



Technology Executive Committee

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Draft technical paper on emerging climate technologies in the energy supply sector

Background note

I. Background

1. As per activity 2 of the thematic area Innovation of its workplan 2019-2022, the TEC is to analyse key emerging climate technologies. At TEC 22, the TEC considered a concept note on future work of the TEC on emerging climate technologies in the energy supply sector, including the preparation of a technical paper and the organization of thematic dialogues.
2. The task force on Innovation worked inter-sessionally to prepare a draft technical paper on emerging climate technologies in the energy supply sector and organized three below dialogues virtually in conjunction with the Asia Pacific Climate Week on 6-9 July 2021.¹

II. Scope of the note

3. The annex to this note contains the draft technical paper on emerging climate technologies in the energy supply sector, as prepared by the task force on Innovation.

III. Possible action by the Technology Executive Committee

4. The TEC will be invited to consider the draft technical paper and provide guidance to the innovation taskforce with a view to finalizing the paper after TEC23.

¹ https://unfccc.int/ttclear/events/2021/2021_event03.

Annex

Draft technical paper on emerging climate technologies in the energy supply sector

Executive summary

At the behest of the UNFCCC Technology Executive Committee (TEC), we reviewed a group of emerging low greenhouse gas (GHG) primary energy supply and transformation and storage technologies (airborne wind energy, tidal energy, wave energy, floating wind, floating solar PV, ocean thermal energy conversion, bioenergy and carbon capture and storage, green hydrogen, thermal energy storage, advanced batteries, and heat pumps). Using a structured literature review, we asked the following three questions for each:

- **What is this technology, and where and how could it be useful?** How does the technology work? Where and when is it likely to contribute to producing globally significant amounts of primary or transformed end-use energy? What markets could it fulfil? What are its co-benefits and costs?
- **What is this technology's potential contribution to mitigating climate change?** Given the latter question, what does this technology provide that other already commercialized and/or relatively less expensive low GHG technologies cannot in globally significant quantities?
- **What are the initial and ongoing social, institutional, economic, and business conditions for successful uptake?** Including but going beyond the simple upfront and lifecycle cost of bulk and firming electricity, what market structure characteristics, cultural preferences and objections, (missing) enabling institutions, and regulatory & liability issues may affect the ultimate penetration of this technology?

Some of the technologies reviewed are very likely to provide global scale climate and broader Sustainable Development Goal benefits (floating wind, floating solar PV, green hydrogen, advanced batteries, thermal energy storage, and heat pumps). However, some of the technologies that have been reviewed are unlikely to provide a large, globally significant level contribution to meeting climate change goals in the near to medium term (airborne wind energy, wave energy, tidal energy, ocean thermal energy conversion), but they may be critical to some countries' or sub-regions' efforts. For this latter group, sub-groups of countries may wish to cooperate, and these technologies may yet surprise us in their scale if engineering and business case challenges are overcome.

Policies to support commercialization and uptake of these technologies will vary by regions, but must include components for clear directionality towards net-zero emissions, innovation, and market shaping to drive their uptake. Stringent carbon pricing or performance regulations to capture the social damages associated with emissions are a necessary but insufficient condition for these technologies to penetrate. More research and development support are also a necessary but insufficient condition. The most expensive stage of technology development, when most companies fail, is mid- to full-scale piloting, when expenses are a maximum, but no revenue is generated; technologies that have demonstrated themselves at the small scale need the most support at this stage. This very expensive and risky stage can be made more bearable by entering into partnership with regions and governments with similar interest in the technology succeeding. These partnerships can also help unblock key technical or other challenges.

After full scale piloting, lead or niche markets must be found that only these technologies can service, or niche markets/allocated market share incentives are required to hit early critical economies of scale and innovation. These early markets are also critical for reducing perceived risk for the financial community to invest as a normal matter of course, and can be included as a sub-component of renewable portfolio standards or feed-in-tariffs, actualized as contracts for difference. In many markets financial policy

supports are no longer necessary for standard solar PV and onshore wind beyond maintenance of a declining GHG intensity standard, and these funds and market share could be transferred to the emerging technologies in this report. All this points to the need for a systemic approach to innovation, commercialization, risk reduction, and lead and broad market uptake to normalize new sustainable supply and enabling technologies.

Table 1 Summary of key technology characteristics for emerging primary energy supply technologies

Technologies	TRL	Current & estimated eventual levelized cost of energy for supply 2019 USD \$/kWh	Size and generality of resource if available	Key co-benefits and other considerations
Airborne wind energy	3-5	Unknown	Large but vague	Can potentially be used for remote sites far from grid with poor solar
Floating solar PV	8+	0.35 historic, current low auction bids at 0.05, projected 2030 ~0.05, ~0.04 2050	Very large and broadly geographically spread: 4,251 to 10,616 TWh per year	When tied with existing hydropower frees water resource for use as firm power, utilizes existing transmission, and reduces evaporation losses
Floating wind	8+	Current auctions at 0.13-0.15	Very large and confined to large lakes & ocean EEZs: Conservatively up to 83,229 TWh per year	When placed in deep ocean very large resource with low siting conflicts
Wave power	5-8	Current 0.30-0.55. 0.22 by 2025 & \$0.165 by 2030	Moderate: 2 TW globally, but highly regional.	Highly regional. No convergence on design.
Tidal power	3-8	Current 0.20-0.45. 0.11 by 2022-2030.	Moderate: Very regional, can be locally large.	Highly regional. Tidal barrages are unlikely to be approved, in stream floating axial turbines showing most promise.
Ocean thermal energy conversion	5-6	Current 0.20-0.67 for 10 MW units falling to 0.04-0.29 for 100 MW units	Very large but localized: 4,000-13,000 TWh/yr	Can be located anywhere between 30° north and south with reasonable access to 1km+ ocean depth. Can provide water desalinization.
Bioenergy with carbon capture and storage (BECCS)	6-8	Variable with application. Fossil unit cost plus CCS cost minus carbon revenue benefit.	Very large.	Net-neutrality is highly vulnerable to what biomass feedstock is used and how it extracted. CCS should be ~\$50-\$100/t, but is only proven with ethanol production plants.

Table 2 Summary of key technology characteristics for emerging enabling technologies

Technology	TRL	Cost 2019 USD	Key applications
Green hydrogen	8+	\$4.5-6/kg, could fall to less than \$2 by 2030 with economies of scale and innovation	Storage of variable renewable electricity; high process heat; steel reduction; ammonia fertilizers; heavy transport
Next generation batteries	3-8+	Lithium ion batteries are now \$150-300/kWh, an expected to fall to <\$75 by 2030	Small and large vehicles; supply and end-use in electricity grids; portable electronic and motor devices

Thermal energy storage	3-8+	Highly variable.	As a supplement to residential heating, electricity firm power,
Heat pumps	8+	At least double the cost of boilers, usually more.	Residential & commercial heating and cooling; industrial steam

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Acronyms

ARPA-E	Advanced Research Projects Agency–Energy
BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage
CCU	Carbon capture and utilization
CfD	Contract for difference
DAC	Direct air capture
DARPA	Defence Advanced Research Projects Agency
EEZ	Exclusive economic zone
EOR	Enhanced oil recovery
FIT	Feed-in Tariff
FSF	Floating Solar Field
GHG	Greenhouse gas
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
OTEC	Ocean Thermal Energy Conversion
PEM	Proton exchange membrane fuel cell
PV	Photovoltaic
R&D	Research and development
RPS	Renewable portfolio standards
SDGs	Sustainable development goals
SOFC	Solid oxide fuel cell
TCP	Technology coordination partnership
TEC	Technology Executive Committee
UNFCCC	United Nations Framework Convention on Climate Change
VRE	Variable renewable energy

Introduction

Objective of this report

Meeting the challenge of climate change, as crystallized in the Paris Agreement's goal of "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels", requires energy system CO₂ emissions to reach net-zero by mid-century, with 2050 being the CO₂ net-zero date for 1.5°C (with 5-20 GtCO₂ negative emissions per year thereafter) and 2070 the net-zero date for 2°C (Edenhofer et al., 2014; Masson-Delmotte et al., 2018). All greenhouse gases (GHGs) must hit net-zero roughly 20 years later. This requires that all currently emitting sources are retrofitted or replaced with abatement technology or new non emitting sources.

The scale of this challenge is huge; GHG emissions must fall by a nominal (non-compounded) 3.5% of 2020 levels per year, and much of the existing global energy using technology stock (e.g., buildings, power generation & industrial boilers) will last longer than this (Tong et al., 2019). Just as one metric, both the IEA and IRENA, using independent 1.5°C scenarios, found the annual incremental additional investment needed is over 4 trillion USD per year through 2050 (International Energy Agency (IEA), 2021; IRENA, 2021a).

While almost all economy-wide Paris Agreement compatible deep decarbonization studies make use of some mix of energy & material efficiency, bioenergy, low GHG hydrogen, CCU, CCS and natural and technical negative emissions, electrification using low GHG generation is a core "backbone" strategy (Bataille et al., 2016; L. Clarke et al., 2014; Williams et al., 2012, 2021); the IEA estimated in its Net Zero Emissions (NZE) scenario (International Energy Agency (IEA), 2021) that not only must all economies decarbonize their electricity supply, developed economies must at least double their output, and developing economies triple to quintuple it to meet development needs. Given this requirement, any and all new low GHG supply sources must be considered, especially if they are preferential to the old fossil supply, e.g., they use less water or emit less local air pollution. Much, and likely most in most regions, of the new electricity generating stock will be variable renewables offering relatively inexpensive bulk electricity & and heat but often not when and where it is needed. A more flexible and integrated grid with market design and supply and demand business models will be needed to maximize the value of variable renewables (IRENA, 2019a), including responsive demand, more transmission to link areas with different resources and demands, and storage on multiple time scales: e.g., batteries over the microsecond to overnight time frame, hydrogen over the hours to weeks' time frame, and pumped hydro over the hours to seasonal time frame. Renewably sourced heat will also need to be stored economically, perhaps seasonally for buildings. What material impact could emerging technologies have to meet these needs? How ready are they for early commercialization, and what enabling conditions could speed this? What barriers and enabling conditions are relevant given: market access; social, institutional and economic preconditions; and social acceptability?

The purpose of this report to analyse a group of pre-selected key emerging primary energy supply, transformation, and storage technologies and elaborate on elements that may affect their successful deployment, commercialization, and long-term sustainability. The report:

- provides an overview of the technologies, their state of play, and potential climate change mitigation and adaptation impacts;
- analyses the technologies' social, institutional, economic and business challenges and solutions related to their development and deployment, including new market access and social acceptability

- identifies ways for policymakers to effectively support the deployment of these technologies, especially using a systemic approach to innovation, commercialization, risk reduction, and lead and broad market uptake to normalize new sustainable supply and enabling technologies.

The overall objective is to provide policymakers and other relevant stakeholders with a set of information and the beginnings of a practical transformative “theory of change” that may help their decision making when defining national and/or regional strategies for accelerating the scale-up and diffusion of these technologies.

Scope & methodological approach

Technology development stage

Climate technologies that are at early stages of development, i.e. still in a conceptualization phase or undertaking preliminary laboratory analytical measurements, were not considered in this work. The focus was on a preselected list of technologies with tested climate change mitigation and adaptation potential but not yet operational technologies from TRL 4 (early prototype, proven in test conditions) to TRL 8 (first of a kind commercial, commercial demonstration).¹ This approach avoids overlapping with and duplication of work conducted by the TEC in the thematic area of implementation of its rolling workplan for 2019-2022, where the focus is on commercially available technologies that are awaiting diffusion or uptake.

Technology sector

The analysis under this work addresses selected key emerging technologies in the energy supply sector, including generation and enabling transformation and storage technologies. The power sector is the largest contributor to global GHGs. In 2010, the energy supply sector was responsible for approximately 35% of total anthropogenic GHG emissions.² As shown in the mapping of emerging climate technologies considered by the TEC at its 21st meeting,³ the energy supply sector offers a wide range of emerging decarbonization technologies with high potential for climate change mitigation.

Emerging decarbonization technologies for energy supply also come with potential environmental impacts, for instance, in terms of reduced local air emissions and changes in land and water use. Although the topic around energy supply may put emphasize on climate change mitigation, its relevance to multiple social and environmental co-benefits (e.g., employment and income generation for local communities, reduced impact on water and land, where data on these is available) of such technologies would allow consideration on climate change adaptation as well.

Specific focus

It is crucial for the TEC to not duplicate analysis of emerging climate technologies produced by other organizations and to make its efforts different from what already produced and attractive to different audiences. The TEC at its 21st meeting provided guidance in this regard and identified the following elements related to the development, diffusion and impacts of emerging decarbonization technologies that should be the focus of analysis under this work:

- **Access to new markets:** markets adopt new technologies at various paces, depending on the broader ecosystem (e.g., services, standards, regulations) that supports them. Penetration rates of new technologies—the percentage of workers in a country using them and their diffusion across

¹ Technology readiness levels (TRL) scale, as originally developed by NASA and eventually modified by the International Energy Agency (IEA), is a common framework applied to assess maturity of technologies. It is a scale ranging from 1 (initial idea, basic principles defined) to 11 (mature technology, proof of stability reach). See Energy technology perspective 2020 by the IEA available at <https://bit.ly/38MGeSR>.

² See https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter7.pdf.

³ See <https://bit.ly/3qGz1dc>.

the population—remain low among developing and transition countries. The penetration and diffusion of climate technologies in developing countries is often too low to sustain new markets that depend on them. Factors that account for the low penetration levels span from country-specific characteristics (for example political risk) to general bottlenecks (business models, access to finance, infrastructure, among other factors), that are common in developing economies.

- **Social, institutional, economic and business preconditions:** when looking for the key ingredients to effectively deploy climate technologies, it is very important to consider the interplay between technological, institutional, economic, business and social factors. Successful deployment is an interplay of several heavily context-specific factors. Innovative emerging technologies without connections to the context may be hopelessly ineffective. Traditional technology transfer models and sustainable development efforts — whether for developing or developed countries — pay insufficient attention to first creating enabling socio-political, economic and business conditions.
- **Social acceptability:** social acceptance is a major driver of the success of climate technologies. Technologies that are economically and technically feasible may not be implemented due to social resistance, lack of awareness of technology. Social or public ‘acceptance’ is defined as a positive attitude towards a technology or measure, which leads to supporting behaviour if needed or requested, and the counteracting of resistance by others. People's perception and awareness help to determine if the technologies are acceptable and in what forms. This is a complex issue depending upon the variety of factors ranging from understanding, people's conviction about risk, security, landscape, economic and political power.

Methodological approach

To accommodate the above objectives and elements, analysis of each technology has been sorted into:

- ***What is this technology, and where and how could it be useful?*** How does the technology work? Given this, where and when is it likely to produce or contribute to producing globally significant amounts of primary or transformed end-use energy? What co-benefits and costs may affect its uptake?
- ***What is this technology's potential contribution to mitigating climate change?*** Given the latter question, what does this technology provide that other already commercialized and/or relatively less expensive low GHG technologies cannot in globally significant quantities?
- ***What are the initial and ongoing social, institutional, economic, and business conditions for successful uptake?*** Including but going beyond the simple upfront and lifecycle cost of bulk and firming electricity, what market structure characteristics, cultural preferences and objections, (missing) enabling institutions, and regulatory & liability issues may affect the ultimate penetration of this technology?

To answer these questions, we conducted a multi-stage, multi-focus literature review. Existing Intergovernmental Panel on Climate Change (IPCC) chapters from IPCC Assessment Report 5 (Edenhofer et al., 2014) & the Special Report on 1.5°C (Masson-Delmotte et al., 2018) were consulted first. International Energy Agency and International Renewable Energy Agency reports were reviewed. Google Scholar was used to search for the latest high quality, peer-reviewed literature review papers for each technology. Topic specific papers containing the technologies as search terms from high quality energy and climate economics and policy journals (e.g., non-exclusively, the *Nature* family of journals, *Science*, *Energy Economics*, *Climate Policy*, *Applied Energy*, *Energy Policy*, *Climate Economics*) with high citation levels were reviewed. Wikipedia was consulted for what it contained for each technology, given it is one of the most widely accessed sources for general knowledge, but the results were cross checked against

the forgoing papers. Finally, a brief review of active companies in the area was carried out to assess continued activity.

