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Enhanced market uptake of climate mitigation options

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The CARISMA Project started in February 2015 and received funding from the European Horizon 2020 programme of the EU under the Grant Agreement No. 642242. CARISMA intends, through effective stakeholder consultation and communication, to ensure a continuous coordination and assessment of climate change mitigation options and to benefit research and innovation efficiency, as well as international cooperation on research and innovation and technology transfer.

Abstract

The Paris Agreement demands fast action on climate change. In order to achieve its objectives of limiting global temperature rise to well below 2°C, and strive for limiting it to 1.5°C, economies have to reduce emissions significantly and rapidly. Innovative climate change mitigation technologies that entail radically different practices than conventional technologies will need to be part of this global endeavour, particularly since incremental improvements and efficiency gains of conventional technologies and methods of producing, transporting and consuming goods and services will not be sufficient to tackle the climate challenge.

Many such new technologies are available to address climate change. However, many also face significant challenges. Based on previous work carried out in the CARISMA project, this working paper explores some technologies needed that enable deep decarbonisation in multiple sectors, in particular hydrogen (in the steel industry and transport), energy storage, carbon dioxide capture and storage, heating, cooling and more efficient envelopes for buildings, biofuels for aviation, and improved fertiliser use and livestock management (agriculture).

We focus our analysis not only on their technological readiness level (TRL) but also on their economic, environmental and social barriers and enablers, once they would be mature enough for increased market uptake and diffusion. We then explore funding streams available to these technologies for research, development and demonstration (RD&D) in order to ready them for society and the market. Recommendations for resolving issues and making use of enabler include living up to the research and development spending commitments made earlier in the EU, aligning innovation funding better with future market uptake, reforming markets and putting the right kind of incentives in place for market uptake, and giving society and users a voice in the development of new technologies.

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CEPS CENTRE FOR EUROPEAN POLICY STUDIES
UNEP DTU PARTNERSHIP
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1 Introduction

Meeting the objectives of the Paris Agreement to limit global warming to well below 2°C or 1.5°C above pre-industrial levels requires deep decarbonisation, i.e. the rapid and substantial reduction of emissions will be necessary (Bataille et al. 2016). A two-degrees limit will require net zero emissions between 2070 and 2090 (IPCC 2014), or earlier for lower temperature limits, and an annual decarbonisation rate of around 6% (PwC 2017). The EU has set itself the target of reducing its emissions by 80-95% up to 2050 compared to 1990 (European Commission 2011) and may be updating this in the light of recent development, such as the upcoming IPCC Special Report on Global Warming of 1.5°C. even if this target would be in line with the objectives of the Paris Agreement, current EU policies to reach this objective fall short (Climate Action Tracker 2017).

This insufficiency also illustrates that while conventional action should be taken rapidly, countries will also need to make sure that new and innovative technologies are deployed rapidly (Rockström et al. 2017). Research carried out under CARISMA looked at several sectors based on United Nations Framework Convention on Climate Change (UNFCCC) classifications, and identified several climate technologies per sector which would contribute to the decarbonisation effort by 2050, rather than taking us only partly there (Elkerbout et al. 2018). It is important to note that we identified the most promising technologies in terms of emissions reductions to meet this objective.

While the decarbonisation potential of those technologies might be well known, some of them are riper for large-scale introduction and diffusion than others. Moreover, having a proven and well-functioning technology is only half of the battle. There has to be a market for those technologies as well, and societal readiness. Both societal and market readiness face several barriers which work against a given technology becoming mainstream. This deliverable selected several technologies elaborated on from an emissions reduction perspective in Elkerbout et al. (2018) for further investigation. Due to limitations, we had to make a selection of technologies elaborated on, but we strove to cover the largest amount of sectors possible and to include technologies from the most emitting, and growing, sectors of the European economy such as energy, transport and industry. Moreover, we chose to describe technologies which have either low technology readiness levels (TRLs) or which have the greatest reduction potential (or are enablers of deep emission reductions, in particular energy storage). We are not covering technologies that would allow for only incremental change or modest emission reductions.

The technologies further analysed in this deliverable are (sector between brackets):

- Energy and electricity storage (energy, including electricity)
- Carbon dioxide capture and storage (CCS) (energy, including electricity, and industry)
- Hydrogen technology pathways (transport and industry)
- Improvements in the chemical industries (industry)
- Heating, cooling and more efficient envelopes (buildings)
- Biofuels in aviation (transport)
- Improved fertiliser usage and livestock management (agriculture)

We pursued two interlinked research efforts. First, we assess these technologies according to the TRL framework, initially devised to assess aeronautics technologies against their technological maturity (Leete et al. 2015). We have carried out a literature review to see not only how those technologies are assessed according to the proposed TRL framework (Chapter 2), but also to identify economic, social and environmental barriers and potential enablers for a technology's large-scale market uptake (Chapter 3). We then seek to gauge, at the European level, which EU-funded research and development (R&D) activities specifically targeted those technologies in order to assess whether funding gaps existed and where therefore technology and market readiness could be improved by additional R&D funding (Chapter 4). Finally, we formulate some conclusions and recommendations for policy makers (Chapter 5).

2 Technology Readiness Level of selected climate mitigation technologies

2.1 Technology Readiness Level assessment

Technologies can be assessed using a variety of frameworks based on a large number of indicators. For analysing relatively new and innovative technologies, the technological readiness level framework is promising. Originally developed by National Aeronautics and Space Administration (NASA) engineers to assess aeronautics and other technologies (Leete et al. 2015; Mankins 2009), it can be adapted and used to assess other technologies as well. Indeed, the EU's Horizon 2020 (H2020) programme specifically encourages the use of the framework (European Commission 2017). TRLs range from TRL 1, the least mature level for a technology to TRL 9, the most mature level. The table below presents the different levels according to the H2020 Work Programme 2016-2017 (European Commission 2017).

Table 1. Technology Readiness Level (TRL) (European Commission 2017)

Technology Readiness Level (TRL)	Performance
TRL 1	basic principles observed
TRL 2	technology concept formulated
TRL 3	experimental proof of concept
TRL 4	technology validated in lab
TRL 5	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	system prototype demonstration in operational environment
TRL 8	system complete and qualified
TRL 9	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies)

It is however important to note that there is no standardisation of assessing the readiness level of a technology and that different institutions (NASA, EU and others) are employing the TRL slightly differently (Héder 2017). This is one of the reasons why different sources might come to different conclusions when it comes to the same technologies and their technological readiness. Moreover, technological readiness should not be confused with market readiness, since a technology with the TRL 9 might not have yet been adopted on a large scale by consumers (Héder 2017) for reasons other than technological maturity. Chapters 3 and 4 will go more into those.

Nevertheless, assessing technologies according to this TRL system offers policymakers some guidance on how to better tailor support policies to those technologies, since some parallels between TRL and innovation diffusion can be drawn. Innovation and transition literature often represent innovative technology uptake and diffusion in an s-shaped curve (Rotmans, Kemp, and van Asselt 2001; Corey, Jaffe, and Sin 2014). After an initial predevelopment and a take-off phase, technology uptake usually accelerates steeply before stabilising. Similarly, Grubb et al. (2017), while acknowledging the limitations of a linear model, visualise technology uptake and diffusion as a step-by-step innovation chain (or journey), where each step would require a different set of policies and instruments (Grubb, McDowall, and Drummond 2017). For example, while 'strategic investment' and R&D spending might help to develop technologies (or creating a technology 'push'), other policies such as standard setting, informational policies or carbon pricing might help to create a market for these technologies, thus facilitating an increased uptake and generating a demand 'pull' (ibid.). These observations can be applied to the TRL scale since optimal policy support for less mature technologies (TRL 1-5) would have to look differently than support for technologies ready for market uptake (TRL 8-9). For example, making demonstration plants operational and ready for market diffusion would need a mature market for this technology while laboratory testing can be carried out without major market-driven policy support. So while the TRL must not be confused with market readiness level, it is useful to adapt support policies to the TRL of each technology.

2.2 Technology Readiness Levels for specific climate technologies

While literature on the TRL of technologies chosen is scarce in most cases, we were able to identify some assessments. Given the diverging methodology used in the sources to assess TRLs of each technology, the findings from these assessments should be interpreted carefully.

Energy and electricity storage

Storing energy and electricity will become of critical importance to allow for a deep decarbonisation of the energy and electricity sector, which will be increasingly based on intermittent renewables. The International Renewable Energy Agency (IRENA) estimates that by 2030, storage capacity has to increase threefold from around 4.6 TWh in 2017 to 11.9-15.7 TWh globally if countries were to double their renewable energy production

(Ralon et al. 2017). Several technologies to do so are available. The US national Energy Storage Association[1] lists six types of electricity and energy storage technologies:

- *Solid State Batteries* which use most commonly electrochemical storage solutions, including advanced chemistry batteries and capacitors such as lithium-ion battery, nickel-cadmium battery, sodium sulphur battery, and super- or double-layer capacitors;
- *Flow Batteries* which are batteries where the energy is stored directly in the electrolyte solution; Those solutions usually are expected to have a longer life-cycle. Zinc bromide flow batteries or vanadium redox flow batteries can also have quicker response times;
- *Flywheels*, which are mechanical devices that harness rotational energy to deliver instantaneous electricity;
- *Compressed Air Energy Storage*, a technology which uses compressed air to create a potent energy reserve;
- *Thermal Storage*, which captures heat and cold to create energy on demand; and
- *Pumped Hydro-Power*, which in its most common form of creating large-scale water reservoirs and harnessing gravitational pull to transform water flows into energy is amongst the most mature technologies (Rehman, Al-Hadhrami, and Alam 2015).

