to eventually gain a prime-mover advantage, combined with low-carbon procurement, could ultimately offer new perspectives to policy-makers and climate change negotiators around the globe.

At the same time, policy-makers still bear very important responsibilities. With respect to buildings and transport, as well as for industry, besides direct procurement, policies have structural and network effects, and may lead to mass-scale learning benefits. Thorough analyses are needed to guide policy decisions in such very complex situations and help identify robust pathways for deploying low-carbon technologies.

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