Each of the technologies is classified with a Technology Readiness Level (TRL). The scope of this project was TRL 4-8, but some applications of these technologies (e.g., floating solar on hydro reservoirs, the first floating wind farms) could be classified TRL 9. The initial TRL scale developed by NASA and went from 1-9, but the IEA has expanded it to 11 as follows (IEA, 2020a), and this is entering into general use in the energy community.

Table 3 Technology Readiness Levels (TRL) and policy implications (uses IEA and NASA definitions)

Broad stage	TRL	Narrow stage	Policy & financial requirement implications
Conceptual or research phase	1	Initial idea, Basic principles observed	At of scale of researcher, small company or individual. Broad R&D support sufficient.
	2	Application formulated, Technology concept formulated	At of scale of researcher, small company or individual. Broad R&D support sufficient.
	3	Concept needs validation, experimental proof of concept	Moderate funds may be needed.
Small prototype (Development Phase)	4	Early prototype, technology validated in lab	Funding needs increase but are not beyond research institutes and fall small firms. Entering realm of ARPA style funding.
Large prototype (Development Phase)	5	Large prototype, technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)	Moderate costs, no revenue, significant support needed. Realm of ARPA style funding.
	6	Full prototype at scale, Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)	Large costs, no revenue, significant support needed. Realm of ARPA style funding.
Demonstration (Deployment Phase)	7	Pre-commercial demonstration, System prototype demonstration in operational environment	Very large costs, no revenue, significant support needed. Funding needed beyond typical ARPA funding, large firm, venture or state capital investment.
	8	First-of-a-kind commercial, System complete and qualified	Strong natural or created lead market necessary, makes compensating revenue generation to balance costs possible.
	9	Commercial operation in relevant environment, actual system proven in operational environment	Strong natural or created lead market necessary “
Early adoption	10	Integration needed at scale	Moderate natural or lead market support necessary.
Mature	11	Proof of stability reached	Natural or created lead market no long necessary.

Emerging technologies for primary energy supply

Airborne wind energy (TRL 3-5)

What is airborne wind energy, and where and how is it useful?

Airborne wind energy aims to harness the potential of high-altitude winds that are hundreds or even thousands of meters above the surface of the earth, using flying aircraft that are tethered to the ground. Conventional wind turbine designs that are mounted on towers are not tall enough to take advantage of high-altitude wind energy, as even the tallest⁴ are only around 200m in height. Wind movements at high altitudes (e.g., 500m+) are much faster than those close to the surface of the earth (Archer, 2013; Archer and Caldeira, 2009) and contain much more potential energy. It has been estimated that the total energy contained in high altitude winds is around 4x the level available to tower-mounted turbines, and 100x the primary energy demand of the entire world (Marvel et al., 2013). An additional advantage for airborne designs over fixed towers is that an airborne system could, in principle, dynamically adjust its height and orientation to maximise its generation output over time, leading to higher capacity factors and better returns on investment (Archer et al., 2014).

The various concepts that exist for airborne wind energy systems can be split into two groups; those where the electricity generator itself is airborne, and those where the flying parts of the system are used to mechanically drive a ground mounted electricity generating station (Cherubini et al., 2015).

Designs with a ground station generator are sometimes called “pumping kite generators” (Argatov et al., 2009) or more simply, “energy kites”, because the airborne elements that drive the system typically have wing surfaces that resemble kites. As of 2018, more than 60 research institutes were involved in airborne wind energy R&D activities around the globe (IRENA, 2021b). A number of companies are working to commercialize energy kites, including KiteGen (Abbate and Saraceno, 2019; Canale et al., 2009), Ampyx Power (Kruijff and Ruiterkamp, 2018; Ruiterkamp and Sieberling, 2013; Vimalakanthan et al., 2018), SkySails Power (Erhard and Strauch, 2018), Kitepower (Salma et al., 2020), and EnerKite (Bormann et al., 2013; Candade et al., 2020).

Designs where the electricity generating unit itself is mounted on a lifting balloon or in a flying wing are sometimes called “airborne wind turbines” (Ali and Kim, 2021). This space has seen a number of high profile companies go out of business in the last decade, including Makani Power (Vance, 2009; Wijnja et al., 2018) and Sky Windpower Corporation (Roberts, 2018; Roberts et al., 2007), though others remain, such as Joby Energy and Altaeros Energies (Vermillion et al., 2013). While there isn’t sufficient information to be definitive, it would seem the firms working on this technology are stuck at the very expensive large prototype development stage, before any revenue or new large commercial financing can be generated.

The concept of airborne wind energy has been under development since at least the 1970s. Momentum in the sector gathered pace particularly in the last two decades, with the worldwide community growing to around 40-50 research groups with various commercial spin-outs (Khan and Rehan, 2016). At the time of writing, a few companies have produced power generating prototypes as large as 600 kWe in size (Vermillion et al., 2021), and regional feasibility studies on high altitude wind energy resources have been carried out in promising locations (Bechtle et al., 2019; Lunney et al., 2017; Yip et al., 2017). However, there are currently no market ready systems available for commercial deployment. The Technology Readiness Level of various individual airborne wind energy systems is estimated to lie on a spectrum between TRL 3 (concepts need validation with prototype) and TRL 5 (large prototype proven in deployment conditions) (Watson et al., 2019). The International Energy Agency ranks the field as a whole at TRL 4 - i.e., early prototypes proven in test conditions (IEA, 2020a).

⁴ At the time of writing, the tallest commercially available wind turbine is the Vestas 164, total height 220m / 722 ft.

Potential Contribution to Climate Mitigation Efforts

Renewable energy resources feature strongly in nearly all global and regional analyses of decarbonization pathways that aim to stabilise the climate below 1.5 °C of warming above preindustrial temperatures. Airborne wind energy specifically, however, does not feature in major assessments e.g., IEA (2021). This is likely due to the immature state of the technology, the lack of widely agreed-upon development roadmaps, and the uncertainties in the data on long-term costs and performance (van Hussen et al., 2018). The urgency of taking early action to reduce emissions in order to mitigate the worst effects of climate change (IPCC, 2018) makes a focus on solutions that are market ready today and available for immediate deployment a priority. As promising as they might appear, airborne wind energy systems do not currently fall into this category. This does not rule out a longer-term contribution to climate stabilization efforts (which are likely to take many decades) from airborne wind energy but it does make any near-term role for the technology highly uncertain. The subject of airborne wind energy continues to feature regularly in discussions of innovation for wind power at major industry workshops and discussion forums (Veers et al., 2019).

Social, institutional, economic, and business preconditions for airborne wind energy

The size of the future market for airborne wind energy devices is difficult to assess, as the breakthrough moment for the technology to be commercially viable has yet to materialise. From a physics perspective, the size of the potential exploitable resource is very large, and the costs of the energy harvesting units themselves are potentially low because they are made of lightweight (but high technology) materials, which in principle makes for a strong value proposition (Zillmann and Bechtle, 2018). They also possess a strong competitive advantage in adding new potential resource extraction zones, with minimal needs for steel and concrete supports and the land and seabed they sit on and in (IRENA, 2021b). But it is not yet clear when, or if, airborne wind energy systems will achieve cost competitiveness at scale with other renewable energy technologies (van Hussen et al., 2018). It is notable that one of the most prominent companies in the field, Makani Power, even when backed by companies as large and well-resourced as Google and Shell, recently exited the market, suggesting that the unresolved barriers to commercialisation remain formidable.

From a technology perspective, safety and reliability remain the main concerns (Salma et al., 2020). The control system for an airborne wind system is much more complex than that of a tower mounted turbine. At the time of writing, the prototypes that have been demonstrated have had only a limited number of flying hours to test their ability to generate electricity as a proof of concept. For airborne wind energy systems to become a credible source of renewable energy, the sector will need to develop (and prove) the capability to enable extended automated operation, including take-off and landing. As well as the control systems, the materials and components used in airborne wind energy units (particularly the tethers which attach the flying elements to the ground) must also be tested to prove their long-term operation and safety. Finally, airborne wind energy developers have yet to demonstrate how safe operation would be maintained in adverse weather conditions including high wind speeds, lightning, ice, rain and snowfall, a set of challenges which must also be resolved. Until more is known about how airborne wind energy systems perform over extended periods of operation, the eventual cost of the energy produced is likely to remain only speculative. A key fundamental challenge is companies in this space are stuck in a cycle where they have low flying hours demonstrated and not much data to prove their reliability to investors, so nobody approves them for further demonstrations – there may be a role for governments and/or consortia of private actors helping accumulate flying hours to prove the commercial concept.

From a regulatory perspective, there is no standardised approach towards airborne wind energy systems in the same way as there exists for commercial freight and passenger aircraft. Current prototypes tend to

operate with special, time-limited permits to utilise small pockets of airspace for testing purposes based on ad-hoc local safety assessments (Salma et al., 2018). This means that the entire regulatory and permitting framework for airborne wind energy has yet to be established. Public resistance towards airborne wind energy systems is expected to be on a similar level to, or greater than that for conventional wind turbines (van Hussen et al., 2018). Noise and safety are expected to be the main sources of concern, followed by the environmental impacts on bird populations (Bruinzeel et al., 2018).

Governments can, if they choose, assist in several key areas, such as providing funding for fundamental research in materials and control systems, expanding the (often very limited) number and size of testing sites, and facilitating future market access through the development of regulatory standards for commercial operations. Obtaining additional data on performance, costs, and reliability as well as establishing a track record of safe operation will be key to securing further investor funding and building public trust in airborne wind technology. The main cross-cutting solution is to obtain more information from small-scale demonstration projects.

Most new technologies that eventually commercialize have an initial niche application that only they can fill (see policy section), which pushes innovation and drives down costs, e.g., in satellites and remote sensing for solar. A promising early niche is believed to be providing power in remote locations where energy costs are already relatively high, and the established competition tends to be diesel generators and solar power (Kamp et al., 2018). Airborne wind energy may have niche application for off grid loads bigger than that which can be met with solar, or in regions with poor solar insolation or needing more 24-hour power than solar and batteries can provide, e.g., mining camps or deep ocean island grids. For this to occur, however, the technology needs to evolve to a higher level of robustness and autonomy as well as lower costs.

Floating wind systems (TRL 8+)

What are floating wind systems, and when and where are they useful?

The majority of existing offshore wind farms are found in water 50m or less in depth (IRENA, 2020a). Floating wind energy generators have the potential to exploit wind energy resources found in much deeper waters than fixed offshore wind towers. The main difference between floating wind turbines and fixed offshore wind towers is the support system. Rather than fixed foundations on the sea floor, floating wind turbines are held in place with various anchoring systems (Jonkman and Matha, 2011; Manzano-Agugliaro et al., 2020), with the “best” design for any given installation depending on multiple criteria (Leimeister et al., 2018). There are two main designs receiving large commercial investment: spar-bouys (e.g., the Equinor lead Hywind project in Scotland) and spar-submersibles (e.g., the Principle Power lead Windfloat project in Portugal, the Ming Yang Yangxi Shapa III floating prototype in China). Spar buoys are single cylinder designs moored to the seabed, are simpler and less costly to initially build, but turbine installation is harder, needing speciality ships, and they need deeper water, i.e., >100m. Spar submersibles are more complex (like small oil rigs), but can be built, assembled and turbine installed in port and towed to their installation area (International Renewable Energy Agency (IRENA), 2016; IRENA, 2021b).

The main rationale for developing floating wind energy is that in many ocean territories, the sea floor rapidly deepens with distance from the coastline, leaving very few locations shallower than 50m to put conventional offshore wind turbines. Many regions have strong offshore wind energy potential but also deep and difficult territorial seafloor geography (known as bathymetry). Examples include Japan (Bardenhagen and Nakata, 2020; Utsunomiya et al., 2020), Portugal (Castro-Santos et al., 2020), Spain (Colmenar-Santos et al., 2016), California (Beiter et al., 2020; Dvorak et al., 2010), Brazil (de Assis Tavares et al., 2020), Mozambique, South Africa, Somalia, Madagascar and Morocco (Elsner, 2019). In these

regions, many sites with attractive wind speeds and wind power density have been identified that could in principle be accessed with floating wind energy platforms.

There are other advantages to floating wind energy that are worth mentioning. In principle, the floating turbines can be assembled on land in the controlled waters of ports and then towed offshore to their intended generation sites. This avoids the requirement to construct the turbines and especially their generating units in the marine environment, exposure to risks from rough weather, etc. which overall has the potential to significantly reduce costs (International Renewable Energy Agency (IRENA), 2016). In mid-depth conditions (30-50 metres), they may in time offer a lower-cost alternative to fixed-bottom foundations, given the potential for standardisation of foundation designs and the use of low-cost, readily available installation vessels. Floating turbines can also be completely removed at the end of their life, with the anchor system taken up and the generating platform towed away for reuse or recycling, something that is difficult to do with a fixed tower turbine where typically the foundation is left behind on the seabed (Topham and McMillan, 2017).

Floating wind energy designs are found at a variety of Technology Readiness Levels (TRLs). The most technologically mature designs are floating horizontal axis wind turbines at TRL 8-9, with other designs, such as floating vertical axis wind turbines, at TRL 4-5 (Watson et al., 2019). Overall, the International Energy Agency (IEA) rates floating offshore wind turbines at TRL 8, i.e. first-of-a-kind commercial demonstration (IEA, 2020a). Various technology demonstration prototypes (typically just one turbine for testing) have been in operation since 2007, with the world's first full-scale floating wind farm opening in Scotland in 2017. Early operational data from the Scottish plant (Hywind, developed by Statoil/Equinor) has exceeded expectations, demonstrating capacity factors over 60% and the ability to survive exposure to hurricane force storms (Dinh and McKeogh, 2019). A second floating wind farm (WindFloat) has been operational in Portugal since 2020. The largest floating wind farm at time of writing (July 2021) is the Kincardine 50 MW+ project, which comprises of a single 2 MW pilot and five 9.65 MW Vestas turbines. In Norway, Hywind Tampen, which began construction in 2020, is projected to be one of the largest floating offshore wind facilities worldwide, with 88 MW of installed capacity (IRENA, 2020b).

Potential Contribution to Climate Mitigation Efforts

The market for floating offshore wind energy grew from 0 – 57 MW in the period 2008 – 2018 (Hannon et al., 2019), while the total global offshore wind energy potential is estimated as being as high as 329,600 TWh/year for capacity factors above 20% when only suitable areas for development are considered (Bosch et al., 2018), i.e. within non-disputed Exclusive Economic Zones (EEZ) and at reasonable depths. According to Bosch et al (2018), if only the potentials in locations with the highest quartile (25%) of capacity factors are summed, 83,229 TWh per year is available. This indicates that multiple order of magnitude increases in the market size for floating wind energy are possible; using the 25% capacity factor limit, Bosch's estimate is double the extra generation needed in the IEA NZE scenario (International Energy Agency (IEA), 2021). Industry expects floating wind energy designs to become commercially competitive during the 2020s (deCastro et al., 2019). Several countries and territories (California and France, for example) have recently released tender offers for floating offshore wind projects. Several very large floating wind farms have been proposed on the US western & eastern seaboard, using very large units, e.g., the 10 MW+ GE Haleide-X system.

The need for large-scale deployment of renewable energy generators in historically unprecedented quantities is a mainstay result of climate mitigation analyses that show reasonable chances of limiting anthropogenic warming to 1.5 °C (Bruckner et al., 2014; L Clarke et al., 2014; IPCC, 2018). Wind and solar photovoltaic energy are generally thought of as the front runner technologies for renewable power generation, with hydropower being largely constrained by the geographical distribution of hydrological resources (deep geothermal, using precision drilling developed for fracking, may provide a surprise).