One should note that those technologies, especially batteries, can be used in different configurations in order to store energy. For instance, while solid state batteries made of lithium have recently been used to build the largest energy storage solution to support the Californian electricity grid (Spector 2017), batteries in Electric Vehicles (EVs) could, theoretically, also be used as energy storage devices although the economic viability of this storage solution is doubted (Peterson, Whitacre, and Apt 2010). Hydrogen storage is another energy storage technology but is covered in the next section. The following table provides an overview of the technologies' TRL levels according to the literature.

Table 2. TRL levels of storage technologies. This table is an approximation since there are many ways to storage energy in devices such as batteries, and their TRL depends on the application, such as chemicals, compounds and technologies

Technology	TRL	Source
Solid State Batteries	8-9	(Cavanagh et al. 2015),
Flow Batteries	6; 9[2]	(Cavanagh et al. 2015; Gruenewald 2012)
Flywheels	7; 9	(Cavanagh et al. 2015; Gruenewald 2012)
Compressed Air (underground)	9	(Cavanagh et al. 2015)
Thermal Storage	3-8, depending on technology (molten salt, latent heat storage etc.)	(Stutz et al. 2017)
Pumped Hydro	9	(Gruenewald 2012)

[1] http://energystorage.org/energy-storage/energy-storage-technologies
[2] Higher TRL dates from the 2015 analysis

One can see, that most of the technologies are assessed as being mature and ready for market adoption, while some of those technologies, such as thermal storage, will need further research and development.

Carbon capture and storage (with a focus on cement production)

CO_2 capture and storage (CCS) involves the capture of CO_2 from a large stationary point source (such as a power plant or cement factory) and subsequent permanent isolation of the CO_2 from the atmosphere, usually in a deep geological reservoir. Literature distinguishes between various carbon dioxide (CO_2) capture technologies: pre-combustion, post-combustion and oxyfuel combustion, depending on where in the process the CO_2 is captured. Pre-combustion happens when chemical reactions produce a mixture of hydrogen and carbon monoxide (jointly known as syngas) thus removing carbon dioxide (CO_2) before combustion and energy production takes place (Metz et al. 2005). In post-combustion, CO_2 is captured upon burning of the fuel source, mostly using a liquid solvent to capture the CO_2 (Metz et al. 2005). In oxyfuel combustion, the fuel is combusted with pure oxygen, leading to a relatively pure CO_2 stream. When there is an industrial source of CO_2, and there is no combustion or gasification, such as in the calcination in cement production, the CO_2 capture technology is industrial capture or use. In all cases, separation of CO_2 will need to take place using a catalyst or a membrane.

TRL assessments of CCS depend on the technology analysed. Bhave et al. (2017) look at CCS applied to bioenergy installations (BECCS) and attribute TRL levels 1 (ionic liquid utilisation) to TRL 5 (oxy-combustion techniques) to the technologies (Bhave et al. 2017). Others, such as Freeman and Bhown (2011) assessed 92 post-combustion technologies, most of them scoring between TRL 3 and TRL 6 (Freeman and Bhown 2011). It is noteworthy that, according to the European Commission, several small-scale CCS demonstration projects exist around the world (European Commission 2018a), which would correspond to a TRL of 7 and that Oko et al (2017) argue that several post-combustion chemical absorption methods would range between TRL 6 and TRL 8, while they opine coned that most technologies using solvent would not go beyond TRL 4 (Oko, Wang, and Joel 2017).

Looking at CCS in cement production in particular, the European Cement Association estimates that the sector could reduce its footprint by 32-80% with available technologies, while CCS technology is seen as a key breakthrough technology in achieving this goal (CEMBUREAU n.d.). Indeed, action would be urgently needed since the sector is thought of being responsible for up to 6% of global greenhouse gas emissions (Gimenez 2016) and has proven to be difficult to decarbonise since emissions from cement production remain almost unchanged in the EU since 2012.[3] Not unlike CCS in power plants, CCS can be applied in cement production with the help of amine scrubbing, calcium looping, full or partial oxy-fuel combustion or by direct capture. Hills et al. (2016) looked at CCS in the cement sector specifically and assigned between TRL 4 (e.g. full oxy-fuel combustion, direct capture) and TRL 6 (e.g. partial oxy-fuel combustion, amine scrubbing, calcium looping) to existing technologies (Hills et al. 2016). Hornberger et al. (2017), also assign

[3] UNFCCC data based on country submissions

a TRL 6-7 to calcium-looping (Hornberger, Spörl, and Scheffknecht 2017) and first tests in the lab suggest a general feasibility of retrofitting existing cement plants with the calcium looping technology (Arias, Alonso, and Abanades 2017).

Compared to battery technology and other forms of energy storage, CCS is less advanced and less mature from a technological perspective. At the time of writing, there are no full-scale CCS demonstration projects in the European Union (Teffer 2017) although the Global CCS Institute reports several, in various industrial plants including two coal-fired power plants, in other parts of the world, such as Canada, the United States and the United Arab Emirates.[4] Many planned projects have been abandoned, mostly because of economic reasons (lower carbon prices in the EU Emissions Trading Scheme (ETS) than budgeted for) or because of vocal public opposition to test sites (see CARISMA D4.4 and D8.3).

Hydrogen

Hydrogen, a gas and an energy carrier, is used in many industries such as refining, metallurgy and electronics (Elsherif, Manan, and Kamsah 2015) and in the transport sector (see below). Singh et al. (2015) even argue that hydrogen can be used in almost any field where conventional fossil fuels such as gas or oil are needed, thus offering significant substitution potential (Singh et al. 2015). In 2010, the European chemical industry was the largest consumer of hydrogen (63%) with the refining industry accounting for about 30% (Fraile et al. 2015). But while hydrogen itself is not harmful for the environment, its production methods generate emissions. Overall, hydrogen can either be produced by reforming steam methane or by splitting it from water by electrolysis (Mehmeti et al. 2018). The steam reforming process can furthermore be based on natural gas, methane, coal (Mehmeti et al. 2018) or biomass (Ni et al. 2006), but can be equipped with CCS fairly cost-effectively. The electrolysis process can be powered by fossil fuel-based electricity or renewable electricity.

Currently, hydrogen is produced almost exclusively through natural gas-based steam methane reforming or even coal in some cases (Singh et al. 2015)(Turner 2004). Looking at more sustainable hydrogen pathways, Zech et al. (2015) consider hydrogen production from biofuels combustion, assessing three steam reforming technologies as between TRL 4 and TRL 6 (Zech et al. 2015). When it comes to hydrogen production by electrolysis using renewable electricity, sometimes called power-to-hydrogen (Götz et al. 2016), the need to adapt to increasingly intermittent power supply from renewables pushes most of power-to-hydrogen technologies towards TRL 5 to TRL 7 (Grond and Holstein 2014). Besides technological challenges, economic challenges remain as well, since power-to-gas is still an expensive and relatively inefficient technology (Götz et al. 2016), one source for example arguing that per unit of H2 more than 32 times the electricity would be needed than by using conventional steam methane reforming (Mehmeti et al. 2018) which raises doubts on whether there would be enough excess renewable electricity on the markets to satisfy this demand (Ball and Weeda 2015).

The following sections explore the TRL of hydrogen in the transport sector, in the steel industry as well as (for some applications) in the chemical industry. Since our literature

[4] Global CCS institute 2017: Global Status of CCS: www.globalccsinstitute.com.

review did not yield any TRL assessment for the refining pathway (and given the fact that some of the products of the current refining industry such as gasoline or diesel, themselves might be incompatible with a deep decarbonisation pathway), we did not analyse it further.

Hydrogen in transport

The EU finances and supports the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), an R&D and development initiative whose members are the European Commission, the EU hydrogen industries represented by *Hydrogen Europe* and the research community represented by *Hydrogen Research Europe*. [5] Hydrogen could be used in the transport sector either by burning it in a combustion engine or by using it to generate electricity chemically using a fuel cell (Pearson, Leary, and Wellnitz 2010). Industry players such as Royal Dutch Shell assess the technology at TRL 8 or 9 for passenger cars for example (Adolf and Fischedick 2017). In 2016, around 4000 hydrogen fuel cell-powered cars populated the world's roads according to the International Council on Clean Transportation (ICCT), which would confirm a TRL 8 or 9 rating. Also, infrastructure to hydrogen-powered vehicles is principally 'ready' and attributed a score of TRL 7 to TRL 9 in the literature (Cardella, Decker, and Klein 2017).

Hydrogen in steel production: the Direct Reduced Iron (DRI) pathway

Hydrogen could be used in the steel making industry to produce Direct Reduced Iron (DRI). In this alternative iron making pathway (necessary precursor for steel production) instead of melting down the iron ore to remove the oxygen, oxygen is removed leaving the ore in a solid state (van Wortswinkel and Wouter 2010). Furthermore, DRI technology lends itself to use other reduction agents than coke (which is used in conventional iron making) such as methane and other gases (Bachner et al. 2017). However, only about 5% of global steel production a route other than cokes (Kirschen, Badr, and Pfeifer 2011).

An advantage from an environmental perspective is the possibility of the DRI value chain to be using only hydrogen as reduction agent which in turn could be produced by electrolysis using renewable energies, thus being essentially carbon-free (Bachner et al. 2017). Also, generating hydrogen using biomass is a theoretical option, but initial economic analyses argue that this route will not be economically viable without significant subsidies and a substantial carbon price (Almansa and Kroon 2016). Therefore, using biogas in DRI should not be assessed higher than TRL 2 or TRL 3. In the same vein, Napp finds that hydrogen steel making is in a very early stage of TRL, assessing different technologies with TRL 1 to TRL 3 (Napp 2016).

