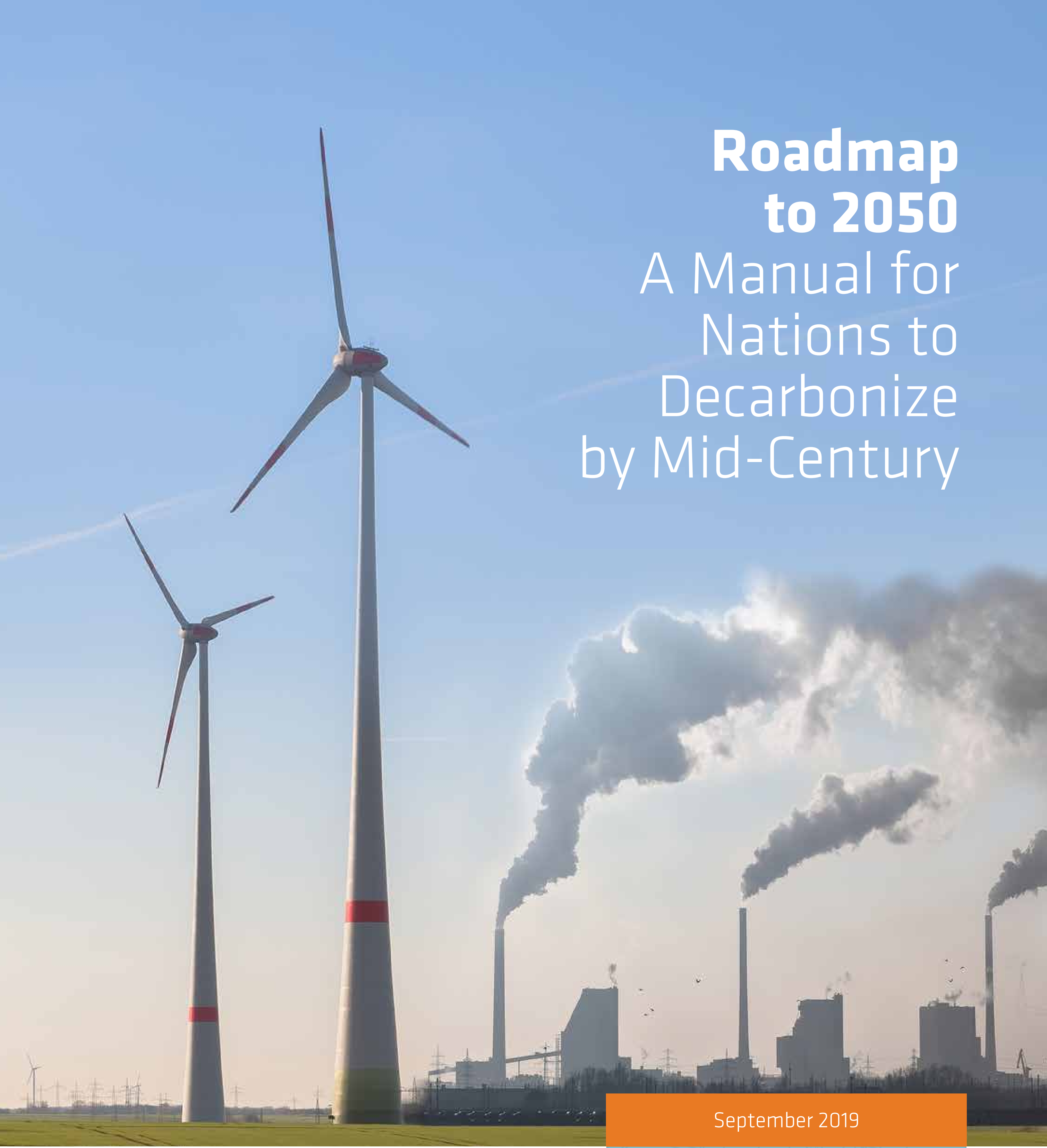
Roadmap to 2050

A Manual for Nations to Decarbonize by Mid-Century



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SUSTAINABLE DEVELOPMENT SOLUTIONS NETWORK
A GLOBAL INITIATIVE FOR THE UNITED NATIONS

FEEM
FONDAZIONE ENI ENRICO MATTEI

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The Sustainable Development Solutions Network (SDSN) has been operating since 2012 under the auspices of SDG Advisor, Jeffrey Sachs. SDSN mobilizes global scientific and technological expertise to promote practical solutions for sustainable development, including the implementation of the Sustainable Development Goals (SDGs) and the Paris Climate Agreement (PCA).

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Disclaimer

The 2019 *Roadmap to 2050 A Manual for Nations to Decarbonize by Mid-Century* was written by SDSN and FEEM and included expert input from more than 60 engineers and industry leaders who participated in an April 2019 workshop organized around power, industry, transport, and buildings decarbonization. Through an online consultation process in the summer of 2019, these experts provided 98 technical comments which were incorporated into this text at the discretion of the Lead Editors and Technical Authors.

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Acronyms

2G	Second Generation Biofuels
AC	Alternating Current
AI	Artificial Intelligence
ATJ-SPK	Alcohol-to-Jet Process
BECCUS	CCUS with Bio-Energy Resources
BEV	Battery Electric Vehicle
BF	Blast Furnace
BOF	Basic Oxygen Furnace
BYD	Build Your Dreams
$CaCO_3$	Calcium Carbonate, or Limestone
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture Utilization and Storage
CEMS	Community Energy Management System
CFC	Chlorofluorocarbons
CGE	Computational General Equilibrium
CH_4	Methane
CO_2	Carbon Dioxide
CRI	Carbon Recycling International
CSP	Concentrated Solar Power
DAC	Direct Air Capture
DC	Direct Current
DHW	Domestic Hot Water
DRI	Direct Reduced Iron
DSM	Demand Side Management
DSS	Decision Support System
EAF	Electric Arc Furnace
EMS	Energy Management Systems
EMSA	European Maritime Safety Agency
EPC	Energy Performance Certificate
ERS	Electric Road Systems
EU	European Union
EV	Electric Vehicle
EWG	Energy Watch Group
FCEV	Fuel Cell Electric Vehicle
FEEM	Fondazione Eni Enrico Mattei
FT-SPK	Fischer-Tropsch Process
GEIDCO	Global Energy Interconnection Development and Cooperation Organization
GHG	Greenhouse Gas
GLOBAC	Global Alliance for Buildings and Construction
H_2	Hydrogen
H_2S	Hydrogen Sulfide
HDV	Heavy-Duty Vehicles
HEFA-SPK	SPK from Hydro-Processed Esters and Fatty Acids Process
HELMETH	Integrated High-Temperature Electrolysis and Methanation for Effective Power to Gas Conversion
HEV	Hybrid Electric Vehicle
HFS-SIP	Hydro-Processed Fermented Sugars
HSR	High Speed Rail
HVAC	Heating, Ventilation and Air Conditioning
IEA	International Energy Agency
ILUC	Indirect Land-Use Change
IoT	Internet of Things
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
LCA	Life-Cycle Analysis
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicles
ICT	Information and Communication Technology
LCOE	Levelized Cost of Energy
LDV	Light-Duty Vehicles
LED	Light-Emitting Diode
Li-ion	Lithium-Ion
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied Petroleum Gas
LUT	Lappeenranta University of Technology Research
MaaS	Mobility as a Service

MCi	Mineral Carbonation International
MEPS	Minimum Energy Performance Standards
MES	Multi-Energy System
MRIO	Multiregional Input Output Tables
MTOE	Million Tons of Oil Equivalent
N_2O	Nitrous Oxide
NDC	Nationally Determined Contribution
NEDO	New Energy and Industrial Technology Development Organization
NGO	Nongovernmental Organization
nZEB	Nearly zero-energy building
NPS	New Policies Scenario
OEM	Original Equipment Manufacturer
P2G	Power-to-Gas
P2H	Power-to-Heat
P2L	Power-to-Liquids
P2V	Power-to-Vehicles
PCA	Paris Climate Agreement
PEM	Proton Exchange Membrane
PET	Polyethylene Terephthalate
PHEV	Plug in Hybrid Electric Vehicle
PV	Photovoltaic
PVT	Photovoltaic/Thermal
RCOT	Rectangular Choice of Technology
REEV	Range Extended Electric Vehicle
RES	Renewable Energy Sources
S	Sulphur
SAF	Sustainable Aviation Fuel
SDG	Sustainable Development Goal
SDS	Sustainable Development Scenario
SDSN	Sustainable Development Solutions Network
SGCC	State Grid Corporation of China
SIP	Synthetic Iso-Paraffins
SOEC	Solid Oxide Electrolyzer Cell
SPK	Synthesized Paraffinic Kerosene
TFC	Total Final Consumption
UCSD	University of California, San Diego
UNFCCC	United Nations Framework Convention on Climate Change
V1G	One Way Charging or 'Smart' Charging
V2B	Vehicle-to-Building
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VPP	Virtual Power Plants
VRE	Variable Renewable Energy
WTM	World Trade Model
WTMBT	World Trade Model with Bilateral Trade
WWR	Window to Wall Ratio
ZEV	Zero-Emission Vehicles

Chapter I

EXECUTIVE SUMMARY

Introduction

The United Nations Intergovernmental Panel on Climate Change 2018 Report stated, *"Limiting global warming to 1.5°C would require rapid, far-reaching and unprecedented changes in all aspects of society."* In recent years it has become clear that this scenario would require not only a transformation of our energy system in order to meet our global emissions targets, but also a rethinking of the way we control the temperature of our homes, travel around our planet, and manufacture our goods. Decarbonizing for a zero-emissions world by mid-century would require clear and efficient measures, adopted and implemented rapidly – and we have the technologies to pursue this direction.

Scientists, engineers, and technical experts will play a crucial role in the design of pathways for the decarbonization process of specific, energy-intensive sectors, notably power, heavy industry, transport, and buildings.

In April 2019, more than sixty technical experts from around the world gathered in Milan to attend a two-day Scientific Workshop hosted by Fondazione Eni Enrico Mattei (FEEM) and the Sustainable Development Solutions Network (SDSN) to discuss the state of decarbonization technologies that can accelerate the global shift towards decarbonization. The four main sectors identified for this exercise were power, industry, transport, and buildings. It should be noted that while land-use and agriculture were identified as critical additional sectors to close the emissions gap, analyses for these sectors are not included in this report.

Following the Paris Climate Agreement's aim to strengthen the global response to the climate crisis "in the context of sustainable development and efforts to eradicate poverty," the Roadmap to 2050 is conceived on a "systems approach," aspiring to simultaneously address multiple objectives and promote policy instruments and technological solutions that can be used across sectors. The multiple objectives span decarbonization and environmental sustainability, economic prosperity (including poverty reduction), and social inclusion. Policy instruments include public investments, phase out of subsidies to fossil fuels, market mechanisms, regulatory framework and regulations on land use, while technological solutions address a wide range of current and emerging solutions, from smart power grids to synthetic fuels.

A systems perspective recognizes the interconnectivity of actions towards any one or more of these objectives, using any one or more of the mentioned policy instruments or technological solutions. An action in one can be detrimental to another, while some combined efforts could amplify their cumulative effects and achieve multiple objectives. For example, the power grid itself represents a complex system that must continue to operate reliably and efficiently even as it undertakes the deepest transformation in its history. No single policy or technology can achieve decarbonization by itself or be implemented without due consideration to its ripple effects, or the delicate state of the current, broader system.

To use the proverbial expression, we must rebuild the airplane while it is in flight.

In taking a systems approach, many complementarities should be considered for managing the complexity of the energy system:

(1) Complementarities of variable renewable energy sources. Wind, solar, and hydropower vary by the minute, day, season, and year. Digital systems will play a large role in coordinating the augmented grid complexity and the required flexibility.

(2) Complementarities among zero-carbon technologies. As one obvious example, zero-emission vehicles depend on complementary zero-carbon energy sources and the infrastructure to fuel them.

(3) Complementarities of public and private investments. Parts of the energy system are in private, for-profit hands, and parts are publicly owned. It will take significant effort and analysis to harmonize public and private investments, to recognise the diverse role they can play and the synergies their joint action can create.

(4) Complementarities of natural and engineered systems. Achieving net negative emissions would require biological storage of carbon dioxide (CO2) in vegetation and soils via preservation of existing forests, restoration of degraded habitats, and reforestation to increase natural carbon sinks. Energy strategies that amplify land-use degradation must be ruled out.

(5) Complementarities of mitigation and adaptation. Adaptation measures can also contribute to mitigation strategies. Forest restoration and protection of coastal wetlands would help resist storm surges from rising sea levels, promote resilient food production, and secure carbon, thereby serving both adaptation and mitigation purposes.

(6) Complementarities of centralized and decentralized solutions. Renewable energy resources are by nature different from one place to another and restrictions on land availability and use may require different power configurations.

(7) Complementarities of actions and strategies in different geographies. Efforts to address decarbonization might be similar for big cities in North America and in Europe, but they would not apply to much of sub-Saharan Africa. Urban areas are also different from rural areas where the fight to bring access to energy and other services to all is still a challenge. Trying to impose the same pathway in different contexts can lead to failure and to the continuation of business-as-usual scenarios.

(8) Complementarities of R&D activities supported by research institutions and academia, funded by public and private sectors. These activities should aim to promote breakthrough innovation which continuously feeds the process of decarbonization and keeps under control any risk of lock-in to solutions that may fail to contribute to total decarbonization in the long run.

In order to make sense of this very complex and integrated system of energy and power, the authors of this report have identified Six Pillars of Decarbonization built on four general premises from which every country can begin to develop their roadmap to decarbonization by mid-century.

Premises

1. The development of comprehensive climate policy will depend on specific geographical and social contexts, particularly in developing or low-income areas, in order to meet the needs of both society and the planet.

2. Great cooperation and coordination in terms of policy design and implementation are required: stakeholders will need to consider the integrated use of different resources, technologies, or processes to guarantee inclusion and socioeconomic development of communities and enterprises' competitiveness in the global market.

3. Flexible and innovation-receptive regulatory frameworks are pivotal to address the challenge.

4. Substantial efforts must be made to allocate consistent investments in research and development, as technological breakthroughs will trigger innovation and shorten the path toward global decarbonization.

SIX PILLARS

ZERO-CARBON ELECTRICITY. A shift towards zero-carbon electricity mix.

ELECTRIFICATION OF END USES. The penetration of electricity, built on existing technologies, can enable a green conversion for the sectors currently using fossil-fuel energy.

GREEN SYNTHETIC FUELS. Deployment of a wide range of potential synthetic fuels, including hydrogen, synthetic methane, synthetic methanol, and synthetic liquid hydrocarbons applicable for harder to abate sectors.

SMART POWER GRIDS.
Systems able to shift among multiple sources of power generation and various end uses to provide efficient, reliable and low-cost systems operations, despite the variability of renewable energy.

MATERIALS EFFICIENCY.
Improved material choices and material flows, such as reduce, reuse, and recycle to significantly improve materials efficiency.

SUSTAINABLE LAND-USE.
Mainly involving the agriculture sector, as it contributes up to a quarter of all greenhouse gas emissions from deforestation, industrial fertilizers, livestock, and direct and indirect fossil-fuel uses.

The drafting process of the *Roadmap to 2050: A Manual for Nations to Decarbonize by Mid-Century* incorporated feedback from an external consultation exercise, through which experts operating in varying but integral contexts – international agencies, academia, research centers, think tanks, nongovernmental organizations (NGOs), public institutions, and the private sector –provided critical, substantive input. The technology recommendations gathered from these expert engineers are summarized in the following section.

Power

The power sector is already undergoing a decarbonization process in multiple countries around the world. The traditional centralized organization of the power system is now facing a paradigm shift to distributed and renewable generation. This new model is closely related to the implementation of smart grids, where the end users act as prosumers by supplying the network with the excess of power generation produced by their distributed photovoltaic (PV) systems. Digital technologies will be at the center of this revolution, unlocking the potential of different business models like virtual aggregators and peer-to-peer energy trading.

The current technologies supporting this transition can be classified into four main groups:

(1) low-carbon energy sources (on- and offshore wind, solar PV and concentrated solar power, hydropower, biomass, nuclear, and geothermal)
(2) short-term and long-term electricity storage solutions
(3) other flexible options such as network interconnections, sector coupling, supply response (hydro reservoirs, bioenergy) and demand-side management (DSM)
(4) carbon capture, utilization, and storage (CCUS), and variants including bio-energy CCUS and direct air capture

While many of these technologies are already cost-competitive and may offer even lower costs in the future, others (e.g. electricity storage and carbon capture) require future technological developments and/or increased economies of scale to support their effective deployment at the levels needed to reach a full decarbonization of the power sector.

The total decarbonization target will require a combination of multiple technologies. Depending on local conditions, the mix of available power options will vary from one country to another, and thus there will be no one-size-fits-all solution. The implementation of transition technologies may also be required. Coal should be phased out earliest given its high carbon content and its contributions to air pollution. While natural gas may play a crucial role during a transition period, it will also need to be either decarbonized or progressively phased out. In all cases, countries should prepare detailed plans exploring all options for decarbonization, and their associated costs. To allow for unanticipated technological breakthroughs and cost reductions, energy policies need to be flexible, to be regularly assessed, and be adaptive to ongoing technology advances in order to allow each potential low-carbon solution to be supported and deployed.

While many national and international policies are heavily oriented towards the electrification of energy systems, electrification must proceed alongside decarbonization in order to fight climate change. Also, the energy efficiency potential along the whole electricity chain should not be underestimated. Moreover, a strongly integrated approach across sectors and energy pathways is essential for addressing climate change issues. Finally, secondary effects and a holistic perspective on the entire lifecycle of technological solutions should be considered to avoid potential rebound effects from specific technology choices.

Industry

Heavy industry emits a large share of global greenhouse gas emissions, because industrial processes employ high temperatures and depend on high energy densities to enable the chemical processes involved. The industrial sector of the worldwide economy consumed more than half (55%) of all delivered energy in 2018. Within the industrial sector, the chemicals industry is one of the largest energy users, accounting for 12% of global industrial energy use.[1] Three energy intensive sectors are considered in this roadmap: cement, iron and steel, and petrochemicals (plastics, solvents, industrial chemicals) which each contribute to emissions of different kinds: i) direct, thermal, ii) direct, chemical and iii) indirect.

Emissions from these types of industries are significant and require solutions that go beyond electrification of the energy inputs, actually adjusting the chemical and physical processes associated with typical huge industrial plants operations. To reduce emissions, these industry sectors will need to displace fossil fuel-based energy inputs with low- to zero-emission electricity, along with improved heat integration and energy efficiency, all by taking advantage of new processes. Fully decarbonizing such complicated and integrated industrial environments requires a multidimensional approach.

Three action areas in this sector include:

- reducing demand for carbon-intensive products and services
- improving energy efficiency in current production processes
- deploying decarbonization technologies across all industries, which in turn can be split between four supply-side decarbonization routes

Electrification | **Use of biomass** | **Use of hydrogen and synthetic fuels** | **Use of carbon capture technology**

1 Sendich, Elizabeth. "Today In Energy -Energy products are key inputs to global chemicals industry." U.S.Energy Information Administration (blog). June 21, 2019. Accessed August 21, 2019. https://www.eia.gov/todayinenergy/detail.php?id=39952&src=email

There are currently no purely technological limitations blocking major decarbonization routes across any industrial sector. The barriers are economic and not technological; we have the technologies today, but they are expensive. Moreover, the complexity of very integrated production plants introduces an additional obstacle: secondary products are used as feedstock for other plant sections. As a major consequence, changes in one process need to be introduced to ensure compatibility with the other processes.

Some material efficiency options for the three industrials sectors analyzed include:

- Cement: building design optimization, concrete reuse, materials substitution
- Iron and Steel: optimization of scrap recycling, product design for efficiency, more intensive use of products
- Petrochemicals: chemical and mechanical recycling, plastic demand behaviour change, use of renewable feedstocks, and product eco-design to better enable recycling

For these industries, improvements in energy efficiency should run in parallel with material efficiency and demand reduction. Appropriate technology for energy efficiency exists today and it can be applied in any country. Some of the key solutions for energy efficiency improvement include:

- Cement: switch to dry kilns, multistage cyclone heaters
- Iron and Steel: re-use of high-pressure gas for power, coke dry quenching
- Petrochemicals: energy efficiency in monomer production, and naphtha catalytic cracking

These solutions may result in a meaningful reduction in emissions, but policymakers must also promote change through economic and policy incentives.

Of course, also geographical contexts will impact technology decision making. Countries investing in new plants should go for zero-carbon technology rather than invest in energy efficiency improvements in plants at the end of their life. In contrast, countries where legacy plants and facilities will continue to operate for years to come should invest in energy conservation and energy efficiency improvements for existing processes. Additionally, the possibility of combining more of these solutions in a given country or facility will vary and depend on the geographical distribution of resources and social acceptability of specific technologies.

The pace at which technological breakthroughs are adopted will determine deployment opportunities over the next decades. Specific geographic and political scenarios play a critical role in the pace of technology development, adoption, and deployment, notably:

- the existence of appropriate policy incentives as well as other policy instruments
- reduction in the cost of alternative zero-carbon fuels, in particular zero-carbon electricity
- trade-exposed industries facing international competition from jurisdictions that have chosen to reduce their emissions at a slower pace

Transport

The transport sector is the backbone of any productive system; enabling the mobility of people and goods means connecting people and nations and fostering economic and cultural exchanges and social development. The complexity of the sector requires deploying a diverse mix of decarbonization solutions to meet the challenges within each of its four main segments: roadways, railways, aviation, and navigation.

Each segment has a different ease of decarbonization. Moreover, transport has strong interactions with other productive sectors and, in order to avoid rebound effects, it requires the power sector to be fully decarbonized and the cradle-to-grave energy supply chain to become increasingly efficient. Effective decarbonization pathways in transport rely mostly on technological solutions, new sustainable fuel development, and fuel shifts and are complemented by demand reduction and modal shift strategies.

Finally, different energy vectors will play a role on transport decarbonization. Direct electricity usage (through either batteries or electrified railways and electric road systems), hydrogen, synthetic fuels, and sustainable biofuels –properly allocated to hard-to-decarbonized modes – will all be important for transport decarbonization. As far as the use of biomass, scarcity of the resource and complexity in overall supply chain may suggest that biofuels could be prioritized in particular modes of transport (e.g. harder-to-abate segments like long-haul aviation) or geographical areas (e.g. those not likely to proceed toward total decarbonization in the power sector in the near term).

The action areas in this sector include:

- A diverse mix of decarbonization solutions and energy vectors need to be sought by each transport segment: roadways, railways, aviation and navigation.
- Effective decarbonization pathways rely mostly on technological solutions, new sustainable fuel developments, and fuel shifts, complemented by demand reduction and modal shift strategies.
- In the road segment, CO_2 emissions are easier to abate due to *electric vehicles* and *fuel-cell electric vehicles* for short-to-medium haul (freight, passenger, light-duty, or heavy-duty categories).
- The pathways for railway decarbonization are mostly based on *fuel shifts from diesel to electricity or hydrogen*.
- Concerning aviation, advanced jet fuels (such as synthetic fuels) are the only way to decarbonize the current fleet and the relevant one in the near future. Modal shift from air to land could be enhanced with innovative alternatives, such as ultra-high-speed trains, with the right policies in place.
- For similar reasons, long-haul navigation is hard to abate while short-haul navigation[2] can be supplied by *electricity or hydrogen technologies*. Ammonia and hydrogen are currently being investigated in long-haul navigation.
- Use of biofuels and the sustainability of biomass for biofuels needs to be carefully assessed so as to avoid: competition with food production; deforestation or loss of biodiversity in natural regions; and, competition with industries that currently use the biomass for higher value products or uses. As sustainable biofuels will only be available in limited volumes, its use should be prioritised in hard-to-abate modes like aviation.
- Regulatory frameworks need to be technology agnostic to create a fertile environment for innovation, unleashing the potential of the research while fostering virtuous behaviours of citizens in all transport modes.
- Research and innovation need to investigate life-cycle analysis (LCA) and indirect land-use change (ILUC) impacts of these technologies to confirm sustainability, avoiding solution lock-in and stranded assets.