Moving air and sunlight are much more ubiquitous resources. An important constraint on wind energy has always been the challenge of finding generation locations that are not constrained by wind availability, restrictive community planning policies, seabed geography, or i.e. Not-In-My-BackYard-ism (NIMBYism) (Graham et al., 2009).

The biggest long-term limitation to uptake of offshore floating wind is not likely technical nor resource availability, but cost. Auction based solar PV prices in the early 2020s in high solar insolation places are at USD \$0.025/kWh and still falling, onshore wind is at USD \$0.03-0.04/kWh, and fixed offshore wind is at \$0.05-0.08/kWh (IRENA, 2021b). All three still have very large amount of build out before them before promising, low conflict sites are exhausted. What floating offshore wind offers at USD \$0.13-\$0.15/kWh is higher capacity factors comparable to fossil plants, very large untapped resources with very much reduced land use and seascape use conflicts.

Put simply, commercially available floating wind would mean in principle that offshore wind power would become much easier to do in many more places. This could make a significant contribution to climate mitigation efforts. For much of the last decade, floating wind turbines did not generally feature in long-term decarbonisation pathway analyses because the costs and feasibility of the technologies were not well understood, but this has recently changed. Floating wind turbines now feature in the International Energy Agency's latest net-zero transition roadmap (IEA, 2021), where they are expected to making a major contribution from the 2030s onwards. IRENA projects that for a 1.5C scenario we will need 2000 GW of offshore wind, and that 300 GW will likely be floating (IRENA, 2021b). They are also starting to appear explicitly in net-zero roadmaps for major economies, such as the United States (Larson et al., 2020).

Social, institutional, economic, and business preconditions for floating wind energy

Despite successes with the early commercialisation of the technology and positive momentum in terms of government support, a range of unknowns persist for floating wind energy that deserve additional attention from researchers. As of 2018, the average depth for floating installations was only around 65m (Hannon et al., 2019). This is already much deeper than is commercially viable for a fixed tower turbine with a foundation on the seabed. However, developers still hope to harness wind power on sites with ocean floor depths that are much deeper, with water depths in the hundreds of meters. As the wind speed is often much faster on sites that are further out to sea, this may require additional work on advanced materials to provide stronger structures (Veers et al., 2019), and designs that can endure repeated exposure to tropical cyclones i.e. hurricanes and typhoons (Han et al., 2014) or icing conditions. More research is also required on how to minimise the impacts of floating wind energy on deep-water marine wildlife and ecosystems, which early work suggests should be positive (more marine organism anchor points) but definitely requires attention (Farr et al., 2021).

Existing floating wind energy systems tend to use marine structures that are adapted from designs used in the offshore oil and gas industry (i.e., they were originally designed for something completely different). It is believed that there remains significant scope to optimise the design of floating wind generators from first principles in order to reduce costs and increase performance (Watson et al., 2019). Multiple possible configurations of floating platforms and anchoring systems still need to be explored and tested (González and Diaz-Casas, 2016; Uzunoglu et al., 2016). For example, using vertical axis wind turbines instead of horizontal axis wind turbines (Hand and Cashman, 2020), using multiple turbines on a single floating platform (Bashetty and Ozelik, 2020), or hybridizing floating wind power installations with other marine energy generation technologies, such as floating solar power (Golroodbari et al., 2021) and wave energy generation (Hu et al., 2020).

Another key issue is transmission planning, and broader integration with the grid. Germany and Denmark provide a positive example, where a joined HVDC system has been constructed to allow two way balancing

and allow more offshore wind from both countries to come to market (IRENA, 2021b). The UK and Norway have also recently built more two-way transmission to allow Norway's hydropower balancing potential to aid uptake of renewables in the UK.

There are also regulatory issues going into the deep ocean. Local seas can be very active with shipping and fisheries, and marine spatial planning with intensive stakeholder consultation is needed to allocate space and corridors to allow floating to wind to work with other uses – Belgium's experience in this area to allow fixed offshore wind is instructive (IRENA, 2021b, p 90). Coastal states have the exclusive right to engage in economic activities, including energy production, in their Exclusive Economic Zone (EEZ) up to 200 nautical miles from the coastline. This provides a solid legal basis for regulation and expansion of this activity, except where there are disputed maritime boundaries between states. In the latter case, settlement or agreement between the states concerned would be a prerequisite to encouraging floating wind in deeper waters. There is also a need to comply with existing rules and standards on decommissioning of offshore installations, in United Nations Convention on the Law of the Sea, the International Maritime Organization Guidelines and Standards for the Removal of Offshore Installations and Structures, and various regional instruments. Issues include protection of marine environment and safety of navigation.

Given the multi decade effort to commercialize floating wind, and the very large size of the eventual prize, a mutually supportive effort between government and private industry is required. Support mechanisms for government to consider include: primary research funding into floating wind energy components and control systems, funding technology demonstration projects in partnership with industry, making sites available for development, and assisting in early market formation through assigned portions of renewable power standards, assigned feed-in-tariffs, capital grants and tax incentives for early commercialization (Bento and Fontes, 2019). See the policy section for a broader discussion.

Floating solar photovoltaic systems (TRL 8+)

What are floating solar photovoltaic systems, and where and how are they useful?

Floating solar photovoltaic (PV) fields (FSF) are not a new technology, but the combination of fully commercialized high TRL technologies combined in new ways, e.g., moored flat bottom boats and solar photovoltaic systems, including panels, transmission and inverters from direct to alternating current. It offers a new place to install solar PV that does not conflict with habitation, agriculture or biodiversity as long as key marine environments are respected, with several very large possible economic and non-economic co-benefits. The literature indicates two classes of opportunities, when the FSF is stand alone, and when it is retrofitted to or built with a hydroelectric facility as a hybrid. All the characteristics of stand-alone systems apply to hybrid hydroelectric systems, so we address the standalone facilities first, then the hybrid ones.

The potential benefits of a stand-alone floating solar PV include:

- **No new land use.** This has been of prime importance in areas with early adoption, e.g., in southeast Asia.
- **Potentially fewer obstacles to solar incidence.** This depends on the local topography.
- **Potentially higher efficiency from built-in cooling.** The theoretical improvement is 5-15% (Sahu et al., 2016), but observed values for early simple projects have been 0.3-2.6% (Oliveira-Pinto and Stokkermans, 2020). There is a natural cooling effect sitting on water, but various postulated active mechanisms that have not yet been commercialized could increase energy harvesting up to 8-10%.

- **Lower potential evaporation losses for hydroelectric dams and irrigation storage dams.** The benefits of this could be quite large, but depend on climate conditions, percentage of the covered surface, and the design of the FSF (Assouline et al., 2011; Sahu et al., 2016). Covers to prevent evaporation are expensive, and if the FSF can serve as least partial duty as an evaporative cover, it could prevent other capital expenditures.
- **Lower costs and less complex installation and decommissioning.** Floating PV plants are more compact than land-based plants, their management is simpler and their construction and decommissioning straightforward. There are no permanent alterations to the landscape, e.g., concrete foundations, so their installation can be totally reversible. Potential retrofits with higher efficiency panels would be faster and easier.
- **Solar tracking (which increases solar harvesting) is potentially easier & cheaper.** A large floating platform can be designed to be turned and perform vertical axis tracking without the need for a complex mechanical apparatus as required for land-based PV plants. A floating PV plant equipped with a tracking system has a limited additional cost, while the energy gain can range from 15 to 25% (Sahu et al., 2016).

The additional benefits of an FSF associated with a hydroelectric dam include (Lee et al., 2020):

- **The capacity to hybridize with existing hydroelectric systems.** Solar PV adds energy capacity to existing hydroelectric dam facilities, while the dams offer dispatchability. This can potentially greatly reduce curtailment in regions with large amounts of installed solar and wind.
- **When hybridized, the PV system can piggyback on existing transmission.** Access to transmission is one of the biggest constraints to new wind and solar PV generation projects.

Potential contribution of floating solar to climate mitigation efforts

Using a combination of geospatial, water body, solar incidence and practical constraints (e.g., distance from shore), Lee et al. (2020) estimate annual possible generation results ranging from 4,251 to 10,616 TWh per year, roughly 12.5-25% of the extra clean power generation needed for the IEA NZE scenario, without increasing land requirements.

Floating solar associated with hydroelectric generation also does not need firm “on-demand” power support, reducing overall system needs for firm power (Jenkins et al., 2018; Sepulveda et al., 2018). These are very large potential contributions, but will require appropriately designed water use, electricity, and climate policies to materialize. Electrification with low carbon electricity is a key strategy in all low carbon development pathways (Bataille et al., 2016; L Clarke et al., 2014; Davis et al., 2018; Williams et al., 2021), but requires combinations of policies to drive decarbonization of the electricity supply as well as broad switching to electricity in buildings, transport and industry.

Once the industry is established, the LCOE for floating solar PV is likely to be about USD \$0.01-0.02 per kWh more than

Social, institutional, economic, and business preconditions for floating solar PV

Most waterbodies have associated stakeholders who may have some reason for the solar field not being built there (e.g., in-shore fisheries, views from shore, swimming and water sports). We have focussed on hydroelectric reservoirs not just because of their proximity to transmission and good pairing with turbine generation (i.e., the FSF saves water for other times), but because utilities operating hydroelectric dams usually control use of the water body as well.

Hydroelectric operators may or may not be aware of the potential for floating solar PV to improve their business model, and they are often highly constrained in their choice of investment in generation and

transmission assets. International electric utility associations may be key to acclimatizing hydropower operators with the opportunity.

All marine environments carry wind & storm risk, and the floating solar PV array must be designed to withstand these.

Wave power systems (TRL 5-8)

What is wave power, and where and how could it be useful?

All wave power systems operate on the principle that moving water carries a substantial amount of energy, transferred from wind to the water by well understood physics. In principle, there is a very large wave power resource, estimated to be roughly 2 TW, but is it highly localized to certain parts of the globe (e.g., northwest Europe, northwest Pacific) (Gunn and Stock-Williams, 2012). Estimates of how much of this could be captured vary hugely from 4.6% across the entire potential to 80+% for site specific applications. Wave power is related to the consistency of wind over the distance the waves are created (a.k.a the “fetch”), and ranges from highly variable to highly consistent by site, meaning wave power can be classified as a variable or firm resource depending on the site.

Wave power has been explored for centuries, with the first applications for power generation being tested at small scale in the late 1800s and early 1900s. The modern study of wave energy did not begin until the late 1940s and was only seriously pursued starting in the 1970s following the 1973 oil crisis. The physics of how waves accumulate, carry, and disperse energy are well understood, and there many different potential wave energy converter (WEC) designs that use different methods to capture wave energy – the challenge is building something with high conversion efficiency that can survive the challenging marine environment while not interfering with local ecosystems, fisheries, etc. Power must also be transmitted to shore, entailing an expensive to install and maintain transmission network. Versions of wave energy conversion systems include:

- A **point absorber buoy** (TRL 7) uses the rise and fall of swells to generate power, using a linear, linear to rotary, or hydraulic generator.
- A **surface attenuator** (TRL 8) has multiple floating segments that translate the wave motion into a mechanical bending motion that turns a generator, either directly or through hydraulics.
- An **oscillating wave surge converter** (TRL 7) is attached to the sea floor, and the up and down motion is used by various means (e.g., floats, flaps, pistons) to make electricity.
- An **oscillating water column** (TRL 8) uses the up and down energy of the wave to compress air, which is then used to generate electricity via an air turbine.
- An **overtopping device** (TRL 9) essentially creates a small hydro dam from waves transferring water into a storage chamber with a turbine.
- **Submerged pressure differential** (TRL 6) devices typically use a flexible membrane to capture the pressure differential induced by waves at various depths, transferring this energy to a hydraulic fluid. They can be near the surface, mid-depth or on the ocean floor, and can be moved and adjusted with incoming waves.

Potential contribution of wave power to climate mitigation efforts?

Wave power is highly localized, with some regions have huge potential (e.g., the UK) and others none. It is also at a much lower level of technical development compared to solar PV, onshore wind, offshore fixed wind, and offshore floating wind, all of which will capture most near-term investment and cumulative

global economies of scale and innovation. For all these reasons, it is not possible to reasonably assess the potential global contribution.

The current levelized cost of energy for wave power is estimated at USD \$0.30-0.55/kWh. Recent estimations by developers with active projects show that costs may be lower, reaching USD \$0.22/kWh by 2025 and USD \$0.165/kWh by 2030 (IRENA, 2020c). These high-cost levels mean wave power systems are not at a level of development where their contribution to climate mitigation can be discussed, but similar criticism were levelled at solar PV and wind before early commercialization and economies of scale and innovation brought their costs down.

Social, institutional, economic, and business preconditions for wave power

All the social, institutional, and governance challenges listed for offshore floating wind above apply to wave power systems. Wave power systems are not at a TRL yet where competitiveness can be discussed.

Given the precarious health of many ocean ecosystems and fisheries globally, there is a higher focus now on potential damages of ocean energy harvesting. There is concern about wave energy devices interfering with fish and other marine life during their installation, operation, maintenance, and decommissioning, both directly and with food sources. All marine environments carry high energy storm risk, and the WEC must be designed to withstand all likely seas; the ocean has really high energy flows, and there are floating lost containers, logs, other debris etc. that can interfere with wave energy conversion devices.

Finally, regulatory protocols for seaborne energy are still being developed, and are currently derivative of offshore oil & gas regulations. As with tidal energy, the UK is perhaps the most advanced in this area, and state of technology can be described as being where wind was in the 1980s and 1990s, with less potential to be expanded elsewhere beyond maritime nations.

Tidal power systems (TRL 5-8)

What is a tidal power system, and where & how could it be useful?

Tidal power makes use of the compound gravitational effects of the moon travelling around the earth and the earth travelling around the sun, raising and lowering the water level and generating strong currents with very high-power density compared to air. There are four main types of tidal power systems that have different potentials and social, institutional, economic, and business preconditions: tidal barrages, tidal stream generators, dynamic tidal power, and tidal lagoons. All share the advantage that moving water carries about 800 times the energy of wind at the same speed, and the disadvantage of working in maritime conditions, with large & random moving obstructions (i.e., lost containers, logs, large marine life), corrosive salt conditions, and relatively large costs for installation, maintenance, and decommissioning.

Tidal barrage (TRL 9)

Tidal barrages make use of strong tidal flows in existing natural estuaries to create temporary hydropower dams. Effectively, the estuary is blocked with a dam that lets seawater in, the dam is closed, and the seawater is let out through a turbine. Tidal barrages can be designed to work bidirectionally as well. The power generated is a function of the volume of water and the height that the water falls. The largest existing tidal power facilities are tidal barrages at La Rance in France (240 MW), and Sihwa in South Korea (245 MW). This is a well understood, fully commercialized technology.

Tidal barrages dramatically alter the flow of water in and out of estuaries, however, and have very large ecological impacts for those with substantial aquatic life. They can also lead to substantial accumulation of toxic agricultural by-products, as happened at Sihwa (the design was modified to partly mitigate this, cutting its potential power in half). Recognition of this fact has largely ended development of new tidal

barrages globally, but there are still legacy proponents for projects in India (Gulf of Kutch, 50 MW), the UK (Wyre Barrage, 61.4 MW; Mersey Barrage, 700 MW; Severn Barrage, 8640 MW), South Korea (Garorim Bay, 520 MW; Incheon, 1320 MW), the Phillipines (Dalupiri Blue, 2200 MW), and by far the largest proposed project, Penzhin Bay at the isthmus of the Kamchatka peninsula in Russia (87000 MW). If the latter went forward, it would be the largest power project in the world by a wide margin.

Tidal stream generator (TRL 5-8)

Tidal stream generators are more akin to wind turbines than tidal barrages, which are more similar to hydropower dams. They sit “in-stream” in the tide without holding it back, generating power using a reciprocating device of some kinds, e.g., a turbine or reciprocating flap. The reciprocating action moves slow enough that in theory it should not disturb passing aquatic life. A successful in-flow tidal stream generator operated at Strangford Lough in Northern Ireland from 2008-2019.