Recent research and development activities carried out in Sweden allow for greater optimism. According to media reports, a consortium called *Hybrit*, consisting of the Swedish steel maker SSAB, energy company Vattenfall and Europe's largest iron ore producer LKAB are dedicated to inaugurate a first demonstration plant for producing iron using hydrogen as reduction agent by 2020 (Simon 2018). Although, at current prices and policies, steel made in this plant would be 20 to 30% more expensive than conventional steel, the

[5] http://www.fch.europa.eu/page/who-we-are

consortium is optimistic that with the right support policies and R&D activities, hydrogen-based steel production could become competitive in Sweden (Simon 2018) although scaling *up* this method for other places is probably not as fast. Similarly, Austrian company Voestalpine is looking into hydrogen-based steel making but they too assess the technology being years away from commercialisation (Pooler 2017).

Improvements in the chemical industry

According to the UNFCCC emissions reporting database, the EU chemical industry is the largest emitter of greenhouse gases after the EU metal industry (steel, aluminium etc.) and the EU cement industry.[6] According to the EU's Joint Research Centre (JRC), the most energy-intensive industry branches in their sample are steam cracking (mainly used in the petrochemical sector), Ammonia/Urea production (mainly used for fertilisers) and the production of either ethylene dichloride and vinyl chloride, accounting for almost 32% of fossil fuel energy inputs of the whole chemical industry (Boulamanti and Moya 2017). If one looks at emissions of the EU chemical industries, the most emitting technologies in 2015 were steam cracking (17.6%), Ammonia/Urea production (21.2%) and hydrogen and syngas production (17.9%) (ibid.). However, emission savings potential of the industry is estimated at only around 36% until 2050 with current technologies in the industries analysed by the JRC (Boulamanti and Moya 2017).

Generally, emissions could be reduced by rendering the processes more efficient, substituting some or all of the processes, switching of input fuels, or by applying CCS (Griffin, Hammond, and Norman 2017). This is in line with Boulamanti and Moya (2017) who recommend combined-heat and power (CHP) and CCS as cross-cutting mitigation actions in the chemical industrial sector (Boulamanti and Moya 2017).

One way to decarbonise the steam cracking process is to use biomass instead of fossil fuels such as natural gas to produce the coveted olefins (Amghizar et al. 2017) or by using renewable naphtha to yield light olefins (Pyl et al. 2011). We were not able to find TRL assessments of these pathways, suggesting a low TRL. In the chemical as in the steel and transport sector, hydrogen could play an important role. Sustainably produced hydrogen could be used by the chemical industry and syngas could be sourced from biomass (Lozano and Lozano 2018). Another way of improving the process of the chemical industry would be to improve on the catalytic reactors which enable and trigger the chemical reactions. However, those technologies are in early TRL stage (3-4), as the results of the DEMCAMER project have shown (Gallucci et al. 2016). When it comes to sustainable forms of ammonia production, see Section 2.2.6.

Buildings

As shown by Elkerbout et al. (2018), the buildings sector accounted for roughly 15% of emissions in the EU. To achieve deep decarbonisation in the buildings sector, two interlinked strategies should be pursued: First, using renewable energy for heating and cooling purposes; and second, increasing the energy efficiency of buildings. The first strategy holds the greatest reduction potential of the two in the EU, as heating and cooling

[6] https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/ghg-data-unfccc

account for 79% of the EU's building stock energy needs and cooling is generally done using electricity.[7] It should be noted that energy efficiency and the use of renewable energy sources in the heating and cooling of buildings usually go hand in hand.

Renewables-based heating and cooling

Using renewable energy for heating and cooling needs can be achieved by employing several devices. For heat, an increasingly common technology is heat pumps, while buildings could also be heated using biomass (such as pellet-fired boilers), solar heat or by conventional electricity heaters, powered by renewables-generated electricity. Although improvements are made constantly (Chua, Chou, and Yang 2010), heat pumps can be generally considered a mature technology (TRL 9) with a variety of commercially available systems (Tanaka 2011). Indeed, the principle of heat pumps has been known for at least 150 years (Karytsas and Choropanitis 2017). The same holds true for solar heating and cooling (Henning and Döll 2012) and other forms of renewable energy. Here, barriers to an increased uptake are to be found in the economic and social context (see Chapter 3), although technological developments can help increasing the attraction of these options for consumers.

Efficient envelopes

Heating and cooling dwellings often go together with increasing the energy efficiency of buildings. But renewable heat and energy efficiency have a complex relationship. On the one hand, good insulation (energy efficiency) in buildings increases the effectiveness of renewable heating technologies such as heat pumps. For example, deteriorating insulation values in buildings due to degradation of materials can even nullify heat pumps' energy savings potential over 20 years compared to conventional boilers in some cases (Eleftheriadis and Hamdy 2018). On the other hand, better insulation and more efficient buildings could reduce the demand for heat pumps and their economic viability (Marmion and Beerepoot 2012) although this is unlikely to ring true in deep emission reduction pathways.

Nevertheless, having well-insulated buildings usually increases the effectiveness of heat pumps (Richter et al. 2003). Achieving more energy efficient buildings can take many routes, and many, such as insulated roofs and walls, have a TRL of 9. But a measure promising to deliver more savings than those incremental measures are the building of more efficient envelopes. One such technology is ultra-light weight concrete (ULWC), which literature currently assesses as TRL 4 (Roberz et al. 2017).

Other technologies include the use and application of phase changing materials (PCM) which are applied on surfaces and allow for the control of radiation going in and out of the building (Vigna et al. 2017). Windows, for example, could be glazed with a electrochromic film that allows for controlling the amount of light and heat that passes through with some considerable energy savings (IEA 2013). This technology however is assessed in the

[7] https://ec.europa.eu/energy/en/topics/energy-efficiency/heating-and-cooling

literature with TRL 4-6 (Vigna et al. 2017) and still suffers from teething troubles (Service, 2018, and Pm 2018).

Biofuels in aviation

The European Commission estimates that about 2% of global emissions come from aviation (European Commission 2016b), a share which is expected to grow given the estimated growth of passenger transport in aviation (ICAO n.d.). Using biofuels in aviation is identified in the literature as one way to decarbonise the sector, particularly since other options such as cryogenic hydrogen or solar-powered planes are not expected to be commercially viable options before 2050 (IRENA 2017; Mawhood et al. 2016).

Of course, as in other sectors which use biomass to generate electricity and heat, or make bio-based materials, sustainability concerns around land-use changes, including associated greenhouse gas emissions, and their social consequences have an impact on biofuels as an alternative jet fuel (Rye, Blakey, and W. Wilson 2010) even though high uncertainty remains on how emissions and land use might change under increasing bioenergy usage (Plevin et al. 2010). Nevertheless, several technology pathways exist to produce so called drop-in fuels, i.e. fuels which could be used in existing engines and infrastructure (IEA Bioenergy 2017). Table 2 gives an overview over the TRL of the most commonly mentioned technologies.

Table 3. Biofuels for aviation technologies

Technology	TRL	Source
Hydroprocessing (hydroprocessed esters and fatty acids or HEFA)	6-8	(Mawhood et al. 2016)
Direct Sugar to Hydrocarbons (DSHC)	5-7	(Mawhood et al. 2016)
Aqueous phase reforming (APR)	6	(Mawhood et al. 2016)
Alcohol to Jet	4-6	(Mawhood et al. 2016)
Conventional Fischer-Tropsch biofuels	7-8	(Mawhood et al. 2016)

According to IRENA, the HEFA pathway is the most widely used globally today but despite the existence of several production facilities around the world and despite the fact that airlines increasingly blend their fuels with biofuels (which is not the same as a 100% biojet), commercial maturity would be at least five to ten years away (van Dyk et al. 2017) thus confirming TRL levels of around 7-8 at most.

Reduced emissions from fertiliser and livestock

Knowledge about climate change mitigation policies and their effects in the agricultural sector is less readily available than for other sectors (Bößner et al. 2017). Not surprisingly, literature on reduction options and their TRL assessment are scarce. Given the prominent share of animal husbandry in the sector's emissions – the FAO estimates that 14.5% of all human induced emissions come from livestock[8] - changing dietary habits is one strategy to reduce emissions, despite the fact that substitutes such as food produced from crops is not necessarily less impactful on the environment (Smetana et al. 2015). Other strategies

[8] http://www.fao.org/ag/againfo/resources/en/publications/tackling_climate_change/index.htm

include using fossil fuels (to power agricultural machineries etc.) more efficiently, to offset emissions by enhancing carbon removals, optimising nutrient use, improving productivity or reusing outputs such as manure and waste for second generation biofuels (Garnett 2011). A more detailed list can be found in Smith et al. (2008). Two technologies can be discerned to significantly reduce emissions: improving fertilisers and bioenergy from animal as well as plant waste.

Improving the emissions profile of fertiliser production is indeed a piece of the decarbonisation puzzle, given the processes' energy intensity[9] and the fact that once applied to the soil, fertilisers release potent greenhouse gases such as nitrous oxide (N2O) (Mole 2014). Recent research argues that N_2O is probably leading to exponential instead of linear emissions growth, meaning that for each kilogramme of additional fertiliser used, emissions from soil would increase more by one unit (Shcherbak, Millar, and Robertson 2014). Indeed, the International Fertilizer Association (IFA) estimates that fertilisers account for roughly 2.5% of global emissions. More than half of that is released post-application.[10] Several options to reduce emissions are discussed below.