2 Short-haul ecompasses in-land waterways, coastal and intra-regional shipping; long haul navigation covers intercontinental or deep sea shipping

Buildings

Buildings represent an estimated 36% of global final energy consumption and 39% of the global energy-related greenhouse gas (GHG) emissions.[3] The goal of total decarbonization in the buildings sector includes the construction of new buildings and districts with zero or almost zero energy consumption from fossil fuels and the total renovation of existing buildings with the same net zero carbon standards. Current renovation rates account for about 1% of existing building stock each year, yet to achieve 100% zero carbon goal by 2050 it is necessary to ensure a renovation rate higher than 3%.

It should be noted that the CO2 emissions resulting from material use in buildings represents almost one third of building-related emissions: the construction industry must radically change its manufacturing structure in order to abate this increasing embodied energy.

In general, using a combination of readily available technologies and approaches, and performance-based design metrics, net zero carbon buildings and districts can be achieved today, according to the following strategy:

A) maximize the buildings energy efficiency first, mainly through passive and low embodied-carbon solutions;

B) Adopt high-efficiency technical systems and advanced control/management strategies: the phase out inefficient solutions, encouragement of low-carbon systems such as heat pumps and district heating and adoption of advanced control/management strategies, is the second priority.

C) Maximize on-site or nearby renewable energy production and self-consumption while electrifying the buildings sector to completely cover or exceed the total energy demand of each building with the minimum exchange of energy with the grid (thus stimulating energy management, storage and exchange at district level).

This will result in different combinations of solutions that are appropriate for each specific context, obtaining buildings that are resilient to climate change effects. Moreover, to achieve the overall decarbonization of the buildings sector, energy consumption related to cooking must also be addressed.

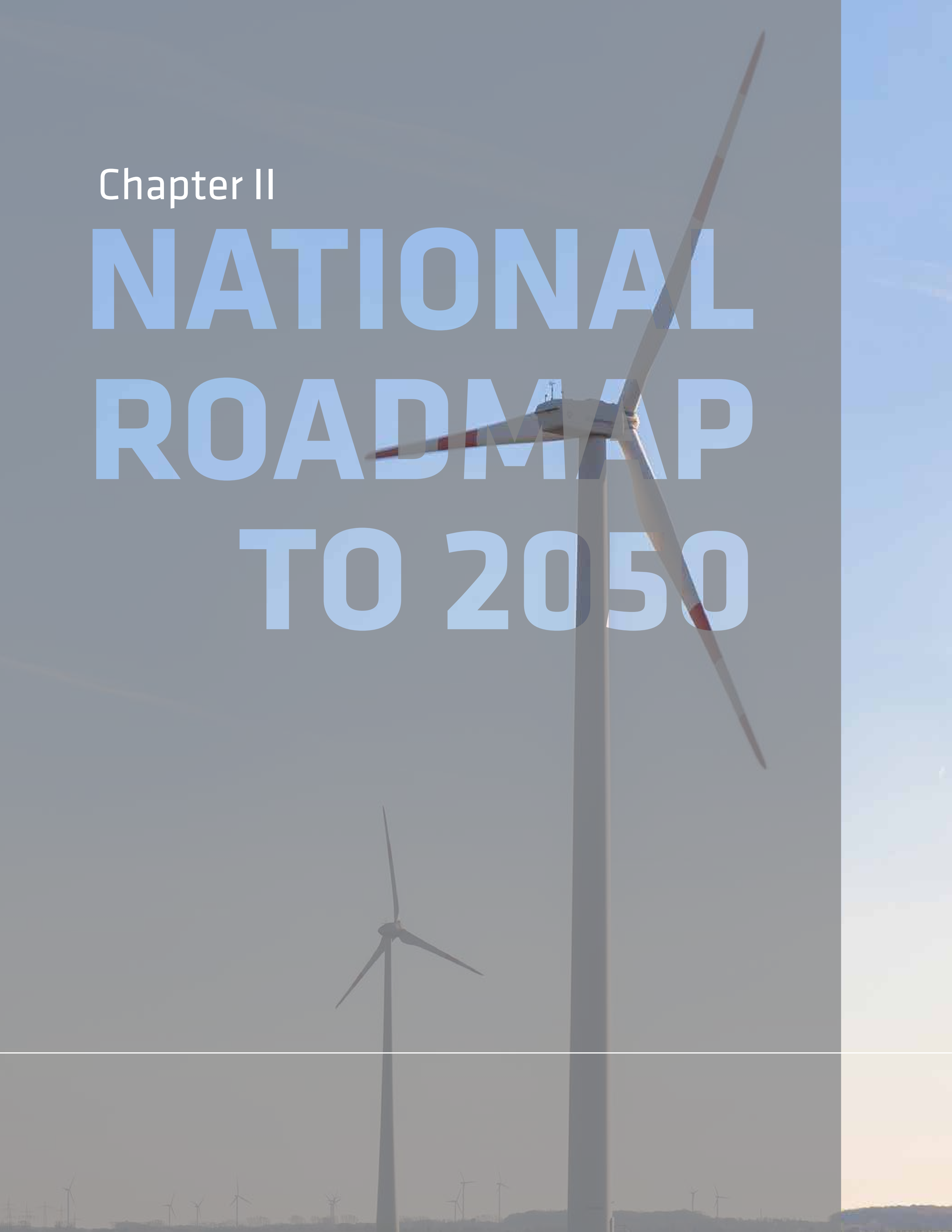
The action areas in this sector include:

- Establish advanced building energy codes with mandatory performance standards and set minimum energy performance levels for existing buildings. Policies and subsidies to favor the retrofit of existing buildings rather than new constructions are absolutely necessary.
- Achieve high-efficiency building envelopes at negative life-cycle cost, mandate energy performance standards for envelope components and work with industry to deliver non-invasive and whole-building retrofit packages. Policy makers should develop strategic frameworks to create the adequate market conditions for low-carbon technologies, guiding building owners and designers in making the correct choices.
- Mandate minimum energy performance standards for stand-alone heating equipment, prevent expansion of fossil fuel heating, and pursue strategy to shift demand to high efficiency and integrated energy solutions with net zero emissions.
- Pursue low-cost solar cooling technologies such as high efficiency and renewable district cooling where appropriate. Mandate use of waste heat from large-scale cooling for heating and hot water use on-site or via district systems; local governments are uniquely positioned to advance district energy systems in their various capacities.
- Regulations and measures obstructing energy self-consumption such as specific additional taxes or levies should be lifted and administrative procedures to allow self-consumption should be user-friendly.
- Achieve affordable thermal storage and low cost solar thermal systems (for low-income countries only).
- Training and capacity building activities for the construction sector must be adequately promoted, while also pushing the development of specific DSS (decision support system) or design-aid tools to strongly increase the application of climate-responsive and integrated building design.

3 Global Alliance for Buildings and Construction (GLOBAC), United Nations Environment and International Energy Agency. "Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector." GLOBAC. Published 2018

Chapter II

NATIONAL ROADMAP TO 2050



In recognition that climate change is the defining challenge of our times demanding bold and urgent action, several dozen countries and hundreds of cities have committed to the goal of reaching zero emissions by 2050. Many of these commitments include policy roadmaps, targets for intermediate years, and organizational frameworks detailing responsible agencies, reporting requirements and metrics. Article 4.19 of the Paris Agreement states, "All Parties should strive to formulate and communicate long-term low greenhouse gas emission development strategies, mindful of Article 2 taking into account their common but differentiated responsibilities and respective capabilities, in the light of different national circumstances." This document is intended to help countries prepare their national policy roadmaps for reducing greenhouse gas (GHG) emissions. These roadmaps will also serve to support official communications with the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat in fulfilment of their Paris Agreement obligations by 2020. Parties face three main challenges in developing their roadmaps. The first is designing a framework that is specific enough to be technologically credible and useful to investors, but remains flexible enough to incorporate future learning and advances in technologies. The second is designing a framework that is fair and politically credible –for example, providing compensation for hard-hit regions and vulnerable populations. The third is designing a system of mutual responsibility and accountability for both public and private stakeholders.

The complexity, comprehensiveness, and urgency of the transformation compound these challenges, as does uncertain trajectories and development of leading technologies that are continually advancing. These challenges call for broad policy frameworks with clear goals (most importantly, zero emissions by 2050); technology roadmaps (for example, the shift to zero-emission vehicles); regulatory assignments to stakeholders (utility companies, energy users, power generators, public agencies, etc.); and strong systems of deliberation, public awareness, reporting on outcomes, and feedback loops based on outcomes and learning. The State of California, as one notable example, has developed such a model decarbonization framework over the past quarter-century that continues to win the political assent of the public and successive state governments. Costa Rica offers another example, where political leadership coupled with sound technical planning has led to the release of Costa Rica's decarbonization plan with 10 cross-cutting focus areas to achieve decarbonization.

Finally, although many actions and policies are focused on the supply side, a comparable effort should be made on the demand side, particularly with regards to energy efficiency and energy savings. The expected increase in energy demand worldwide should be limited as much as possible, but without compromising economic development and energy access. An optimal energy management is the basis for the potential success of decarbonization policies throughout the main sectors. Moreover, both for supply and demand, the focus should be on the desired targets rather than pushing specific technologies or solutions.

All Parties should strive to formulate and communicate long-term low greenhouse gas emission development strategies, mindful of Article 2 taking into account their common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.

Chapter III

POLICY FRAMEWORKS TO SUPPORT THE NATIONAL ROADMAPS

The global climate regime, governed by the UNFCCC and the Paris Climate Agreement (PCA), leaves most actions to national governments. Each national government offers Nationally Determined Contributions (NDCs) that are supposed to be consistent with meeting the objectives of the PCA. The first round of NDCs were offered upon ratification of the PCA during 2015-16 and generally covered the period to 2025-30. The next round of NDCs will come in 2020 and will presumably cover the period of 2030-35. In addition to the NDCs, countries are requested in Article 4.19 of the PCA to submit low-emission development strategies, presumably on a time horizon to mid-century or beyond.

Three points must be emphasized:

1) National plans should cover the time period to at least 2050. NDCs that have a time horizon of just 10 to 15 years are far too short to plan for energy system and land-use transformations. Incremental planning based on short intervals does not produce the desired long-term effects, since decisions made today (2019) determine outcomes far beyond a 10- to 15-year planning horizon. Power plants built today will still be operational beyond 2050. New or retrofitted buildings will be standing well beyond 2050. Land-use choices made today can result in irreversible effects after 2030 in the form of species extinction or permanently degraded ecosystems.

2) According to the UN Environment Programme's Emissions Gap Report 2018, the sum of the NDCs to date would put the planet on a path of reaching around 3° C by the end of the century, and continuing to rise thereafter, rather than the limit of "well below 2° C and aiming for 1.5° C" set in the PCA.[4] This means that current NDCs fall far short of the ambition needed to achieve the PCA objectives. Since the NDC process is "bottom-up," with each country submitting its contribution on a voluntary basis, the ensemble of the NDCs don't add up to the requested global effort.

3) While countries are responsible for their own resources and energy choices, cross-border solutions are required to achieve common goals of reducing GHG emissions. Climate Change is a global issue, which transcends national boundaries. Therefore, we need to keep cross-border solutions in mind, in addition to national approaches.

Every country should be guided by a basic global standard in the 2020 submissions to the UNFCCC under the Paris Climate Agreement:

> *National plans should cover the period to at least 2050 and should aim to equitably reach net zero emissions by 2050 and net negative emissions in the second half of the century.*

Moreover, each national plan should be based on national efforts backed by global enablers. The national efforts are the actions under the control of each individual country. The global enablers are the changes in the global systems needed for each country to be consistent with the goal of zero net emissions by 2050.

4 UN Environment. "Emission Gap Report 2018." *UN Environment.*Published 2018. https://www.unenvironment.org/resources/emissions-gap-report-2018

Table 1 summarizes national efforts and global enablers and illustrates the complementarity between them. Each national or local authority has the responsibility for its own power grid, building codes, transport infrastructure, and land-use policies. Yet each nation also depends on global-scale technological systems – for battery electric vehicles, zero-carbon aviation and ocean shipping, clean industrial processes, and zero-carbon heavy industry – in order to achieve znet zero emissions at the national level. Nations should plan their national policies based on the expectation of global supply chains for the needed zero-emission technologies, while also taking into consideration the diversity of socioeconomic status and access to affordable technology and innovation.

There are important signs that new global supply chains are coming into existence to enable the transition. For example, some automobile manufacturers are declaring their intention to move away from internal combustion engine (ICE) light-duty vehicles and shift towards zero-emission vehicles (ZEV). In the same line, more than a dozen countries, including China, have initiated actions to phase out progressively ICE vehicles, in many cases by 2030.[5]

TABLE 1. National Efforts and Global Enablers to Reach Zero Net Emissions by 2050

MAIN PILLARS TO ZERO NET EMISSIONS BY 2050	NATIONAL ACTIONS	GLOBAL ENABLERS
Zero-Carbon Electricity	Zero-carbon electricity grid, mainly based on renewable energy	Reduced costs of renewable energy, mass scale-up of solar photovoltaics and wind turbines, improved energy storage technologies, and expanded R&D of new energy sources
Electrification	Infrastructure for battery electric vehicles, retrofitting of buildings for electric heating and cooking	Global phaseout of ICE vehicles, global mass production of battery electric vehicles (BEVs)
Synthetic Fuels	Infrastructure for trade and distribution of synthetic fuels and biorefining	Global R&D and scale-up of synthetic fuels for heavy-duty vehicles, ocean shipping, aviation, heavy industry
Smart Power Grid	Introduction of a digital power grid and the Internet of Things (IoT)	R&D of artificial intelligence (AI)-backed smart grid systems
Materials Efficiency	Introduction of the circular economy and national waste management systems	R&D of alternatives to cement, plastics, and other pollutants (persistent pesticides)
Sustainable Land-Use	Sustainable land-use regulations (reforestation, restoration of degraded lands), precision agriculture, reduced food wastage, shift towards plant-based protein diets	Sustainable global supply chain management for major crops, global real-time monitoring systems for land management

5 Burch Isabella and Gilchrist Jock. "Survey of Global Activity to Phase Out Internal Combustion Engine Vehicles." *Center for Climate Protection.* Published 2018. https://climateprotection.org/wp-content/uploads/2018/10/Survey-on-Global-Activities-to-Phase-Out-ICE-Vehicles-FINAL-Oct-3-2018.pdf

At the national level, each country will need to take responsibility for the following major actions: 100% zero-carbon electricity; infrastructure for electrification of buildings, vehicles, and industry; infrastructure for synthetic fuels; smart grid management, including implementation of technology like the Internet of Things (IoT); waste management (reduce, reuse, recycle); and sustainable land management, including land conservation, sustainable farm practices, reduced food wastage, and a shift towards healthier diets through public health initiatives and food industry regulations. Further, stronger international cooperation supported by innovative blended finance and investment allocations will be needed to fund the transition. Such mechanisms would further strengthen international partnerships and ensure cooperation in the decarbonization of heavily traded global commodities.

At the core of the national effort should be an expanded zero-carbon electricity grid to be achieved by mid-century at the latest, and ideally by 2040 or even earlier. Many national and sub-national governments are already committed to reaching zero-carbon electricity by 2040. The options for doing so are favorable. Several scenarios – including those presented in reports by the International Renewable Energy Agency (IRENA)[6] and the International Energy Agency (IEA)[7], supported further by academic exercises by the Global Energy Interconnection Development and Cooperation Organization (GEIDCO)[8] and Lappeenranta University of Technology Research-Energy Watch Group (LUT-EWG)[9], among others – suggest that rapid progress towards zero-carbon electricity is possible based on renewable energy resources at low cost, and even below the costs of current energy systems. While such reports utilize different assumptions and somewhat differing timing, they all indicate movement in the same direction, suggesting the feasibility of global decarbonization in the coming decades. Special attention would need to be given in the light of the Agenda 2030 to low income countries and developing regions where the transition will have to occur without increasing the poverty gap and exacerbating global inequality. The fourth target[10] of SDG 7 is indeed created for this purpose: where national capacity or resources are not enough to proceed with the needed speed towards the energy transition, the international community should create the right support via international cooperation and fund allocations.

The precise design of national and regional electricity markets to accommodate 100% renewable energy remains in debate.

The issue is this: In a traditional, centralized fossil fuel-based power system, system-level reliability and flexibility is achieved largely through the characteristics of the fossil fuel-based technologies. Base load fossil fuel plants, for example, provide the inertia needed for frequency control; as turbine power provides reliable, low-cost dispatchable power.

For systems with high penetrations of variable renewable energy, by contrast, systems reliability and flexibility must be built into the system alongside power generation capacity. Variable renewable energy sources such as wind and solar power are intermittent and non-dispatchable. Therefore, the challenges of frequency control and dispatchability must

6 IRENA Coalition for Action. "Towards 100% Renewable Energy: Status, Trends and Lessons Learned."*IRENA Coalition*. Published 2019. Accessed June 25, 2019. https://coalition.irena.org/-/media/Files/IRENA/Coalition-for-Action/IRENA_Coalition_100percentRE_2019.pdf

7 IEA. "Sustainable Development Scenario." *IEA.* Last modified 2019. Accessed June 25, 2019. https://www.iea.org/weo/weomodel/sds/

8 GEIDCO. "Energy Interconnection No.1." *GEIDCO.* Accessed June 25, 2019. http://www.geidco.org/html/qqnyhlwen/col2017080820/2018-03/06/20180306095627610693558_1.html

9 Manish Ram, Dmitrii Bogdanov, Arman Aghahosseini, Ashish Gulagi, Solomon A. Oyewo, Michael Child, Upeksha Caldera, et al. "Global Energy System based on 100% Renewable Energy - Power, Heat, Transport and Desalination Sectors" *Study by Lappeenranta University of Technology and Energy Watch Group.* Last modified April 2019. Accessed August 19, 2019. http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf

10 "By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology

be achieved through technologies that are complementary to power generation. Intermittency of renewable energy must be accommodated through larger interconnected transmission grids, storage technologies (e.g. pumped hydro, grid-scale batteries), demand-side flexibility, byproducts of biorefineries and other means. How these complementary services are incentivized and managed will depend on many specific characteristics of the electricity market, such as the ownership structure of power generation, transmission, and distribution, the availability and ownership of pumped and fully dispatchable hydro storage, and the regulatory and financing authority of the systems operators.

Among all other key figures to be involved at a national level, finance ministers have a distinctive and central role to play in the design and implementation of national zero-emission plans, a role that has recently been recognized in the formation of the Coalition of Finance Ministers for Climate Action. This role centers on the financing and regulation of the zero-emission plans with the policy tools summarized in Table 2. Financial policies range from financing of public infrastructure, to regulation of private financial institutions, to collection of carbon taxes, to compensatory transfer payments to individuals and regions that will incur unusually heavy costs during the transition from fossil fuels to renewable energy.

TABLE 2. Major Fiscal and Financial Policies for Zero-Emission Policies

ACTION AREA	MAJOR FISCAL AND FINANCIAL POLICIES
Zero-Carbon Electricity	Regulatory framework for power grid operators; public investments in renewable energy transmission and distribution; income support for fossil fuel-producing regions and sectors experiencing social costs of transition; redesign of electricity markets; financial market regulations to avoid stranded assets in the financial system; carbon pricing and taxation; green bonds
Electrification	Public investments in infrastructure (e.g. charging facilities for BEVs); building codes for zero-emission buildings; regulations for phasing out ICE vehicles (coupled with incentive schemes to address equity issues); public procurement of BEVs; retrofitting and design of public buildings
Synthetic Fuels	R&D outlays for synthetic fuels; public infrastructure for synthetic fuels (e.g. adaptation and upgrading of existing pipelines for hydrogen, e-fuels, etc.), regulation to ensure ethical sourcing of biomass. These fuels should be generated by RES and may require 5 to 6 times more RES electricity units to generate one unit of synthetic fuel.
Smart Power Grid	Public investments in digital technologies for the power grid; regulations on AI and big data; design of IoT
Materials Efficiency	National and local regulations on waste management and recycling; policies for waste valorization
Sustainable Land-Use	Land-use regulations; public investments in national land-use monitoring systems and enforcement mechanisms; public payments for ecosystem services (e.g. payments for protected areas); green bonds
International Cooperation and Investment Allocation	Result based Investment for all public aid at bilateral and multilateral level, national support to de-risk private investment for the energy transition.

Chapter IV

SYSTEMS APPROACH EXPLAINED

The Paris Climate Agreement (PCA) aims to strengthen the global response to climate change "in the context of sustainable development and efforts to eradicate poverty." The Roadmap to 2050 is therefore based on a "systems approach," to ensure that multiple objectives are simultaneously addressed. These *multiple objectives* include the three main pillars of sustainable development: economic prosperity (including poverty reduction), social inclusion (leaving no one behind), and environmental sustainability. More specifically, the strategy to address climate change must simultaneously aim to achieve the 17 Sustainable Development Goals (SDGs).

A systems perspective is vital because actions in one area can trigger outcomes in other areas that are detrimental to sustainable development. Therefore, the overall package of measures in the Roadmap to 2050 must simultaneously address and satisfy the globally agreed objectives of sustainable development. An overreliance on biofuels, for example, could reduce the carbon content of energy, thereby slowing the contribution to climate change from anthropogenic emissions, but at the expense of biodiversity and therefore at the expense of SDG 14 (sustainable marine ecosystems) and SDG 15 (sustainable terrestrial ecosystems). This is not to say it is not a critical part of the solution. Similarly, a reliance on geoengineering via solar radiation management to cool the climate (e.g. through the injection of aerosols into the stratosphere) might reduce anthropogenic warming, but exacerbate other sustainable development challenges (such as crop productivity). The aim of the Roadmap to 2050 is meeting the needs of both society and the planet by relying on the integrated use of different resources, technologies or processes, while avoiding short-sighted *competition* among them.

A systems approach recognizes that we have multiple instruments (public investments, income redistribution, elimination of subsidies to fossil fuels, carbon taxation, R&D promotion, regulations on land-use, etc.) that should be combined in order to achieve multiple goals (economic prosperity, the eradication of extreme poverty, climate adaptation, and of course, the limits on anthropogenic warming adopted in the PCA). No single policy – such as carbon taxation – can by itself address the multiple dimensions of the socio-economic-physical systems needed to combine climate actions with other sustainable development policies. Therefore, a systemic approach needs to penetrate the national and global policy dialogue.

Even within the narrower purview of climate mitigation, a systems approach is needed to plan and implement a strategy to limit and stop anthropogenic contributions to climate change. The transition to zero-carbon energy involves many interconnected components that need careful coordination. The power grid itself is a complex system, including power generation, transmission, distribution, and the system must be coordinated continuously to maintain high performance, prevent blackouts, forced shutdowns, and other instabilities. Grid systems managers coordinate across a plethora of public and private institutions, and technological and socioeconomic domains. This complex system must continue to operate reliably, efficiently, and economically even as it undertakes the deepest transformation in its history.