Tidal stream generators can come in many different potential forms, and there is not yet a dominant technology as in wind turbines. Axial generators, the most common, resemble short and stubby wind turbines, and can sit on the ocean floor, be suspended, or float with the turbine submerged. Shrouded turbines and oscillating “kites” have also been tested.

Dynamic tidal power (TRL 4)

Dynamic tidal power is a newer concept that takes advantage of differential tide states along a coast to create pressure or head differences from which power can be generated. Discrete differential tide states are created by long barrages (~30km) that extend into the ocean, without entrapping any water bodies, in theory preserving dynamic tidal ecosystems in place. An optional “T” is placed at the end to maximize power. One barrage is estimated to have the potential to provide the necessary power for several million people, but unfortunately the effects do not scale down to shorter barrages. No full scale dynamic tidal power station has yet been built, but the concept, pioneered by two Dutch engineers, is being explored in China.

Tidal lagoons (TRL8+)

Tidal lagoons are simple concepts in that effectively an artificial encircled barrage is built in open water. Existing ecosystems are not affected. Only very small tidal lagoons have been piloted.

Potential contribution of tidal power to climate mitigation efforts?

The potential contribution of tidal power to climate mitigation is highly localized to maritime regions if it can be commercialized, and highly uncertain. No new large tidal barrages are likely to be allowed for environmental reasons. For tidal power to succeed it is likely that some form of tidal stream generator will need to be commercialized that is both highly robust and amenable to different environments and conditions globally. This may require a jump forward in maritime engineering.

The current levelized cost of energy for tidal is estimated at USD \$0.20-0.45/kWh. As with wave power, recent estimations by developers with active projects show that costs may be lower, and an LCOE of USD \$0.11/kWh is expected to be reached between 2022 and the early 2030s (IRENA, 2020c). This would make tidal power competitive with floating ocean wind auction prices for the early 2020s today, which will keep improving, and its prospects must be seen in this light. Again, similar criticisms were levelled at solar PV and wind before early commercialization and economies of scale and innovation brought their costs down.

Social, institutional, economic, and business preconditions for tidal power

For tidal stream generators to succeed commercially, especially against already commercialized solar PV, onshore and offshore fixed and floating wind, they will need to first prove their robustness and that they are cheaper or have an application not met by the other renewable sources. The UK is perhaps the most advanced in this area, and the state of technology can be described as being where wind was in the 1980s and 1990s. Marine estuary blockage systems are incredibly disruptive to local sea-life & fisheries and are highly unlikely to be approved in the future. Future systems, to meet complex multi-attribute social and economic goals, must be able to “sit in” the tidal flow without disrupting fisheries, local sea life, tourism, etc.

Ocean thermal energy conversion systems (TRL 5-6)

What is ocean thermal energy conversion (OTEC), and where & how could it be useful?

OTEC is a fairly simple and theoretically well understood potential source of primary energy that utilizes the difference between ocean temperatures at the surface (it is therefore a form of derivative solar energy) and at depths of 1000+ metres. It requires a 20°C thermal differential, and because the ocean is at a roughly constant 4°C at depth, this means the surface temperature must exceed 25°C, which only occurs between 30° North and 30° South. While there are various basic designs (e.g., “closed cycle” using ammonia or another working fluid, “open cycle” directly using seawater, and hybrid systems) they all draw in cold water from the deep ocean using long pipe systems and utilize the temperature differential with surface water to run a heat engine and thereby generate electricity. Most OTEC designs also have several promising co-benefits: they provide firm, round the clock power, in contrast to solar PV & wind; they can produce cold water for air conditioning; and, perhaps most importantly in some contexts, they can produce desalinated water for drinking and irrigation. This has spurred interest in these systems for island needs in the deep ocean.

OTEC faces several technical and potentially costly to fix challenges to widespread adoption. First and foremost is building and maintaining the piping system into deep water in the face of ocean energies and storm potential. Shore mounted OTEC piping must pass through the wave shore, and ocean mounted OTEC has to transmit back to shore. Secondly, because ocean water must contact the heat exchangers at some point in either a closed or open system, microbial fouling has proven difficult to avoid without using chemicals toxic to marine life, and only a small amount of fouling can dramatically reduce efficiency. These challenges have been by and large overcome in pilot facilities, but at considerable cost.

Potential contribution OTEC to climate mitigation efforts?

OTEC technology is still in the R&D & early prototype phase, and unlike wave and tidal technologies the players are not commercial but are mainly research institutes and universities. The technology saw a surge in interest from the 1970s through late 1980s which ended in the early 1990s. While there are many site-specific case studies and conference presentations there is very little high quality peer reviewed literature on OTEC, with much of it predating 2005. The only modern, systematic and peer reviewed literature review we could find was Langer et al (2020), and it found numerous methodological deficiencies in the existing 2005-2020 literature (e.g., lack of systematic costing, handling of interest rates, discounting, absence of technological learning).

While the potential primary energy from OTEC has been calculated using a global marine circulation model to be very large (~30 TW), translating to roughly 44,000 TWh per year, and the technical potential 3.4-10 TW (Langer et al., 2020), the complexities and capital costs of operating in the ocean environment will likely limit its use to deep ocean islands that need locally sourced firm “round the clock” power and desalination services. Even in these conditions, OTEC will be competing against solar PV, wind, and green

hydrogen made using electrolysis as a storage medium. It is indicative that most large experiments with OTEC have been in Japan (with its large population to surface area and large deep ocean contact), Hawaii, and at remote islanded US military bases. Several 100 kw sized pilot systems have been successfully run, and 10 MW sized systems have been seriously studied for US military bases in the Pacific and Indian oceans.

Mainly due to capital costs and operating in a marine environment, costs per kWh are estimated across many studies at USD 2019 \$0.20-0.67 per kWh 2019 for 10 MW sized units (Langer et al., 2020), falling to USD 2019 \$0.04-0.29 per kWh for 100 MW sized units with learning and scale, which puts it above solar PV (\$0.02-0.05 per kWh) and wind (\$0.03-0.07 per kWh) costs including battery (+\$0.01-0.02 per kWh for overnight kWh) or hydrogen storage (+\$0.02-0.05 per kWh plus pressure vessel storage at 40-50% round trip efficiency). OTEC's key advantage against other renewables is likely to be its capacity to do desalination for drinking water and irrigation on arid islands with limited space for solar PV & wind, but this will limit economies of scale and learning enjoyed by the other renewables.

Social, institutional, economic, and business preconditions for OTEC

While there are as yet no serious social or institutional barriers to OTEC (large MW scale systems may provoke resistance by local ocean users such as fisher people due to the discharge of deep ocean water in the local ecology), there are very serious economic and business barriers to widespread OTEC adoption.

A South Korean has successfully seasonally operated a 20 KW OTEC system, and is now working to build a 1 MW system for Kiribati, which would represent 1/6 of its electricity generation system. This pilot will provide both engineering data and feedback on social, institutional, and business conditions for operating OTEC systems (IRENA, 2020c).

Bioenergy associated with carbon capture and storage (TRL 6-8)

What is BECCS, and where & how could it be useful?

To set the stage for our discussion, bioenergy refers to plants (a.k.a biomass) that can be harvested and used to extract energy, from the simplest forms of wood burning to sophisticated gasification and refining techniques more familiar to fossil hydrocarbons and alcohols. It can include plants (e.g., corn for making ethanol), food wastes, forestry waste, pelletized wood, sugar bagasse waste (which is used in Brazil and other places for making ethanol), grasses, almost anything that is grown. The net CO₂ effect of using bioenergy is highly dependent on the type of biomass and how it was extracted (Hepburn et al., 2019) – very broadly speaking, cutting a forest for bioenergy while destroying soil cover will tend towards carbon positive, while growing annual switchgrass for bioenergy on degraded agricultural lands (thereby increasing soil carbon) will tend towards carbon neutral. The results are, however, highly site, process, and ecology specific.

Very simplistically, there are four ways by which biomass is turned into energy: burning, which produces mainly CO₂ and steam; anaerobic digestion to CO₂ and methane; fermentation to CO₂ and alcohols (methanol and ethanol); and cellulosic transformation of woody biomass to hydrocarbons or alcohols by a multistage process that transforms woody cellulose into fermentable sugars, again with by-product CO₂.

Bioenergy with Carbon Capture and Storage (BECCS) refers to the use of biologically derived fuels or feedstocks (as above), either in energy generation or manufacturing, combined with the means to capture the CO₂ waste stream. This latter step prevents the release of CO₂ to atmosphere and the corresponding contribution to anthropogenic global warming. The captured CO₂ can then either be processed for long term geological storage (CCS) or used in a variety of industrial applications, often referred to as carbon capture utilisation, (CCU). The final net GHG effects vary with retention time and method of final disposal, i.e., to the air as waste, or into geological sequestration. BECCS is frequently discussed as if it is a single

technology category or a type of technological artefact but is more akin to a type of supply chain strategy that could have different inputs and different performance characteristics when implemented in different regions. Widespread real-world deployment of BECCS might involve a mixture of different fuel types (e.g., from agricultural by-products, energy crops, harvested wood from forestry management activities), CO₂ capture and storage approaches (e.g., saline aquifers, depleted oil fields), and target industries (e.g., power and/or heat generation, manufacturing, synthetic fuel production).

BECCS has the potential to be a negative emission technology, one that (on balance) removes atmospheric CO₂ and contributes to a reduction in mean global surface temperatures (Gasser et al., 2015; van Vuuren et al., 2013). For this to be the case, the bioenergy fuel used in the process would need to absorb more CO₂ from the atmosphere during the plant growth cycle than is used in cultivation, and most of the waste stream would need to be captured and stored (Hepburn et al., 2019; Smith et al., 2015). BECCS can be considered an early stage technology, with only five operational facilities found worldwide; one of which is a large-scale facility (in Decatur, Illinois, United States) and four of which are demonstration or pilot scale plants (Global CCS Institute, 2019). Depending on the application (power generation or industry) the International Energy Agency considers BECCS to be at Technology Readiness Levels 7 or 8, i.e. considered either pre-commercial demonstration, or first of a kind commercial (IEA, 2020a).

Potential Contribution of BECCS to Climate Mitigation Efforts

The earliest mention of the concept of sequestering emissions from bioenergy use in the peer reviewed literature appeared in 2001 (Obersteiner et al., 2001) as a so-called “backstop” technology (Nordhaus et al., 1973), something to be used when the preferred course of action (i.e. mitigation through more established technologies) has failed. BECCS as a technology category within energy models and energy scenarios saw a rise in prominence during the 2010s, appearing with increasing frequency in modelling assessments as the most prominent of negative emission technologies in IPCC AR5. This emergence in the literature can be tied to institutions working on climate mitigation increasing the stringency of their transition pathways in line with increasing global and national levels of ambition. BECCS is the focus of much discussion in work aimed at understanding how to implement the Paris Agreement aspiration for “net zero” emissions by mid-century (UNFCCC, 2015).

The IPCC’s 5th Assessment Report (AR5) (L Clarke et al., 2014) found that 101 of the 116 scenarios (87%) that would limit warming to below 2°C required BECCS to deliver this transition (Fuss et al., 2014). Since the time that AR5 was conducted, a broader range of climate mitigation options, including reductions in energy demand (Grubler et al., 2018), afforestation and land use change (Humpenöder et al., 2014; Reilly et al., 2012; Smith et al., 2015), and direct air capture (Fasihi et al., 2019; Keith et al., 2018; Sanz-Pérez et al., 2016; Wilcox et al., 2017), have come to feature more prominently. Transition pathway analyses that use these alternative options often find that their absolute reliance on BECCS to achieve climate stabilisation is reduced, but usually not eliminated. For example, the IPCC Special Report on 1.5 °C (IPCC, 2018) shows a strong role for BECCS at scale, as does the International Energy Agency’s latest net zero study, but at a reduced level (International Energy Agency (IEA), 2021). BECCS in various forms also continues to be prominent in detailed regional studies of transitions towards net zero emissions, e.g., for the United States (Larson et al., 2020; Williams et al., 2021), China (Huang et al., 2020), and the EU (Solano-Rodríguez et al., 2016).

Social, institutional, economic, and business preconditions for BECCS

As noted above, BECCS is an early-stage technology that (at the time of writing) is just moving past the demonstration stage towards limited commercial deployment. Due to relatively high costs compared with other mitigation options, the uptake of BECCS would need to be driven mainly by climate policy initiatives in different regions. The complexity of the overall supply chain and the lack of non-climate related

incentives makes it unlikely that BECCS projects would spontaneously emerge under current market forces. If BECCS is to ever be deployed at scale, a very strong climate policy environment with Paris Agreement linked targets and appropriate transition planning to introduce the technology would be mandatory. The other preconditions for BECCS deployment are the availability of both bioenergy fuels and carbon capture and storage infrastructure, which face their own social, institutional, and economic barriers.

Bioenergy resources

The sustainability potential of bioenergy has been the subject of intense debate (Searchinger et al., 2009, 2008). The production, processing, and transportation of the bioenergy fuel itself may generate emissions that offset or reduce the negative emissions potential of BECCS. In an extreme case, if more emissions are generated in cultivating the fuel input to BECCS than is captured from atmosphere then this would compromise the assumption that BECCS is a negative emission technology (Agostini et al., 2013; Vaughan and Gough, 2016). In order to avoid this possibility, the use of BECCS would need to be accompanied by robust regulations stipulating that low carbon bioenergy inputs be used, trusted standards to certify the life-cycle emissions of the fuel are employed, and that capable institutions are empowered to monitor and enforce compliance. Establishing a life-cycle accounting and management process for validation and verification of the whole supply chain for BECCS fuels is likely to be challenging and would require significant investment and an accompanying incentive structure.

Depending on the source, bioenergy fuel requires many of the same inputs as food production (i.e., water, fertilizer, land etc.). Much analysis has explored whether or not the use of land for bioenergy might negatively impact food prices for consumers, ecosystem diversity, and agricultural livelihoods (Creutzig et al., 2015; Tilman et al., 2009). Supplying bioenergy fuel to meet the upper range of BECCS use found in model assessments that stabilise the climate at 1.5 or 2° C has potentially onerous requirements. Studies have contextualised the scale of the challenge by illustrating that widespread use of BECCS might involve land use comparable to the total surface area of India (Anderson and Peters, 2016), and water use that is equal to double the amount used globally for agriculture (Fajardy and Mac Dowell, 2017).

It is difficult to conclude with the kind of certainty desired by policy decision makers exactly how much bioenergy can be produced in the future before competition with food production or with natural ecosystems might make this activity socially unacceptable or ecologically irresponsible, and the upper and lower bounds of estimates can be wildly divergent depending on a range of broadly plausible assumptions (Slade et al., 2014). The suggested remedy for this lack of policy certainty found in the literature is to incrementally fund progressively more ambitious energy crop demonstration projects with a view to obtaining more data on the costs and trade-offs involved.

Carbon capture and storage infrastructure

From a technological perspective, carbon capture and storage is a mature process with few knowledge barriers – it reutilizes known oil and gas extraction and processing technologies in new ways. The process of injecting CO₂ into oilfields as a means of enhancing flow rates, a process called enhanced oil recovery (EOR), has been employed in the oil extraction industry for decades. The barriers to widespread deployment are largely socioeconomic and institutional in nature. While captured CO₂ can and does have a variety of industrial applications, the investment required to capture CO₂ from power generation is relatively expensive compared to the value of the CO₂ itself. As a result, carbon pricing market structures sufficiently broad and stringent to incentivize the development of the extensive infrastructures needed for capture and storage have not existed to date and may only be coming into existence now. In effect, the price of emitting CO₂ must reach at least \$20-40 per tonne on all emissions to trigger CCS for existing concentrated flows, and \$50-\$125 per tonne to trigger post combustions CCS projects (Kearns et al., 2021;

Leeson et al., 2017; Mac Dowell et al., 2017). The market for CCS and BECCS, like many emission mitigation technologies, must be politically constructed as part of a deliberate effort to transition away from the status quo (Meadowcroft, 2013). Even in high income countries with climate policy agendas, the policy support for carbon capture and storage has historically been weak and inconsistent (Scott et al., 2013). Active policy support from government to directly fund or create market incentives for the technology is required (e.g., direct fiscal payments, carbon taxation).