First, ammonia, the main ingredient of fertiliser and normally produced by reforming natural gas, could be reformed using hydrogen[11] which in turn could be produced using a low-carbon pathway such as from biomass or by electrolysis (see above). Moreover, ammonia could be sourced from nothing but renewable energy and hydrogen by using solid electrolyte cells for example (Garagounis et al. 2014; ISPT 2017). However, current research argues that these technologies are far from scale in the fertiliser industry (Baltrusaitis 2017). Also, replacing the Haber-Bosch process, the conventional way to produce ammonia by heating and pressurising hydrogen using a metal catalyst, is in its infancy, and the existing process is almost fully optimised for energy use. Researchers at the University of Central Florida recently delivered a proof-of-concept of an electrical conversion process at room temperature, which would make this technology a TRL 3 (own judgment). Another way of making fertilisers more sustainable would be to use urea-based fertilisers which would release less nitrogen into the soil is a potential solution (Robinson, Brackin, and Schmidt n.d.) but this pathway is also not yet commercially scalable.

Besides improving the fertiliser value and production chain and making fertiliser production less carbon intensive, the agricultural sector might also increasingly use its waste products (ligno-cellulosic materials such as straw and wood waste or even animal manure) to generate energy and fuels. One main advantage of using waste products is that they usually do not compete with other crops or with land. This process is known under second generation bioenergy production and two pathways exist. Either ligno-cellulosic (i.e., woody) feedstocks could be biochemically reduced to sugar to produce ethanol, or they could be produced in a thermo-chemical process (also called BTL for 'biomass-to-liquids') where pyrolysis and gasification produce a synthesis gas (Sims et al. 2010). Müller-Langer et al (2014) assess ligno-cellulosic pathway for bioethanol with TRL 7, citing efficiency

[9] https://www.siemens.com/global/en/home/markets/chemical-industry/continuous-processes/fertilizer-production.html
[10] https://www.fertilizer.org/En/Knowledge_Resources/Topics/Climate_Change/Reducing_Emissions.aspx?WebsiteKey=411e9724-4bda-422f-abfc-8152ed74f306
[11] http://ietd.iipnetwork.org/content/steam-reforming

gains as needed improvements (Müller-Langer, Majer, and O'Keeffe 2014). BTL is assessed by the authors as TRL 6, citing efficiency and syngas treatment improvements as main improvements (ibid.). This is in line with an experimental plant in Karlsruhe, Germany, showcasing a TRL of 6 (Dahmen et al. 2017). It is important to note than conventional (or first-generation) biofuel production is ranked by the authors as TRL 9; such plants are widely used all over the world. Generating gaseous biofuels is assessed by Müller-Langer et al. (2014) as either TRL 9 (biomethane/biogas) or TRL 7 (biomethane/synthetic natural gas) (Müller-Langer, Majer, and O'Keeffe 2014).

2.3 Discussion

This short overview of the TRLs of climate change mitigation technologies which would be needed for deep decarbonisation has shown that some technologies are still not technologically mature enough to be introduced to the market.

While energy storage technologies are more or less mature (despite the fact that their exact TRL depends on the specific technology, compounds and chemicals used in their manufacturing), several hydrogen pathways particularly in the chemical, cement and steel making industries still have a low TRL. Here, fundamental research and development as well as targeted innovation investment could drive those technologies forward. The CCS pathway, on the other hand, seems to be stuck at TRL 8 and 9.

As mentioned above (and as the analysis of uptake of renewable energy technologies such as heat pumps in the buildings sector described), this shows that having a mature climate mitigation technology at hand does not automatically mean rapid diffusion and market uptake. At the later stage of technological development, other policies targeting market development specifically through instruments such as standards, or by economic incentives such as a sufficiently high carbon price, might facilitate the uptake of this technology. But besides lacking technological maturity and the absence of a market for those technologies, a variety of other barriers can impede rapid technology adoption and diffusion. The next chapter discusses some of those barriers and potential enablers. It is not a complete list and it should be noted that both barriers and enablers are highly context-specific and may vary from jurisdiction to jurisdiction, but sets up the discussion of what to do next for mature technologies in chapter 4.

3 Barriers and enablers of increased technology uptake

When it comes to technology uptake and diffusion, many barriers exist, ranging from technological barriers as seen in Chapter 2, investment barriers (Ang 2015), more general economic barriers (Philibert 2006) or barriers in the policymaking environment (Foxon and Pearson 2008) or regulatory barriers (Brown and Sovacool 2011). At the same time, opportunities may arise, as, for example lower costs of renewable electricity enable electrification or hydrogen use in industry. Sustainability concerns can present a barrier, for example when land used to cultivate crops for energy usage enters in competition with land used to feed the world (Rathmann, Szklo, and Schaeffer 2010).

In this chapter, we focus on an illustrative discussion of economic, environmental and social barriers because those barriers were discussed thoroughly in the literature on the more mature of the technologies discussed in chapter 2. Such barriers and enablers are highly context-specific and vary not only from technology to technology but also from location to location. For instance, barriers to electricity storage in a small town in one EU Member State are not necessarily the same as those in a large city in another EU country, let alone in cities in developing countries due to an almost uncountable number of diverging variables such as income, population size, grid quality, political will and decision-making processes, or cultural factors. However, similar barriers could also arise in other contexts and countries. We will only focus on relatively mature technologies as studies on technologies with a low TRL are often not yet available. We will focus on battery storage, CCS, hydrogen in industry and renewable energy in heating and cooling in buildings.

3.1 Electricity storage

Some of the key factors that determine worldwide economic viability of electricity storage solutions such as batteries are global reserves of raw materials such as lithium (Speirs et al. 2014), production and consumption assumptions, recyclability of materials (e.g. of chemicals for batteries), as well as location of the technology application, tariff structure on markets and (customer) expectations of an acceptable payback period (Brinsmead et al. 2015). Given the many variables, providing precise cost estimates is difficult. A study for consumer cells in US markets found that overall cost of electricity storage in 2017 stood at around $120/kWh (Kittner, Lill, and Kammen 2017) while the International Renewables Agency (IRENA) estimates that the average installation cost for stationary lithium-ion batteries stood at currently between $200 – $1260/kWh (Ralon et al. 2017). Average wholesale electricity prices on the day-ahead markets in Germany, one of Europe's most expensive countries when it comes to electricity, stood at around €50/MWh or 5€cent/kWh (Market Observatory for Energy 2017). While those are just approximations and cost recovery depends on many factors such as operating hours and the time storage would be needed (peak vs. baseload prices), high investment costs might not be fully recoverable on current markets, thus scaring off storage investors.

However, case studies concerning the profitability of storage solutions for RES installations, in Australia found that for large - size commercial customers installing new integrated storage and solar PV systems on a standard tariff, the payback period in 2015 would stand at 7–9 years or 17-29 years on a time-of use only tariff (Brinsmead et al. 2015). Of course, those analyses are very context-specific and a lot depends on market design and whether storage is needed for long or short term energy storage (Jülch 2016). Moreover, significant cost reductions (up to 61% by 2035) are expected in the near future (Kittner, Lill, and Kammen 2017; Ralon et al. 2017) and a market design that rewards flexibility services (and which lets storage providers participate in markets) might help to make electricity storage more economically viable (Ugarte, Larkin, and van der Ree 2015). Furthermore, it is worth mentioning that an increased uptake of electric vehicles (EVs) could play a balancing role on the electricity grid, thus effectively becoming storage solutions (Rotering and Ilic 2011). Nevertheless, other studies are doubtful whether battery storage solutions will be able to compete in the medium term with more established forms such as pump storage, given the small scale and the relatively low storage capacity of even grid scale batteries (Newbery et al. 2017).

Storing electricity in form of batteries is not a carbon-neutral endeavour since raw materials for the batteries have to be mined, transported and processed and batteries have to be produced. According to a study by the Swedish Environmental Research Institute, around 50% of emissions are generated in the production stage, leaving ample room for improvement (Romare and Dahllöf 2017).

Hall and Lutsey (2018) show that life-cycle emissions for lithium-ion batteries used in EVs range from 30 kgCO_2e/kWh (assumed to be produced in US) to 200-400 kgCO_2e/kWh (assumed produced in Asia), with an average of around 150 kgCO_2e/kWh (Hall and Lutsey 2018), results similar to Romare and Dahllöff (2017).[12] Aside from emissions related to the production process, recycling the batteries will become increasingly problematic in the future particularly since every producer of batteries uses slightly different chemical formulas (Sanderson 2017). Also, the growing market share of EVs might be of concern given the fact that there is not yet a fully established recycling system in place since most of EV batteries will not reach their end of life in the short term (Gaines 2014) and despite the fact that modern lithium-ion batteries are said to contain 80% of recycled materials (Gordon-Bloomfield 2011).

3.2 Carbon dioxide capture and storage in different sectors

In 2011, the Global CCS Institute, an industry organisation, estimated that costs for storing CO_2 using CCS would range between \$23 and \$92/tonne of CO_2 (Aberella and Short 2011). Rubin et al. (2015), analysing the power sector, provide a more careful analysis, indicate that costs would range from \$59 – \$143 for new gas-fired power plants and from \$46 to \$99 for new supercritical coal-fired power plants (Rubin, Davison, and Herzog 2015). Retrofitting existing plants is estimated to be more expensive (Nuortimo et al. 2018) since CCS usually lowers the efficiency of the generating plant, driving up emissions and costs indirectly (Service 2016). According to the European Energy Exchange, the price for a tonne of CO_2 on the EU ETS stood at around €13/tonne of CO_2 in May 2018, although recently the prices have seen an increase.

As far as other sectors are concerned, estimates vary greatly, as the costs depend on the concentration of CO_2 in the flue gas and the cost of the technology to separate the CO_2. According to Leeson et al. (2017) the costs in the iron and steel industry range from \$9.8/tCO_2 (use of steel slag for carbonation) to \$115.8/tCO_2 (use of steel slag for mineral carbonation of CO_2 from blast furnace (Leeson et al. 2017). In the refining sector, costs would range from \$40/tCO_2 (post-combustion capture of CO_2 from gasifier) to \$128.3/tCO_2 for post-combustion on FCC (ibid.).