Here are some of the complementarities in managing the complex energy system:

(1) Complementarities of variable renewable energy (VRE) sources. Wind, solar, and hydropower vary by the minute, day, season, and year. This variability must be addressed in a systematic manner, through storage, backup reserves, interconnections across uncorrelated or anti-correlated primary energy sources, demand side management, etc. The usefulness of any potential source of VRE depends on the other VRE sources in the grid, and that in turn depends on the extent of the transmission and distribution systems, the nature of the electricity market, and other design features of the power grid. Digitalisation systems like metering and remote control can play a big role in addressing this challenge.

(2) Complementarities of zero-carbon technologies. As one obvious example, zero-emission vehicles depend on complementary infrastructure to fuel the vehicles. Battery electric vehicles (BEVs) will require charging sites; hydrogen vehicles will depend on a network of refuelling stations and pipelines or trucks to transport the hydrogen. Geological carbon capture and storage (CCS) technologies will depend on a network of CO_2 pipelines and sequestration sites. A biorefinery that ferments sugars into ethanol provides one of the cheapest forms of CO_2 capture given the clean and concentrated stream of CO_2. That CO_2 can then be coupled with hydrogen produced with green electricity to produce power fuels. Nuclear plants hinge on the critical problem of nuclear waste, proliferation, and safety concerns that influence public opinion and compromise long term sustainability of this option in the future energy mix, although there are some 4th generation technologies working to address these concerns. All solutions therefore depend on patterns of land-use, transport, transmission networks, etc.that must be remade depending on the types of zero-carbon energy sources. A life cycle and supply chain perspectives are both useful and mandatory to design long-term effective solutions for decarbonization with little or no drawbacks on other productive sectors of a national economy.

(3) Complementarities of public and private investments. In virtually every economy, parts of the energy system are in private, for-profit hands, and parts are publicly owned. In each case, significant effort must be made to harmonize these public and private investments. It is common, for example, that the public sector (or a not-for-profit entity) owns the transmission grid, while private operators own the power generators. Rules of access to the transmission grid are needed to ensure the transmission and distribution of power. There are significant debates and unsolved problems on how to share the costs of an integrated public-private system. Who pays, for example, for energy storage, grid reliability services (e.g. frequency management), transmission lines, etc.? Moreover, special attention needs to be given to areas where private investments are not competitive but the need of transportation services for the mobility of goods and services is strongly needed to guarantee access and local development.[11]

11 E3 in consultation with Southern California Edison and California PUC has been attempting to quantify a "VRE cost adder". Available at: *California Public Utilities Commission.* "Integration Cost Adder Status Report." California Public Utilities Commission. Accessed August 20, 2019. http://www.cpuc.ca.gov/WorkArea/DownloadAsset.aspx?id=10755 and Jaquelin, Cochran, Paul Denholm, Bethany Speer and Mackay Miller. "Grid Integration and the Carrying Capacity of the U.S. Grid to Incorporate Variable Renewable Energy." *U.S. Department of Energy Office of Scientific and Technical Information.* Accessed August 20, 2019. https://www.osti.gov/biblio/1215010-grid-integration-carrying-capacity-grid-incorporate-variable-renewable-energ

(4) Complementarities of natural and engineered systems. The world must reduce net anthropogenic GHG emissions to zero by around 2050 and then reach net negative emissions in the second half of the century. One obvious path to net negative emissions is biological storage of CO_2 in vegetation and soils via preservation of existing forests and/or restoration of degraded habitats.[12] As such, land-use and energy-system strategies must be intimately interconnected. Energy strategies that amplify land-use degradation (e.g. through the overuse of those biofuels that contribute to land clearing and deforestation) must be ruled out. Moreover, we must recognize that ecosystem functions will be degraded by human-induced climate change, thereby threatening positive feedback effects. Recent studies have found that global warming is likely to contribute to the natural release of methane from tropical wetlands and permafrost.[13] For that reason, emissions reductions from fossil fuels should be accelerated to avoid dangerous natural GHG feedbacks.

(5) Complementarities of mitigation and adaptation. Climate policies should combine mitigation and adaptation strategies for two reasons. Most obviously, even the most ambitious mitigation strategies will result in several decades of further warming, and an intensification of the adverse impacts of anthropogenic climate change: heat waves, droughts, floods, extreme storms, rising sea levels, etc. Damages and risks will continue to rise, so that investments in adaptation will be vital in many circumstances. The second reason for linking adaptation and mitigation is that adaptation measures can contribute to mitigation strategies. Forest restoration and protecting coastal wetlands, for example, can protect landscapes, resist storm surges from rising sea levels, and promote resilient food production in the face of global warming, while also securing larger biological stocks of carbon, thereby servicing both adaptation and mitigation.

Because of these complementarities, an "all-of-government" approach to climate change is more than a slogan or symbol of commitment. It is a logical response to a set of interconnected challenges. The head of government should convene a cross-cabinet committee to oversee national planning and implementation, especially in the context of national commitments under the PCA, discussed in more detail below.

(6) Complementarities of centralized and decentralized solutions. Renewable energy resources are by nature different from one place to another. For cities and urban or rural areas with a sufficient density of population, distributed generation systems are suitable to be installed and connected to local distribution networks. And for areas with available space and high quality renewable energy resources, renewable electricity could be generated locally and transmitted over long distance high voltage grid to where it is needed, which is more viable economically. With that being said, we need both a large and robust transmission grid, which may extend beyond national boundaries, and a smart and flexible distribution grid, which could facilitate the integration of distributed generators in a more efficient way.

12 European Academies Science Advisory Council. "Negative Emission Technologies: What role in meeting Paris Agreement targets?" *European Academies Science Advisory Council.* Published 2018. Accessed August 20, 2019.
https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Report_on_Negative_Emission_Technologies.pdf
13 Yale Environment 360. "Scientists Zero in on Trees as a Surprisingly Large Source of Methane." *Yale Environment 360.* Accessed June, 2019.
https://e360.yale.edu/features/scientists-probe-the-surprising-role-of-trees-in-methane-emissions

(7) Complementarities of actions and strategies. Climate policies should combine a different set of actions and mitigation and adaptation strategies for two reasons. The global challenge of decarbonization can be split according to a geographical criterion taking into account economic and cultural differences that are mirrored, at large scale, by different geography. There are some common features that can pool together different geographical areas: a big city of North America can be very similar to a metropolitan area in Europe but this would not apply all the same to a big city in Sub Saharan Africa. Urban areas are also different from rural areas where the effort to bring access to energy and other services to all is still a challenge. One solution does not fit all and trying to impose the same pathway to different contexts can lead to failure with the risk to come back to business-as-usual practises.

(8) Complementarities of R&D activities promoted by research institutions and academia and funded by private or public sector. These activities should aim at promoting breakthrough innovation that continuously advances the process of decarbonization and controls any risk of lock-in to solutions that may fail to contribute to total decarbonization in the long run.

Indeed, technologies and related services are inextricably linked to geography. Technologies require resources and, in the majority of the cases, they have specific geographical distribution. Moreover, the same services and their quality are judged differently in different geographical areas also according to local behaviour and perception of priorities. The risk to neglect this point is that deep decarbonization strategies may further push inequality at global level thus affecting development of some geographical regions. Within this document, the author recognise the relevant of this diversity issue and support a fair and equitable approach at local and global level.

Chapter V

THE SIX PILLARS OF CLIMATE MITIGATION

There are six pillars of climate mitigation, all needed to reach zero net emissions of greenhouse gases (GHGs) by 2050 and negative emissions thereafter. The first five pillars aim to eliminate carbon dioxide (CO_2) emissions from the energy system, hence "decarbonization." The sixth aims to eliminate greenhouse gas emissions from agriculture: CO_2, methane (CH_4), and nitrous oxide (N_2O). All six pillars benefit from reduced wastage and improved resource efficiency and rely on 4 premises.

1. The development of comprehensive climate policy will depend on specific geographical and social contexts, particularly in developing or low-income areas, in order to meet the needs of both society and the planet.
2. Great cooperation and coordination in terms of policy design and implementation are required: stakeholders will need to consider the integrated use of different resources, technologies, or processes to guarantee inclusion and socioeconomic development of communities and enterprises' competitiveness in the global market.
3. Flexible and innovation-receptive regulatory frameworks are pivotal to address the challenge.
4. Substantial efforts must be made to allocate consistent investments in support of research and development, as technological breakthroughs will trigger innovation and shorten the path toward global decarbonization.

The six pillars are built on the underlying fundamental of Agenda 2030: "leave no one behind". While global solutions and fast actions are needed to obtain the expected results in compliance with the Paris Agreement, it is fully recognised that the speed at which the transformative change may occur will be different according to the different socio-economic conditions of the diverse geographical areas. For example, the current situation of the power sector in most developing countries cannot be neglected and may require different "initial conditions" for the transformative change compared to developed countries; this element will inevitably influence the speed at which electric penetration can increase in different productive sectors and the role of synthetic fuels. Also the opportunity to leapfrog the central grid through microgrids in developing countries may be more of less pertinent in different contexts. These countries are particularly open to the great opportunities that may come from the digital revolution and the associated services and are also advanced in terms of policy aimed at shifting efficient material uses. Therefore, developing countries will need to be engaged in a fair and equitable way within the transition and their contribution will be essential.

14 Ram, Manish et al. "Global Energy System based on 100% Renewable Energy."

SIX PILLARS

ELECTRIFICATION OF END USES.
The penetration of electricity, built on existing technologies, can enable a green conversion for the sectors currently using fossil-fuel energy.

GREEN SYNTHETIC FUELS.
Deployment of a wide range of potential synthetic fuels, including hydrogen, synthetic methane, synthetic methanol, and synthetic liquid hydrocarbons applicable for harder to abate sectors.

ZERO-CARBON ELECTRICITY.
A shift towards zero-carbon electricity mix.

SUSTAINABLE LAND-USE.
Mainly involving the agriculture sector, as it contributes up to a quarter of all greenhouse gas emissions from deforestation, industrial fertilizers, livestock, and direct and indirect fossil-fuel uses.

SMART POWER GRIDS.
Systems able to shift among multiple sources of power generation and various end uses to provide efficient, reliable and low-cost systems operations, despite the variability of renewable energy.

MATERIALS EFFICIENCY.
Improved material choices and material flows, such as reduce, reuse, and recycle to significantly improve materials efficiency.

a) *Zero-carbon electricity.* This is the most important single step toward decarbonization, as "green" (zero-carbon) electricity can be used directly (in battery electric vehicles, for example) or indirectly to create zero-carbon fuels (hydrogen, for example). Zero-carbon electricity therefore involves a shift towards zero-carbon primary energy sources and a very significant overall expansion of electricity production for end uses.

   Zero-carbon electricity can engage multiple possible types of power generation. These include renewables (broadly defined to include wind, solar, hydro, geothermal, ocean, and tidal); nuclear; bioenergy; and carbon-capture and storage (CCS) of fossil-fuel generated electricity. Countries differ markedly in their attitudes towards nuclear energy, and this policy difference is likely to remain in the coming decades. Recent studies have emphasized the special role of renewables in zero-carbon electricity.[14] This is because the costs of renewable energy have plummeted (especially solar photovoltaics), while energy alternatives – nuclear, biofuels, and CCS – each pose major technical and social obstacles leading to significant public opposition. Nuclear power raises public concerns over nuclear accidents and nuclear weapons proliferation. Bioenergy raises serious concerns about ecosystem degradation and competition with food supplies. CCS raises strong opposition over technological doubts (e.g. leakage of CO_2), land-use obstacles (e.g. pipelines to carry the CO_2), and high costs.

b) *Electrification of end uses.* There are many sectors currently using fossil-fuel energy that can be converted to direct use of (green) electricity thanks to existing technologies. These include battery electric vehicles (BEVs), heat pumps for residential and commercial buildings, electric cooking (e.g. induction and microwave stoves), and direct reduction of ores in metallurgy. These pathways of electrification seem more likely today than just a few years ago. Major automakers are now making significant commitments to BEVs, for example, with dates set for the phase-out of conventional ICE vehicles. A key aspect to this pillar will include the expansion and upgrade of an interconnected smart power grid to support the electrification of various sectors.

c) *Green synthetic fuels.* These are applicable for harder to abate sectors that are not easily electrified. As one example, in aviation, there is continuing debate about the feasibility of electrification. It seems increasingly likely that electrification will cover short-haul flights (e.g. under 1 hour) but that longer-haul flights will continue to require liquid fuels of high energy density. Overall, there is a wide range of potential synthetic fuels, including hydrogen (for direct combustion, industry, or use in fuel cells), synthetic methane, synthetic methanol, and synthetic liquid hydrocarbons. These synthetic fuels can be manufactured using green electricity and can facilitate the circular economy by processing materials from municipal and agricultural waste into energy. We should also note the synergies between biorefining and direct air capture technologies which can provide the CO_2 for green synthetic fuel development This third pillar relies on full accomplishment of the two previous pillars.

d) *Smart power grids.* Built with contributions from big data, artificial intelligence, and the IoT, smart grids are self-regulating systems that can shift among multiple sources of power generation and multiple uses to provide reliable and low-cost systems operations despite the variability of renewable energy. There are many aspects of a smart grid. On the supply side, a smart grid will integrate variable renewable energy from many sources in order to smooth the variability of power generation. A larger connected grid, covering more geography and more sources of variable renewable energy, will generally have a lower coefficient of variation of power. Various storage options, including batteries, pumped hydro, compressed air, and conversion of renewable energy into synthetic fuels, will help to stabilize the supply side. The demand side will also show flexibility by enabling smart meters to turn on and off electricity consumption of users depending on temporal needs, urgency, and shifts in market prices that reflect supply-demand conditions.

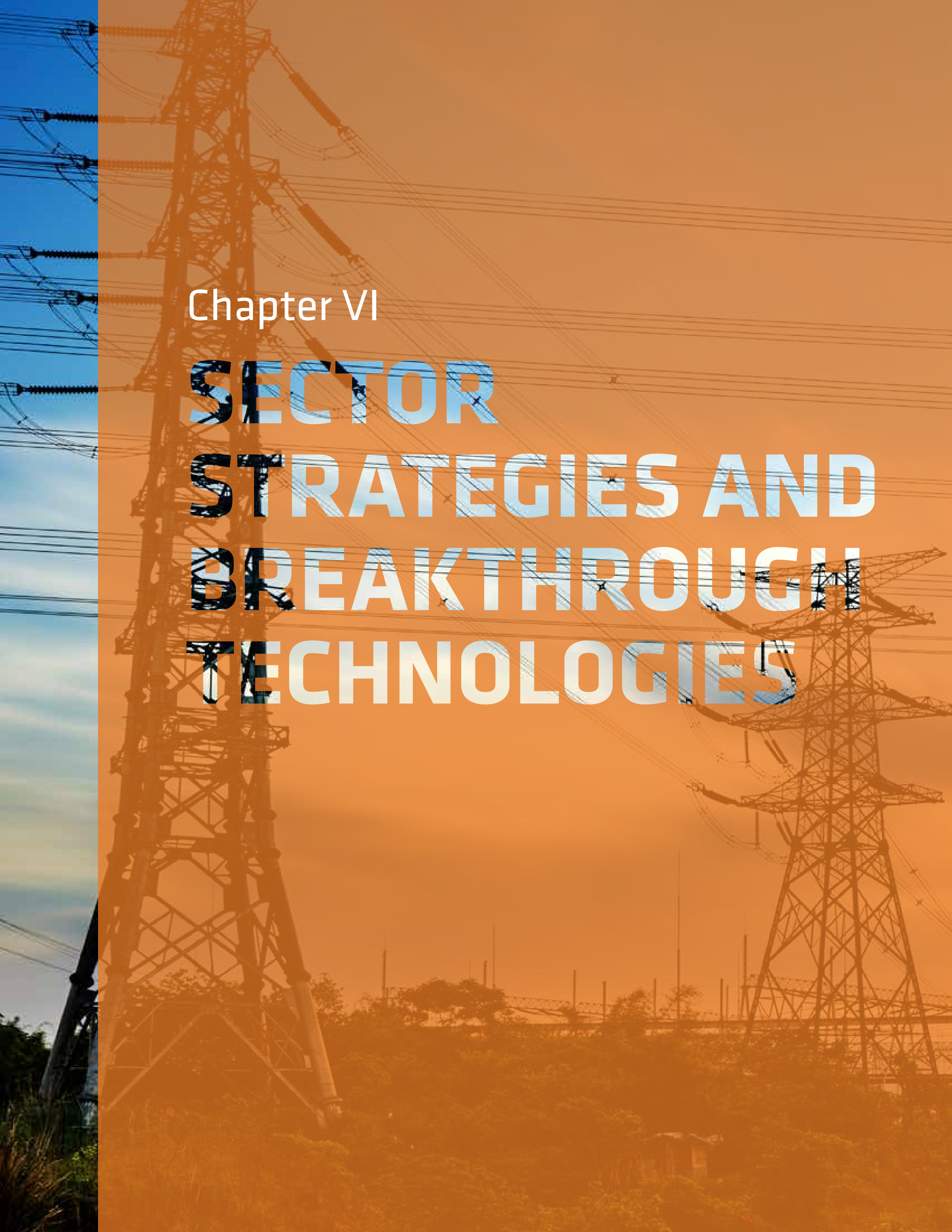
e) *Materials efficiency.* Designed to economize on the use of plastics, metals, cement, and other industrial materials that emit CO_2 in their production processes, improved materials and material flows such as reuse and recycling can significantly improve materials efficiency, reduce the process emissions of CO2 (such as in the manufacture of clinker for cement) and slash energy inputs in industrial processes.

f) *Sustainable land-use,* mainly involving the agriculture sector. Agriculture contributes up to a quarter of all greenhouse gas emissions, including: the CO_2 from direct fossil-fuel use in agriculture; the CO_2 emitted in the industrial production of chemical fertilizers and other agricultural inputs; the CO_2 emitted from deforestation and the degradation of farm lands; the methane released by ruminant animals (especially cattle) and from flooded rice paddies; and nitrous oxide emissions from the use of nitrogen-based fertilizers. Agricultural practices also harm biodiversity and ecosystem functions in many ways beyond GHG emissions, including: overuse of freshwater resources; destruction of habitat (e.g. through deforestation); overharvesting of plant and animal life, both marine and terrestrial; chemical pollutants to the air, water, and soils in addition to GHGs, including pesticides, hormones, antibiotics in animal feeds, etc.; destruction and degradation of top soils; aerosol pollution from peat burning and slash-and-burn agricultural generally; eutrophication of coastal environments due to phosphorus and nitrogen flows; and more. All of the environmental challenges of food production are exacerbated by the extensive waste and losses of food along the entire value chain, from post-harvest losses to food wastage among consumers, notably in high-income countries. One-third of all food is lost due to wastage along the supply chain.

The challenge of sustainable land-use also critically includes the delineation and management of protected areas, which not only act as major carbon sinks through their soils and vegetation, but as safe harbors for threatened and endangered species. Such protected areas should be considered across both marine and terrestrial ecosystems.

The challenges of sustainable land-use in regards to agriculture are made enormously complex by several considerations ,and will be the object of a specific analysis which will be carried out next year.

In order to implement these six pillars, international cooperation and investment allocation in line with the Agenda 2030 and the principle of share but not equal responsibility which is also at the base of the Paris Agreement, two actions are crucial. From one side a stronger international cooperation supported by innovative and consistent blended finance is needed to fully unveil the energy transition toward full decarbonisation in all countries. Public-private partnership together with new global alliances dedicated to support the choice of emerging and developing economies. From the same perspective, at the national level, each government needs also to be able to prioritise their investment taking into proper consideration the relevance decarbonisation may play on local socioeconomic development and long term quality of life for the citizens.



Chapter VI

SECTOR STRATEGIES AND BREAKTHROUGH TECHNOLOGIES

a. Power

Lead by: Manfred Hafner and Michel Noussan, FEEM; Christian Breyer and Dmitrii Bogdanov, LUT University

i. Enabling Conditions: stakeholders, assumptions, key geographies, and scaling

Global electricity demand has grown by 3% a year since 2000, around two thirds faster than total final energy consumption, reaching a value of 22,200 TWh in 2017.[15] The IEA's New Policies Scenario (NPS) estimates a global electricity demand of 26,400 TWh in 2025 and 35,500 TWh in 2040 representing an average annual growth rate of 2.6%. Electricity will represent the fastest growing energy vector, reaching a share of 24%, up from 19% in 2017. Bloomberg reports slightly different numbers, highlighting a global demand of 25,000 TWh in 2017 increasing to 38,700 TWh by 2050,[16] corresponding to an average annual growth rate of 1.7%. In addition, as of 2017, 840 million people still lack access to electricity,[17] down from 1.2 billion in 2010, mainly in Africa, and increased strategies will be needed to address this issue, since according to the NPS 720 million people worldwide will still be without access by 2040.

Both historical and expected trends highlight the importance of electricity in worldwide energy demand. A part of the future growth is driven by specific policies supporting the electrification of specific sectors (i.e. building heating and transport) as a strategy to increase the benefits of electricity generation from renewable energy sources (RES) as an affordable pathway towards decarbonization. Other aspects are also worth mentioning, including the decrease of local pollution in cities via electric vehicles, or the higher efficiency of heat pumps compared to traditional heating technologies. When high shares of electricity are generated from non-dispatchable sources, additional flexibility solutions are needed to manage and operate the power grid.

While much emphasis is put on non-dispatchable RES, other potential solutions for electricity decarbonization include nuclear power, CCUS to support fossil-based generation, or coupled with advanced bio-energy sources (BECCUS) to lead to negative emissions for electricity. Some of these options show challenging economics.

The specific characteristics of different world regions present significant diversity in a number of drivers that are involved with RES, electricity planning, current power mixes, policy priorities, electricity access, energy poverty, and local regulations. For this reason, specific strategies need to be developed by considering the local conditions, which will result in different approaches in different regions. Particularly challenging conditions are expected in Asia, where RES development is not keeping pace with the strong rise in energy demand, as well as in Africa, where the need of increasing electricity access is currently the main priority in energy planning strategies.

15 IEA. "World Energy Outlook 2018." *IEA*. Last modified 2019. Accessed August 20, 2019. https://www.iea.org/weo2018/

16 Bloomberg NEF. "New Energy Outlook 2019." Bloomberg NEF. Last modified 2019. Accessed August 20, 2019. https://about.bnef.com/new-energy-outlook/.

17 IEA, IRENA, UN Statistics Division, World Bank Group, World Health Organization. "2019 Tracking SDG 7 - The Energy Progress Report Executive Summary." Tracking SDG 7. Published 2019. Accessed August 20, 2019.
https://trackingsdg7.esmap.org/data/files/download-documents/2019-tracking_sdg7-execsumm-withoutembargoed.pdf

The stakeholders of the power sector include many different players due to the complexity of the sector: from power generation, to transmission, distribution and finally consumption. In many countries, the traditional centralized organization of the power system is now facing a paradigm shift to distributed and renewable generation. This new model is tightly related to the implementation of smart grids, where the end users act as prosumers by supplying to the network the excess of power generation produced by their distributed PV systems. Digital technologies will be at the center of this revolution, by unlocking the potential of different business models, including virtual aggregators and peer-to-peer energy trading. Also, the number of stakeholders is growing and diversifying, as companies from other sectors are entering the market.