With appropriate policy support, long-term storage of carbon in reservoirs would mainly be constrained by geology and societal preferences. Captured CO₂ can potentially be stored in a variety of geological structures, such as depleted oil fields, coalbeds, and usually most securely, deep saline aquifers. The distance of these geological formations from power generation or industrial generation facilities, and the costs of infrastructure to connect from polluting sources to the CO₂ injection sites are key considerations that may influence the viability of CCS at scale (Rubin et al., 2015).

Research into the public perception of carbon capture and storage reveals a mixture of perspectives. Different actors in the public sphere perceive CCS differently, with for example, NGOs being more sceptical of CCS than governments (Fridahl, 2017). There is also a heterogeneity of viewpoints both within countries and between different countries. Broadly speaking, studies have shown that the issue of storage is perhaps the most controversial aspect of CCS for the public. The perceived risk of leakage from CO₂ storage reservoirs is often mentioned as a major concern (Johnsson et al., 2009), with residents who live close to proposed storage sites being significantly more likely to oppose CCS than those that live further away (Braun, 2017). Widespread public opposition to CCS projects has already led to projects being cancelled in the Netherlands (Brunsting et al., 2011) and in Germany (Dütschke et al., 2016), with the degree of opposition being so great in Germany that CCS has been almost completely absent from climate policy planning over the last decade (Vögele et al., 2018). A wide ranging meta-analysis of 42 different studies on public attitudes to CCS in 14 countries found that framing the role of CCS in the context of broader efforts to control GHG pollution is required to counter the perception that the technology represented an unwarranted “tampering” with nature (L’Orange Seigo et al., 2014). Successful CCS (and by extension, BECCS) deployment will require sustained communication and outreach efforts by governments to obtain a social license to operate, and regionally differentiated strategies are likely to be required (Gough and Mander, 2019).

Bioenergy with Carbon Capture and Storage appears in model-based exercises as an extremely important technology for future efforts to stabilise the climate but is simultaneously under-prioritized in terms of policy support and investment relative to other mitigation options (Fridahl, 2017). The anticipated political and social constraints to BECCS deployment are expected to be high (Fridahl and Lehtveer, 2018), and the controversies about the long-term sustainable use of bioenergy and the societal acceptability of long term storage of CO₂ underground are enduring. There remain concerns that net-zero pathways that emphasise BECCS are placing too much emphasis on a technology that may never be used at the scale imagined in models (Buck, 2016; Kartha and Dooley, 2015), and that this distracts from an important focus on other approaches to climate mitigation (Creutzig et al., 2021; Larkin et al., 2018).

For any of the mitigation potential of BECCS shown in model assessments to be realised in future, a number of hurdles would need to be overcome. Governments would need to successfully align the interests of agricultural producers, power generators and manufacturing industries in order to create a new supply chain for emissions sequestration. Policy support for BECCS would need to be massively increased over their current levels through market design or direct payments, as well as successfully obtaining societal buy-in from the public. A credible emissions accounting system for bioenergy fuels would need to be established alongside regional limits on land and water use to protect established ecosystems and food production. Lingering concerns about the safety of long-term CO₂ storage underground would also need to be addressed.

Emerging energy transformation and storage technologies to enable clean end-use energy

The next four technologies are not energy supply technologies, but technologies that expand the supply of end-use energy available using clean but variable primary energy sources, such as the ones listed in the last section.

Green hydrogen (TRL 8+)

What is green hydrogen, and where and how is it useful?

Hydrogen is a highly combustible, energetic gas that produces no greenhouse gases when oxidized (combusted), widely used as a chemical industry and refinery feedstock. It can be used for direct process heating at all widely used temperatures, it is a potential end-use fuel in internal combustion engines & turbines and is transformable into electricity using fuel cells for vehicles or stationary use. It is widely suggested as an alternate or complementary pathway to electrification for economy wide decarbonization (Bataille et al., 2018; L. Clarke et al., 2014; Davis et al., 2018; IEA, 2019a; IRENA, 2019b; Williams et al., 2021). How the hydrogen is made, however, is critical to its GHG impact.

While ideally hydrogen GHG intensity would be reported on its CO₂ emitted per kg produced basis, a common nomenclature has grown up around hydrogen production that works passably well but is not strictly informative as to the GHG intensity of the different production methods (IEA, 2019a):

- **Black hydrogen** is made via steam methane reformation of **coal** into H₂ and carbon monoxide or dioxide, generally for use as a chemical feedstock – it is the most GHG intense way to produce hydrogen.
- **Grey hydrogen** is made via steam methane reformation of fossil **methane**, usually followed by a water gas shift reaction to maximize the amount of hydrogen extracted from methane. It is usually the most economical way to create hydrogen today, usually for hydrotreating in crude oil refineries (i.e., the addition of hydrogen to carbon chains to make them “lighter”, generally more liquid and more combustible). It is also how most hydrogen is made for ammonia (NH₃) fertilizers globally, with the hydrogen and nitrogen catalysed into NH₃ using the Haber Bosch process, and then into urea.
- **Blue hydrogen** is the same as grey hydrogen, but the CO₂ produced by the steam reformation and gas shift reactions are captured and sequestered, normally underground. With 90%+ capture a 30-40% energy loss from combusting methane is incurred, but there is a 90%+ reduction in CO₂ released. The net GHG intensity of blue hydrogen is, however, like all uses of methane highly contingent on the methane leakage rate from well to reformer.
- **Green hydrogen** is a fundamentally different process for making hydrogen, where electricity is used in an electrolyzer to split water into hydrogen and oxygen. Electrolysis has been commercialized since the 1880s using large and heavy alkaline electrolyzers. However, there are two new ways to make green hydrogen that are entering the market. The first is the proton exchange membrane electrolyzer (PEM, TRL 8), which is lighter, smaller, and more modular, and therefore better suited to vehicles. It also typically uses expensive platinum catalysts. The second is solid oxide fuel cells (SOFC, TRL 6-7), which are larger, heavier and operate at higher temperatures, but are potentially more efficient and can operate in a dual directional mode, making them ideal for electricity to H₂ back to electricity operations. When operated at higher temperatures they do not need the expensive platinum catalysts used in PEM fuel cells. Because of the high temperatures at which they operate, they can also operate on lighter hydrocarbons such as methane, propane, butane, etc. If paired with CCS to capture the resulting CO₂ SOFCs can

be used to make clean electricity. There is another thermal version of electrolysis, where 600-800°C heat is used to separate hydrogen and oxygen (this has been done commercially with nuclear reactors), and it often goes under the moniker **purple hydrogen**.

Blue hydrogen is currently much cheaper than green hydrogen in most regions (\$1.5 vs. \$4-5+ per kilogram), and will continue to be so likely until at least 2030 (IEA, 2019a). The cost of green hydrogen is highly dependent on two things: the capital cost of electrolyzers (currently more than \$900/KW), and the cost of electricity (which needs to be \$0.02 per kWh or less to be remotely competitive with blue hydrogen (IRENA, 2020d). Economies of production are building for PEM electrolyzers, however, and over the coming decade or so their capital costs could fall to \$500/KW and perhaps even to \$200/KW. In regions with exceptional sun, poor CCS geology and strong hydrogen demand (e.g., southern Europe), green hydrogen could be cheaper than blue hydrogen by the end of the 2020s. This could start a virtuous circle of stronger demand and resulting lower costs, which will lead to more demand. Most global deep decarbonization scenarios show green hydrogen taking over from blue by the late 2030s or early 2040s and dominating thereafter (CCC, 2020; International Energy Agency (IEA), 2021). Blue hydrogen will likely hold market share well into the 2050s in regions with very cheap methane and good CCS geology (e.g., North America, the Middle East, and Russia).

Potential contribution of green hydrogen to climate mitigation efforts

The key attribute of green hydrogen is that it allows a means for transforming variable intermittent wind and solar PV electricity into a highly useful, storable energy carrier that can also be transformed back to electricity as needed. Round trip efficiencies are about 30-40% today but are expected to rise to 49% by 2030 with innovation (IEA, 2019a); this effectively means wind and solar produced for \$0.02-0.03 per kWh can be resold when needed as firm on demand power for \$0.05-0.07 per kWh, which could eventually transform the decarbonization of electricity grids. It also reduces the loss of renewable wind and solar through curtailment. In effect, it has the potential to add time and space option value to instantaneously generated wind and solar electricity, for on demand electricity, process heat, or chemical feedstocks (e.g., for making fertilizer, upgrading biogasification products, reducing iron ore to make steel, etc.). The potential contribution of green hydrogen could be very large but is highly contingent on the availability of relatively inexpensive wind and solar PV electricity. The IEA NZE report shows a quintupling of hydrogen use by 2050, with green hydrogen's contribution rising from 5% to 63% by 2050 as solar PV and electrolyzer costs fall. It is the largest single use of electricity by 2050 in the IEA NZE 2021.

Social, institutional, economic, and business preconditions for green hydrogen

The only commonly discussed objection to hydrogen in general is its flammability, with much of its cultural reputation being associated with the Hindenburg zeppelin disaster. All energy forms have handling and storage issues (e.g., electricity, natural gas, gasoline, LPG, diesel, ammonia), however; the only additional characteristic that may make hydrogen more difficult to handle is that it burns very fast and transparently, with no colour. It also has no smell - methane doesn't have a smell either, so to identify leaks mercaptan is added, which smells like sulphur or rotten eggs.

Hydrogen is also corrosive to steel in that it scavenges carbon atoms from stainless steel. Dedicated hydrogen pipelines & storage tanks would need special steel grades or plastic liners to prevent corrosion while operating at the higher pressures and volumes needed to deliver the same amount of energy in the same time as methane (hydrogen has 1/3 the energy per unit volume at the same pressure as methane). Plastic gas piping is impervious to hydrogen corrosion, which is partly why blue hydrogen is being experimented with as a heating fuel in northern England, where the gas piping has all been replaced with plastic.

Perhaps the greatest challenge hydrogen faces is the chicken and egg problem of infrastructure and end-use supply and demand. Substantial amounts of hydrogen are already made and used already for fertilizer production and hydrotreating in crude oil refining. In both cases the hydrogen is made, generally from methane or coal, on site where it is to be used. In early applications of green hydrogen, likely as chemical feedstocks for making ammonia fertilizers (Philibert and IEA, 2017), reducing agents for iron ore reduction (Vogl et al., 2018), or making CCU or biomass sourced CO₂ methanol (IRENA, 2021c), the hydrogen will likely be made & stored on site.

Another earlier bulk application is where green hydrogen is stored in salt caverns to provide on demand electricity (using turbines or fuel cells) when wind and solar based systems cannot meet demand. Balancing through transmission and batteries are likely to provide most firm power support on the day-to-day scale; where stored hydrogen will matter is seasonal support, e.g., for the weeks that arrive without wind in the northern continental winter.

A simple challenge in all businesses is that demand is required to justify supply investment. Beyond the niche applications described above, where dedicated hydrogen would be made and stored on site, the presence or absence of infrastructure to transport hydrogen to heavy truck fuelling sites, etc. may determine its speed of long-term uptake, and success against alternatives like battery electrification and biofuels.

Innovation is crucial to reduce cost and improve the performance of the electrolyser. The ultimate goals are to: 1) reduce cost by standardising and simplifying manufacturing and design to allow for industrialisation and scale-up; 2) improve efficiency to reduce the amount of electricity required to produce one unit of hydrogen; and 3) increase durability to extend the equipment lifetime and spread the cost of the electrolyser facility over a larger hydrogen production volume. Governments can support innovation in electrolysers by issuing clear long-term signals that support policy on:

- Facilitating investment in production, logistics and utilisation of green hydrogen, including all areas that will help this low-carbon energy carrier to become competitive; technology cost and performance improvements, material supply, business models and trading using common standards and certifications.
- Establishing regulations and design markets that support investments in innovation and scale-up the production of green hydrogen. This includes approaches such as setting manufacturing or deployment targets, tax incentives, mandatory quotas in hard to decarbonise sectors and other de-risking mechanisms, while enabling new business models that can guarantee predictable revenues for the private sector to invest at scale.

Next generation batteries for behind-the-meter and utility-scale storage (TRL 3-8+)

What advancements are available for batteries, and when and where could they be useful?

The use of electrochemical batteries for portable power in consumer electronics, industrial equipment and vehicles has come to be a daily experience for people worldwide in a way that would be unrecognisable three or four decades ago. Over this time, manufacturers have pioneered the development of new battery chemistries, making consistent incremental improvements to proven battery technologies. Most consumers will be familiar with lithium-ion batteries, which have been the dominant form of energy storage in portable electronic devices such as computers and mobile phones over the last two decades, and lead-acid batteries, which are used in internal-combustion vehicles to provide the initial current to engine starter motors. The only battery chemistry family that comes anywhere near to lithium-ion across key performance parameters such as energy density, power density, charge time, cycle life and

safety is nickel-metal hydride, which continues to be used in niche applications where energy density is less critical.

Lithium-ion batteries are a family of electrochemical devices with heterogeneous characteristics in terms of their exact chemistry, size, shape and performance (Goodenough and Park, 2013). Incremental improvements over time, such as experimenting with new materials, new chemistries, and new physical cell structures have led to great improvements in performance and cost. On average, lithium-ion battery costs have fallen 91% since their commercial introduction in 1999, while the maximum possible energy density in finished products rose by a factor of 3.5x (Ziegler and Trancik, 2021). These continual improvements have already brought lithium-ion batteries into new markets beyond portable electronics. Market solutions for both electric vehicles and electricity storage, whether grid-connected or installed behind-the-meter (i.e., in a home or at a business), are already commercially available at the time of writing. These technologies are finding success in profitable niches, such as electric bicycles, scooters and motorcycles (Weiss et al., 2015), passenger cars (Rietmann et al., 2020), and uninterruptible power supplies in datacentres.

The competitiveness of battery systems appears likely to keep on improving rapidly. A promising breakthrough in 2021 has meant that solid-state lithium-metal batteries, long considered “the holy grail” of lithium-ion battery technology, have now moved from the realm of theory into reality (Ye and Li, 2021). These next-generation batteries offer large non-marginal improvements over existing battery technology in terms of energy density⁵, battery durability and safety, while also enable charging times that are extremely rapid by today’s standards. If production can be successfully scaled, the use of solid-state batteries could be transformative, particularly for the automotive market, as it potentially enables the development of electric vehicles with batteries that have lifetimes comparable to internal combustion engine cars (10-15 years), which have driving ranges that compete with gasoline and diesel fuels (e.g., 300+ miles / 480+ km), and that can be fully recharged in as little as 10-20 minutes. Solid-state lithium batteries could also be safer than existing batteries, which have flammable electrolytes and can create a self-heating chemical reaction that ends in an explosion if short-circuiting occurs, such as after a collision (Feng et al., 2018).

Going beyond the all-solid state lithium battery, breakthroughs in lithium-air technology might provide a similar step-change in the energy density available from batteries. There is of course a big difference in performance between a battery in idealised laboratory conditions and a commercially deployed battery pack, but even so, simple back-of-the-envelope calculations show that lithium-air batteries potentially provide the kind of energy densities⁶ that compete directly with or even supersede fossil fuels, bringing for example, electrification of large aircraft within the realms of technological possibility (Schäfer et al., 2019; Viswanathan and Knapp, 2019).