In the cement industry, the IEA estimates the marginal abatement cost for a tonne of CO_2 to be between \$40-170 (IEA 2009). Other studies have estimated the costs at between

[12] Emission profiles in the studies depend heavily on the inputs used for calculation which differ from study to study. Also, the electricity mix used to power the production process (coal-heavy vs. lower on carbon) explains this stark difference.

$51-137 for a tonne of CO_2e avoided, but argue that CCS in the cement industry is the only option for the sector's emission reduction from the calcination step (Li et al. 2013), as energy (responsible for about half of the cement plant's emissions) can be decarbonised through renewables. Newer studies suggest that costs might be lower but point to the scarcity of cost data on CCS technologies in several industries, including cement. Nevertheless, the technology of calcium looping is assessed in studies with a cost of between $17-76 per tonne CO_2 avoided, reaching $165/t$CO_2$ for post-combustion amine scrubbing (Leeson et al. 2017).

Interestingly, industrial processes which produce a high-purity CO_2 are estimated to be much less costly. For example, Leeson et al. (2017) argue that CO_2 could be captured in the hydrogen production part of ammonia production at very low costs of as $3.9/t$CO_2$, as steam methane reforming produces a pure stream of CO_2. However, another barrier for application of CCS technology, particularly in the cement sector, might be the alleged exposure of this sector to carbon leakage, i.e. the outflow of emissions from industrialised countries to producing sites in developing countries where production is expected to be cheaper. Despite the fact that relatively little evidence for carbon leakage has been found in the literature (Branger, Quirion, and Chevallier 2013), and although international trade is not as strong as for instance for chemicals or steel, in part of the cement sector, higher carbon prices might lead to leakage (Bukowski 2013) and the EU supports its energy-intensive industries by providing free EU ETS allowances (including for the cement industry).[13] Nevertheless, the EU cement industry has increased their carbon intensity in recent years, pointing to the need to find solutions for a more sustainable pathway in cement production (Lytton 2016).

CCS might have some negative environmental impacts. Koornneef et al. (2012) report that while this technologies allow to remove CO_2 emissions from the process, emissions from other gases such as from nitrogen oxides (NOx), Ammonia (NH3) or Hydrogen Fluoride (HF) as well as particulate matter might increase, as might water consumption (by between 32 and 93%) (Koornneef et al. 2012). Moreover, there remains a risk of accidental CO_2 release and leakage both during transport and once it's stored underground, although the latter risk is considered low (Koornneef et al. 2012). Nevertheless, some sources argue that CO_2 injection could lead to earthquakes which in turn could release CO_2 once stored (Zoback and Gorelick 2012). These environmental barriers to application, e.g. the decision not to build CCS units based on environmental concerns might cause another, social barrier, for instance the lack of social acceptance of CCS technologies.

Public concerns about CCS are mainly security- and health-related, namely the fear of leakage and negative consequences for health and environment (Wennersten, Sun, and Li 2015). A survey in France has shown that some strata of society, like environmentally minded people, oppose CCS in the power sector from the viewpoint that it would be an "ecological alibi" and as an excuse not to change the way an economy produces its energy (Ha-Duong, Nadaï, and Sofia Campos 2009). Studies in Germany have also confirmed a not-in-my-backyard attitude of people living close to proposed sites (Braun 2017), although evidence from the Netherlands suggests that some of the opposition to CCS may

[13] https://ec.europa.eu/clima/policies/ets/allowances_en

stem from misconceptions of the technology, poor communication and an absence of procedural justice (de Best-Waldhober, Brunsting, and Paukovic 2012). Nevertheless, failure to understand public opinion and to address concerns of proposed CCS projects would jeopardise CCS projects, as was the case the Dutch town of Barendrecht, where year-long organised opposition and organised public opposition has led to the abandonment of a CCS storage site (Feenstra, Mikunda, and Brunsting 2010). Many studies have in the meantime focussed on how to improve communication around CCS sites, recommending intensive engagement with communities, building trust, giving people a real say in the project, and providing them with benefits.

3.3 Hydrogen production and use in industry and transport

According to literature consulted, if the hydrogen production pathway of electrolysis is considered, costs would depend very much on the cost of the electrolyser (a critical component in the production of hydrogen) and on the electricity purchase price during the time of operation (Ball and Weeda 2015). Also, transforming electricity into hydrogen by means of electrolysis is further limited by the availability of excess electricity from renewables (if low- or zero-carbon hydrogen is to be considered) and doubts remain as to whether there will be enough surplus renewable energy on the grid to make hydrogen pathways economically viable (Ball and Weeda 2015).

Economic considerations

The existing literature argues that hydrogen produced by electrolysis is still more expensive than hydrogen produced by using fossil fuel inputs. Jia et al. (2016), citing the US Department of Energy figures, put the price for conventional (fossil fuel based) hydrogen at $2-$4/gallon of gasoline equivalent, while estimating the price for electrolysis based hydrogen at $3.26 – $6.62/gallon of gasoline equivalent (Jia et al. 2016). In the same vein, other studies have found that generating hydrogen from wind energy is almost seven times more expensive ($6.64/kg) than from coal ($0.96/kg), while conversion efficiency would not be higher than 50% (Hosseini and Wahid 2016). Other studies, while acknowledging the difference between conventional and sustainable hydrogen production, argue that with the right tax incentives and with lower electricity prices (expected to come about due to higher renewable energy penetration which usually drives down prices), hydrogen from electrolysis could become competitive. They argue that the levelised cost of energy (LCOE) for electrolysis based hydrogen could come down to €107-143/MWh by 2020, which would be almost comparable to the retail price of diesel fuel which for example retailed for €105/MWh in Ireland in 2017 (McDonagh et al. 2018).

Similarly, ICCT estimates that the whole battery costs for hydrogen-powered cars range from €770 – €780 kWh while power trains for battery powered electric vehicles are estimated at €280 – 300 kWh (Wolfram and Lutsey 2016) which is still more expensive per kWh than the price for a conventional combustion engine car. The ICCT also estimates that efficiency gains and economies of scale might push hydrogen prices to €4/kg of hydrogen after 2025 at which point it would become competitive with even gasoline cars on a € cent/km basis (Isenstadt and Lutsey 2017).

This same economic barrier is true for hydrogen applications in the industrial sector. Bachner et al. 2017 find that hydrogen-based DRI would come with a significant price premium of about 50% per unit of steel produced (Bachner et al. 2017), even a higher estimate compared to stakeholders of the *Hybrit* consortium who estimate a 20-30% price premium (See 2.2.3.).

Environmental barriers

The carbon footprint of hydrogen depends on how it is produced, ranging from 2.21 kg/CO_2e for the electrolysis pathway using wind power to 24.2 kg/CO_2e per kg of H2 produced from coal (Mehmeti et al. 2018). That means that hydrogen pathways are only as sustainable as the electricity mix used to feed the system. For instance, hydrogen produced in Scandinavian countries with a high share of hydropower and nuclear power would be much less carbon intensive than hydrogen produced in countries like Poland or Germany, which are still highly dependent on coal for their electricity generation. When it comes to vehicles, and similarly to EVs, there are several sustainability concerns with hydrogen powered fuel cell vehicles (FCVs). Besides the production of the power trains (FCVs also use batteries), FCVs seem to be even more sensitive to the composition of the electricity mix used to generate hydrogen than EVs, given the low efficiency of this process. One study in four Canadian provinces found that in Alberta, the life-cycle emissions from hydrogen generated by electrolysis was more than twice as carbon-intensive than conventional gasoline cars due to the province's coal usage in electricity generation (Ahmadi and Kjeang 2015).

Social aspects

Quite generally, fuel cell vehicles might be rejected by users based on the same arguments used against EVs. In a study carried out by IPSOS Mori, 39% of surveyed individuals in Britain were worried about the range of EVs and 42% about the unavailability of charging stations when needed (Ipsos MORI 2017). This range anxiety seems to materialise despite the fact that a study carried out using US data showed, that 95% of analysed vehicle were shorter than 30 miles (van Haaren 2012), largely superior of the range of a typical EV. While, theoretically, refuelling hydrogen cars would not take longer (2-3 minutes) than cars with a conventional internal combustion engine (The Economist 2017) and range would be comparable to gasoline or diesel powered vehicles (around 300 miles) (Mok 2016), infrastructure for fuel cell vehicles is largely absent in Europe. For example, Germany, with more than 80 million inhabitants with a share of 555 cars (all models, internal combustion, electric or hybrid) per 1000 inhabitants[14] had only 45 publicly available refuelling stations for hydrogen powered cars ready at the end of 2017.[15] This classic 'chicken and egg' situation might work as a barrier against FCV uptake, as might the competition between EVs and FCVs.

[14] Eurostat

[15] https://fuelcellsworks.com/news/germany-had-the-highest-increase-of-hydrogen-refuelling-stations-worldwide-in-2017

3.4 Renewables-based heating and cooling in the buildings sector

As indicated above, heat pumps for heating and cooling purposes are a well-established technology (TRL 9) and its principles go back to the 1850s. There are several system designs available, ranging from open to closed vertical and horizontal systems. Karytsas and Choropanitis (2017) estimate that on average, in Europe, a residential 10kW closed loop system would come at a cost of between €11,000 and €21,000 (Karytsas and Choropanitis 2017). This is a significant investment, despite the fact that even when competing against a system using natural gas, the payback time is estimated by the authors at up to 10 years in Greece (Karytsas and Choropanitis 2017) while heat pumps are said to last between 20 and 30 years. Further economic barriers in the Greek case study, which carried out large surveys amongst practitioners and experts, included the inadequate financial support due to the effects of the economic crisis and the divergence between the value of the installation and the actual value of the dwelling (ibid.). Another study, conducting a Strength-Weakness-Opportunities-Threats (SWOT) analysis of heat pump systems, also indicates that heat pumps systems are 2 to 3 times more expensive than conventional (fossil fuel based) systems (Pezzutto and Grilli 2017). However, economic comparison in the heat pump case only tells half of the story. Heat pumps, with a TRL of 9 are quite telling when it comes to social barriers.