While many national and international policies are strongly oriented towards the electrification of energy systems, electrification must proceed with decarbonization in order to fight climate change. A strongly integrated approach across sectors and energy pathways is essential for addressing climate change issues. Secondary effects and a holistic perspective on the entire life cycle of technological solutions should be considered to avoid potential rebound effects on specific technology choices.

ii. Key technologies

Energy technologies involved in the power sector include multiple applications ranging from power generation to network flexibility, electricity demand, and other services that may be strictly related to this sector when dealing with decarbonization (e.g. CCUS). The key technologies for the power sector categorized into four main groups:

- Renewable energy sources: mostly solar PV and onshore wind, hydropower, and an interesting potential for other technologies, including offshore wind and concentrated solar power (CSP)
- Electricity storage solutions, both for short-term (daily) and long-term (weekly/seasonal) storage
- Other flexibility options, including sector coupling, supply response (hydropower reservoirs, bioenergy), and demand side management (DSM)
- Carbon capture, utilization, and storage (CCUS), and variants including bio-energy and carbon capture and sequestration (BECCS) and direct air capture (DAC).

Among generation technologies, a significant development of non-dispatchable RES has been observed in recent years, especially on solar PV and onshore wind, although with some differences across world regions. The strong cost decrease for PV has been driven by efficiency improvements in technologies and industrial processes, as well as a strong upscaling of manufacturing and low-price production in China. Ongoing technological processes development must support further cost reduction via reducing the need for raw materials, increasing efficiencies, and minimizing energy demand. The solar PV learning curve has been stable for decades and costs are expected to continue declining. As far as wind is concerned, the decrease of investment costs have been based on increasing competition between suppliers along the entire supply chain. In parallel, a decrease of the levelized cost of energy (LCOE) has also been favoured by increased lifetime of components, as well as a better load factor thanks to the installation of taller wind turbines and improved designs based on lower rotating speeds.

Increasing expectations are being put on the development of offshore wind and CSP, whose costs are not yet competitive with PV and onshore wind, although a similar pathway is envisaged for their future deployment.

Offshore wind appears to have a greater potential for cost decrease, being still an immature technology. A massive upscaling of technology production is expected in China according to the Roadmap 2050 workshop participants, which through learning curves and economies of scale may trigger a strong decrease in specific costs for these technologies in China as well as in other markets.

Nevertheless, to support high penetrations of non-dispatchable sources in power networks, it is necessary to support the development of multiple flexibility solutions. Many options are already available, with different levels of maturity, including interconnections to adjunct markets, backup dispatchable capacity, electricity storage (mainly in the form of hydroelectric water reservoirs), DSM, and sector coupling. Important technological progress is generally expected across the last three options. A fast growing number of research articles for highly renewable energy systems demonstrate their technical feasibility and economic viability.[18] This research supports the 100% renewable energy policy targets that are being set in several states/countries around the world.[19]

Electricity storage has traditionally been supplied by pumped hydropower storage in certain regions of the world, mainly for dealing with strong demand variations and for avoiding frequent fluctuations of fossil or nuclear power plants. The increased need for storage to support strong penetration of non-dispatchable renewable energies over the last few years has led to the analysis of other options--electric batteries in particular.

Currently, a strong push for Lithium-ion (Li-ion) batteries comes from the electric vehicles (EVs) industry, where weight and density of power are the key requirements, while the economies of scale in the so-called "giga-factories" may also lead to potential applications for grid storage, which are being evaluated and tested in different countries. There are controversial opinions on the future evolution of Li-ion batteries, especially concerning costs and availability of materials. Other technological solutions may prove to be breakthrough options by enhancing the performance and lowering the cost of electrochemical batteries (e.g. solid-state batteries). Additional issues are related to the end-of-life of batteries, since recycling is currently not economically viable, due to its higher cost in comparison with the use of raw material. However, an increasingly large number of second-life batteries from EV could be used for stationary applications, where performance requirements are less stringent. Specific regulation needs to be developed that mandates battery recycling. On the other hand, the challenges associated with Li-ion batteries upscaling are similar with those that were associated to PV technology in the early stage of its development, which have been overcome. The issues related to scarcity of raw materials, especially lithium and cobalt, may become a bottleneck in the short-term, due to the need for strong upscaling in mining and in their current supply chain. Engineers are also working on alternative materials.

Demand Side Management may be a strong tool in supporting the matching of demand and generation, to be integrated with electricity storage. While it is currently applied to mainly industry, whose power demand is easier to predict and control and where it often represents an important value input in the production process, DSM has also been applied to other end-users, for instance, through the development of variable tariffs for peak and off-peak hours. A strong support to DSM can come from the evolution of smart appliances in buildings, which through

18 Hansen, Kenneth, Christian Breyer and Henrik Lund. "Status and Perspectives on 100% Renewable Energy Systems." *Energy* 175, (2019): 471-480. doi: 10.1016/j.energy.2019.03.092

19 REN21. "Renewables 2019 - Global Status Report." *REN21.* Last modified 2019. Accessed August 20, 2019. https://www.ren21.net/reports/global-status-report/

IoT may become a tool for detailed monitoring and control of electrical loads, leading to integrated platforms of users with significant potential to provide flexibility to the power grid. These platforms are generally referred to as "Virtual Aggregators," and allow for the possibility of exploiting information and communication technology (ICT) to coordinate a wide number of consumers, generators, and prosumers to combine the features of different players and provide a single (virtual) interface with the power grid. These virtual aggregators, which are being experimented in a number of countries, are unlocking the flexibility potential of small users which would not be able to participate in current flexibility markets.

The last of these flexibility options, referred to as sector coupling, includes different solutions to exploit clean and cheap electricity by connecting the power grid to other sectors, such as power-to-gas (P2G, generally towards hydrogen or methane), power-to-liquids (P2L, for the generation of synthetic fuels, often referred as electro-fuels), power-to-heat (P2H), power-to-vehicles (P2V), power-to-chemicals (e.g. methanol, ammonia, etc.) and power-to-desalination. In some cases, sector coupling can also be operated as storage, when the product can be converted again into electricity at a later stage, such as power generation from hydrogen or electricity storage for grid services through electric vehicles. While some of these technologies are already applied, in multiple cases electricity market prices are not low enough to compensate the lower performance or the high costs of such solutions. A strong push for these technologies could be envisaged if the full costs of fossil solutions would be priced in, via emission standards and greenhouse gas emission costs on real cost levels, further supported by very low marginal cost of electricity from RES at times of oversupply. This topic is explored in greater detail in a later chapter.

Finally, as already mentioned in the previous section, non-dispatchable RES are not the only solution towards the decarbonization of the power sector. Nuclear power remains a viable option in a number of countries worldwide, although problems related to public acceptability and challenging economics are limiting its deployment in multiple regions. Potential breakthroughs in nuclear generation may come from 4th generation fission (with improved safety, sustainability, efficiency, and cost) in the mid-term and from fusion in the longer term, the latter still being seen as a potentially disruptive game changer, and thus the object of multiple research projects worldwide. This may include small-scale nuclear reactors, both for fission and fusion, that may help in overcoming specific issues both for technological development and installation costs. However, it has to be stated that nuclear power is becoming increasingly expensive due to strict safety standards. Whether nuclear fusion can emerge as a key technology depends not only on overcoming the current massive technological and physical barriers, but also whether very low-cost electricity supply will be possible. New nuclear has to compete against declining cost of renewable options based on PV, wind energy, and storage solutions.

Another option to support decarbonization is the development of CCUS systems, which has gained momentum in recent years but still remains well below the amount that would be needed to provide an effective impact, also due to public acceptability issues and high costs. While current demonstration projects are mainly focused on fossil-fired power plants, the coupling of BECCUS may open the way to negative emissions systems, which will be required in the long-term to reach the tight carbon budget available for this century. Another carbon sink option is the development of DAC systems, which separate CO_2 from the air through different methods, including absorption, adsorption, membranes, or mineralization. While BECCUS systems provide a net electricity generation, DAC systems are perceived to be expensive as they require a significant amount of power consumption for their operation. For this reason, from a system perspective, the optimal solution may be a combination of both technologies. Availability of land and total cost of CO_2 removal will decide the relative mix of the BECCUS and DAC option.

In CCUS technologies, a final remark is due on the difference between the utilization and the storage of CO_2. Current systems are generally focused on the underground sequestration of CO_2 in geological formations, or in some cases using it for enhanced oil recovery from oil fields. At the same time, the deployment of underground storage projects may result in issues of public acceptability. Conversely, the CO_2 that is extracted can be used in various promising applications, ranging from the production of synthetic fuels to other chemicals including carbonates and concrete. The use of carbon capture and utilization (CCU) for synthetic fuels is actively studied and will be incorporated into laws and regulations within the EU, based on the Renewable Energy Directive. However, specific analyses on their impact of different production pathways with a life-cycle perspective will need to be performed. Additionally, mineralization of CO_2, creating thus a solid instead of a gas to be stored, may have a much-improved public acceptability, although the low market value of the end product may reduce interest in the application.

As discussed above, the decarbonization of the power sector will require a combination of multiple technologies, since there is no one silver bullet to reach the required targets, and every option has disadvantages. Therefore, different options should be deployed, as long as they contribute to the aim and they are sustainable. Depending on local conditions, the mix of options may vary from one country to the other. Moreover, to allow for potential breakthrough technologies that are currently not envisaged, energy policies need to be technology agnostic, to allow each potential low-carbon solution to be supported and deployed. However, to achieve net zero by 2050, technological options should always be consulted within a systematic, cradle to grave life-cycle analysis (LCA). Whilst there is progress in CCU technology, their usefulness in achieving net zero emissions becomes clear only within a systematic evaluation with LCA for entire processes, including their usage.

A key question is how do we best support the development of such innovations, as policy strategies adapt to the maturity of each solution based on the context in which the policy evolves. Moreover, there is a need for stronger international cooperation on these themes, since excessive policy fragmentation across countries may lead to ineffective results in the path towards global decarbonization.

iii. Case Studies

As discussed above, a strong decarbonization of the power sector needs multiple flexibility solutions to support a large integration of variable renewable energy sources. For this reason, this section presents some case studies focused on new flexibility solutions, including battery grid storage, vehicles-to-grid (V2G), power-to-gas, and virtual power plants. A final conclusion will be devoted to present some cases of carbon capture and utilization.

Battery grid storage

Electricity storage has always been challenging at the grid level, and generally the only commercial solution for large-scale and medium- to long-term electricity storage is the use of pumped hydro storage in countries that have compatible geographic conditions. However, the need to integrate non-dispatchable RES is pushing the deployment of batteries at the grid level, with Lit-ion batteries taking the lead, as already discussed in the previous section. While the main challenges and aspects have already been cited, this paragraph aims at presenting some case studies to highlight some technical features of large-size power batteries.

At 100MW/129MWh, the Hornsdale Power Reserve, developed by Tesla, is the largest Li-ion battery in the world, and it provides network security services to the South Australian electricity power grid.[20] The storage system has been in operation since December 2017, and it was built with a challenging timeline to ensure that the battery was available during the 2017 peak demand summer season, after blackouts in the previous year. The system provides frequency control and short-term network security services, and a portion of the battery will also be dedicated to trading on the electricity market. The battery is connected to the Hornsdale Wind Farm, whose excess power output is stored when demand is low and dispatched to the grid when demand is high.

NEC Energy Solutions provided a Li-ion phosphate battery in Maui, Hawaii[21] in a 21 MW wind farm. The battery has an output power of 11 MW and a capacity of 4,300 kWh. It was installed to manage wind farm ramp rates to comply with local interconnection requirements that are in place to ensure local power grid stability by limiting feed-in variability of generating resources. The project was not directly subsidised, but it was part of the wind farm which qualified for a 30% investment tax credit. Overall project costs were mainly related to equipment cost, with the largest part due to the Li-ion cells of the battery. Variable costs are driven by energy losses and auxiliary consumption, mainly due to the thermal management equipment (chillers). The round-trip efficiency of the storage system is about 80% (AC-to-AC), including losses due to power conversion from AC to DC and back to AC, the energy storage cells, busbars, battery management systems, and thermal management systems.

In February 2012, a large-scale utility project was built in Zhangbei, Hebei Province, China, developed by Build Your Dreams (BYD) and the State Grid Corporation of China (SGCC). The installation includes 100 MW of wind power, 40 MW of solar PV, and 36 MWh of Li-ion electricity storage. It is worth mentioning that the batteries used in the system are second-life Li-ion car batteries, which were used before in 36 taxi cars operated by BYD for about 4000 cycles.[22]

Vehicles-to-grid

The Vehicle-to-grid (V2G technology enables a bi-directional energy transfer from/to electric vehicles. This is an evolution of the traditional one-way charging and of the 'smart' charging (often referred as V1G), where the rate and time of charge can be varied based on specific objectives (e.g. maximizing the use of available generation from RES). The increase of EV penetration leads to new challenges for the power grid management, but at the same time, additional opportunities can be unlocked by exploiting the storage potential of the EV batteries. While the large majority of the current EV fleet and charging infrastructure is not supporting V2G technology, there are a number of pilot projects worldwide that aim at demonstrating its feasibility and exploring its potential.[23] Some case studies are presented here, to highlight the main challenges and opportunities of V2G.

20 "Hornsdale Power Reserve."*Hornsdale Power Reserve.* Accessed August 20, 2019. https://hornsdalepowerreserve.com.au/

21 IRENA. "Case Studies: Battery Storage." *IRENA*. Accessed August 20, 2019.
https://www.irena.org/documentdownloads/publications/irena_battery_storage_case_studies_2015.pdf

22 Jäger-Waldau, Arnulf. "PV Status Report 2014." *JRC*. Published 2014. Accessed August 20, 2019.
http://publications.jrc.ec.europa.eu/repository/bitstream/JRC92477/pv%20status%20report%202014%20online.pdf

23 Everoze & EVConsult. "V2G Global Roadtrip: Around the world in 50 projects." Published 2018. Accessed August 20, 2019.
http://parker-project.com/wp-content/uploads/2018/12/VGI-Summit-Day-2-S1-Initiatives-UKPN001-S-02-B.pdf

One of the first deployments of V2G infrastructure has been carried out in the JUMPSmartMaui project, on the island of Maui, Hawaii.[24] The installation of 80 Vehicle-to-home (V2H) chargers was part of a larger project aimed at developing a smart grid with the integration of renewables, EV, energy storage, and controllable loads. The project has been carried out by Hawaiian and Japanese stakeholders and is headed by the New Energy and Industrial Technology Development Organization (NEDO) of Japan. The V2H chargers were used to help manage the evening peak of the power demand (6-9pm), by discharging their batteries in response to grid signals related to distribution system loads and frequency events. The first part of the trial involved two years of V1G operation, to collect reliable data on driving patterns and ease the introduction of the V2G technology. One of the main outcomes of this project has been the EV battery's ability to provide very fast and flexible services to the grid that can be very valuable when combined with other flexibility resources. Some lessons learned included the importance of focusing on the incentives for the final users towards EV plug-in. In the absence of such incentives, i.e. if the families use their EVs normally, the EVs are not always plugged in at the evening, especially when they can charge them during the day using the public fast charging stations.

The Parker project,[25] developed in Denmark from 2016 to 2018, was the world's first fully commercial V2G hub. The project has investigated the grid applications that contemporary EVs can provide to power systems, by systematically listing potential power and energy services in a so-called 'service catalog'. The emphasis has been on frequency regulation services, since they are not only the most demanding (reaction time and need of V2G) but also the most commercially interesting services currently required in Denmark. Among the aims of the project were the comparison of the capability of different cars, as well as the identification of potential barriers to commercialisation. By integrating different vehicle fleets in multiple locations (municipalities, commercial companies, and ports), the project was able to provide a 24/7 service to the grid. The test highlighted the importance of understanding the schedule of each customer, as well as their required state-of-charge at a specific time, in order to optimize the organization of the system. The main barriers that have been found include the long duration of the frequency services required (limited by the small capacities of the batteries), the low efficiency when operating the chargers at power levels lower than the rating, and some battery degradation.

The INVENT project (Intelligent Electric Vehicle Integration),[26] represents a large-scale trial in the UC San Diego campus, with multiple vehicle types and chargers, supporting the move towards commercial deployment in California. The trial is in collaboration with UC San Diego's Triton Ride Program, which operates a fleet of EVs that safely transport students around campus at night. Thus, the combination of the university fleet charging at night and the workplace charging during the day allows a 24-hour service. The project will test vehicle-to-building (V2B) integration, demand response, frequency regulation, and interaction with solar forecasting in the framework of the UC San Diego microgrid that is also equipped with solar generation and storage. Both AC and DC chargers are tested, with more than six different vehicle types. The main challenges include the availability of cars, the drivers' varying personal schedules, and the optimization of plug-in times by assigning convenient parking locations to project drivers. Among the first results of the project, there is evidence that V2G does cause some additional battery degradation, but much smaller than that experienced through driving behaviour (and particularly regenerative

24 Irie, Hiroshi. "NEDO Smart Community Case Study." *NEDO*. Accessed August 20, 2019. https://www.nedo.go.jp/content/100864936.pdf

25 "Parker." *Parker*. Last modified 2016. Accessed on August 20, 2019. https://parker-project.com/

26 Nuvue. "UCSD Invent." *Nuvue*. Last modified 2019. Accessed on August 21, 2019. https://nuvve.com/projects/ucsd-invent/

braking). Potential damage depends on the service, with full charge/discharge cycles being the worst. Car manufacturers may move towards a certification system to become an approved aggregator or charger.

Power-to-gas

The power-to-gas (P2G) technologies represent the solutions available for the generation of a low-carbon synthetic gaseous fuel, either hydrogen of methane, by exploiting the electricity produced from renewable energy sources. Hydrogen generation through electrolysis is commercially available, but it currently represents a very limited share of worldwide hydrogen production due to higher costs in comparison with other processes using natural gas and coal as input resources. In this section, some case studies of P2G systems for the production of synthetic methane based on electricity from renewables are presented.[27]

The largest industrial facility built in the world to produce synthetic natural gas from electricity is the Audi e-gas plant, under operation since 2013 and located in Werlte (Germany), with a nominal rated power of 6 MWe. The technology is based on the catalytic methanation of pure hydrogen and carbon dioxide in a single isothermal fixed-bed reactor. The hydrogen is produced by three alkaline electrolysers connected to an offshore wind park co-financed by Audi AG and a regional power-supply company (four 3.6 MWe turbines). In addition, the flow of CO_2 required for methanation is separated from the raw biogas of a neighbouring biomethane plant, by means of amine scrubbing. The entire P2G process has an efficiency of 54% (without accounting the useful heat produced in the process). The maximum output flow of the facility is 325 Nm^3/h, but the limited availability of input power (around 4,000 h per year) leads to a production of 1,000 tonnes per year. The P2G plant, in contrast to the biogas plant, is not operated on a continuous basis but rather at variable load following the power supply pattern of the wind park. Furthermore, the plant has been qualified for participating in the electricity balancing market, after successfully drawing 6 MWe of power from the grid within five minutes as well as running prescribed load profiles. The thermal management of the heat recovered from electrolysis and methanation, to supply the various heat consumers in the biogas and CO_2 removal plants (mainly amine regeneration), is highly complex.[28]

The HELMETH project (Integrated High-Temperature Electrolysis and Methanation for Effective Power to Gas Conversion)[29] has been co-financed by the European Union's Seventh Framework Programme and took place from 2014 to 2017, coordinated by the Karlsruhe Institute of Technology (Germany). This project demonstrated the feasibility of a highly efficient P2G technology by thermally integrating high temperature electrolysis (a solid oxide electrolyzer cell (SOEC) technology) with methanation. The demonstration plant's operations were semi-automated. Although the coupling wasn't completely successful, an efficiency of the integrated system of about 76% HHV could be achieved.[30] Some technical issues identified within the project are the difficulty of operating at extremely low volume flow rates at the electrolyser inlet, and the performance of insulation materials operating at high temperatures and pressures. According to the promoters, by scaling up the HELMETH concept, an overall P2G

27 Bailera, Manuel, Pilar Lisbona, Luis M. Romeo and Sergio Espatolero. "Power to Gas projects review: Lab, pilot and demo plants for storing renewable energy and CO_2, Renewable and Sustainable Energy Reviews." *Renewable and Sustainable Energy Reviews* 69, (2017): 292-312. https://doi.org/10.1016/j.rser.2016.11.130

28 Ibid., 292-312.

29 Helmeth. "Integrated High-Temperature Electrolysis and Methanation for Effective Power to Gas Conversion." *Helmeth*. Accessed August 21, 2019. http://www.helmeth.eu/index.php/project

30 Helmeth. "Helmeth Periodic Report No 2." *Helmeth*. Accessed August 21, 2019. http://www.helmeth.eu/images/joomlaplates/documents/Publishable_summary.pdf

efficiency over 80% could be obtained by reducing the parasitic losses. In addition, a scale up techno-economic study was performed in the project, as well as an LCA report of the overall process against benchmark scenarios.[31]

The P2G-BioCat project,[32] developed in Denmark from 2014 to 2016, had the objective of designing, engineering, constructing, and operating a 1-MW power-to-gas facility to produce and inject grid-quality methane under intermittent operations using hydrogen from alkaline electrolysis and methanation reactor based on biological catalyst. The project's technical and business goals have largely been achieved, providing useful elements for the commercial development of biological methanation and P2G for the benefit of the Danish energy system. The system operated for 8 months during the projec,[33] with a total consumption of 42,193 Nm^3 of biogas, 170 m3 of water, and 708,215 kWh of electricity for the system operations, to produce 129,290 Nm^3 of hydrogen making available ~15,000 Nm^3 of renewable methane and recovering 85,000 kWh of heat for use at a nearby facility.

Power-to-liquids

Power-to-liquid (P2L) technologies represent solutions available for the generation of low-carbon intensity synthetic liquid fuel, such as methanol, by CCU and electrolysis. The largest industrial facility to produce a liquid fuel from electricity is Carbon Recycling International's (CRI) renewable methanol plant in Svartsengi, Iceland, under operation since 2011.[34] The plant captures CO_2 from power-plant flue gases by means of amine scrubbing and utilizes three alkaline electrolyzers with a rated capacity of 6 MW electric to produce up to 12 tons of methanol per day. The output of this plant has been used by clients for gasoline blending, under EU standards, as a neat fuel (M100) for internal combustion engine vehicles as well as direct methanol fuel cell vehicles, biodiesel production, water purification and various chemical products, thus demonstrating the diverse uses of the low-carbon intensity methanol in both fuel and chemical applications.

Virtual power plants

Virtual power plants (VPP), also known as virtual aggregators, are made by exploiting digital technologies to coordinate power generators, end users, and storage systems with the aim of optimizing the aggregated load based on the evolution of market prices, or to provide ancillary services to the power grid. VPPs are often implemented to increase the profitability of distributed generation from RES, by providing to small players access to pools and markets that generally have a limiting threshold on the minimum capacity. Some VPPs are commercially implemented in Europe, the USA, and Australia.

One of the biggest VPPs in Europe is operated by Next Kraftwerke,[35] which spans its energy network all over Germany and has begun to implement VPP in other countries (Austria, Belgium, France, the Netherlands, Poland, Switzerland, and Italy). As of March 2019, more than 7,500 units are connected to the system, for a total capacity

31 Helmeth. "Deliverable 5.2: Final LCA Report." *Helmeth*. Accessed August 21, 2019. http://www.helmeth.eu/images/joomlaplates/documents/HELMETH_DELIVERABLE_5.2_R1.0.pdf

32 BioCatProject. "BioCatProject - Power-To-Gas Via Biological Catalysis." *BioCatProject.* Accessed August 21, 2019. http://biocat-project.com/

33 BioCatProject. "Final Report." *Energiforskning.* Accessed August 21, 2019. https://energiforskning.dk/sites/energiteknologi.dk/files/slutrapporter/12164_final_report_p2g_biocat.pdf

34 Carbon Recycling International. "The George Olah Renewable Methanol Plant." *Carbon Recycling International.* Accessed August 21, 2019. https://www.carbonrecycling.is/george-olah

35 "Next." *Next*. Accessed on August 21, 2019. https://www.next-kraftwerke.com/

reaching almost 6.9 GW, resulting in around 12 TWh of electricity traded annually. Different power-producing assets are connected to a central control platform, from renewable sources such as biogas, wind, and solar, to commercial and industrial power consumers and electricity storage systems. Kraftwerke, which has started its activities in 2009, has also specialized in short-term dispatch and trading.