Batteries for energy storage applications have different design constraints and possibilities when compared to batteries for transport. Stationary batteries do not need to be mobile or packaged into a vehicle, so weight and energy density are less of a concern, as is a requirement to tolerate mechanical damage in a hypothetical collision accident. At the same time, the market for energy storage batteries points towards a need for longer lifetimes, better performance across a range of temperature conditions, and lower per unit costs (Trahey et al., 2020). Lithium-ion batteries are already cost competitive and used

⁵ For example, a typical lithium-ion battery with a liquid electrolyte might have an energy density of 260 Wh/kg (Janek and Zeier, 2016), while the recent laboratory prototype for a solid-state battery developed by Ye & Li performs at 631 Wh/kg (Ye and Li, 2021), which is an improvement of at least 2x.

⁶ Laboratory constructed lithium-air battery prototypes already show energy density in the range of 1600 Wh/kg, and theoretically could be as high as 5000 Wh/kg (Kribus and Epstein, 2021). This vastly outperforms a conventional lithium-ion battery with 260 Wh/kg (Janek and Zeier, 2016). For perspective, liquid fossil fuels like gasoline and aviation jet fuel (kerosene) have an energy density of around ~1200 Wh/kg.

for grid electricity storage in a range of markets (Hesse et al., 2017), and in the near future, so-called flow batteries may also emerge as stiff competition for lithium-ion (US Department of Energy, 2020a).

Unlike traditional batteries which have the electrolytes and the electrodes packaged together in the same container, flow batteries keep the electrolytes separately in external holding tanks and pump them through the power generating stack when needed (Soloveichik, 2015). Flow batteries have a much lower energy density than lithium-ion, and as a result are much heavier and bulkier by comparison. However, they possess other key advantages. Flow batteries do not compete with automotive applications for lithium, can discharge and provide power for as much as 10 hours, use components that do not degrade from cycling, have very long lifetimes (30+ years), and do not use flammable electrolytes, making them potentially safer to operate (Skyllas-Kazacos et al., 2013). At the time of writing, pricing looks to be competitive for grid-scale systems (e.g., 100 MW, 10-hour duration), with flow batteries being slightly more expensive in capital cost terms than lithium-ion, but offering lower overall annualized costs due to their longer lifetimes (US Department of Energy, 2020b). For these reasons, industry projections estimate that flow batteries could capture almost half of the global utility scale energy storage market by 2030 (Bloomberg New Energy Finance, 2020a).

Alternative battery chemistries to lithium are a popular subject for battery research, e.g., sodium, potassium, magnesium, calcium, and aluminium (Zhao et al., 2018). Having a wider variety of battery chemistries available potentially reduces costs (if cheaper and more abundant metals are used), lowers the dependence of future battery technologies on lithium alone (Kribus and Epstein, 2021), and mitigates the risk that supply shortages for one or a few critical materials introduce price volatility (Ballinger et al., 2019; Grandell et al., 2016). Within this family of lithium-alternatives for high energy density applications, aluminium batteries are perhaps the most well researched (Das et al., 2017; Leisegang et al., 2019).

While alternative battery chemistries do show promise, lithium-ion currently dominates across a range of industries, due to its technological maturity and the ability of existing supply chains to already manufacture and distribute batteries at great scale. In technological development terms the timescale for efforts to limit warming to 1.5°C by mid-century in line with the Paris Agreement (UNFCCC, 2015) is extremely short, and immediate action is required to avoid the most damaging effects of anthropogenic warming (IPCC, 2018). For these reasons it is likely that lithium-ion batteries or their direct successors will, at least initially, be the main component of key climate mitigation technologies such as electric vehicles and grid-connected electricity storage, potentially defining their early market success or failure during this decade. The International Energy Agency ranks lithium-ion batteries at Technology Readiness Levels 9 (commercially available) for grid-scale electricity storage, and 10 (a competitive commercial solution that needs integration at scale) for electric vehicles (IEA, 2020a). The same reference source ranks flow batteries at TRL 8 (first of a kind commercial) for electricity storage.

Potential contribution of next generation batteries to climate mitigation efforts

Both global scale models (International Energy Agency (IEA), 2021) and detailed studies of decarbonisation in major world economies (Larson et al., 2020; Tsiropoulos et al., 2019) that explore strategies consistent with achieving Paris Agreement linked climate targets are remarkably consistent across regions in that nearly all personal transport becomes electrified. The implication is that nearly all forms of transport that today are powered by fossil fuelled engines are replaced by electric drive motors with energy stored in batteries. The more rapidly this can occur, the better the outcomes are for climate stabilisation (IPCC, 2018).

The electricity used to power the personal transport fleet must also be produced with close to zero emissions for the environmental benefits of electrification to be realised. This means that the power grid needs a rapid transition to non-polluting forms of generation. When compared to the big picture for electric vehicles, which is remarkably consistent globally, there is less agreement between national studies

about the best way to approach power system decarbonisation, but electrical energy storage at a variety of scales is often considered to be potentially transformative for the grid (Lott and Kim, 2014). Improved batteries potentially increase the rate at which renewable energy resources can be used as storage in batteries enables the time shifting of energy demand (Arbabzadeh et al., 2019; Kittner et al., 2017).

Batteries for energy storage, whether dedicated behind-the-meter or utility stationary or transport batteries, have another large potential benefit as “virtual power lines” (International Renewable Energy Agency (IRENA), 2019; IRENA, 2020e). Variable resources by definition are unmatched to demand, and are dependent on the capacity of the transmission system to transfer the power to end-use demand. But new transmission is difficult to site and expensive to build. Storage near generation and demand, that utilizes unused off-peak capacity in existing transmission, increases the value of variable generation and existing transmission, and makes end-use electrification cheaper. These financial and mitigation values are potentially very large, but highly dependent on regional context and scenario assumptions. Key to their realization are regulatory and market institutional environments that value and encourage their potential multi-service business cases (e.g., transmission deferral, frequency regulation, black start, instantaneous demand response and ramping, reduced generation curtailment, system redundancy) as well as the digital supply-storage-end-use connection that allows and encourage these strategies and the physical storage they enable (Griesheim et al., 2020; IRENA, 2019c).

Social, institutional, economic, and business preconditions for next-generation batteries

Lithium-ion batteries are today used mostly in personal electronics (laptops, phones etc.) but as discussed above, could soon also become much more widespread in transportation and in the power grid. These are large markets. Taking the US economy as an example, personal electronics represent only 2% of total energy use, while transport and the electricity grid account for 66%; this means that the size of the potential market for next-generation batteries is at least a full order of magnitude (i.e. 10x) larger than the present day battery market (Crabtree et al., 2015).

At least one recent industry battery price survey puts the average cost of producing lithium-ion battery packs at US\$137 per kWh with some manufacturers in China already able to deliver at US\$100 per kWh (Bloomberg New Energy Finance, 2020b). This means that the long-held target of US\$125/kWh for a battery pack posited by the US Department of Energy and a number of major auto manufacturers (Blomgren, 2017) is either already here or about to arrive imminently. Even without dramatic technology breakthroughs (e.g., radically new chemistries), continued reductions in the costs of existing technology will make electric vehicles cost competitive with combustion engine cars this decade (Crabtree, 2019). Lithium-ion batteries (alongside flow batteries) are also likely to be one of the most competitive options for the majority of electricity storage applications from 2030 onwards (Schmidt et al., 2019).

Any future advances in battery technology beyond this point have the potential to rapidly accelerate the deployment of electric vehicles and renewable electricity generation. Researchers at the European Union’s Joint Research Centre have explored a number of scenarios where the rapid growth of the electric car market would create the innovation conditions that drive costs down in the battery electricity storage market (Tarvydas et al., 2018), as there are clear synergies between the two in terms of supply chains. With batteries and the use of battery using devices already intertwined into the fabric of daily life in much of the world, the societal barriers to their use are already low. Reduced costs and improved performance seem to be the main prerequisites to driving increased adoption.

Accelerating battery technology development and deployment requires continued investments in fundamental research and electrochemistry (Trahey et al., 2020). This is true for almost all promising new battery types that are under investigation, such as lithium-air (Liu et al., 2020) and aluminium-ion (Leisegang et al., 2019), but also for continued improvements in conventional lithium-ion batteries, which are far from obsolete (Grey and Hall, 2020). As well as fundamental research, continued funding of work

investigating state-of-the-art manufacturing and production methods is also required to scale new innovations beyond laboratory settings (Liu et al., 2021). For example, a key challenge for solid-state lithium batteries is that entirely new production processes need to be developed and applied (Schnell et al., 2018). Due to the size, scale and immediacy of the climate challenge, contemporary innovation policy thinking suggests that a strong role for governments in directly or indirectly funding the needed research would be appropriate and needed (Mazzucato, 2018; Myslikova and Gallagher, 2020).

Finally, there are rapidly developing issues with security of supply for key material in batteries, as well as recycling systems to process them. Suffice to say, new supplies of lithium and electrode materials are emerging quickly, driven by price surges in these materials. More problematic in the long run is there is no clear development of a recycling system for battery materials nor standards for design for recyclability. This is an area for significant new research and rapid policy development to keep up with growing global stock of operating batteries.

Thermal energy storage (TRL 3-8+)

What is thermal energy storage, and when and where could it be useful?

Thermal energy storage allows heat or cooling energy to be stored and used at a later date across multiple time and spatial scales (with steam or hot water transport), and as such is a useful complement to variable renewable energy sources, such as direct solar heating (IRENA, 2020f). Its economic value is in its capacity to transfer operationally free variable renewable energy to the time period when it is needed (Sodano et al., 2021). It thus also has the capacity to help reduce strain on and investment needs in other parts of the energy system, especially electricity supply & transmission.

There are three primary forms of thermal energy storage: sensible, latent, and thermochemical. Sensible is the most direct and intuitive, where a material is heated, stored in an insulated container, and the heat released as needed. Latent is based on a phase change, e.g., from gas to liquid, or liquid to solid, where the phase changes but not the temperature. Thermochemical is based a reversible exothermic (heat extruding) or endothermic (heat absorbing) chemical reaction in a specific material.

All three basic methods of thermal energy storage enjoy the same basic advantages in that they use typically free solar energy as the energy source, and the same disadvantage that they are capital and material intense.

Sensible direct thermal storage

Many materials are used for sensible thermal storage: rock and concrete, molten salts, water, silicon, and metals (like aluminum). All have different thermal capacities and costs in a given application.

Rock and concrete, because they are cheap and ubiquitous, are very commonly used for thermal energy storage in passive buildings applications. They are typically placed behind glass (which has a greenhouse heat trapping effect) with an air gap towards the sun. They heat through the day and release their heat at night. The performance of these systems depends entirely on the building design, orientation, thermal envelope efficiency, and local climate.

Molten salts are the current storage medium of choice in concentrated solar applications, where a system of mirrors is used to heat the liquid salts which are stored in system of insulated tanks. Water is run through the salt in an isolated loop and becomes steam, running an electricity generation turbine as needed, and then recirculates back. The salts, which become liquid at 130°C, are typically cycled from 288°C to 566°C and back. This method has been used to successfully power a concentrated solar power tower system around the clock in Spain for 36 days, but the technology cannot yet be described as fully reliably commercialized.

Underground thermal energy systems are a derivative of commercial ground source heat pumps, which use electricity and working heat transfer fluid to move naturally occurring underground heat energy into a building. A heat exchanger is used to transfer the heat into the building while the fluid is relooped underground. In a storage mode, thermal energy is moved underground in water into natural or constructed impermeable formations in times of surplus (day/summer), and then extracted in times of need (night/winter). While very efficient and inexpensive in operation, both ground source heat pumps and their use for heat storage are subject to the capital costs (which can be >10x the cost of a natural gas furnace) for drilling the access boreholes, as well as pumps and heat exchangers.

Latent phase change storage

Latent phase change storage makes use of the heat absorbing and extruding nature of some materials when changing phase from solid to liquid to gas. Materials that experience these properties include various salts, polymers, gels, waxes, metal alloys and ice. With the significant exception of ice as a coolant, there are no broad uses of phase change materials for energy storage to date, but many have been tested because of their capacity to hold significant amounts of energy without a large temperature change, in contrast to sensible thermal storage.

Thermochemical storage

Thermochemical storage is based on using reversible endothermic (heat absorbing) and exothermic (heat giving) chemical reactions to store energy. There are many possible reactions, but a simple example with a potentially broad utility is the use of salt hydrates from commonly available chemicals, e.g., sodium hydroxide. Solar energy could be used to evaporate a 50% solution of sodium hydroxide, leaving salts. When water is added again, heat is released at 50°C. The system is especially useful for seasonal energy storage for building heat, because the salts for a heating season for a family home could be stored in 4-8 m³, or purchased on the open market (https://www.merits.eu/heat_battery). Experimentation is ongoing with different salt compounds.

Potential contribution of thermal storage to climate mitigation efforts

At one time many predicted that concentrating solar power towers (CSP) with molten salt storage would be the biggest source of solar generated power, but solar photovoltaic panels seem to have fundamentally outcompeted them on bulk cost per kWh, limiting this potential use of high temperature storage. Wind and solar PV provide intermittent and variable power, however, whereas CSP is dispatchable, so there may yet be a need for large storage for CSP projects once large amounts of wind and solar PV are installed and more electricity is needed for low GHG electrification.

Given this, the biggest contributions that could be made by thermal energy storage is likely in buildings and light industry, where there is the largest potential to transform and transfer solar or ambient heat in the range of 25-50°C into useful heat for other time periods, including low temperature steam, both as is and with the use of heat pumps, which use electricity to concentrate heat from a source (the ground, air, or a district heating loop) and move it somewhere else (e.g., into a building). Industrial scale heat pumps, if they have enough access to sufficient lower temperature heat, regularly lift temperatures to 80-90°C, and the current generation of state-of-the-art industrial heat pumps can go to 150°C, meeting most lower grade steam needs (see next section on heat pumps). Residential thermal energy systems could have a very large impact in cold, low humidity regions where heat pumps are less effective (e.g., parts of the Canadian Prairies), but much development and commercialization works needs to be done first.

A key area for future research, investigation and deployment of thermal energy systems outside the scope of this project is in developing and newly industrialized country “cold chains”, especially for food, e.g., (Dong et al., 2020), to minimize the need for clean electrification for refrigeration. The author was present

for a presentation by Chinese researchers, unfortunately unreferencable, that indicated that the Chinese cold chain is responsible for at least a 1 GtCO₂ per year of electricity use.

Social, institutional, economic, and business preconditions for thermal energy systems

Passive solar water heating and storage systems (i.e., black plastic water tanks on top of buildings with optional heating arrays) for residences and buildings are an already commercial technology around the world.

In terms of more sophisticated systems, heating systems, especially in residences, apartments, and small and medium sized enterprises, are mostly not a conscious choice of homeowners, building owners or light industrial firms – they use what is made available to them by local infrastructure and the market. While ground source thermal storage can be retrofitted to existing homes and buildings, they are significant projects with relatively large capital outlays, time and physical disturbances to the tenant and grounds, and require a skilled contractor. They are more likely to be incorporated in new buildings, either by owner specification or local regulation.

Solar heating and thermal storage systems for light industry (e.g., food processing, beer making) are highly viable in most latitudes and are gaining ground, but not at a sufficient pace to make a large dent in energy demand or climate targets. Most literature on the use of solar energy for industrial purposes to date focusses on supplementing other electric and gas sources to reduce GHG emissions, not replace them entirely as overnight and seasonal storage allows.

To be reliable and cost effective, solar heating and thermal storage systems require specialist design and construction with good knowledge of the client facility's needs. Enabling more uptake, to the point where it is self-sustaining based on demand and capacity to deliver, would likely require education and finance programs, ideally delivered by a specialty contractors hired by government agencies to enhance market uptake.

Heat pumps (TRL 8+)

What are heat pumps, and where and when are they useful?