The extensive survey carried out by Karytsas and Chotopanitis (2017) also confirmed the information deficit of large parts of potential customers still have when it comes to heat pumps as well as the insufficient installation capacities of heat systems providers (Karytsas and Choropanitis 2017). Moreover, studies in Germany have shown that convenience and habits might play a significant role in adopting (or not adopting) heat pumps, and more generally new, innovative technologies which require a behavioural change. In their study, Michelsen and Madlener (2013) show that most people in their survey wanted a heat technology which fitted neatly with their habits and which did not require them to spend much time on thinking about fuel acquisition and maintenance (Michelsen and Madlener 2013). This is an important finding since surveys carried out in the UK indicate that some behaviour adjustment is required to fully exploit the functionalities of the heat pump technology (Caird, Roy, and Potter 2012). If behaviour of adopters does not change accordingly, the uptake of heat pump systems and other technologies could suffer.

3.5 Discussion

This chapter has shown that besides barriers concerning the technology readiness level of climate mitigation technologies, other factors might hinder market uptake of those technologies once those technologies are more mature or even as they are still experimented on in the lab. One major barrier is the fact that conventional technologies are still cheaper to produce and to apply than technologies necessary for deep decarbonisation. If one kilowatt hour of electricity is more cheaply produced using fossil fuels than to be produced by renewables and stored in batteries, there is little incentive for private sector players to invest in storage solutions. This is particularly the case if those stakeholders can’t recover their high up-front costs if the market does not grant them sufficient access to make use of their services. The same holds true if hydrogen production costs more than to reform conventional gas. However, it’s not only economics but also environmental and social barriers that plays a role in technology uptake and diffusion. Some technologies might need (difficult to achieve) behaviour change of their users, while others are simply opposed on grounds of security and environmental concerns. CCS is a telling example, despite the fact that some concerns might be exaggerated. Lastly, even if a technology is ready for the market and the cost-benefit analysis would 'make sense' from a user's point of view, the lack of information or of a market for services related to the technology (as seen in the Greek heat pump case) does pose some additional barriers.

Overcoming those barriers is not an easy task and there are many strategies to be employed (see chapter 5). One major aspect certainly is to further the understanding of those barriers (and how to overcome them) and to render technologies more mature (e.g. increase their TRL) and cheaper for market uptake. One way of doing so is to strengthen the role of research, development (R&D) and innovation and to increase funding to those technologies with lower TRL and, potentially, to those technologies facing market barriers despite a TRL of 9. Ambitious German R&D activities on solar PV technologies provides for a telling example on how research activities (paired with generous Feed-in tariffs and Chinese mass production) brought down the cost of solar PV significantly over the past decade thus making the technology almost as cheap as fossil fuel based electricity generation, even in Germany (Kost et al. 2018). The next chapter illustrates some of the EU's R&D spending in order to see whether some of above-describe technologies are supported by EU R&D activities.

4 Research and development flows to chosen low carbon innovative technologies

4.1 Overview

When it comes to low-carbon technologies, the EU pursues a policy of mainstreaming climate change into all of its funding programmes with the objective of making at least 20% of its expenditure 'climate related'.[16] This past and present spending on climate mitigation and adaptation has made the EU quite successful when it comes to driving climate technologies forward. According to the European Patent Office and IRENA, more than 34% of global high value climate technology innovations originated in the EU in 2013 (IRENA and EPO 2017). However, this competitive advantage might be eroding since in 2015, China's R&D intensity (i.e. R&D expenditure per GDP) has eclipsed the EU's intensity.[17] Also, the EU target of spending 3% of its GDP on R&D activities seems far away since in 2016, only 2.03% (down from 2.04% in 2015) was spent.[18] In order to put these figures into perspective, a closer look at how the EU spends its R&D money on climate change and low-carbon innovation is warranted.

[16] https://ec.europa.eu/clima/policies/budget_en
[17] http://ec.europa.eu/eurostat/statistics-explained/index.php/R_%26_D_expenditure
[18] Eurostat, data set 'rd_e_gerdtot'

4.2 EU funding streams available for climate mitigation in general

There are 2 large pillars of funding for climate action in general. The first pillar is formed by the European Structural and Investment (ESI) funds. The ESI are made up of five individual funds through which almost 50% of all EU funding (climate and non-climate) is channelled: The European Regional Development Fund (ERDF), the Cohesion Fund (CF), the European Social Fund (ESF), the European Agricultural Fund for Rural Development (EAFRD) and the European Maritime and Fisheries Fund (EMFF). Together, those funds received about €114 billion for climate change mitigation and adaptation between 2014 and 2020 (European Commission 2015a). While most of this funding is dedicated to project finance, economic or administrative support which usually goes directly to national and sub-national governments, parts of this money is dedicated to research. For example, the ERDF provides €2.6 billion for research activities (ibid.).

The second pillar is the H2020 programme, which unifies most of the EU's R&D spending and runs from 2014 to 2020. It's predecessor, FP7, ran from 2007 to 2013. Contrary to ESI funds, the focus of H2020 (and FP7) is clearly research and development. Between 2014 and 2020, this programme is endowed with around €77 billion (DG Research and Innovation 2018) while its FP7 was endowed with around €55 billion.[19]

In addition to those two pillars, there are several other programmes. The LIFE programme for example supports environmental and climate action (with €3.4 billion between 2014 and 2020), but it excludes most research projects due to potential overlaps with H2020 (European Commission 2018d). There is the NER300 fund which is the 'world's largest funding programme for low-carbon energy demonstration projects'[20] and was supposed to support both renewables and CCS projects. It was financed from the sales of EU ETS allowances and in the first phase, more than €1 billion has been disbursed to renewable energy, but no operational CCS demonstration plant came into existence so far under the NER300 (see above and CARISMA D8.3).

Besides those funds and programmes, R&D activities can be channelled through specialised institutions such as the Fuel Cell Hydrogen Joint Undertaking (FCH JU), now in its second phase, which dedicates its resources purely to the hydrogen value chain.[21] Another funding stream are special instruments such as the Connecting Europe Facility (CEF) which leverages investment in energy, transport or telecommunications infrastructure. While the support is not for research but for concrete project implementation on energy, transport and communication infrastructure, some projects are to drive forward the energy transitions and support is for instance lent to feasibility studies concerning offshore wind or deployment of infrastructure for smart grids (European Commission 2018b).

Lastly there are EU-wide strategies such as the Strategic Energy Technology (SET) Plan, supposed to drive forward clean and low-carbon technology innovation (European Commission 2015b) or the Regional Smart Specialisation Strategy (RiS3), aimed at

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[19] http://europa.eu/rapid/press-release_IP-16-145_en.htm
[20] https://ec.europa.eu/clima/policies/lowcarbon/ner300_en
[21] http://www.fch.europa.eu/page/governance

fostering regional innovation clusters.[22] While these strategies usually don't provide funding and are not aimed at research institutions, they still provide policy guidelines for research and innovation actors.

4.3 A closer look at H2020 and FP7

Looking more closely at the H2020 programme, sectoral data for the first three years reveal that around €24.8 billion were spent in total on R&D. Of this amount, about €1.9 billion were spent on energy-related research, €1.7 billion on transport and €1.1 on climate and environment (DG Research and Innovation 2018). The energy efficiency or buildings sector is not indicated separately thus hinting at the fact that some of the R&D in this sector is subsumed into the energy or other pots. The Figure 1 gives an overview.

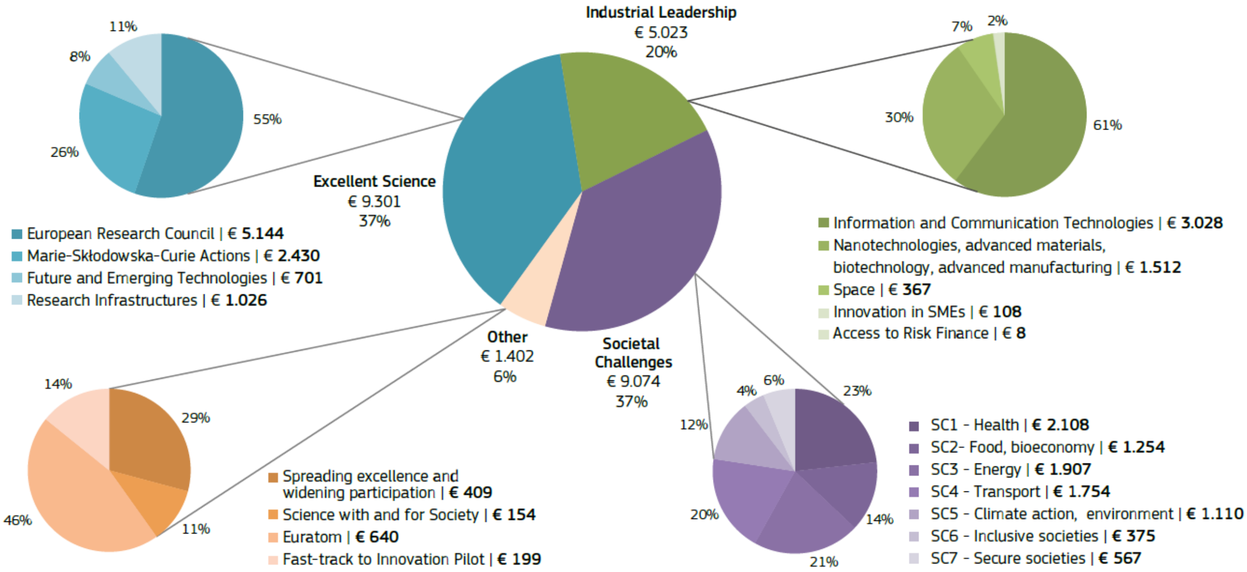

Figure 1. H2020 funding from 2014 – 2016 differentiated by research area (source: DG Research and Innovation)