Another interesting case study, although in an earlier stage of maturity, is being deployed in South Australia. Tesla is working with the South Australian Government and a local electricity retailer to create a VPP that could eventually include up to 50,000 households.[36] The VPP, which is being introduced as a trial with three phases, is currently in the second phase, after the phase was successfully tested on 100 households. After the completion of Phase II, 1,000 households will have home electricity storage systems installed, and another 320 households will share in the benefits of the VPP as program participants. If the Phase II trial meets its objectives and obtains private financing, Phase III could start scaling up to an additional 49,000 households from mid-2019. Operating at full scale, the VPP could generate 250MW and store 650MWh. At full scale the VPP will make electricity more affordable and reliable across the state by introducing competition to the market, adding new dispatchable supply, and boosting the security of the network by increasing the role of existing renewable assets.

Carbon capture and utilization

Carbon capture and utilization (CCU), sometimes also referred to as carbon-to-value, includes the multiple technologies that allow recylcing of the CO_2 stream obtained by flue gases or air to manufacture a range of products, including cement, carbonates, chemicals, plastics, fuels, etc. The aim of these processes is to find an alternative to CCS, by overcoming the concept of burying carbon emissions underground and instead providing effective value by creating products that would have consumed other resources for their production. In some cases, e.g. when producing fuels, the carbon dioxide may be released again into the atmosphere, but the entire cycle will become (almost) carbon neutral, if no fossil CO_2 is involved. There is a growing interest in CCU applications worldwide, and some companies are already providing commercially-competitive solutions, although often at a limited scale. As a result, the case studies presented below generally have a lower maturity in comparison with the ones illustrated in the previous paragraphs.

Mineral Carbonation International (MCi),[37] an Australian based privately-owned company, is developing a technology platform for large scale transformation of CO_2 into magnesium carbonate, which can be used to produce cement, paving stones, and plasterboard. The CO_2 is combined with minerals or waste streams through an accelerated natural process called mineral carbonation. In July 2018 the company completed a 5-year research pilot plant program funded by Australian Government and Industry, reaching a solid techno/economic validation of the technology. If successful at scale, this would assist as a transition technology for the major emitting countries as they move away from carbon intensive industry to more sustainable energy mixes and low carbon economies. The current pilot plant is at the basis for a demonstration plant that could process 5,000-10,000 tonnes per annum of CO_2, planned in the next three years. This would then scale roughly every three years to a further 10-fold scale increase in capacity, the final target scale being 1 million tonnes of CO_2 produced per plant.

36 Government of South Australia. "South Australia's Virtual Power Plant." *Government of South Australia*. Last modified 2019. Accessed August 23, 2019. https://virtualpowerplant.sa.gov.au/

37 "Mineral Carbonation International." *Mineral Carbonation International.* Last modified 2019. https://www.mineralcarbonation.com/

Founded in 2003, after over a decade of research, Newlight,[38] based near Los Angeles, California, has developed a carbon capture technology able to produce high-performance bioplastics from carbon emissions. This technology converts greenhouse gases into high-performance biodegradable plastic replacement called AirCarbon®, which is estimated to have the ability to out-compete fossil-fuel based plastics globally both on sustainability and price basis.[39] This biopolymer is made by combining air with methane or carbon dioxide greenhouse gas emissions, resulting in a material that is approximately 40% oxygen from air and 60% carbon and hydrogen from captured carbon emissions by weight. The technology is at an early commercial stage and the materials produced by the company have already been commercialized or adopted for commercialization programs by multiple companies worldwide.

Another interesting CCU application is related to the concrete industry, which is responsible for a significant amount of carbon emissions worldwide. CarbonCure is a Canadian company that developed a technology which uses recycled CO_2 to improve the manufacturing process of concrete, with nearly 100 installations in concrete plants across North America.[40] Their process exploits existing production equipment to produce, in situ, a nano-sized mineral carbonate embedded within the concrete by using the recycled CO_2 stream without impacting normal plant operations. In a process known as CO_2 mineralization, the carbon dioxide is converted to a mineral and it is permanently captured, improving the compressive strength of the concrete.

38 Newlight Technologies, Inc. "Newlight." Last modified 2019. https://www.newlight.com/

39 XPRIZE. "Transforming CO_2 Into Valuable Products." *XPRIZE*. Last modified 2019. https://carbon.xprize.org/prizes/carbon

40 Carboncure. "From Carbon to Simply Better Concrete." *Carboncure*. Last modified 2019. https://www.carboncure.com/

b. Industry

Lead by: Maurizio Masi, Politecnico di Milano and Ed Brost, Bowman Centre for Sustainable Energy

iv. Enabling Conditions: Stakeholders, Assumptions, Key Geographies, and Scaling

Heavy industry emits a large share of global greenhouse gas emissions because industrial processes employ high temperatures and depend on high energy densities to enable the chemical processes involved. These chemical processes, in some cases, result in GHG emissions in excess of those resulting from fossil fuel combustion to drive the chemical process.

This chapter will focus on three energy intensive sectors:

i) Cement,
ii) Iron and Steel, and
iii) Petrochemicals (i.e. Plastics Solvents, and Industrial Chemicals).

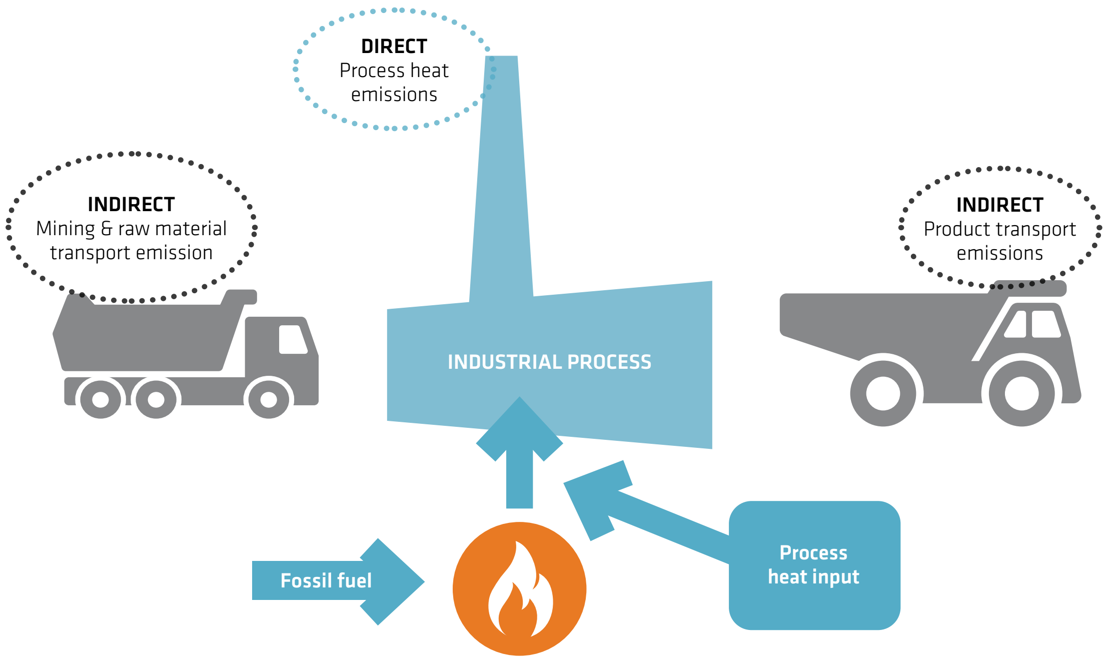
Additionally, this section deals with heavy industry considering the following three types of industrial emissions to the atmosphere:

- Direct, thermal emissions i.e. due to raising process streams to temperatures required to enable desired chemical reactions.
- Direct, chemical emissions i.e. due to the chemical process itself, or emissions that result from the desired reactions that are in addition to emissions related to use of fuels used to raise temperatures.
- Indirect, emissions resulting from electricity generation using fossil fuels such as coal, or emissions resulting from shipping materials to and from an industrial facility.

A typical industry will bear carbon burdens associated with extraction, processing, and transport of materials to the industrial site. These emissions are indirect because they were not directly caused by the industry. However, emissions associated with converting the material inputs to the industry into products, for example due to process heat inputs, are direct emissions. This group of industries directly emit GHG derived from burning fossil fuels for their heat content. Finally, emissions associated with transporting the finished product to market are another source of indirect emissions. Other indirect emissions could include emissions resulting from electricity generation required by the industrial process. This type of industry is illustrated in Figure 1 Process Heat Emissions and is typical of many heavy industries such as automobile manufacturing, the food and beverage industry, and many chemical industries and others.

In addition to these industries, there is another group that carries an additional source of carbon burden. That industrial group has similar indirect emissions, as well as direct emissions associated with burning fossil fuels to take advantage of the heat content in the fuel. However, in addition to fossil fuel derived emissions, they also create emissions due to chemical changes resulting from the transformation of their raw material, or feedstocks, into finished products. Often the energy inputs go beyond the energy required to raise the feed, or chemical reactants, to the desired reaction temperature. Many of these reactions are 'endothermic' meaning that they require energy

FIGURE 1. Process Heat Emissions[41]

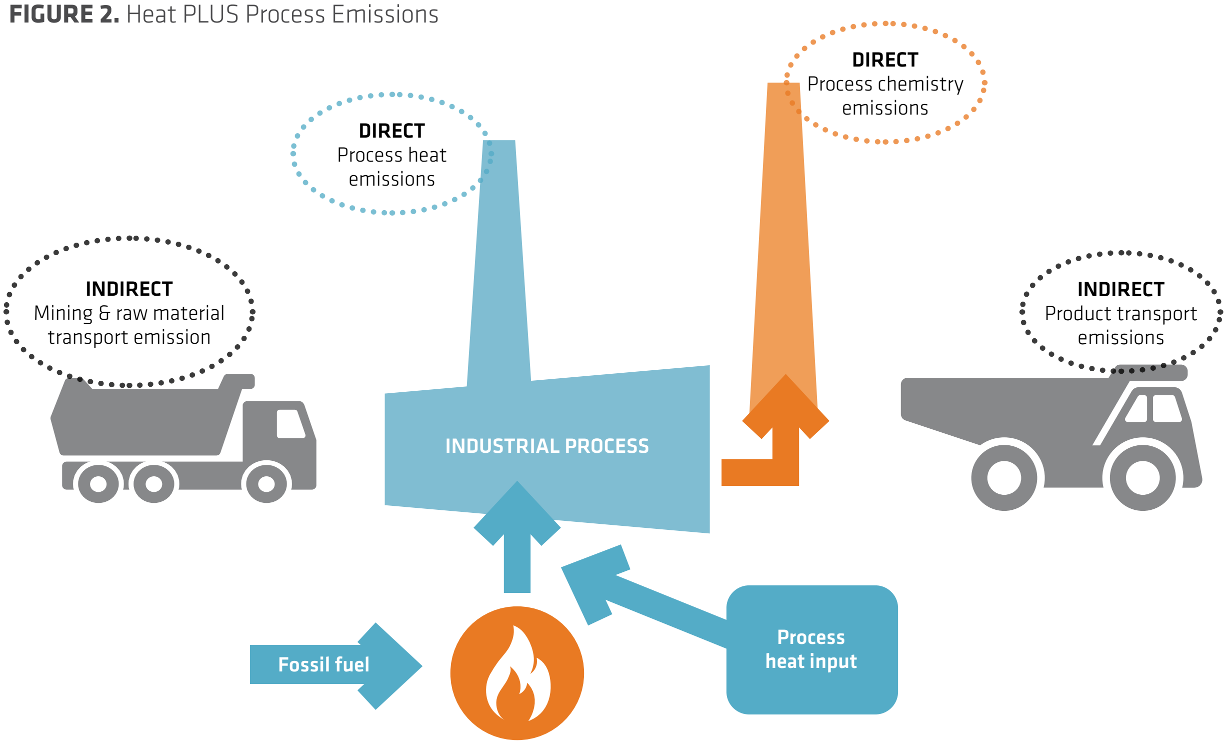


input to sustain the chemical reactions, which is over and above the energy required to heat the feeds. CO_2 emissions associated with overcoming the endothermic nature of the reactions are technically process chemistry emissions. Manufacturing cement from limestone is a good example of such an industry. Limestone ($CaCO_3$) is heated (using fossil fuels) to high temperatures. At these temperatures, the limestone releases CO_2 (as a by product of a chemical reaction) to produce CaO, the primary ingredient in Portland cement. The only way to produce concrete cement is to liberate CO_2 from limestone ore. Historically the liberated CO_2 is released into the atmosphere. In light of this, the decarbonization of this sector is not a trivial challenge.

The three sectors of heavy industry mentioned above present different features and contributions. In particular, for the case of cement, all three types of emissions are relevant, and spread across geographic spaces at different plants, thus affecting the transport and logistic organization. In the case of metals and steel, all three types of emissions are also relevant but the geography is slightly different, as plants tend to be large and strictly localized. Finally, there are many chemicals industries that bear carbon burdens associated with direct thermal and indirect emissions, but there are other chemical industries that carry process derived GHG burdens, such as those that

41 Free Images Live. "Free Stock Photo 10867 Fire." *Free Images Live.* http://www.freeimageslive.co.uk/free_stock_image/fire-jpg
All White Background. http://www.allwhitebackground.com/images/2/1851.jpg
Pixaby. https://cdn.pixabay.com/photo/2017/05/18/17/52/truck-2324237_640.png

FIGURE 2. Heat PLUS Process Emissions



require hydrogen.[42] Examples include ammonia production for fertilizers and reforming hydrocarbons to produce specialty chemicals.

Emissions from these industries are significant and require solutions that go beyond electrification of the energy inputs. Having said that, energy inputs to the chemical industry sector are enormous. To place this in context, the following quote was taken from the US Energy Information Agency[43] and supported by Figure 2;

"The industrial sector of the worldwide economy consumed more than half (55%) of all delivered energy in 2018, according to the International Energy Agency. Within the industrial sector, the chemicals industry is one of the largest energy users, accounting for 12% of global industrial energy use. Energy—whether purchased or produced onsite at plants—is very important to the chemicals industry, and it links the chemical industry to many parts of the energy supply chain including utilities, mines, and other energy product manufacturers.

The chemicals industry is often divided into two major categories: basic chemicals and other chemicals. Basic chemicals are chemicals that are the essential building blocks for other products. These include raw material gases, pigments, fertilizers, plastics, and rubber. Basic chemicals are sometimes called bulk chemicals or commodity

42 Hydrogen in this case is assumed to be manufactured from hydrocarbons such as steam methane reforming.

43 Sendich, Elizabeth. "Today In Energy."

chemicals because they are produced in large amounts and have relatively low prices. Other chemicals—sometimes called fine or specialty chemicals—require less energy to produce and sell for much higher prices. The category of other chemicals includes medicines, soaps, and paints.

The chemicals industry uses energy products such as natural gas for both heat and feedstock. Basic chemicals are often made in large factories that use a variety of energy sources to produce heat, much of which is for steam, and for equipment, such as pumps. The largest feedstock use is for producing petrochemicals, which can use oil-based or natural-gas-based feedstocks.

In terms of value, households are the largest users of chemicals because they use higher value chemicals, which are often chemicals that help to improve standards of living, such as medicines or sanitation products. Chemicals are also often intermediate goods—materials used in the production of other products, such as rubber and plastic products manufacturing, agricultural production, construction, and textiles and apparel making."

This intense use of energy contributes directly to the sector's GHG emissions, directly in the form of exhaust gases used to provide process heat and directly as a result of chemical transitions that occur as part of the industrial processes.

In 2014, direct and process emissions from heavy industry sectors amounted to 8.3 Gtonne CO_2/year. Figure 3 shows that 21% of total emissions in 2014 were due to energy and industrial systems. Single contributions from cement, steel, and chemicals were respectively about 2.2 Gtonne CO_2e/year, 2.3 Gtonne CO_2e/year, and 1.1 Gtonne CO_2e/year plus another 2.7 Gtonne CO_2e/year from other industry.

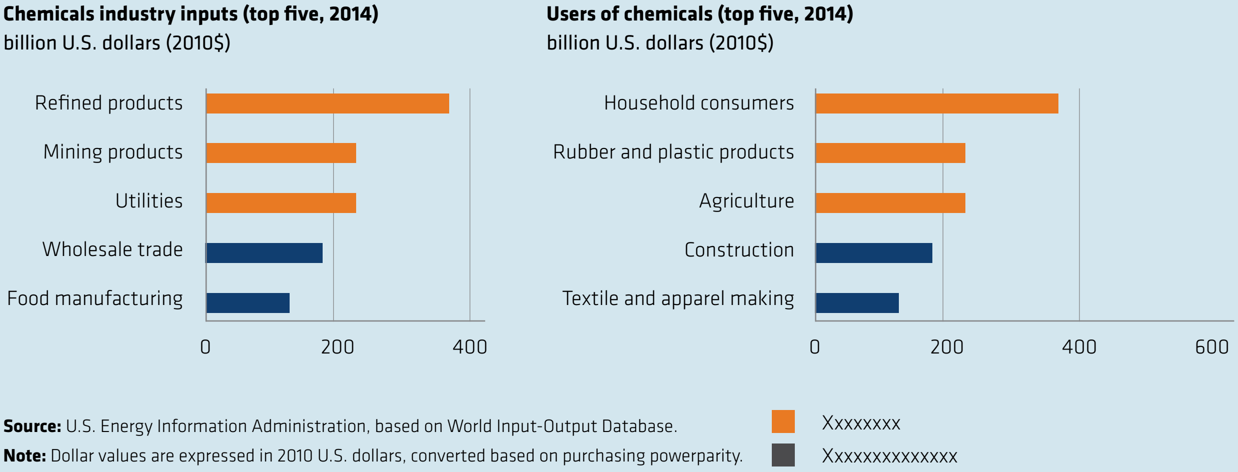
All these emissions are projected to grow by 24% from 2014 to 2050, according to the latest International Energy Agency Reference Technology Scenario (roughly 26% of the total energy and industrial systems emissions),[44] with contributions from the three main sectors being 2.3 Gtonne CO_2e/year for cement, 3.3 Gtonne CO_2e/year for steel, and 1.6 Gtonne CO_2e/year for chemicals.

This is not aligned with the goal of limiting global temperature rise to 1.5° Celsius by 2050. The reference scenario calculates a decrease of emissions from heavy industry to 5.9 Gtonne CO_2e/year (split in 1.7, 1.3, 1.0, and 1.8 Gtonne CO_2e/year respectively for cement, steel, chemicals and other industry).

As utilities commit to, and achieve, ambitious emissions reduction goals, we can expect these industrial sectors to face increasing pressures to match the utility sector performance, first by improving efficiencies and then by fundamentally rethinking production processes. Difficulties arise from the fact that, in order to abate emissions, fuel switching is not enough;a deeper change in industrial process, especially endothermic processes, is required. The latter is harder to implement, as it gets to the essence of the chemical reactions that underpin production of the desired chemical products (steel, cement, plastics, etc).

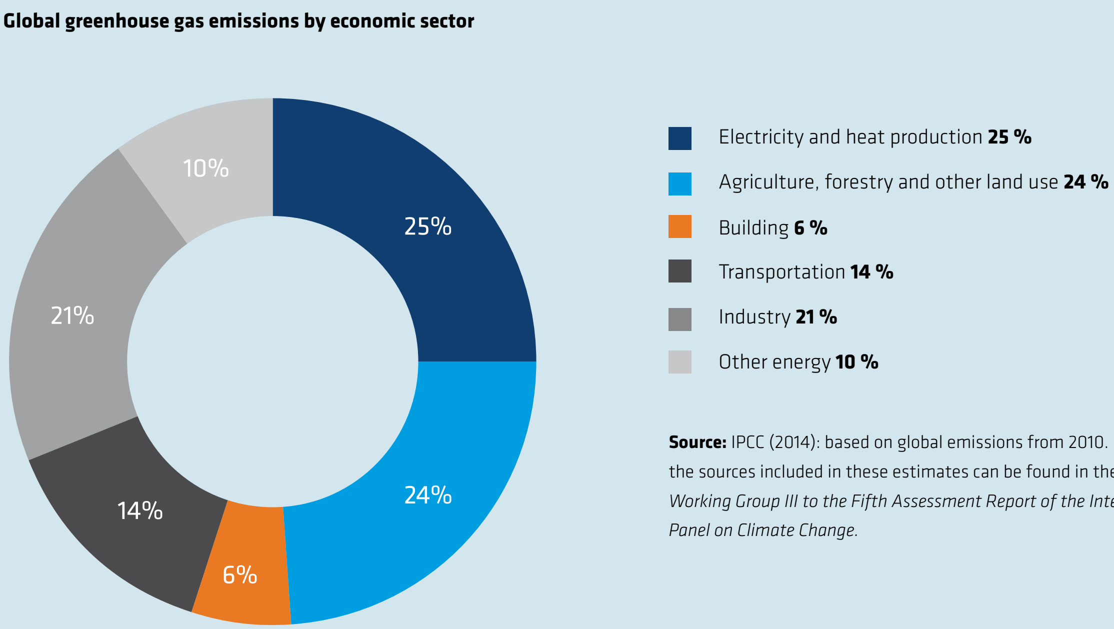
44 IEA."Energy Technology Perspectives 2017." IEA. Last modified 2019. https://www.iea.org/etp/

FIGURE 3. Chemical Industry Products and Users



Source: U.S. Energy Information Administration, based on World Input-Output Database.
Note: Dollar values are expressed in 2010 U.S. dollars, converted based on purchasing powerparity.

FIGURE 4. Global Greenhouse Gas Emission by Sector



Source: IPCC (2014): based on global emissions from 2010. Details about the sources included in these estimates can be found in the *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*

As mentioned at the beginning of this section, extremely high temperatures (between 700°C and 1600° C) are involved in the industrial processes considered. Therefore, to reduce emissions these industrial sectors we will need to displace fossil fuel-based energy inputs with low to zero emission electricity, along with improved heat integration, energy efficiency, and by taking advantage of new processes.

This will involve retrofitting furnaces and other heat input equipment which represent high economic investment and technological advancements. Additionally, from an economic point of view, most industrial facility components have economic lifetimes exceeding 50 years. That implies a need for expensive retrofitting, reconfiguring or rebuilding existing industries to achieve GHG emission reductions at a scale that contributes meaningfully to global decarbonization activities.[45]

In addition to retrofit costs, other practical and technological issues are involved. Most large, heavy industry facilities consist of individual processing units operating in highly integrated series. Implementing changes to one or more process units will inevitably impact the entire production line, thus requiring systemic changes. Although process unit integration may compound decarbonization within a facility, integration between industry sectors may offer decarbonization opportunities.

For example, substitution or partial displacement of steel and concrete with chemicals may be possible. For example, concrete often requires reinforcement, usually with steel rebar, advanced materials such as carbon fibre and plastics might reduce the amount of steel required for reinforcing concrete as well as require less concrete for the same project. Further, rebar corrosion in roads and bridges is a key contributor to the longevity of those applications. Carbon fibre or other substitutes could lengthen the life of infrastructure, further reducing concrete demand. It should be noted that carbon fibre manufactured by current industrial practices has a fairly high GHG intensity. Technological improvements are required to capture the potential benefits associated with carbon fibre, and perhaps some day, graphene.