Heat pumps are a family of heating devices found in domestic, commercial, and industrial settings that take low temperature heat from a source location and use it to increase the temperature in a target space. The simplest way to think about a heat pump is that it operates on the same thermodynamic principles as a refrigerator, but in reverse. A refrigerator maintains a cold interior that is used for chilled food storage by taking thermal energy out of the air inside the cabinet and rejecting it via cooling coils at the rear of the unit. A domestic heat pump on the other hand, takes thermal energy from the surrounding environment (air, water, or the ground) or another heat source (like industrial waste heat), and pumps it to a target destination (like inside a home), raising the temperature. Just like a refrigerator, a heat pump needs electricity to operate⁷, but is a significantly more efficient way to provide heat than direct electric heating (e.g., an electric fan or bar heater).

The global installed base of heat pumps was estimated at 800 million units in 2010 (IEA, 2011), with year on year growth since that time in excess of tens of millions of units annually (Zhao et al., 2017). In terms of the regional breakdown, China is the world's largest heat pump market, with Japan second (IEA, 2020b). It is estimated that around 10% of households in the United States use heat pumps as their main heating source (Kaufman et al., 2019), partly because heat pumps can also act as cooling air conditioners. In

⁷ Heat pumps that operate without electricity and instead use heat provided from a fuel source do also exist, although when discussing climate mitigation technologies, the electrically driven heat pump features far more prominently in discussion because of the potential to use zero-carbon electricity.

Europe it is challenging to precisely compare official statistics on heat pump installations across the region (Zimny et al., 2015) but overall market growth is on a strong upward trajectory (Thomaßen et al., 2021).

Heat pumps are a well-established technology, but also one where innovations continue to be made in areas like improved refrigerants, compressors, heat exchangers and control systems (Zogg, 2008), which has resulted in strong performance and efficiency gains over time. It is challenging to compare how heat pumps for home heating compare across different markets and over time as this is affected by climate, building thermal standards, and the precise technical specifications of the units being compared. However as a guide, the typical seasonal performance factor over the year for most new air-source building heat pumps at the time of writing is believed to be around 4 (IEA, 2020b), whereas values around 2.5 were typically found in field studies from the early 2000s (Lazzarin, 2007)⁸.

Historically, most building heat pump installations have used ambient air as the heat source, and were installed in comparatively mild climates (Lazzarin, 2007). This is changing, not only as thermal standards for buildings improve (which makes it easier to use the same heat pump in a colder climate) but also because of ongoing performance improvements to operate in cold weather. New state-of-the-art air-source heat pumps can provide reliable heat even in locations that frequently experience temperatures well below freezing for extended periods, such as Northern China or Canada (IEA, 2020b). Using thermal energy from the ground rather than the air (ground-source or geothermal heat pumps), in locations where it is technically possible to do so⁹ can further improve performance in cold climates.

Another option for heat pumps that is gaining traction is for them to be used as the heat source in existing district heating networks, which supply heat to homes via a buried network of centrally heated hot water pipes (David et al., 2017; Kontu et al., 2019). This potentially enables these large networks, common in northern Europe, northern China, and northern North America, to switch from fossil fuels to electricity without needing entirely new units to be installed in every connected building. The IEA ranks air-source and water-source heat pumps for building heating at Technology Readiness Level 10 (commercially competitive solution that needs further energy system integration), state-of-the-art cold climate air-source heat pumps at TRL 8 (full scale commercial demonstration has been completed – they are now dominant in some Canadian markets), and large-scale heat pumps for district heating at TRL 9, where solutions are commercially available (IEA, 2020a).

Heat pumps have been used in industry to supply process heat at low temperatures since at least 1877 (Zogg, 2008). Different industrial applications require different temperatures to perform processes such as drying, evaporating, boiling, steaming etc. Most industrial applications require heat in excess of 80°C, which was not possible to achieve using 20th century heat pump technology (compressors, refrigerants, materials etc.). However, in the last ten years there has been a significant improvement in delivered temperatures available from heat pumps, and commercial solutions from multiple manufacturers are now able to supply heat in the 90-150°C range (Arpagaus et al., 2018).

Around 30% of industrial process heating needs are believed to be below 150°C (Bataille et al., 2018), so the appearance of high-temperature heat pumps in the last decade that can provide these temperatures opens up many possibilities for electrification of industry, particularly in the paper and food sectors (Madeddu et al., 2020). Going above 150°C is also likely to be possible in the near future, with many demonstration and commercialization projects either recently completed or close to completion. Work

⁸ Higher numbers reflect improved efficiency, and express heating energy extracted per unit of electrical energy input. A value of 4 indicates that for every 1 unit of electricity consumed, 4 units of heat would be produced (on average, over a defined period, usually the heating season). By comparison, an electric resistance heater at 100% efficiency produces only 1 unit of heat for each unit of electricity consumed.

⁹ Air-source heat pumps take heat from the air, and so can be installed anywhere where there is space to mount the units on the outside of a building, whereas ground-source heat pumps require heat collection coils to be run in the ground, which can be challenging if the building owner does not own any adjacent land or does not have sufficient space available.

to supply heat from electric heat pumps between 280-400°C, which would enable heat pumps to electrify parts of the chemical processing industry, are at the concept stage (Zühlsdorf et al., 2019).

Potential Contribution to Climate Mitigation Efforts

The buildings and industry sectors account for around 56% of global emissions, around 28% each (IEA, 2020c, 2019b). In the buildings sector, around 33% of final energy demand is heat for space heating and between 12-24% is for providing hot water (Ürge-Vorsatz et al., 2015), while in industry, process heat is around 46% of all energy consumed (Eisentraut and Brown, 2014). Global¹⁰, regional scale¹¹, and sectoral¹² analyses of technological options for decarbonizing the energy system show that the need to provide future heat demands using electricity generated from zero carbon sources is a critical and consistent finding. Achieving Paris Agreement (UNFCCC, 2015) compatible targets for limiting anthropogenic global warming to 1.5°C is not believed to be possible without large scale electrification of heat demand (IPCC, 2018). Heat pumps are the front runner technology for electrifying heat, owing to their track record, technological maturity, ability to be manufactured and distributed at scale, and ongoing continual development.

Social, institutional, economic, and business preconditions for heat pumps

The potential future growth in the market for heat pumps is very large. For example, heat pumps are only 5% of the global building space heating market but have the potential to supply as much as 90% of global space heating and water demand (IEA, 2020b). If industrial applications for heat pumps are considered, then there is the potential for at least an order of magnitude (i.e., 10x) growth in the market in the coming decades. Heat pumps are already a rapidly growing market segment in many countries; market research firms put annual growth trajectories for the 2020s as high as 8-10% per annum (Allied Market Research, 2019; Market Study Report, 2021). Analysis of housing market data based on 150 million homes in the United States suggests that heat pumps are increasingly popular with some consumers, and that residences with a heat pump enjoy a 4-7% price premium over equivalent homes in 23 out of the 50 states (Shen et al., 2021). Despite these encouraging signs, achieving Paris Agreement aligned targets for emissions reductions are likely to require additional support from government to accelerate the transition to electric heating, as heat pumps are starting from a very low installed base.

Heat pumps face several economic, regulatory, infrastructural, and societal barriers to deployment in the buildings sector. The upfront costs of heat pumps in markets without widespread deployment are often higher than fossil fuelled alternatives, a factor which research suggests is providing a deterrent to adoption (Barnes and Bhagavathy, 2020; Karytsas, 2018). Past experience in markets with high penetrations of heat pumps suggests that their increased rollout over time will help push them down the cost curve (Kiss et al., 2014). A variety of policy tools are available to reduce costs, including direct public procurement to stimulate market development, establishing streamlined guidance on installation and code compliance within the construction industry, and public information campaigns for consumers. During the early deployment stage, governments can also consider direct subsidies, low interest loans, or other financial incentives to bring the costs of heat pumps in-line with fossil fuelled alternatives, such as China has done with its Electric Heating Policy initiatives (Wang et al., 2020).

Heat pump performance and operational costs are closely correlated with the energy efficiency of the buildings that they are installed in. Optimum outcomes are found when heat pumps are installed in well-insulated buildings. Alignment with building construction codes has been identified as particularly important for encouraging heat pump uptake. This means that any policies to stimulate heat pump market

¹⁰ e.g., International Energy Agency (IEA, 2021).

¹¹ e.g., USA (Larson et al., 2020), EU (Tsiropoulos et al., 2019), China (Shi et al., 2016).

¹² e.g., buildings (GlobalABC/IEA/UNEP, 2020), industry (Bataille et al., 2018; Napp et al., 2014).

growth must also be carried out in concert with a broader set of measures to raise energy efficiency standards for new build construction and to have a strategy for retrofitting older buildings that might have lower thermal performance (Chaudry et al., 2015; Hannon, 2015). Efforts to enact a market-push policy for heat pumps without also addressing energy efficiency in the building stock may stall or fail.

Large-scale deployment of heat pumps in markets that have not historically seen large electric heating loads in winter may require additional electrical generation and reinforcement of existing electrical distribution infrastructure to handle increased peak demand. Different regions can integrate varying levels of additional electric heating before additional investment is required in the broader electrical system. Studies suggest that 53% of heating can be electrified in the USA without additional infrastructure (Waite and Modi, 2020), while for the European Union the equivalent figures (depending on EU Member State) range from 29-45% (Thomaßen et al., 2021).

In some countries, existing actors in the building heating market (e.g., in the United Kingdom (Martiskainen et al., 2021)) have a vested interest in maintaining their market share, which is often directly threatened by a future large-scale shift to electric heating. Research shows that in response to the threat of losing market share to electrification, incumbent heating providers have assembled resources to push an alternative narrative of “green gas”, i.e. reusing the existing gas grid with alternative fuels such as hydrogen, synthetic natural gas, or biogases (Lowe et al., 2020). However, the technical feasibility, costs, and safety of these suggested approaches (particularly hydrogen) remain unknown. A large-scale hydrogen gas replacement program is being conducted in the northern UK to assess the feasibility of heating buildings directly using reformed methane based hydrogen with CCS; this project is made feasible by the fact that the retail gas network, dating from the 1880s town gas era, was replaced with plastic piping impervious to hydrogen corrosion over the last two decades.

Other than for legacy high value buildings that are hard to retrofit with heat pumps or district heating, the window of opportunity for decarbonised gases to be the dominant pathway for reducing building heating GHG emissions has arguably already passed. To be competitive at the global level outside of a few niche environments, the technology would need to already be market ready for deployment at scale in the 2020s, and it is not. While it is true that hydrogen/methane blends are fairly well researched (Melaina et al., 2013), direct methane combustion for building heating has no future in a net-zero emissions world unless combined with carbon dioxide removal technologies such as direct air capture of CO₂, itself a technology with uncertain future costs and performance (Chatterjee and Huang, 2020; Realmonte et al., 2019), or bioenergy with carbon capture and storage, a technology that is similarly plagued by uncertainties surrounding costs and feasibility (Fuss et al., 2014; Smith et al., 2015). Typically, these have been thought of as so-called “backstop” technologies (Nordhaus et al., 1973), to be used in a hypothetical desperate situations of climate emergency when nearly all other avenues for climate stabilisation have failed (Hanna et al., 2021). In terms of technological complexity and affordability the challenge of adding some more capacity to the electricity grid is arguably very small compared to the challenge of decarbonising the gas grid. Some amount of biogenic or synthetic net-zero methane will likely be required to allow portions of the buildings stock to decarbonize until they are ready to be torn down and replaced (Bataille et al., 2018).

In industry, increasing the uptake of heat pumps needs to be carried out in the context of a broader policy package for decarbonizing the industrial base so that potentially scarce resources, like sustainably produced bioenergy, can be allocated effectively (Bataille, 2020; Bataille et al., 2018; Rissman et al., 2020). As noted in earlier discussion, heat pumps that can provide temperatures above 150°C are not yet market ready at the time of writing but temperatures in the 250-400°C range are believed to be on the cusp of technological feasibility. Continued investment into fundamental research is required to improve heat pump components to resist higher temperatures and increase cycle efficiencies (Arpagaus et al., 2018), as well funding technology demonstration projects with cross-industry collaborators to facilitate learning

by doing (Arrow, 1962) and investigate the best way to integrate heat pumps into existing process chains. Accelerating the deployment of industrial heat pumps is also likely to require upfront investments in educational and training materials, industrial standards and guidelines (de Boer et al., 2020).

Heat pumps are a key emerging climate technology for decarbonizing heat in buildings and industry. They are at an advanced stage of technological maturity, continue to be improved over time, and can be scaled to meet the needs of the global decarbonisation challenge. Their market growth in recent years has been very strong in several regions but deployment rates must be substantially accelerated to meet the Paris Agreement targets. The main challenges for heat pumps in buildings stem from high upfront costs, the need to align policy measures for heat pumps with those for the energy efficiency of buildings and the electric grid, and the potentially disruptive nature of the switch to electric heating, which in some markets threatens incumbent business interests. The main challenges for heat pumps in industry are to improve performance to address a wider range of delivery temperatures for process heat, and to better understand and share knowledge on how to integrate them into new and existing industrial facilities.

Table 4 Summary of key technology characteristics for emerging primary energy supply technologies

Technologies	TRL	Estimated eventual levelized cost of energy for supply 2019 USD \$/kWh	Size and generality of resource if available	Key co-benefits and other considerations
Airborne wind energy	3-5	Unknown	Large but vague	Can potentially be used for remote sites far from grid with poor solar
Floating solar PV	8+	0.35 historic, current low auction bids at 0.05, projected 2030 ~0.05, ~0.04 2050	Very large and broadly geographically spread: 4,251 to 10,616 TWh per year	When tied with existing hydropower frees water resource for use as firm power, utilizes existing transmission, and reduces evaporation losses
Floating wind	8+	Current auctions at 0.13-0.15	Very large and confined to large lakes & ocean EEZs: Conservatively up to 83,229 TWh per year	When placed in deep ocean very large resource with low siting conflicts
Wave power	5-8	Current 0.30-0.55. 0.22 by 2025 & \$0.165 by 2030	Moderate: 2 TW globally, but highly regional.	Highly regional. No convergence on design.
Tidal power	3-8	Current 0.20-0.45. 0.11 by 2022-2030.	Moderate: Very regional, can be locally large.	Highly regional. Tidal barrages are unlikely to be approved, in stream floating axial turbines showing most promise.
Ocean thermal energy conversion	5-6	Current 0.20-0.67 for 10 MW units falling to 0.04-0.29 for 100 MW units	Very large but localized: 4,000-13,000 TWh/yr	Can be located anywhere between 30° north and south with reasonable access to 1km+ ocean depth. Can provide water desalinization.
Bioenergy with carbon capture and storage (BECCS)	6-8	Variable with application. Fossil unit cost plus CCS cost minus carbon revenue benefit.	Very large.	Net-neutrality is highly vulnerable to what biomass feedstock is used and how it extracted. CCS should be ~\$50-\$100/t, but is only proven with ethanol production plants.

Table 5 Summary of key technology characteristics for emerging enabling technologies

Technology	TRL	Cost 2019 USD	Key applications
Green hydrogen	8+	\$4.5-6/kg, could fall to less than \$2 by 2030 with economies of scale and innovation	Storage of variable renewable electricity; high process heat; steel reduction; ammonia fertilizers; heavy transport
Next generation batteries	3-8+	Lithium-ion batteries are now \$150-300/kWh, an expected to fall to <\$75 by 2030. New chemistries will add capability.	Small and large vehicles; supply and end-use in electricity grids; portable electronic and motor devices
Thermal energy storage	3-8+	Highly variable.	As a supplement to residential heating, electricity firm power,
Heat pumps	8+	At least double the cost of boilers, usually more.	Residential & commercial heating and cooling; industrial steam

Policy options for effective deployment of emerging technologies

There is a wide and ranging literature on the effective deployment of emerging technologies, with some disagreement but also a lot of functional agreement based on first principles.