To compare those figures, the preceding funding programme FP7 disbursed €2.2 billion between 2007 and 2013 for energy and €3.3 billion for transport related research, although the climate and category does not exist in the reporting.[23]

It is difficult to say how much money was spent on technologies described in chapters 2 and 3. For example, research on new and innovative steel production might have been funded under the "Nanotechnologies, advanced materials, biotechnology, advanced manufacturing" stream or under the "Future and emerging technologies" stream. Research and development on energy storage might be financed under the item "Energy" but new, innovative batteries also depend on nanotechnologies. Hydrogen research, in turn, might be carried out under transport (fuel cells) or energy (power to gas). The CORDIS database offers a repository of all H2020 and FP7 financed projects, but extracting data proved to be difficult and earlier work on this (see the database on the CARISMA website[24]) was

[22] http://s3platform.jrc.ec.europa.eu/
[23] https://ec.europa.eu/research/fp7/index_en.cfm?pg=budget
[24] http://carisma-project.eu/research-and-innovation

therefore not included in this study. Nevertheless, we were able to provide some illustrative data on technologies and pathways on Chapters 2 and 3.

Energy storage

According to the EU's Innovation and Networks Executive Agency (INEA), an institution which manages large parts of H2020 funding for sectors such as energy and transport, energy storage is currently (2014 – 2020) financed with €113 million although not all calls might have been opened for tenders yet.[25] Other sources put the figure to up to €195 between 2014 and 2017 for R&D on energy storage solutions.[26] This sample contains only one project dealing with energy storage via the power-to-gas pathway.

Carbon dioxide capture and storage

Journalistic sources put the figure of CCS support between 2007 and 2017 at almost €600 million (Teffer 2017). The INEA database accounts for H2020 projects on CCS worth €85,5 million between 2015 – 2021. For CCS, not all projects initially foreseen might have been opened for tender yet.

Hydrogen

Overall, according to its website, the FCH JU, a specialised institution set up to drive forward the hydrogen pathway, has a budget of €665 million while industrial stakeholders are expected to double that amount, pushing the envelope to about €1.3 billion in the period of 2014 to 2020. For the years 2014, 2015 and 2016, the annual report of the FCH JU speaks of €244.9 million of EU money spent on 46 hydrogen related R&D projects (FCHJU 2017). However, the large majority of R&D was spent under the reports energy and transport category with only 3% of the funding flowing into "cross cutting" projects, thus suggesting that hydrogen applications for the industrial sector were either included in other non-FCH JU funding streams (see above) or were not a R&D priority in the period scrutinised (ibid.).

Buildings

According to the European Commission, the EU funded renewable energy uptake in heating and cooling in the buildings sector with €166 million between 2012 and 2015 (European Commission 2016a). This figure includes funding from other streams than H2020 such as its predecessor FP7 or the Intelligent Energy Europe programme, another since expired EU R&D stream.

[25] https://ec.europa.eu/inea/en/horizon-2020/h2020-energy/projects-by-field/storage

[26] Presentation during the Business Models Working Group Meeting of the EU Bridge project in March 2018, Brussels

4.4 Putting European research and development in context

The interpretation of these data needs to be handled with care. As shown, EU channels its R&D funding through a panoply of channels, using a variety of institutions and instruments which often don't even have a similar time frame and whose information on projects finance might significantly overlap. To make matters even more complex, it is important to note, that EU R&D funding analysed does not include projects financed by Member States only. For example, Germany spent more than €870 million on energy research (*Energieforschung*), money which is not reflected in our research effort. On top of that, we did not include private sector investment in R&D. This is an important limitation since private sector accounts for 55% of all R&D spending in the EU.[27] And as a last caveat, the amount of money spent might be independent from the quality of the research and the importance of the results thus making it difficult to argue that a specific amount would be the "right" amount for any technology.

Therefore, figures provided above can only provide an incomplete snapshot of current EU R&D funding on climate change mitigation actions and the technologies elaborated on in Chapters 2 and 3. However, several observations can be made.

First, funding increased between the FP7 and H2020 programmes from €55 to €77 billion.

Second, a first snapshot of H2020 indicates that funding in sectors such as energy has increased in importance since energy accounted already for €1.9 billion in the first three years of H2020 than the total of €2.2 billion between 2007 and 2013 under FP7. However, the transport sector might have fallen back in importance (relative to energy) given the fact it has been funded with €1.7 billion in the first years of H2020 but with €3.3 billion under the 7 years of FP7. This may reflect the aim of the European Commission to spend a greater share on societal challenges, and about a third on climate action.

Third, the question remains of whether R&D funding destined to technologies elaborated on in Chapters 2 and 3 is enough to meet the EU's climate ambition. For instance, the first three years of H2020 allocated €245 million to the hydrogen pathway. Compared to overall spending on R&D in those years (€24.8 billion), this amounts to less than 1%. The same question might be raised concerning energy storage. Even assuming the higher figure at around €200 million for three years, this means less than 0.8% of H2020 research went into energy storage. Both figures seem low compared to the technologies' potential versatility (hydrogen) and importance for decarbonisation efforts, particularly in the power sector (energy storage).

Lastly, several of sub-technologies of those pathways have low TRLs, such as some battery models, hydrogen in steel making or power-to-hydrogen. Our research did not yield any projects dealing for example with hydrogen applications in the steel industry. Several projects (GrInHy, HFuture) supported by about €16 million can be found in the CORIDS database after the cut-off date of sources used above and important funding streams might be missing from our analysis as private sector stakeholders might drive those and other

[27] http://ec.europa.eu/eurostat/statistics-explained/index.php/R_%26_D_expenditure

technology pathways forward. However, given the industry's important emissions profile and the challenges the sector has to deep decarbonisation, at least the question should be asked whether EU R&D funding is aligned with deep decarbonisation pathways if only a few projects look into the low-carbon steel pathway.

5 Conclusions and recommendations

Low- and zero-carbon technologies to allow the EU to meet its 2050 objectives and to align itself with the objectives of the Paris Agreement are increasingly available. It is well known that these technologies suffer from a mix of barriers. Our closer analysis of several technologies reveals whether those barriers are related to technological maturity, what is the extent of economic, environmental and social barriers to market uptake. This section will go into what can be done to enable hydrogen in industry/transport, energy storage, CCS and renewable energy for heating and cooling of buildings to play their role in the decarbonisation challenge.

First, not all of the technologies likely needed to meet the EU's 2050 and Paris Agreement targets are "ready" from a technology point of view. Some energy storage solutions such as flow-batteries or power-to-hydrogen pathways are not mature enough for market diffusion. The same holds true for hydrogen applications in the steel, cement and chemical industries or for biofuels and low-carbon fertiliser production.

Second, even if the TRL of certain technologies is advanced (TRL 8-9), this does not automatically mean rapid market diffusion as our examples of CCS and heat pumps in buildings have shown. Across the board, the greatest barrier seems to still be economic since many low carbon technologies described still come at a significant price premium compared to more conventional, fossil fuel-based ones. The economic barriers can also be systemic. For instance the cost of electricity storage to balance intermittent renewables comes on top of the often already higher cost of renewable electricity, as the current electricity system is designed for non-intermittent fossil fuels and the infrastructure for that is already paid for.

Third, R&D activities are an appropriate means not only to increase the TRL of certain technologies but also to understand what kind of situation certain technologies will face in the market place and society. However, our snapshot of current EU R&D funding streams indicate that it might be necessary to increase and realign R&D spending with the needs – both technical (TRL) and non-technical (barriers) – of analysed technologies. The energy storage and hydrogen pathways could particularly benefit from a closer analysis and performance evaluation of R&D spending as to whether spending is in line with the EU's decarbonisation objectives.

As a way forward, several recommendations can be made. Those recommendations are not an exclusive and exhaustive list. Like a red thread, policy makers are called upon to provide stringent and adapted regulation which reflect the needs of technologies of the 21st century. Another call to arms should reach the private sector because business stakeholders have a key role in embracing the low carbon transition since deep-decarbonisation can't be achieved without their support. And finally, much will come down to our own behaviour which means to embrace low-carbon technologies and demand for clean products and services.

5.1 Enabling through smart R&D and market diffusion policies

The EU and its Member States are world leaders when it comes to innovations in climate change mitigation technologies (IRENA and EPO 2017). But this position should not be taken for granted. Other countries, like China, are catching up fast and are making a welcome difference in, for instance, costs of renewables. If the competitive advantage of high value climate innovation is to be conserved, EU policy-makers might need to address not only the funding gap between 2% of R&D intensity in 2015 and the 3% target as reiterated by the Estonian Council presidency in 2017 (EU2017.EE 2017) but also redirect R&D spending to technologies which will become increasingly important, but which are not yet ready for large-scale market uptake, and early on explore the market potential. As we have shown, many important sectoral technologies have low TRLs which could be addressed by targeted R&D spending.

In addition, understanding, from many perspectives, what hinders technologies to become mainstream is as vital as building successful prototypes. Policy makers might ask themselves the question whether enough funding is made available for 'low-TRL high-barrier' technologies. But because EU funding will not be enough, private sector players should do their share to bring the EU economy on a pathway compatible with the Paris Agreement's objectives. Here, industrial sectors such as steel, cement or chemicals are well positioned to collaborate with Member States and EU institutions to find a way to decarbonise their value chains with examples such as *Hybrit* showing the way, even when the risk of carbon leakage looms.