Industry interdependence in the context of decarbonization is very important and is an area ripe for technological development. An interconnected systems approach is required, rather than viewing industries and their technologies in silos. Doing so should accelerate decarbonization and, eventually, result in net negative emissions.

45 De Pee, Arnout, Dickon Pinner, Occo Roelofsen, Ken Somers, Eveline Speelman and Maaike Witteveen. "How Industry Can Move to a Low-Carbon Future." *McKinsey.* Last modified 2019.
https://www.mckinsey.com/business-functions/sustainability/our-insights/how-industry-can-move-toward-a-low-carbon-future?reload

v. Key technologies

Fully decarbonizing these complicated and integrated industrial environments requires an integrated and multidimensional approach. All possible solutions must be considered and integrated into the specific regional situation, depending on the availability of sustainable resources locally and their related costs. The "Mission Possible" report published by the Energy Transitions Commission[46] identifies three action areas:

- Reducing demand for carbon-intensive products and services
- Improving energy efficiency in current production processes
- Deploying decarbonization technologies across all sectors, which in turn can be split between four supply-side decarbonization routes: Electrification; Use of biomass; Use of hydropower; and Use of carbon capture technology

There are currently no purely technological limitations blocking major decarbonization routes across any industrial sector. The barriers are economic; for the most part, we have the technologies today, but they are expensive. Future technological advancements might very well reduce these barriers. Given this situation, we can start by looking at demand.

The demand reduction route is inextricably linked to social issues. This makes demand reduction challenging to model and drive with an acceptable level of confidence. But meaningful demand reduction can be achieved through greater material efficiency, circularity, and recycling. This is especially true for plastics and metals, where technology is ready. Leadership, coupled with education and effective policy, can lead to better coordination across the value chain and improve the effectiveness and efficient use of plastics and metals.

Recycling is a relatively low-cost opportunity with a high GHG emission reduction reward. Again, this is one component in a range of possible actions to reduce emissions from the heavy industry sector, especially in the short-term. As with other opportunities, technology for recycling, reuse, and repurposing products largely exists today. The challenge is that new products often compete economically with recycled materials. For example, it is currently less expensive to produce new Li-ion batteries than it is to recover the lithium, cobalt, and other materials from spent batteries. In the case of Li-ion batteries, technology advancements coupled with increasing raw material costs will change the economic characteristics.[47] [48] [49]This is but one example of how technological advancement in the metals sector is reducing the economic barriers to recycling, reuse, and repurposing.

Indeed, by maintaining business as usual, in 2050 the emissions from cement, steel, and plastic are projected to contribute respectively 2.9, 2.8, and 2.2 Gtonne CO_2e/year to our atmosphere. This is a significant drain on our carbon budget. Assuming instead that consumer and industry behaviours change and we follow good practices

46 Energy Transition Commission. "Mission Possible - Reaching Net-Zero Carbon Emissions From Harder-to-Abate Sectors by Mid-Century." *Energy Transition Commission*. Accessed on August 21, 2019. http://www.energy-transitions.org/sites/default/files/ETC_MissionPossible_FullReport.pdf

47 Tesla and Fortum (Finish recycling company) recently announced Li, Co and other metal recoveries from spent Li ion batteries

48 Slav, Irina. "Has Tesla Solved the World's Battery Recycling Problem?" *Oilprice* (blog). April 16, 2019. Accessed August 21, 2019. https://oilprice.com/Latest-Energy-News/World-News/Has-Tesla-Solved-The-Worlds-Battery-Recycling-Problem.html#

49 Prieto, Matias. "Finnish Company Boosts Battery Recycling to Over 80 Percent." *The Green Optimistic* (blog). April 14, 2019. Accessed August 21, 2019. https://www.greenoptimistic.com/finland-battery-recycling-20190412/#.XLW8GzAzaHt

such as materials and product recycling, a 40% decrease of emissions is expected. In a fully circular scenario, by 2050 only 2.0, 1.9, and 0.9 Gton CO_2/year of emissions respectively from cement, steel and plastics. This reduction can be allocated to materials reuse and product circulation as 1.7 and 2.0 Gton CO_2/year respectively.[50] For the three analyzed industrials sectors, we present the following options as examples:

- Cement: Building design optimization, concrete reuse, materials substitution
- Iron and Steel: Optimization of scrap recycling, product design for efficiency, more intensive use of products
- Petrochemicals: Chemical and mechanical recycling, plastic demand behaviour change, use of renewable feedstocks and product eco-design to better enable recycling

It is, however, important to note that a growing world population implies a growing demand for GHG intensive products, and this will impact global consumption of resources.

Improving energy efficiency is the first line of action (together with material efficiency and demand reduction) to begin reducing carbon emissions in the short-term. This is true even when the supply-side decarbonization technologies are developed and deployed. Indeed, the energy efficiency route is the easiest to implement, since some of the decarbonization technology options are not currently ready commercially. For energy efficiency, the technology exists today, and it can be applied in both developed and developing countries, offering a big margin for improvement. In particular, some of the proposed key solutions for the energy efficiency improvement routes are:

- Cement: Switch to dry kilns, multistage cyclone heaters
- Iron and Steel: Re-use of high-pressure gas for power, coke dry quenching
- Chemicals: Energy efficiency in monomer production, naphtha catalytic cracking.

These solutions may result in a meaningful reduction in emissions from the cement, iron and steel, and chemicals industries. Of course, geographical situations can differ from country to country. Countries investing in new plants should go for zero-carbon technology rather than investing in energy efficiency improvements. In contrast, countries where legacy plants and facilities will continue to operate for years to come should invest in energy conservation and energy efficiency improvements for existing processes. This is because it is difficult to economically justify deployment of new and disruptive technologies unless emission costs are internalized. This is especially true for regions where there is overcapacity and incentives are lacking, for example, in Europe. In these situations, policy makers will need to play a key role in enabling change by internalizing externalities through economic as well policy incentives.

Fortunately, the are currently some incentives and policy instruments, such as carbon pricing or command and control regulations that are facilitating decarbonization routes using existing and emerging technologies available today. However, it is important to understand that many of the relevant technologies described in the following paragraphs are not yet commercially ready. Further, there are emission reduction and control technologies that currently present low technology risk but face significant economic challenges. Given these caveats, the technological opportunities described below warrant further development and deployment.

50 Energy Transition Commission. "Mission Possible"

For instance, while electric trucks could be cost-competitive by 2030, cement kiln electrification may not be commercially ready until a decade later. The latter depends more on the availability of low carbon electric power being cost competitive with fossil energy and/or the expanded use of biomass to supply the necessary heat inputs. This is an example where little, if any technology advances, are required. The barriers to deployment are primarily economic.

Note that electrification of kilns would address the direct emissions associated with heating the ore to required chemical conversion temperatures and to sustain the endothermic reactions, however electrification of the kiln would not mitigate the CO_2 emissions from the chemical reaction resulting from the conversion of limestone ore to portland cement, i.e. the process emissions. Process emissions could be controlled by carbon capture processes coupled with use and storage, which at a technical level, are well understood. But carbon capture faces significant economic and social acceptance challenges. In some regions, certain carbon capture technologies may be deployed to capture CO_2 emissions from kiln reactors by reactions with serpentine or olivine ores, producing carbon silicates. Added to the Portland cement, these carbon silicates create a cement with pozzolanic features.

Hydrogen-based industrial processes require significant development. The technology underpinning electrolytic production of hydrogen is essentially available. These plants are scalable and therefore can reach the desired size simply by adding modules. However, there are still limitations to scaling them up due to limits to the size of the polymeric membranes. Currently electrolytic hydrogen manufacturing faces stiff economic competition from well-established processes that involve reforming hydrocarbons to produce hydrogen and CO_2, i.e. steam-methane reforming. One of the reasons the latter benefits from an economic advantage is that the CO_2 emissions to the atmosphere are free, thus the costs are 'externalized'. A policy correction to this issue would be to internalize those costs by placing meaningful prices on carbon emissions.

Additionally, the possibility to combine more of these solutions to a given country or facility will vary and depend on the geographical distribution of resources and social acceptability of specific technologies. Some examples of options identified for the industrial decarbonization path through the deployment of decarbonization technologies include:

- Cement:
- Kiln electrification
- Carbon capture technology for process emissions
- Biomass for heat generation
- Hydrogen for heat generation
- Decrease the clinker-to-cement ratio

- Iron and Steel:
- Scrap-based
- Electric arc furnace (EAF)
- Direct iron electrolysis
- Charcoal in blast furnace (BF)/Basic oxygen furnace (BOF)
- Carbon capture technology on energy emissions
- Renewable energy derived hydrogen-based direct reduced iron (DRI)

- Chemicals:
  - Electrification of furnace heat
  - New electro-chemical processes replacing oxidation and reduction steps[51]
  - Carbon capture on energy emissions
  - Biomass for heat generation
  - Hydrogen for heat generation
  - Use of recycled materials
  - Use of biomassed based feedstocks or biomass derived synthetic feedstocks

These biomass feedstocks would displace fossil fuel (natural gas, hydrocarbon condensates, and crude oil) based feedstocks thus reducing the GHG emissions associated with resource extraction and processing into finished products. To achieve net reductions, it is important to use low emission technologies to process biomass into feedstocks. Further, once recycling and circular economy approaches to the finished products are exhausted, the ultimate fate, whether as fuel for waste product heat content or other degradation process, will result in biogenic CO_2 rather than fossil CO_2. Carrying this one step further, capturing and sequestering the CO_2 from destruction of the biomass-based products would in effect remove CO_2 from the atmosphere.

This sample of options in the selected industrial sectors, along with biomass related opportunities have been evaluated but need further development. However, it should be recognized that biomass opportunities present additional and challenging constraints regarding sustainability. Of these options, the use of electricity to provide heat input is the most straight forward. Subject to energy pricing and electricity supply, this technology is ready now.

The electrification option, either direct or indirect, is ready for deployment, especially for long-term plans because:
i) Renewable electricity prices are expected to continue to fall
ii) Implementing electricity-based solutions can use existing infrastructure; it does not require the build-up of storage and transport infrastructure as is the case for carbon capture. This electrification is technically easier to implement in terms of social and political acceptability
iii) Direct electrification, even if not market-ready, comes with some process intensification that may be advantageous for industry players. Direct electrification heating is a hot research topic today. Electrical heating also has the advantage to reduce the size of the heat exchange apparatus, reducing the amount of steel required for their construction.

Looking to this range of opportunities, six generic innovation areas to fully decarbonize the heavy industrial sectors can be highlighted for further development. As part of the process for development, these options may be classified as incremental innovation or breakthrough innovation as part of the process for development.

51 However, this step, in many cases involve the use of new electro-conducting solvents, because many reactions are not compatible with the aqueous media

TABLE 3. Heavy Industry Innovation Areas: Innovations and Breakthroughs

Electrification	- Incremental innovation: › Cheaper and more efficient electrochemical batteries - Breakthrough innovation: › Electric furnaces for cement and chemicals › Electrochemical reduction of iron for steel production
Hydrogen technology	- Incremental innovation: › Cheaper electrolysis (targeting $250/kW) › Cheaper hydrogen fuels cells and hydrogen tanks › Long-distance transport of hydrogen - Breakthrough innovation › Liquid organic hydrogen carrier (LOHC) technology › Direct steam electrolysis at high temperature (i.e., the reverse process of a fuel cell). This process also produces also pure oxygen (O2) that can be used for oxy combustion to obtain CO_2 at high concentrations, thus reducing the cost for carbon capture.
Biochemistry and synthetic chemistry	- Incremental innovation: › Biofuel and bio-feedstocks, from lignocellulosic sources and/or algae, as a fuel for thermal energy input. This involves redesigning conventional biofuels for use in industrial applications. These biofuels would be diverted from transportation to industrial use as electrification of transport proceeds, alleviating the demand for increased biofuel production. - Breakthrough innovation: › Synthetic chemistry, including direct air capture of CO_2 as a chemical reducing agent for industrial chemical process, for example conversion to metallurgical grade charcoal for steel production › Gasification of biomass to manufacture chemicals and feedstocks from syngas. Capturing the CO_2 from biomass gasification could result in negative GHG emissions.
Materials efficiency and circularity	- Incremental innovation: › New designs for consumer products › Materials traceability › Collection, sorting and recycling technologies › New business models (product-as-a-service, sharing, etc.)
New materials	- Breakthrough innovation: › Low-carbon cement and concrete chemistries › Biomaterials for construction › Cellulose-based fibers as a substitute for plastics › Carbon fibre or other advanced reinforcing materials to reduce demand for concrete

contiues >

Carbon capture and use/storage	- Incremental innovation: › More efficient carbon capture, especially for cement, and use of the carbon in concrete, aggregates and carbon fibers › Explore and identify suitable geological formations, such as deep saline aquifers with low seismic activity, to serve as supercritical CO_2 sequestration sites › Public awareness of the risks and opportunities associated with carbon capture - Breakthrough innovations: › Advancement of oxy firing technologies to create CO_2 rich flue gas in order to reduce the cost of carbon capture › Advanced technical and economic opportunities for CO_2 as a feedstock to manufacture durable goods including substitutes for conventional concrete

Many of these opportunities come with some tricky and cross-sectoral challenges. For instance, the fact that many of them are not yet commercially available leads to uncertainties associated with future costs and technology mix. The pace at which technological breakthroughs occur will determine deployment opportunities over the next decades. Another obstacle for the introduction of new technologies in the chemical industry is due to the very high integration among the different production lines. Usually, hundreds of products leave a petrochemical plant based on a single feedstock like natural gas or virgin naphtha. A simple process update may impact several value chains making it operationally challenging to do so. This is in part due to societies current willingness to allow industries to externalize their emissions, i.e. emit GHGs without meaningful costs. This factor is not to be overlooked as large, worldwide petrochemical plants can be a major obstacle to the introduction of new technologies.

Focusing just on electrification and carbon capture, the breakeven point at which electricity-based solutions become lower-cost than carbon capture and storage is calculated to be between US $40 and $50 per MWh,with an abatement cost of around $100 per tonne of CO_2.[52] However, carbon capture technologies can only capture about 80-90% of the CO_2 stream, releasing the remaining 10-20% into the atmosphere. They alone cannot solve the problem These losses may be attributed in large part to CO_2 compression costs and emissions if the energy is derived from fossil fuels. If the electricity used to drive the carbon capture processes is carbon free, then higher capture efficiencies may be achieved.

52 Sendich, Elizabeth. "Today In Energy."

Importantly, and perhaps more challenging than the technical barriers, deployment of carbon capture and storage technologies depends on the social acceptability of the deployment of these infrastructures. Public acceptance of this technology can vary significantly from region to region. In contrast, major direct or indirect electrification would result in higher power demand by industry, however public acceptance would likely not be an issue provided industry pays for the incremental infrastructure.

Although there are significant technical challenges associated with the electrification of industry, hydrogen offers the potential to play an important role in the future of heavy industry. Therefore, exploring this opportunity and the eventual transition to a hydrogen economy should be a priority for the future of heavy industry sector. Such an initiative should proceed in parallel with the development of other 'near ready' technologies.

As implied, specific geographic and political scenarios play a critical role in technology development and deployment. The pace at which disruptive technologies could be adopted and deployed in heavy industry sectors depend on:

i) The existence of appropriate policy incentives as well as other policy instruments
ii) Reduction in the cost of alternative zero-carbon fuels, in particular zero-carbon electricity
iii) Trade exposed industries facing international competition from jurisdictions that have chosen to reduce their emissions at a slower pace. This results from differences in regulations and incentives between countries, regions and even jurisdictions within countries and causes competitive distortions.

The shift to new energy or feedstocks (e.g. power with combined energy storage, power-based fuels like hydrogen, or synfuels and bioenergy) will significantly increase the demand for these alternative low-carbon fuels. This could, on the one hand, create transitional tensions on the energy supply and price increases. In the longer term, it is likely to lead to drastic cost reductions, for instance in hydrogen production, due to, competition, economies of scale, and learning curve effects.

Finally, this perspective is not only limited to the carbon footprint of the industrial sectors. Many issues influence the need to decarbonize the heavy industry sector, including land and water consumption, as well as process safety, a critically import aspect. There is a need for an organized and well-structured roundtable to discuss decarbonization options and pathways because every choice will influence other components of the industry sector and society at large. Decarbonization must be implemented in an integrated manner, not in sector-based silos. Individual sectors often do not, in isolation, represent majority shares of national economies, but they do have significant symbolic weight associated with them. Industry can either serve as a roadblock in terms of political shift to renewable resources or enabler in the advancement of sensitive options such as carbon capture. Leadership, political will, and courage will be required in order to reach net zero carbon emissions by 2050.

Reducing carbon emissions in the chemical sector can be generally classified as green chemistry. Use of the term 'green' must be used with caution to avoid falling into a "green washing" trap. 'Green' chemistry in this context refers to reductions that come from the use of Joules derived from renewable energy, including biomass, hydrogen generated using renewable energy, and other process changes that are demonstrably sustainable and emission free. Green chemistry is a progression, from "greening the brown" that is the reduction of the carbon impact of traditionally oil based processes to "green green" that is the direct use of bio feed stocks, achieving a circular economy. The technology is already available, the main improvement needed is taking them to scale.

Examples of greening the brown:

- Desulphurization of very acid gas reservoirs transforming hydrogen sulfide (H2S) into sulphur (S) and hydrogen (H2)
- Production of olefins by any kind of natural gas with energy efficient processes (i.e. reducing the flaring)
- Improving the efficiency of fertilizers like urea through controlled release formulation (i.e., reducing the amount of highly soluble fertilizer dispersed on soil)

Regarding the chemical aspects of the circular economy, possible improvements can be:

- Waste to hydrogen, that is the production of hydrogen from municipal wastes
- Using waste to produce chemicals and renewable fuels
- Improve the mechanical recycling of plastics
- Chemical recycling of plastics, mainly through two routes: gasification to syngas or de-polymerization (either to naphtha, the relevant feedstock of petrochemical plants, or to specific secondary feedstocks, like de-polymerizing polyethylene terephthalate (PET) to polyols used in polyurethanes)

It is relevant to consider that the electrification of the energy supply could enhance the carbon sustainability of these endothermic processes.

Finally, regarding the “green green” sector, possible examples, all from non-food competition biomasses, could be:

- Second generation of bioethanol as biofuel
- Biochemical and biopolymers production like oleochemicals, such as omega3 from algae,
- New fertilizers that control release of the active ingredient produced only through renewable energy

vi. Case Studies

An example of the use of CCS technology with an industrial process is demonstrated at scale with the Quest Carbon Capture and Storage project in Alberta Canada where the CO_2 emissions (about1MTonne/year) from a hydrogen manufacturing plant are captured, compressed to supercritical conditions, and then permanently sequestered in a saline aquifer about 900 meters below the surface.

https://www.shell.ca/en_ca/about-us/projects-and-sites/quest-carbon-capture-and-storage-project.html

Although the Quest project is being used to reduce emissions from an oil sands project, this case demonstrates that the technology is currently available. Effective carbon pricing and/or regulations are required for significant application to other heavy industrial applications.

c. Transport

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vii. Enabling Conditions: Stakeholders, Assumptions, Key Geographies, and Scaling

In 2016, the transport sector accounted for 2748 Mtoe, almost 28% of the Total Final Consumption (TFC) at the global level, 92% of which was represented by oil products.[53] From 1973 to 2015 the TFC in transport by energy supply carriers increased by a factor of 2.5, showing that oil products are the major source of energy supply of the sector even if, in recent years, natural gas, biofuels, and electricity have been gaining relevance.

Breaking down TFC by transport mode, road transport represents three quarters of the total and confirms its growing relevance with an increase of more than 10% of the total share compared with the 1970s. Within the road transport sector, the share of oil products is almost 94% approaching 100% for domestic aviation and navigation. Within the rail mode, electricity covers 42% of the energy need.[54] According to the International Energy Agency, the share of TFC for transportation is expected to be 29% in 2040, and consumption is predicted to amount to 3617 Mtoe in the New Policies Scenario (NPS), while the oil products' share is expected to decrease to 82% and electricity to account for 4%. Within the Sustainable Development Scenario (SDS), the 45% increase might be reduced by 6% while the share of oil products is expected to experience a further reduction and electricity to account for 14%.[55] These scenarios are completely incompatible with the goals of the Paris Agreement.

As population and the economy grow, transport demand continues to increase. This is a trend observed over the last few decades and is expected to continue into the future. Passenger transport will increase nearly three-fold between 2015 and 2050. Global freight demand will triple between 2015 and 2050 based on the current demand pathway.[56]

Different energy vectors will play a role in transport decarbonization. Direct electricity usage (through either batteries or catenary lines, both for rail and road), hydrogen, synthetic fuels and sustainable biofuels, properly allocated to hard-to-decarbonized modes, will all be important for transport decarbonization. In all cases, they will rely on vast amounts of renewable electricity, either as a vector itself, or to produce a transport energy vector. The role of batteries and hydrogen in transport will depend on many aspects that deal with the technology cost of batteries and fuel cells, the deployment of the charging stations for the road sector, the sustainability of production (hydrogen feedstock from renewable sources), and the policy framework and resource endowments of a country.

In the case of batteries, IEA Global EV Outlook 2019 reports the global electric car fleet (both battery electric and plug-in hybrid vehicles) exceeded 5.1 million in 2018[57] and over 2 million electric vehicles were sold. In the short term,

53 IEA. "World Energy Outlook 2018."

54 Ibid.

55 IEA. "Sustainable Development Scenario."

56 Ibid.

57 IEA. "Global EV Outlook 2019 - Scaling up the transition to electric mobility." *IEA*. Last modified 2019. https://www.iea.org/publications/reports/globalevoutlook2019/

sales are expected to increase to at least 12 million by 2025, and (22 to 41) million in 2030. Falling battery prices, increased charging infrastructure, and consumer acceptance is driving these developments.[58] The automotive industry is responding with very high investments that confirms the escalating momentum for the electrification of transport. Recent announcements by vehicle manufacturers are ambitious regarding intentions to electrify the car and bus markets. The EV uptake and related battery production requirements imply bigger demand for new materials in the automotive sector, requiring increased attention to raw materials supply.

The demand for these raw materials raises concerns and risks[59] about:

- Production (e.g. lack of reserves or resources, and lead times for new capacity)
- Economy (demand/supply balance, including demand fluctuations and sudden disruptions, stockpiling, policies affecting production or import/export options)
- Geography (highly dependent on national policies and strategies, and often exacerbated in cases of geographical concentration of extraction and/or refining)
- Society (impact on the well-being of communities at all scales, local, regional, national and transnational)
- Environment (e.g. local pollution, supply chain related carbon dioxide (CO_2) emissions, impact on local ecosystems and water resources, landscape destruction)

Battery chemistry and density is evolving fast, in parallel with ultra-fast charging capabilities and infrastructure deployment. Apart from light-duty vehicles, battery vehicles are also evolving for heavy-duty vehicles and short sea shipping.[60]

In the case of hydrogen, advanced applications are spreading in the non-electrified trains, as well as heavy-duty and light-duty vehicles (HDV, LDV), ensuring an extended fuel autonomy. Fuel Cell Electric Vehicles (FCEVs) are now comparable to the conventional vehicles with a range of (450 to 550) km per tank and fuel quickly (less than 5 min).[61] Fuel-cell cars are still quite rare in Europe; some 253 units were sold in 2017, with the lack of dedicated hydrogen infrastructure being a major barrier to wider consumer acceptance, in combination with the high price of the vehicle and the fuel.[62] Overall, in hydrogen production and filling procedures, consumption of additional primary renewable electricity is between two and three times more with respect to direct electricity charging.[63]

In 2017, biofuels accounted for 3% of the total TFC in transport and it is envisaged to grow up to 6% in NPS to reach 13% in SDS in 2040.[64] In the road transport sector it is foreseeable that in the short term the use of liquid biofuels that are not in competition with food, as well as biomethane, can immediately guarantee a high saving of

58 Ibid.

59 Ibid.

60 Ibid.

61 IEA Hydrogen. "Global Trends and Outlook for Hydrogen." *IEA Hydrogen.* Published 2017. Accessed August 21, 2019. http://ieahydrogen.org/pdfs/Global-Outlook-and-Trends-for-Hydrogen_Dec2017_WEB.aspx.