One of the fundamental challenges faced by both energy efficiency investments and renewable energy technologies of most types is that the initial capital expenditure is higher, compensated by typically lower energy costs in the long run. For private sector households and firms, that must make most of the investments in the energy transition, this is extremely important. They must borrow more money upfront, pay interest on it and pay it down, for a payback later. *This fundamentally reduces the value of the investment for private sector actors, and the higher the real interest rate they must pay, the greater the value reduction.* Governments of all types, and especially national government, have the capacity to borrow capital less expensively than firms and households. They can also justify borrowing money to make investments to protect future generations. This indicates there is a strong role for governments to work with households and firms to transfer their lower long-term cost of borrowing to them for long term social goals, e.g., via lower interest loans tied to the investment, tax credits, and direct investment related subsidies. These issues are particularly acute in developing countries, because their risk weighted costs of capital are higher. This speaks to the need for some sort of global facility to help reduce the risk weighted cost of capital for investments in emerging mitigation technologies in developing countries.

For the demand and supply sides of markets to incorporate climate damages, these damages must be included as GHG pricing, regulation, some form of performance regulation, or other constraint on emissions. While carbon markets are evolving fast, e.g., in the EU, UK, California, Canada, the northeast US, China and elsewhere¹³, the damages associated with climate change are mostly not costed into goods and services, or otherwise constrained. The coverage of these systems is usually less than all emissions, and the prices are far below most estimates of damages (Ricke et al., 2018). Simply put, low and high GHG intensity electricity provides the exact same service to the end user, and until recently, the former was much more costly. All the low GHG primary electricity technologies listed in this report, with the possible exceptions of floating solar PV and floating wind in some cases, are much more expensive than coal, oil or gas-based electricity generation in the absence of a sufficiently high carbon price. But pricing or regulation is normally not enough to bring emerging clean energy technologies to market; some form of research, development, piloting, and early and late stage commercialization plan is required (Geels et al., 2017).

Economic and technological systems have physical and institutional inertia on both the supply and demand side (Geels et al., 2019; Rosenbloom et al., 2020), and participants will keep on doing what they are doing unless there is a shock or a significantly better way of providing the needed service, however that is defined. Supply chains for supply and end-use equipment often take decades to reach maturity. End-users can't switch to a new technology that needs a new fuel if there is no supply, and a supplier can't sell if there is no demand. The supply and demand sides of the market must evolve together, often starting with small "niche" or "lead" markets, which can grow given the opportunity.

New technologies, whether pushed or not, often penetrate in niches or lead markets where they provide a better service, and from there build innovation and production economies of scale. Solar PV's first niche was powering satellites, and then remote electronics (Kavlak et al., 2018a). It then moved to calculators, etc., building economies of innovation and production scale, leading to today's "cheapest electricity in history" (International Energy Agency (IEA), 2020).

The large capital investments, risks, and lead times necessary to get emerging technologies with social value to market are often beyond the capacity of single firms, and consortiums and/or public private

¹³ https://carbonpricingdashboard.worldbank.org/map_data.

partnerships are necessary to take a technology through to commercialization. Two of the most successful public private emerging technology partnerships have been the UK Offshore Wind Accelerator and the family of US (Defence) Advanced Research Project Agency (DARPA) initiatives.

The UK Offshore Wind Accelerator (Carbon Trust, 2017; Jennings et al., 2020) was the result of the UK government identifying it had a very large offshore wind potential at very high capacity factors (60-70%), but the technology to exploit them was blocked somehow. The UK Carbon Trust was entrusted with bringing together the existing turbine companies to sit down and analyse the key blockages to commercialization, which turned out to be amongst other things servicing vessels. The UK government allocated funds to solve these challenges collectively with the firms. Once solved, all parties walked away with the intellectual property, and the normal reverse auction mode of allocating licences was resumed. This program, amongst other efforts, can be partially credited with the arrival of \$0.05-0.07 per kWh USD offshore wind auctions.

The US (D)ARPA model¹⁴ is also held up as a model for public private partnerships to advance technology, funding amongst other things the early pilot of the internet (ARPANET) and providing early funding for mRNA vaccines. The ARPA model is not designed for early R&D nor late state commercialization; it's method is to: 1) identify key, socially important unsupported areas to support; 2) gather information from potential stakeholders and fundees; 3) enter into supportive, low transaction cost partnerships with ideas between these stages, including providing financing and networking, and 4) provide continued support if progress is being made, and 5) to exit if a technology stalls. Failure by some technologies is expected and is not counted as an overall program failure.

Some new technologies have global applications (e.g., technologies working with solar PV or wind), and economies of scale and learning will be global, but some do not, with lower potential economies of scale and learning. Countries and regions with specific regional resources (e.g., wave or tidal energy) may need to partner with others with the same type of resource if they wish to make progress with commercialization.

New technologies that can “plug into” existing infrastructure will find it easier, e.g., electric vs. hydrogen fuel cell cars, but government will likely have a role in establishing key new infrastructure. For example, while there is a widespread electricity transmission network, the existing hydrogen transmission network is minimal, and used only for transport of chemical feedstock hydrogen. Early application of green hydrogen will likely require that the end-use, e.g., on-demand electricity, fertilizer feedstock or steel reduction, is co-located with the producing electrolyzers and storage (Bataille, 2020; Bataille et al., 2018; Rissman et al., 2020). On the other hand, because of minimum economies of scale (“network externalities”), government will likely have a role in facilitating & investing in infrastructure for clean energy technologies, e.g., regulation and basic investment in core charging or refuelling networks (Till et al., 2019).

New technologies with co-benefits will find market uptake easier. Floating solar, for example, not only plugs easily into the existing network, it provides several potential market co-benefits: it doesn't consume new land; it can add bulk power to hydropower, allowing the water in the dam to be used for on-demand firming power; and it lowers evaporation from hydropower or irrigation dams. OTEC, on the other hand, is much more expensive than solar PV, wind and battery backup, and its key co-benefit may be to operate where there isn't land for solar PV or wind, or bulk desalinization for drinking water or irrigation is required.

Variable energy resources have a highly varying value (from on-demand market value to zero) on regional electricity grids or paired with enabling technologies that transform them into on-demand

¹⁴ <https://www.nature.com/articles/d41586-021-01878-z>.

services. On the other hand, enabling technologies like batteries, green hydrogen, and heat pumps need low GHG electricity to be useful. Their technological development and deployment to first lead/niche markets and then broader markets should be considered and planned in this context.

More broadly, emerging technologies must cost less, provide a better service, or be somehow pushed into the market, justified by a social benefit. How can these technologies be “pushed”, and to what extent should they be? There is no question more research and development are required, but full-scale piloting is expensive and generates almost no revenue, making it very difficult for smaller firms (Table 3). Bigger decadal scale projects are also risky for bigger firms (e.g., in steel decarbonization). Full scale piloting must also be following by some form of revenue generating niche market that can pay the usually initially higher costs. How do we get these technologies from TRL 4 to 8 & 9, keeping in mind society’s resources are limited and time is fleeting to meet the Paris Agreement goals? Most technologies with a non-priced social benefit will need some level of support to get to a competitive lift-off point, but not all technologies will lift off - when do we quit and refocus our resources on other technologies?

Some principles for policy packages, and specific policies to include, to support emerging energy technologies are suggested below. These are divided into two broad classes: policies for directionality toward the social goal, and market shaping to meet those social goals.

- **Directionality: Given the Paris Agreement goals and need for net-zero emissions by 2050-’70, economy wide scenario formation and planning, done with input from all key stakeholders, is required** (Waisman et al., 2019). All key stakeholders, especially those with an effective veto on action in any key sector must be included to hear their challenges and options for how the society wide objective can be achieved, and to help them understand the constraints other sectors are operating under. Ideally, working consensus can be achieved to allow the government of the day and any political opposition to proceed with stable policy package formation.
- **Directionality: Based on the planning exercises above, specific social goals must be defined that allow technological agnosticism and measurable performance standards** (e.g., to reduce overall GHG intensity per kWh generated to less than 30 grams CO₂ per kWh by 2050 (Bataille et al., 2016; Williams et al., 2021)). This also allows the promotion of positive surprises, e.g., as yet unknown technologies (i.e., “white swans”), or technology reapplications from other uses. These metrics can also be used as guidance for minimum performance standard for market inclusion.
- **Directionality: Standard sets of co-benefits, ideally corresponding to the Sustainable Development Goals, should be defined or at least acknowledged, and their pursuit included in support policy.** These should include, at minimum, minimization of local air pollutants and water use by energy technologies. By their nature, wind and solar PV use far less water than thermal generation technologies. The ability for OTEC to provide desalinated water would potentially be included as a co-benefit, depending on the site application. Associated employment and maintainability in less-than-ideal conditions by lower skilled labour with limited access to repair supply chains could also be included.
- **Directionality: Expanded research, development and small-scale piloting funding for emerging primary energy supply and enabling technologies.** Access to the funding should be based on projected capacity to meet the direct decarbonization and SDG goals listed above.
- **Directionality: Countries and regions need to assess their potential competitive advantages and their capacity to capitalize on them on their own and seek our partnerships with others in the same situation where necessary.** Fully commercializing airborne wind, OTEC, wave and tidal energy may be beyond any one country, and research, development and commercialization partnerships should be struck by those jurisdictions with the necessary resources and interest.

- **Directionality:** Based on all the above, establish targeted innovation and early commercialization programs as needed to identify and break commercialization blockages, e.g., the UK Offshore Wind Accelerator or the US ARPA-E (Advanced Research Projects Agency-Energy).
- **Markets shaping to meet social goals:** Lead markets are needed to support economies of innovation and production, followed by full carbon pricing to support commercialized technologies. Once a technology has reached the early commercial stage it will likely be more expensive than incumbent technologies but have a social competitive advantage that must be monetized somehow. Lead/niche markets are needed to build learning, economies of scale and innovation, and familiarity with the technologies (Agora Energiewende and Wuppertal Institut, 2020; Sartor and Bataille, 2019). This can be done through **renewables obligations or feed-in-tariffs with carve outs for early-stage technologies**. Solar PV and wind's early market success, after initial R&D and niche applications in space and at remote locations, was directly due to renewable portfolio standards (RPS) and feed-in-tariffs (FITs) in the UK, EU, and various North American jurisdictions. The RPSs & FITs were actualized through contracts for difference, or CfDs (Sartor and Bataille, 2019). If electricity market prices were less than the necessary minimum price for the technology to be invested in and operated, a dynamic subsidy pegged to the market prices was provided. If market prices were high enough, no subsidy was provided.
- **Market shaping to meet social goals: Removal of fossil fuel subsidies and full carbon pricing will be needed for uptake once the technologies are commercialized.** In most cases carbon pricing cannot be raised fast enough or high enough to justify high risk innovation, but it can help sort technologies effectively once they are commercialized (Cullenward and Victor, 2020).
- **Market shaping to meet social goals: Phase outs of high emitting, not retrofittable technologies to reduce emissions and make room for new, lower emitting technologies.** While electrification with low GHG power is identified as a key strategy in all net-zero pathways, practically it will be difficult for low GHG power sources to build economies of scale and innovation until there are widespread coal, oil and then gas power phase outs.

Final Recommendations

The core technologies for wind and solar PV can be described as being commercialized to the point where market forces and moderate carbon pricing or GHG intensity performance standards can ensure their continued uptake and development. Their commercialization took broad scale R&D, innovation, and supply and demand development and policies spanning several countries & regions (the US, Germany, China, amongst many others) and decades; see Kavlak et al. (2018) in the case of solar PV. The surprisingly successful integration of high levels of variable renewables came from the synergies of different innovations across different dimensions, such as technology, market design, business models and systems operation (IRENA, 2019a). Far more grid flexibility was found in the system than was expected. This now allows many new permutations of wind and solar to be experimented with, but, with its very success, it demands development of enabling technologies like batteries, green hydrogen and heat pumps be sped up so that variability and specific heat needs do not become a barrier to the uptake of cheap wind and solar PV.

If the Paris goals are to be met, we do not have decades to find out if the primary energy supply and enabling technologies listed in this report will become commercially available, and we do not have more decades for this to happen if successful. At minimum, as identified in the IEA NZE scenario (2021) and (IRENA, 2021a), on and offshore wind, green hydrogen, heat pumps of all sizes and temperature, thermal storage technologies for building, and floating solar all need to be commercially available by 2030

(batteries are cheap but need to get cheaper and more recyclable); no new emitting technologies can be invested in past this date if the Paris goal are to be met. BECCS or its cousin direct air capture and storage (DACs) will also need to be commercially viable in the 2030s (Masson-Delmotte et al., 2018).

A key consideration is many of the markets for these technologies will be in in-transition and developing countries, which cannot be expected to fund their development along with all their other priorities. Aggressive and fast research, development, piloting, and early commercialization programs are needed to test whether these technologies are viable in the short term, and worth investing in for the long term. These programs will be expensive and will be more effective if shared by several countries with a long-term interest. Arguably the funding should be provided by better resourced countries, and especially those proportionally accountable for historic cumulative emissions.

Some technology needs are shared, some aren't – finding partners

Countries and sectors need to develop net-zero decarbonization pathways (Waisman et al., 2019) based on their physical resources, sustainable development needs and local politics. If their physical resources and need for clean electricity for electrification and heat indicate one or more of the included technologies may be useful (e.g., if a Caribbean island state has little land for solar, lacks a clean firm power source, and has a strong need for desalinized water for drinking and irrigation it may wish to join a coalition to commercialize OTEC), they need to find governmental and firm partners to work with to make the technology happen.

Breaking technology logjams – shared accelerator projects & saving accumulated technology

As noted, not all these technologies will succeed or be needed, but speed is of the essence to determine which ones can make a significant contribution. Many of the companies working on airborne wind, wave, tidal, thermal storage and OTEC are very small and subject to failure and loss of accumulated knowledge and capacity if their funding runs out. For example, a very promising Scandinavian manufacturer of the world's highest temperature industrial heat pumps, Viking Ltd., failed when orders did not materialize. Hundreds of millions USD of Norwegian government money was lost, and the intellectual property went up for sale for a few million USD – it is unknown if it will be revived at time of writing. Failure is one of the risks of business, but the climate change goals indicate that accumulated knowledge of these technologies should not be lost with companies. Some form of international heat pump accelerator program, with shared investment by international firms and governments, could have taken on Viking's technology with lower risk to all parties. The same could be said of many of the emerging technologies in this report. There are existing IEA Technology Coordination Partnerships (TCPS) that could form the core of such accelerators, or the UK model for the Offshore Wind Accelerator could be duplicated – there are many possibilities.

Ad hoc, start and stop innovation won't do - a systemic innovation and market uptake approach is needed

Over the last decade there have been spectacular success in reducing the cost of variable renewables and integrating them in grids at high farther market shares than anyone expected. This was not accidental. There were conscious efforts by many governments over many years on R&D, commercialization of and market making for wind and solar. The integration of high level of VREs was enabled by such physical flexibility options as grid strengthening, demand-side management, energy storage, sector coupling and flexible conventional generation, but also institutional and market innovations such as feed-in-tariffs, contracts for difference and renewable portfolio standards. Policy efforts must encompass the complete

technology innovation lifecycle and all aspects of integration in the energy supply and demand system, including demonstration, early and later deployment (technology learning) and early and broad commercialisation stages (International Renewable Energy Agency, 2017; IRENA, 2019a). Furthermore, the innovation ecosystem should extend across a whole range of activities, including creating new market designs, building innovative enabling infrastructure, and creating new ways to operate energy systems, establishing standards and quality control systems, and implementing new regulatory measures.

While some of the technologies that have been reviewed in this report are unlikely to provide a large, global level contribution to meeting climate change goals and the SDGs (airborne wind energy, wave energy, tidal energy, OTEC), they may be critical to some countries' efforts, and may yet surprise us in their scale if engineering and business case challenges are overcome. Some of the technologies are very likely to provide global scale benefits (floating wind, floating solar PV, green hydrogen, batteries, thermal energy storage, and heat pumps), and need to be fully commercialized and brought to market as soon as possible. Policies to support this will vary by regions, but must include components of both clear directionality, innovation, and market shaping to drive their uptake.

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