From a policy perspective, this means that helping technologies onto the market would need adapted policies. Borrowing from Grubb et al. (2017), while increased 'strategic investment' and R&D spending could help less mature technologies, technologies with a TRL of 8 or 9 would need different policies. Market creation and market support by dedicated instruments might be a good way forward. Instruments such as carbon pricing or environmental standard setting to level the playing field come to mind as well as adapting the current market to new technologies to reflect their cost and application profile better (see next point) (Grubb, McDowall, and Drummond 2017). This would create a necessary market pull factor, after the technology push factor was achieved (ibid.).

The negotiations around the Multiannual Financial Framework (MFF), or the EU's "budget", offer an outstanding opportunity to re-orient, climate-proof and increase European R&D spending. At first sight, the Commission proposal on a new MFF between 2021 and 2027 looks promising as the new research funding stream, *Horizon Europe*, is allocated €100 billion including Euratom training and research activities (European Commission 2018c), up from the roughly €77 billion between 2014 and 2020. This is a welcome step as research and innovation would represent 7.8% of all proposed EU spending[28] (up from 7.1%) but negotiating parties should make sure that enough money will be earmarked for climate change mitigation technologies, particularly to technologies assessed here and in Elkerbout et al. (2018).

5.2 Enabling through bringing down economic barriers

Almost all of our analysed technologies in chapter 3 face economic barriers. The most pronounced is surely the fact that the costs for many low-carbon technologies and climate solutions such as hydrogen usage in industry and transport or energy storage (except pumped hydro storage) are often still too high to compete with conventional technology pathways. Here, several solutions could help to overcome those barriers.

First, market-based solutions could be sought by adapting current markets and business models to the specific profiles of new technologies. For example, intermittent decentralised renewable energy need different infrastructure and a different form of market than a centralised, base load heavy fossil fuel one. Energy storage is an illustrative example. Last year, the German Academy of Sciences argued that by reforming the EU electricity market, energy storage solutions could become economically viable. This could be achieved by better integrating individual storage providers into electricity markets. Another floated idea was to adjust bidding zones (where electricity and storage providers can bid for power delivery contracts) to reflect true bottle necks and constraints, thus increasing the price for storage in these neuralgic spots where electricity is needed. Moreover, the researchers recommend to reduce dispatch periods to bring production, delivery and actual consumption closer together and to allow for a more flexible market, including price spikes, negative as well as positive ones (EASAC 2017). While particularly the last measure might be a difficult sell politically as consumers (and mainstream media) become increasingly weary of high prices, price spikes would affect principally wholesale markets where a few hours of very high prices (several 100s of euros per MWh) could make storage capacity profitable. Furthermore, energy storage providers could offer profitable grid stabilising services such as frequency stabilisation or other network strengthening measures (Newbery et al. 2017). Indeed, case studies in the (more liberalised) US market have shown that storage services used for grid balancing and frequency regulation have been able to recover their costs (Avendano-Mora and Camm 2015). So, while the technology should be made suitable for the market, the market and business models could also change to accommodate new technologies.

Second, while reforming the market is one strategy, supporting less mature technologies financially is another. EU Member States apply a large variety of instruments ranging from Feed-in tariffs to more market-based solutions such as Feed-in premiums or Contracts for Differences (CfDs) where renewable energy providers receive a top-up of current market prices. These instruments might be applied to energy storage providers to help to make

[28] https://ec.europa.eu/commission/sites/beta-political/files/budget-proposals-modern-eu-budget-may2018_en.pdf

their storage solutions profitable, or might even support to electricity-to-(hydrogen) gas pathway.

For technologies that underpin less homogeneous products than electricity and are therefore less susceptible to FiTs, like low-carbon vehicles such as hydrogen cars, could be helped by tax credits or rebates. While the evidence on hydrogen cars is limited, much can be learned from electric vehicles, which are populating the roads in greater numbers. Indeed, up-front price reductions such as exemptions from VAT when buying a low-carbon vehicle are said to have been the most effective measure in Norway (Bjerkan, Nørbech, and Nordtømme 2016), pushing the EV stock in the country from just over 5000 in 2011 to almost 100,000 in 2016, representing a market share of all EVs including hybrids of 29%, the largest in the world (IEA 2017). This may be explained by earlier work by Anderson and Newell (2004), who found that SMEs were 40% more susceptible to upfront cost savings than to annual savings when deciding on implementing energy efficiency measures (Anderson and Newell 2004). Here, reducing the up-front costs for more expensive technologies such as FCVs could serve as necessary demand pull factors, deemed necessary for increased market uptake (Grubb, McDowall, and Drummond 2017).

Of course, support instruments such as FiTs, tax rebates and grants have to be accounted for in governments' budgets, still under stress in many Member States.[29] However, EU governments do not only subsidise renewables but also fossil fuel energy. Although defining fossil fuel subsidies proves to be difficult, the European Parliament Environmental Committee estimates that EU Member States spent between €39 and €200 billion in 2015 (Hayer 2017) while the Overseas Development Institute (ODI) estimates that the EU and its institutions supported fossil fuels and their infrastructure with annually over €4 billion between 2014 and 2016 (Gencsue et al. 2017). Even at the lower end of these estimations, there seems to be ample room for improvement by shifting subsidies from harmful technologies to low- and zero-carbon ones. This would not only free up money for support instruments and tax rebates but also reduce emissions significantly (Hayer 2017).

Lastly, carbon pollution must become more expensive so that the market for new, low- and zero-carbon technologies can be strengthened. Without a significant uptick in carbon prices, particularly the private sector will most likely not invest in low-carbon technologies. It is true that companies might be motivated to adopt climate mitigation technologies by other factors such as the wish to convey (and commercialise on) a 'green' image (Corey, Jaffe, and Sin 2014), but if it is cheaper to pollute than to invest in mitigation technologies, companies seem to have the tendency to prefer business as usual as the stagnant emissions in the industrial sector show.30 In the same vein, research is slowly emerging that phase I and phase II of the EU ETS had only moderate impact on company-level low-carbon innovation (Marcantonini et al. 2017) although patent activity is higher under EU ETS registered firms (Muuls et al. 2016). And despite the system's recent reform, analysts doubt that the compromise reflecting measures such as the market stability reserve (MSR) and the increase of the allowance reduction factor of 2.2 from 2021 will lead to a carbon

[29] http://ec.europa.eu/eurostat/documents/2995521/8118661/2-20072017-AP-EN.pdf/83147478-c193-40e9-8a0a-b76e56a5cebc

[30] UNFCCC data

price high enough to allow for steep decarbonisation (Buckley 2017), if such transformations . In the absence of a further revision of the EU ETS (or in the absence of a carbon tax), one way forward might be the adding of a carbon price floor in order to strengthen the market signal (Edenhofer et al. 2017), a policy already adopted in the UK, partly decided on in the Netherlands and considered in France (Felix 2017).

5.3 Enabling climate mitigation environmentally

As shown in Chapter 3, many clean technologies (and their composites) still need to be produced and distributed, emitting harmful greenhouse gases along their value chain and having a direct impact on the environment. For example, hydrogen fuel cell vehicles are only environmentally friendly if the hydrogen is sourced from low or zero carbon sources. The same holds true for industrial applications of hydrogen. Similarly, about 50% of greenhouse gas emissions in battery manufacturing are emitted during the production stage, and other, non-climate environmental and health impacts are looming: lithium to build them has to be mined, including in geopolitically sensitive regions (Sanderson 2018). And crops used for biofuel or biogas applications might enter in competition with food crops and induce harmful land-use changes.

In order to anticipate and mitigate these negative impacts, it would be necessary for decision makers to go beyond the immediate value chain of a climate technology and to include life-cycle impact assessments into their policy making process. It is particularly important to look at environmental impacts from the cradle to the grave and to pursue a system-wide decarbonisation, meeting both climate and other sustainability targets, even at the product level. Stringent environmental regulations, mandates and even labelling could facilitate improving production processes such as batteries, making them more environmentally friendly.

5.4 Improving societal readiness

Many climate mitigation technologies are perceived as risky and detrimental to health, wellbeing and security (See CARISMA D4.4). Such fears might even exist despite scientific evidence suggesting that either those fears are exaggerated or not grounded in reality, as the example of CCS shows. Taking those fears and concerns seriously and engaging in an honest dialogue with stakeholders is vital to ready society for uptake of certain technologies. Failure to do so and to force technologies from the top down can lead to negative consequences and even the abandonment of test cases of climate mitigation technologies.

Second, providing information about climate mitigation technologies and their effect seems to be equally vital in order to increase their acceptance and their market share. Even when it comes to relatively mature technologies such as heat pumps, lack of information on how to use and install the systems or on which financial incentives by governments exist proves to be a significant barrier. Moreover, people often lack the necessary information about potential cost savings when investing in energy efficiency (Ramos et al. 2015) or even other climate mitigation measure. Here, increasing and sustaining information efforts should go hand in hand with programmes to train people on the installation, usage and maintenance of climate technologies. Also, informational policies to address misconceptions about technologies might play an important role in alleviating fears and making climate technologies more attractive.

Enabling societal readiness might eventually have knock-on effects on a change in consumption patterns and behaviour which, even though the extent is highly dependent on the technology, would help reducing emissions (Barbu, Griffiths, and Morton 2013). Although behaviour change of energy and technology consumers is not a straight-forward process (Frederiks, Stenner, and Hobman 2015), if the potential for behaviour and technological change can be combined, it could become greater than the sum of its parts, every euro invested in climate mitigation R&D could have a higher emission reduction payoff.

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