62 Cambridge Econometrics Limited. "European Climate Foundation - Low-Carbon Cars in Europe: A Socioeconomic Assessment." *Cambridge Econometrics Limited.* Published 2018. Accessed August 21, 2019. https://www.camecon.com/wp-content/uploads/2018/02/Fuelling-Europes-Future-2018-v1.0.pdf

63 Transport & Environment. "Roadmap to Decarbonising European Cars." *Transport & Environment.* Accessed August 21, 2019. https://www.transportenvironment.org/sites/te/files/publications/2050_strategy_cars_FINAL.pdf

64 IEA. "World Energy Outlook 2018."

CO_2 replacing the still predominant share of fossil fuels. Furthermore, the use of biofuels is comparable in terms of CO_2 emissions with the BEVs if the entire production chain is considered (life-cycle analysis), starting from the construction of the car and the batteries passing through the production of fuels and electricity using different power mixes. However, crop-based biofuels have been debated for over a decade as they are responsible for land-use change and can be worse than the fossil fuels.[65] [66] [67] For biofuels to reduce greenhouse gas emissions without adversely affecting the environment or social sustainability, they must be produced in a sustainable way. Therefore rigorous sustainability criteria for biofuels and bioliquids must be set, such as that described by the European Commission.[68]

According to the IEA, bioenergy's contribution in the transport sector will grow up to reaching nearly 25 EJ in 2050 and providing about 20% of total transport final energy demand. At least 100 EJ of sustainable biomass could be available in 2050 from low-ILUC crops (50%), agricultural waste (40%) and municipal waste (10%) and that potentials up to 300 EJ may still be considered reasonable, notwithstanding the contribution coming from micro-algae whose development seems very promising.

Growing biofuels on existing agricultural land can displace food production to previously non-agricultural land such as forests. As trees absorb CO_2 from the atmosphere, removing them for biofuel production may result in an increase of net greenhouse gases instead of a decrease, a process known as indirect land-use change (ILUC). Nevertheless, numerous analyses have shown ethanol and second generation biofuels (2G) can provide substantial GHG reductions (also when accounting for ILUC).[69] Further, it is worth noting that scarcity and potential competitive effects on the resource and complexity in overall supply chain may suggest that the use of biofuels in priority modes of transport (e.g. harder to decarbonize sectors like aviation) or priority geographical area (e.g. characterized for instance by a low penetration of renewable energy in the power sector, like developing regions).

Natural gas, in 2016, represented less than 4% of the total final consumption concerning transport sector.[70] Further development is registered in heavy duty road transport and in the navigation sector.[71] Natural gas cannot lead to decarbonization of transport as it is a fossil fuel that only can, in the best case scenario, contribute to marginally reduce the climate impact of the sector.

65 Searchinger, Timothy, Heimlich Ralph, R. A Houghton, Fengxia Dong, Amani Elobeid, Jacinto Fabiosa and Simla Tokgoz. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change." *Science* 319, no 5867 (2008): 1238–1240.

66 IEA. "Technology Roadmap - Delivering Sustainable Bioenergy." *IEA*. Published 2017. Accessed August 21, 2019. https://www.iea.org/publications/freepublications/publication/Technology_Roadmap_Delivering_Sustainable_Bioenergy.pdf

67 Energy Transition Commission. "Mission Possible"

68 European Commission. "Sustainability Criteria." *European Commission*. Last modified 2019. Accessed August 21, 2019. https://ec.europa.eu/energy/en/topics/renewable-energy/biofuels/sustainability-criteria

69 Transport & Environment. "Globiom: the basis for biofuel policy post-2020." *Transport & Environment*. Published 2018. Accessed August 21, 2019. https://www.transportenvironment.org/publications/globiom-basis-biofuel-policy-post-2020

70 NGVA Europe. "Natural gas: a solution for a clean and decarbonized transport system." *NGVA Europe*. Accessed on August 21, 2019. https://www.ngva.eu/medias/natural-gas-a-solution-for-a-clean-and-decarbonized-transport-system/

71 International Transport Forum and OECD. "ITF Transport Outlook 2017." *OECD ilibrary*. Last modified 2019. https://www.oecd-ilibrary.org/transport/itf-transport-outlook-2017_9789282108000-en

Transport is second only to electricity and heating for the highest CO_2 emissions. In fact, transport produces 25% of total carbon dioxide emissions, having more than doubled emissions over the last 45 years. Carbon dioxide emissions from road, air and water transport represent 74%, 12% (excluding non-CO_2 impacts, which is estimated to double the warming impact of the sector)[72] and 12%, respectively. 60% of the carbon dioxide emissions can be attributed to passenger traffic (10% air, 50% land), of which nearly 50% is generated by urban travel and the leftover 40% by freight (15% maritime transportation, 25% road and rail traffic).[73] According to the International Transport Forum,[74] CO_2 emissions for several modes of transport will increase in the coming years, mainly due to goods handling, non-urban surface passenger transport, and the urban passenger sector. Power is currently the most carbon-intensive sector, but the rapid technological evolution, especially within the SDS, is expected to lead to deep decarbonization by 2040. In the transport sector, GHG emissions reduction is not likely to follow the same decreasing trend envisaged for the power sector, since new available technologies, assuming no significant improvement in vehicle or battery manufacturing, still may have life-cycle CO_2-equivalent emissions of approximately the same order of magnitude of conventional powertrains.[75]

In any case, battery electric vehicle (BEV); plug-in hybrid electric vehicle (PHEV); hybrid electric vehicle (HEV); and fuel cell electric vehicle (FCEV), according to IEA Global EV Outlook 2019, have lower CO_2-equivalent emissions with respect to conventional internal combustion engines, and this gap can be further increased as renewable penetration grows in the global energy mix.

Moreover, as far as transport is concerned, the relevance of environmental issues, such as land consumption and air quality, should be considered from a life-cycle perspective. As a result of growing urbanisation, transport is expected to further impact land consumption (1.5% of the total land surface is currently taken up by roads and parking lots) and air quality (70% of emissions of other pollutants are associated to the sector). The impacts on the quality of water, soil, and noise pollution cannot be neglected.

The decarbonization of the transport sector offers the opportunity to combine climate protection and environmental safeguard with a positive economic and social balance. Policy makers' roles are to develop the necessary framework to realise these benefits and successfully combat climate change, with the engagement of industry and other stakeholders. Carbon neutrality in the transport sector may be achieved in a number of ways, and different technologies and solutions still have different pros and cons.

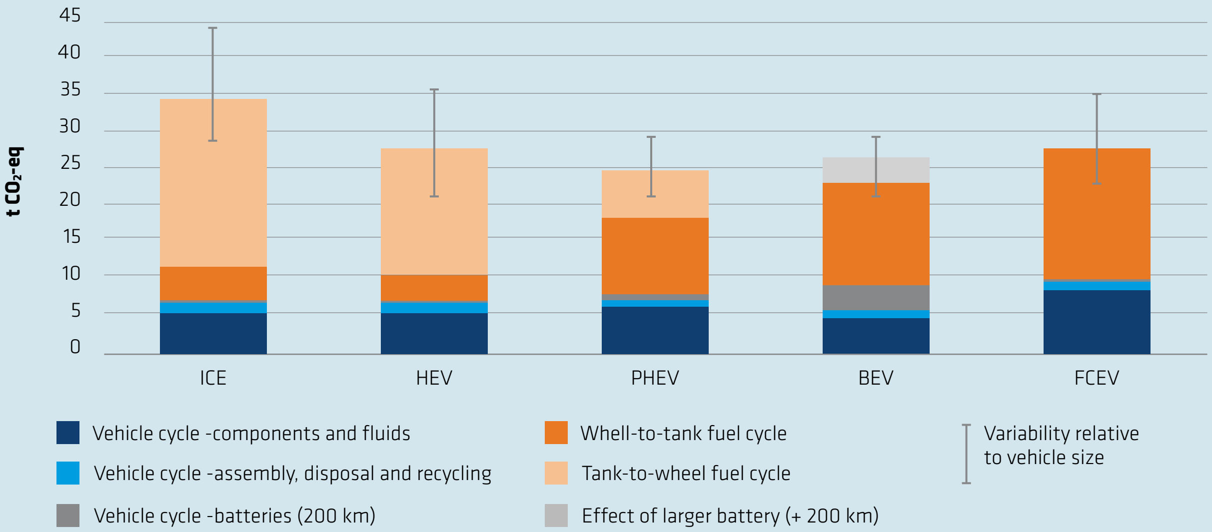
72 Lee, David S., Giovanni Pitari, Volker Grewe, Klaus M. Gierens, Joyce E. Penner, Andreas Petzold and Michael J. Prather et al. "Transport impacts on atmosphere and climate: Aviation." *Atmospheric Environment* 44. no 37, (2010): 4678-4734. https://doi.org/10.1016/j.atmosenv.2009.06.005

73 Rodrigue, Jean-Paul. *The Geography of Transport Systems.*

74 International Transport Forum and OECD. "ITF Transport Outlook 2017."

75 IEA. "Global EV Outlook 2019."

FIGURE 5. Comparative Life-cycle GHG Emissions of a Mid-size Global Average Car by Powertrain, 2018[76]



Source: IEA 2019.

Note: This figure portrays mid-size vehicles having similar performance with the exception of driving range. The BVE refers to a vehicle with 200 km range, the addition of the shaded area refers to at vehicle with 400 km range. The ranges suggested by the sensitivity bars represents the case of small cars (lower bound) and of large cars (uper bound) – for BVEs, the lower bound of the sensitivity bar represents a small car with 200 km range, and the upper bound represents a large car with 400 km range. The carbon intensity of the electricity mix is assumed equal to the global average (518 g CO_2/kWh). FCEVs are assumed to rely entirely on hydrogen produced from steam methane reforming. Other assumptions used to develop this figure are outlined in chapter 4 of the *Global EV Outlook 2019*.

TABLE 4. Transportation Stakeholders[78]

STAKEHOLDERS	DESCRIPTION
Consumers	Individual travellers or shipping recipients (for commercial goods), the end users for the transportation system.
Service providers	Owners of resources who sell transportation services.
Infrastructure providers	Anyone who plans and approves the deployment of infrastructure resources.
Manufacturers	Firms that design and produce transportation resources.
Regulatory authorities	Those who impose rules, laws and regulations to reach some safety and/or environmental objectives.
Society	The aggregated interests of citizens, from research agencies and communities, to the national/international level, including civil society groups.
Research agencies	Academia develops transportation technologies and new mobility and energy curricula.

Stakeholders and classification

Concerning the transport sector, the variety of stakeholders is characterised and summarised in (Table 4)[77] organized into the following categories: consumers, service providers, infrastructure providers, manufacturers, regulatory authorities, society, academia and research agencies. Public and private bodies may play different roles at the same time: for instance, some municipalities and car/truck drivers may be at the same time owners and operators. Public bodies such as national and international institutions and regulatory authorities play a key role in routing the sector towards increasingly higher environmental and safety targets. All these institutions are actors in political processes and can tackle problems with a top-down approach.

Nevertheless, by its nature, the transportation sector has an important bottom-up component governed by public behaviour and users' decision-making power as users. In this complex arena, academia can support public and private stakeholders with independent research.

Two approaches are pivotal for supporting decarbonization in the transportation sector, provided that the needed services are guaranteed and improved: i) introducing available state-of-the art technologies as opportunities to serve a range of transport modes; and ii) promoting the improvement of existing technologies (enhancing efficiency and performances). The latter represents the low-hanging fruit for improving the current situation, but does not necessarily comply with the objective of a net zero emissions scenario.

Assumptions

All efforts to achieve the complete decarbonization of the transport sector by 2050 rely on a number of assumptions. For instance, electrification appears as the most plausible way to sensibly reduce the greenhouse emissions and reach net zero emissions, but only when two crucial hypothesis are met. The two assumptions considered are: (i) a 100% renewable electricity mix at global level and (ii) no constraints in producing batteries for electric vehicles batteries (whatever technology is adopted). This second assumption may be faulty due to constraints on the capacity of manufacturing facilities and/or the scarcity of raw materials to produce batteries. This can be minimised for instance with the use of catenary lines or inductive charging.

Concerning the feasibility of 100% renewable electricity system scenarios, we refer to the chapter IV4a on power, and we devote the rest of this paragraph to batteries. The mining sector is extracting cobalt, nickel, and other materials employed in battery manufacturing and can represent a bottleneck in the diffusion of electric mobility as mentioned earlier.[79] However, battery chemistry is evolving fast and minerals can be recycled, or better still, repurposed (or given second life) in other applications. In addition, vehicle battery manufacturers are working to reduce the amount of raw materials employed in these applications and also developing new technologies, such as carbon-based battery-packs, which do not use scarce minerals. In general, the use of batteries can be

76 Ibid.

77 DeLaurentis, Daniel, Jung-ho Lewe and Daniel Schrage. "Abstraction and Modeling Hypothesis for Future Transportation Architectures." AIAA\ICAS International Air and Space Symposium and Exposition: The Next 100 Years, American Institute of Aeronautics and Astronautics, (2003). doi:10.2514/6.2003-2514

78 Ibid.

79 Söderman, Maria Ljunggren, Duncan Kushnir and Björn Sandén. "Will Metal Scarcity Limit the Use of Electric Vehicles?" In: *Systems Perspectives on Electromobility* edited by Sandén, Björn and Pontus Wallgren, 80-94. Gothenburg: Chalmers University of Technology, 2017. https://www.chalmers.se/en/areas-of-advance/energy/publications-media/systems-perspectives/Pages/Systems-Perspectives-on-Electromobility.aspx

minimised for instance by using overhead catenary lines (for heavy duty vehicles), ground rail power, or mobile inductive charging.

The IEA forecasts two different scenarios of electric vehicle penetration. According to the NPS diffusion of EVs will be about 127 million units in 2030. Instead, the EV30@30 scenario set the volume of electric vehicles at 228 million units.[80] According to Benchmark Mineral Intelligence, the global yearly production of Li-ion batteries will increase from 221 GWh in 2018 to 1100 GWh in 2028, setting a potential of between 70 and 210 million vehicles with a battery packs ranging between 35 kWh and 100 kWh. Beryll Strategy Advisors forecasts an electric vehicle demand that can range between 26 and 101 million vehicles in 2025, considering the battery pack size raging in between 20 kWh and 75 kWh. The maximum production capacity of EVs can potentially allow for the diffusion of (41 to 160) million vehicles.[81] According to Deloitte, EV demand may reach 150 million units, while the maximum production capacity is more than 1.5 times greater.[82] According to Bloomberg New Energy Finance, the demand for Li-ion batteries will go up to 2000 GWh by 2030, and there will be 500 million EVs on the road by 2040.[83]

The production of batteries should be governed by stringent rules and strict environmental standards, guaranteeing enhanced performances, the circular economy, and higher material efficiency.[84] It should be mentioned that there are alternatives to direct use of electricity in transport, such as Electric Road Systems (ERS), which are particularly relevant for freight road transport.

Finally, the validity of assumptions is heavily dependent on geography; indeed, the feasibility of a 100% renewable electricity needs to be properly assessed for developing areas where many people lack access to electricity, renewable or otherwise. On the other hand, direct electricity usage has the potential to fuel transport in a more independent way through isolated renewable production when compared to other energy vectors such as hydrogen. In rural areas, depending on the maturity of the transport infrastructure (such as roads), distributed electricity production based on renewable sources, in locations where already other anchor loads are already present (productive use for agriculture, rural industries, etc.), could contribute to reduce dependency on fossil fuel.

Further assumptions should be introduced and possibly tested via effective modelling tools, some of which you may find in the Appendix. Indeed, for even partial electrification of transport (excluding those sectors in which electrification is a hard task, such as long-haul navigation and aviation), the technical features of electricity grids must comply with specific attributes related to the dispatchment of reliable supply.

Policy assumptions are also relevant. If we compare this to the banning of chlorofluorocarbons (CFC) at the global level under the Montreal Protocol, we can imagine similar action in the transportation sector. For instance, in aviation

80 IEA. "Global EV Outlook 2018."

81 Berylls. "Battery Production Today and Tomorrow - Too Many Manufacturers, Too Few Customers." *Berylls.* Accessed August 21, 2019. https://www.berylls.com/wp-content/uploads/2018/03/20180323_Studie_E-Mobilitaet_EN.pdf

82 Deloitte. "New market. New entrants. New challenges. Battery Electric Vehicles." *Deloitte.* Accessed August 21,2019 https://www2.deloitte.com/content/dam/Deloitte/uk/Documents/manufacturing/deloitte-uk-battery-electric-vehicles.pdf

83 Bloomberg NEF. "Electric Vehicle Outlook 2019." *Bloomberg NEF.* Last modified 2019. Accessed August 23, 2019. https://about.bnef.com/electric-vehicle-outlook/

84 Drabnik, Eleanor and Vasileios Rizos. "Prospects for Electric Vehicle Batteries in a Circular Economy - CEPS Research Report." Published 2018. Accessed on August 21, 2019. http://aei.pitt.edu/94326/1/RR_2018_05_Circular_Impacts_batteries.pdf·

and navigation, the so-called command and control strategy, related to the regulation of fuels, can be tackled in the same way. Countries and regions leading in expanding electric mobility use a variety of measures, such as fuel economy standards and incentives for zero- and low-emissions vehicles.[85] [86]

Geographies

The global challenge of decarbonization can be examined geographically. The regions highlighted here are: Europe, North America, South America, Asia, Sub-Saharan Africa, Oceania and those countries that massively impact on global emissions such as India and China. Pathways to decarbonization should consider economic and cultural differences that are mirrored, on a large scale, by geography. Also, there are some common features, such as population density, road congestion, urban design, and climate conditions that highlight similarities across different geographical areas; for example, a big city of North America can be very similar to a metropolitan area in Europe. However, there are few *one size fits all* solutions; applying the same pathway to different contexts can lead to failure, which risks a return to business-as-usual practises.

Moreover, the actual picture of global CO_2 emissions from the transport sector suggests that the problem is confined to developed countries, but the risk of leaving emerging and developing economies out of the loop may lead to worse emission scenarios in the future.

It is worthwhile to mention that technologies are inextricably linked to geography. Technologies require resources and, in the majority of the cases, they have a specific geographical distribution. The risk of neglecting this point is that deep decarbonization strategies may exacerbate neo-colonisation, thus affecting development in the geographical regions where prices will be low. Nickel and lithium are also present in developed countries, but the price of extracting them will be higher than those extracted in less developed areas.[87]

Moreover, local policies represent relevant game changers, as proved by the following examples.

- In 2005, China decided to push electric transportation to improve local air quality. Pollution is a key driver to achieving zero CO_2 emissions, since air quality has strong effects on human health. The Chinese policy regulated to have two-stroke wheelers banned and thus the private sector adapted to the new policy. The role of authorities is also to issue new targets and give new inputs to the industrial sector. This can generate problems in converting the workforce, but it is up to governments to deploy a package of policies to ensure a fair and equitable transition, and possibly to turn the change into an opportunity. In this example, the policy shift occurred right after Europe decided to ban food imports from China. The Chinese government developed a new policy to help small farmers produce biofuels.[88]

85 Hall, Dale, Hongyang Cui and Nic Lutsey. "Electric vehicle capitals: Accelerating the global transition to electric drive". *The International Council on Clean Transportation.* https://theicct.org/publications/ev-capitals-of-the-world-2018

86 Rokadiya, Shikha, Anup Bandivadekar and Zifei Yang. "Regulatory pathways for zero-emission vehicle mandates." *The International Council on Clean Transportation.* Accessed August 21, 2019.

87 European Commission. "Report on Raw Materials for Battery Applications." *European Commission.* Published 2018. Accessed August 21, 2019. https://ec.europa.eu/transport/sites/transport/files/3rd-mobility-pack/swd20180245.pdf

88 Zhao, Jun. "Development of China's Biofuel Industry and Policy Making in Comparison with International Practices." *Science Bulletin* 60, no. 11 (2015): 1049-1054

- The State of California implemented a holistic approach to decarbonize transport. Their Zero Emission Vehicle reform is built on renewable energy credits, limitations on the carbon intensity levels of refineries (also called renewable portfolio standards), and efficiency mandates on transport. It is worth noting that a deeply integrated scheme is necessary to successfully achieve robust targets, and a supporting policy structure is required to guide the transition.

- According to ITF Transport outlook 2017,[89] the estimated subsidies needed in Europe to equalize the purchase price of a currently available electric car with an ICE vehicle is about 15,000 €. However, it is estimated that in the medium term (3-5 years) the purchase price will reach parity. From a total cost of ownership perspective, cost parity has already been reached. Indeed, scaling up green transport should be incentivised not only on the demand side, but also on the supply side.

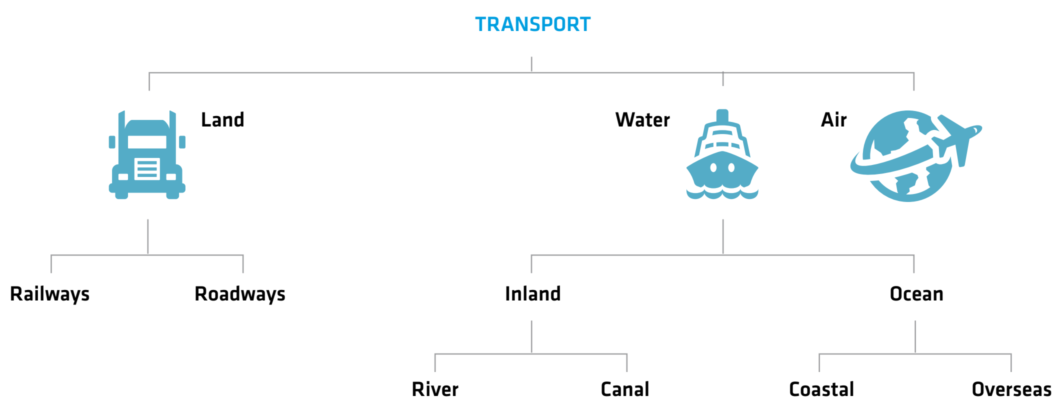
Risks

Each technology option suitable for reaching the 2050 target should be evaluated in its whole life-cycle. Further, the strategies that are selected should take into account the technical, socio-economic, and environmental implications including changes in sectors' structures and supply chains, as well as implications for the broader energy system.

The major risks can be:

i. Technological lock-in caused by both new technologies but also stranded assets
ii. Poor flexibility for certain technologies that are unable to easily adapt to changes
iii. High solution flexibility that can lead to business lock-in
iv. Unclear policy schemes for which industry cannot rely on
v. Short-term vision in policy definition or lack of transparency.

FIGURE 6. Modes of Transportation



89 International Transport Forum and OECD. "ITF Transport Outlook 2017."

viii. Key technologies

The transport sector can be analyzed according to the *ecosystem* where the "modes" are operated (land, water, air), the *service provided* (passengers and freight), and the *legal entity* of the actors managing the modes (public or private). Figure 6 groups key technologies according to the ecosystem.

Land transport

Light-Duty Vehicles (passenger cars and light commercial vehicles)

The strategy of decarbonising the light-duty vehicle segment is based on the short to medium term on a mix of solution that includes energy carriers like electricity , hydrogen, new fuels, and sharing mobility solution. The future energy mix in the light road transport sector might include hydrogen depending on infrastructure diffusion and the price of both vehicles and fuels. Hybrid vehicles are considered transitional technologies. It is important to note also that another important step towards decarbonization could be market-based, i.e. the replacement of current fleets with new models less emitting. What follows is a list of key technologies and new type less emitting fuels .

- (P)HEV* – (Plug-in) Hybrid Electric Vehicles are parallel hybrid configurations of electric and internal combustion engine (ICE) drives. The PHEV configuration gives the possibility to recharge the batteries by connecting it to the grid. (P)HEV are characterised by a small battery pack charged by the ICE and by the recovery of braking energy. The fully-electric drive is only used at low speeds and for short distances. Hybrid technology has better fuel economy than conventional ICE, with a similar range.

- REEV* - Range Extended Electric Vehicles are a hybrid configuration of an electric and a small ICE based generator, or range extender. This technology can have a smaller battery capacity than BEVs, reducing the material consumption. The vehicle still relies on carbon-based fuels to extend the range.

- BEV - Battery Electric Vehicle. This technology is based on a purely electric drive powertrain. It requires a large battery capacity based on current Li-ion technology, in the absence of capillary and quick charging infrastructure. The vehicle is characterised by a variable range, including long ranges with state-of-the-art batteries. Currently, batteries can be recharged only in stationary mode.

- FCEV - Fuel Cell Electric Vehicle. These vehicles are equipped with a fuel cell stack based on proton exchange membrane (PEM) technology and electricity storage based on Li-ion technology. It is capable of medium to high ranges but depends on the diffusion of hydrogen charging infrastructure.

- New fuels:
  HVO (hydrogenated vegetable oil) is a hydrotreated vegetable oil that can be obtained from various sources and waste, such as UCO (used cooking oil, animal fats, vegetable oils, but also from algal oil and ligno-cellulosic material

  Bio-methane: Biomethane is as a green non-fossil source of energy. Biomethane is produced from biogas derived from organic matter (often from sewage, landfill, food waste or distillery waste) which makes it a renewable source of energy.

E-fuels: E-Fuels can be produced starting carbon dioxide, water, and electricity with a process powered by renewable energy sources. Methanol or Fisher Tropsch products are typical examples of E-fuels produced starting from Carbon dioxide reduction

*(P)HEV and REEV are considered transitional technologies.

Heavy-Duty Vehicles

Heavy-Duty Vehicles are used mainly for freight transport but also on occasion for mass passenger transport.

- ICEV – PtL: These are ICE vehicles, but diesel is replaced by bio- or synthetic fuel generated from renewable energy resources (e.g. carbon neutral fuels, if CO_2 is captured from the air). The main issue is that it requires high amounts of renewable energy to produce such synthetic fuels, and advanced biofuels can only be produced in limited volumes.

- BEV – Battery electric vehicles are suitable for urban, as well as short- to medium-distance applications. However, several heavy-duty vehicle manufacturers are preparing to offer vehicles with long-distance ranges of up to 800 km[90] in the coming years. Different sources, including truck manufacturers, estimate that cost parity with diesel will be reached within the next decade.[91 92 93]

- (P)HEV – Parallel (plug-in) hybrid electric vehicles couple ICE and electric motors together. This reduces the battery size. Parallel configuration is best suited for heavy-duty vehicle applications.[94]

- FCEV – In fuel cell electric vehicles hydrogen storage is coupled with an electric battery pack in order to cover the vehicle's power peak energy demand and to optimise the operational efficiency. The vehicle is equipped with a fuel cell stack for on-board power generation. Electric batteries are also used to store braking energy. FCV powertrains benefit from technological advancement in both fuel cell and battery storage technologies. Compared with batteries, hydrogen at 70 MPa has a higher energy density compared to current battery density; it is about 2 to 4 times higher per unit of volume and about 150 to 220 times higher by unit of weight, albeit requiring around two times more energy to deliver the same transport work as batteries. Hydrogen-powered trucks can benefit from the higher energy density of hydrogen storage tanks as their costs are somewhat insensitive to weight and range. Hydrogen is stored on vehicles in dedicated tanks at pressures of 35 MPa to 70 MPa. As 70 MPa tanks allow higher ranges per unit volume, trucks need to rely on high-pressure tanks.

90 Earl, Thomas, Lucien Mathieu, Stef Cornelis, Samuel Kenny, Carlos Calvo Ambel and James Nix. "Analysis of Long Haul Battery Electric Trucks in EU - Marketplace and Technology, Economic, Environmental, and Policy Perspectives." *European Federation for Transport and Environment.* Published 2018. Accessed on August 21, 2019.

91 Scania. "The Pathways Study: Achieving Fossil-Free Commercial Transport by 2050." *Scania.* Accessed August 23, 2019. https://www.scania.com/group/en/wp-content/uploads/sites/2/2018/05/white-paper-the-pathways-study-achieving-fossil-free-commercial-transport-by-2050.pdf

92 Heid, Bernd, Russell Hensley, Stefan Knupfer and Andreas Tschiesner. "What's sparking electric-vehicle adoption in the truck industry?" *McKinsey.* Accessed August 23, 2019. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/whats-sparking-electric-vehicle-adoption-in-the-truck-industry

93 Ibid.

94 Delgado, Oscar, Felipe Rodríguez and Rachel Muncrief. "Fuel Efficiency Technology in European Heavy-Duty Vehicles: Baseline and Potential for the 2020–2030 Timeframe." *The International Council on Clean Transportation.* https://theicct.org/sites/default/files/publications/EU-HDV-Tech-Potential_ICCT-white-paper_14072017_vF.pdf

Despite this, hydrogen storage still needs four times more space to achieve the same values of conventional diesel technology.[95]

In the context of increasingly stringent automotive emissions regulations, the future expectations of the FCEV market are growing, but uptake is predicted to be significant only in the long term. This is due to significant constraints, such as cost reductions by original equipment manufacturers (OEMs), development of infrastructure, and the identification and standardization of the most efficient hydrogen production. To promote and accelerate the adoption of FCEVs, various policy options could be put into action, but this also depends on governments' industrys' willingness to invest in hydrogen technology.

Other potential solutions within the heavy-duty category are:

- ERS - Electric Road Systems. These systems rely on vehicles that can be supplied with electricity from power transfer infrastructure built along the road. The charging process is contextual to driving. Furthermore, the vehicles using ERS can be hybrid, battery-electric, or equipped with hydrogen fuel cells and have the ability to conduct normal driving operations, such as overtaking and driving autonomously off the electric roads. The main infrastructure concepts for ERS are:

  - Overhead catenary lines, also requiring the installation of an overhead retractable pantograph on trucks.
  - Inductive transfer of power requires the installation of coils just below the road surface that generate an electromagnetic field.[96] Inductive charging has a number of disadvantages including lower efficiency, higher material requirements per lane - km, more invasive changes to the existing infrastructure, and more complex components.[97]

Along with decarbonization technologies, an improvement in efficiency is required in order to further reduce the impact of the transport sector. Some of the most promising strategies are listed below.

- Platooning. This is the practice of driving heavy-duty trucks (primarily tractor-trailers or rigid trucks) in a single line with small gaps between them to reduce drag and thereby save fuel during highway operations. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies can enable trucks to drive in a very close proximity without compromising safety or maneuverability. The fuel savings from platooning are estimated to range from 5% to 15% for a three-truck platoon travelling at 80 km/h.[98] This reduction can be obtained regardless of which technology is used to power the trucks.

95 NGVA Europe, "Natural gas: a solution for a clean and decarbonized transport system."

96 Lucsko, David. "Machines of Youth: America's Car Obsession by Gary S. Cross." *Technology and Culture* 59. no 4, (2018): 983–85. doi:10.1353/tech.2018.0105

97 NGVA Europe. "Natural gas: a solution for a clean and decarbonized transport system."

98 IEA. "The Future of Trucks - Implications for Energy and the Environment" *IEA*. Accessed August 21, 2019. https://webstore.iea.org/the-future-of-trucks

- Road pricing schemes: This typically requires vehicles to pay for the use of the road infrastructure and the resulting environmental impacts (e.g. emission of air pollutants). It may also include charges to managing travel demand and reduce congestion, increase logistics efficiency, and increase road safety. Road pricing can also be useful in generating sources of revenue to fund the development of new green infrastructure.[99]

Railways

Trains are used for both passenger and freight transport. Globally, according to the IEA, electrification penetration in the railway segment in 2016 was 42%. In developed countries, legacy infrastructure in the transport sector is extensive and thus additional rails is challenging and may have a large environmental cost. However, in developing countries, the potential has not yet been fully exploited. There is room for increases in both freight and passenger transport. Possible strategies towards complete decarbonization are:

- Electrification of the rail networks that rely on diesel.
- Battery powered trains suitable for running on electrified and non-electrified rail tracks.
- Hydrogen-powered fuel cell electric trains on non-electrified rail tracks.

Additionally, energy saving solutions such as increasing the use of lighter materials, implementation of on-board energy recovery devices (e.g. regenerative braking or energy storage technologies), and the use of less energy intensive power electronics could help to improve the energy efficiency of the sector.

Maritime

By 2050, CO_2 emissions from shipping are projected to increase between 50% and 250% unless drastic action is taken.[100] Although no breakthrough technology is currently available, there are a number of solutions that are available (or nearly available) to reduce the environmental impact of and decarbonise the shipping sector.

Maritime transportation differs from land transport in both solutions and opportunities. Some solutions to improve the efficiency of this sector are:

- Technological: Light materials, slender design, less friction (using air lubrication, hull chemical coating, etc.), waste heat recovery, and wind assist (such as exploitation of renewables sources with on-board devices such as kites[101] or towing kites)[102] [103] could allow fuel reductions of up to 20%, with the possibility to retrofit entire fleets easily.[104]
- Operational: Lower speeds (slow steaming), ship size, ship-port interface.[105]

99 Ibid.

100 International Transport Forum. *"On Course Towards Carbon-neutral Shipping?."*

101 Airseas. "Airseas - To Power with Wind." *Airseas.* Accessed August 21, 2019. https://www.airseas.com/

102 Traut, Michael, Paul Gilbert, Conor Walsh, Alice Bows, Antonio Filippone, PeterStansby and RuthWood. "Propulsive Power Contribution of a Kite and a Flettner Rotor on Selected Shipping Routes." *Applied Energy* 113, (2014): 362–372. https://doi.org/10.1016/j.apenergy.2013.07.026

103 Fritz, Falko. "Application of an Automated Kite System for Ship Propulsion and Power Generation." In Airborne Wind Energy. Green Energy and Technology, edited by Uwe Ahrens , Moritz Diehl and Roland Schmehl. 359-372. Berlin, Heidelberg: Springer, 2013

104 The project SeaWing promoted by AirSeas and supported by the French Agency for Environment and Energy aims at bringing this technology to maturity

105 International Transport Forum. *"On Course Towards Carbon-neutral Shipping?."*

Decarbonization of shipping fuel is needed but there are also several alternatives, each with pros and cons:

- Battery-electric and fuel cell-powered ships for coastal, short range, and river travels.

- Renewable liquid hydrogen and ammonia for medium- to long-range distances. Ammonia production technology is easily scalable and requires less energy than renewable, synthetic production of methanol and ethanol.[106] Like hydrogen, it is carbon free if produced using renewable energy. Furthermore, it has a higher volumetric energy density than liquid hydrogen and a more practical storage temperature and pressure.
- Shift to synthetic fuels and advanced sustainable biofuels.[107] However, synthetic fuels require more primary energy to produce, and monitoring is difficult to enforce in this sector. Currently, sustainable advanced biofuels are scarce, and have competing uses within the bioeconomy, as mentioned above.

As a general consideration, the production of clean ammonia and clean hydrogen will require the installation of additional renewable power plants. Other infrastructure is also needed, starting with the expansion of the electrical grid, generation facilities, and distribution networks. Finally, ports will need to be equipped with new refuelling stations.

Finally, iIt is worth mentioning the case of inland waterways and short sea shipping. As many countries ban internal combustion engines on inland waterways, the recreational boating (in coastal, marine protected areas, lakes, rivers, and canals) is driving the largest and fastest transformation.Many different solutions are on-the-market or near-market. The trend for inland water vessels and other small pleasure and leisure boats is to move straight to pure electric versions due to the short ranges required, and the potential for opportunity charging. There is also a trend towards pure electric ferries, which have very well-defined routes and predictable operations making it easy to size the battery and plan when/where to charge (e.g. during loading and off loading). Norway and Denmark, for example, are already operating electric ferries. As a result, ferries have become a testbed for a variety of energy storage technologies, including supercapacitors and fuel cells, as well as batteries. In this kind of scenario, the use of the flow-batteries can be an interesting perspective.[108]

106 Laursen, Wendy. “With Ammonia, There’s No “Chicken or Egg” Dilemma.” *The Maritime Executive.* Last modified 2019. https://www.maritime-executive.com/article/with-ammonia-there-s-no-chicken-or-egg-dilemma

107 Abbasov, Faig, Thomas Earl, Carlos Calvo Ambel, Bill Hemmings and Lucy Gilliam. “Roadmap to Decarbonising European Shipping,” Transport & Environment. Last modified 2018. https://www.transportenvironment.org/sites/te/files/publications/2018_11_Roadmap_decarbonising_European_shipping.pdf

108 Valentine, Harry. “Competition Increases in Maritime Battery Technology.” *The Maritime Executive.* Last Modified 2019. https://www.maritime-executive.com/editorials/competition-increases-in-maritime-battery-technology

Air

The aviation sector is highly-regulated and technology diffusion depends largely on policies. Moreover, the number of influential stakeholders is limited, and they can cooperate with regulatory authorities in order to define milestones towards decarbonization. Transition in this mode of transport is based on new technologies and alternative jet fuels. There are some measures that can decrease the impact of the sector, even if progress is eaten away by increasing demand, ashas been observed the past decades:

- Efficiency solutions, such as decreasing the fuel consumption of aircrafts, electric device substitution for heavy hydraulic and improvement of planes' design.[109]
- Employment of new materials and processes for advanced composites and airframe metal alloys, unitized construction, and multifunctional and meta materials.
- Modal shift to existing technologies (shifting to other forms of transit): the recent revival of night trains and improving key connections using high speed rail (HSR) (300 km/h) can help reduce air travel demand.

Solutions for the sector are to shift to sustainable alternative fuels, while managing demand:

- Shifting to sustainable aviation fuel (SAF) includes sustainable advanced biofuels as well as alternative synthetic fuels. The main obstacles are the viability, availability (due to limitations in raw materials in the case of advanced biofuels), and the certification. Most of the new proposed solutions are drop-in fuels which can be directly blended with carbon-based vectors. Synthetic fuels require high amounts of renewable electricity. Additionally, the production and distribution of jet fuels is limited to specific sites in a way that almost eliminates supply chain issues.[110] Usually, these fuels have low energy densities and a freezing temperature that inhibit running on 100% state-of-the-art SAFs.

- Electric plane construction has been demonstrated but the technology has some limitations, such as the low load capacity and a short-range that mirrors battery issues.[111] Emissions from aviation are dominated by difficult-to-electrify long haul flights (flights under 600 nautical miles account for 50% of departures but only 15% of fuel use).[112] If these developments are transferred to the airline industry, electric or hybrid airplanes might become feasible sooner than expected. Hybrid electric air crafts are a more likely solution for commercial flights. However, it is important to bear in mind that the fleet renewal of the sector is extremely slow, 30 years on average.

- Shifting of medium-range and domestic travels to very high-speed ((500 to 1000) km/h) rail transport, such as Maglev and Hyperloop. These rail technologies can exploit electricity as the main vector and life-cycle assessments are under way to evaluate the impact of such ground-breaking infrastructures.

109 Chen, Jiawei, Chengjun Wang and Jie Chen. "Investigation on the Selection of Electric Power System Architecture for Future More Electric Aircraft."*IEEE Transactions on Transportation Electrification* 4. no 2 (2018). 563-576. https://ieeexplore.ieee.org/document/8254402

110 Air Transport Action Group and Climate Action Takes Flight. "Beginner's Guide to Sustainable Aviation Fuel." *Aviation Benefits Beyond Borders.* Last modified 2017. https://aviationbenefits.org/media/166152/beginners-guide-to-saf_web.pdf

111 Brelje, Benjamin J., Joaquim R.R.A. Martins. "Electric, hybrid, and turboelectric fixed-wing aircraft: a review of concepts, models, and design approaches." *Progress in Aerospace Sciences* 104, (2018): 1-19. https://doi.org/10.1016/j.paerosci.2018.06.004

112 Schäfer, Andreas W., Steven R. H. Barrett, Khan Doyme, Lynnette M. Dray, Albert R. Gnadt, Rod Self, Aidan O'Sullivan, et al."Technological, economic and environmental prospects of all-electric aircraft." *Nature Energy* 4, (2018): 160-166. https://www.nature.com/articles/s41560-018-0294-x

Demand Reduction and Modal Shift in the Transport Sector

Some solutions are exclusively technological, while others are operational improvements to reduce emissions. Some additional strategies that could contribute to reduce the climate impact of the sector (but not to achieve decarbonization) are:

- Mobility as a Service (MaaS) (). MaaS is a transport concept that integrates existing and new mobility services into one single digital platform, providing customised door-to-door transport, and offering personalized trip planning and payment options. Instead of owning individual modes of transportation, or to complement them, customers would purchase mobility service packages tailored to their individual needs, or simply pay per trip.

Many suggest that MaaS will improve the travelling experience, reduce travellers' costs and efficiently manage travel demand while also improving environmental and social outcomes. Such frequent claims rely on a scattering of limited yet insightful research findings.[113] [114]

A report by the Nordic Council of Ministers discusses different models of the potential CO_2 emission reduction from passenger transport based on the evolution of vehicle fleet, the CO_2 emissions from electricity and battery production, the passenger transport activity, the biofuel usage, the reduced car ownership and the better environmental performance of vehicles.[115] Considering different scenarios to 2050, it seems that CO_2 emissions are greatly reduced when the penetration of MaaS is higher.

A paper presented at the 5th International Conference on Information and Communication Technology for Sustainability describes the contribution from MaaS as it contributes to decarbonization in urban areas in the following ways.[116]

- Modal Shift. A modal shift occurs when one mode (e.g. road) has a comparative advantage in a similar market over another (e.g. rail). Comparative advantages can take various forms, such as costs, capacity, time, flexibility, reliability, consumption, emissions, and pollution. Depending on what is being transported, the importance of each of these factors varies. For some, time is of the essence and a modal shift will occur only if the new mode offers time reduction or new capacity is no longer available, while for others it is mostly a matter of cost. The outcome is a series of decisions made by firms (for freight) or individuals (for passengers) to shift to another mode if the comparative advantages are significant enough. The higher a comparative advantage is, the higher the incentive to switch from one mode to another.

113 MaaS4EU." *MaaS4EU.* Accessed August 22, 2019. http://www.maas4eu.eu/

114 Durand, Anne, Lucas Harms, Sascha Hoogendoorn-Lanser and Toon Zijlstra. "Mobility-as-a-Service and changes in travel preferences and travel behaviour: a literature review." *KiM Netherlands Institute for Transport Policy Analysis.* Accessed August 21, 2019. https://english.kimnet.nl/publications/documents-research-publications/2018/09/17/mobility-as-a-service-and-changes-in-travel-preferences-and-travel-behaviour-a-literature-review

115 Laine, Anna, Tommi Lampikoski, Tuukka Rautiainen, Marika Bröckl, Christian Bang, Nina Stokkendal Poulsen and Anders Kofoed-Wiuff. "Mobility as a Service and Greener Transportation Systems in a Nordic Context." *Nordic Council of Ministers.* Last modified 2018. http://norden.diva-portal.org/smash/get/diva2:1267951/FULLTEXT01.pdf

116 Kramers, Anna, Tina Ringenson, Liridona Sopjani and Peter Arnfalk. "AaaS and MaaS for Reduced Environmental and Climate Impact of Transport." *EPiC Series in Computing* 52, (2018): 137-152. https://easychair.org/publications/paper/Jcb7

- Shared mobility. Shared mobility is the notion of sharing (instead of owning) bikes, cars, or even on-demand rides and the use of technology to connect users and providers. The following models are identified: (1) peer to peer provision with a company as a broker, providing a platform where individuals can rent their cars when not in use; (2) short term rental of vehicles managed and owned by a provider; and (3) companies that own no cars themselves but sign up ordinary car owners as drivers. Shared mobility can trigger modal shifts, increasing the efficiency of public transport and reducing CO_2 emissions. Shared mobility and inter-modality are two faces of the same coin.[117] [118] Public authorities have a key role in decision making and implementing actions to plan a reliable, efficient, competitive, equalitable, and sustainable urban mobility system. Public authorities can take some of these actions alone, while others require a dialogue with the private sector. The actions are:

– Adopt a planning vision to be developed and executed
– Adjusting infrastructure and land-use planning to make space for new mobility services;
– Public transport management;
– Transport data acquisition and sharing;
– Public-private partnership.

- Ride-hailing. An emerging urban mobility service that private car owners drive their own vehicles to provide for-hire rides. The rate of adoption is significantly higher among young, highly educated adults who work full time, have higher incomes, reside in urban areas, are childless, have lower rates of car ownership, and already undertake multimodal trips. Alemi et al. (2017) found positive correlations between the adoption of ride hailing and the frequent use of smartphones for daily travel and social media, shopping online, and previous bike sharing and/or car sharing use.[119] Among ride-sourcing users, the most-cited reasons for using such services are convenience, reliability, short travel times, avoiding drunk driving, and not having to park.[120] However, it has been observed in many cities that ride-sourcing can increase congestion and move passengers away from public transport into more polluting modes such as cars.[121]

117 Nijland, Hans, Jordy van Meerkerk and Anco Hoen. "Impact of car sharing on mobility and CO_2 emissions." PBL Netherlands Environmental Assessment Agency. *Planbureau voor de Leefomgeving.* Last modified 2015.
https://www.pbl.nl/sites/default/files/cms/publicaties/PBL_2015_Note%20Impact%20of%20car%20sharing_1842.pdf

118 IPCC, 2014. "Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change" Edenhofer, Ottmar, Ramon Pichs-Madruga, Youba Sokona, Ellie Farahani, Susanne Kadner, Kristin Seyboth, A. Adler et al. (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

119 Alemi et al. "The Adoption of Shared Mobility in California and Its Relationship with Other Components of Travel Behavior" 2017.
https://ncst.ucdavis.edu/wp-content/uploads/2016/10/NCST-TO-033.1-Circella_Shared-Mobility_Final-Report_MAR-2018.pdf

120 IEA. "Global EV Outlook 2019."

121 Clewlow, Regina and Gouri Shankar Mishra. "Disruptive Transportation: The Adoption, Utilization, and Impacts of Ride-Hailing in the United States." *Institute of Transportation Studies - University of California, Davis.* Last modified 2017.
https://itspubs.ucdavis.edu/wp-content/themes/ucdavis/pubs/download_pdf.php?id=2752

ix. Case Studies

The following section outlines some of the most promising technologies in the decarbonization of transport. Some solutions may not be viable at large scale until the technology is more mature and it has been tested but there are a variety of solutions available.

Land transport

Light-Duty Vehicles

- Battery range improvement. One of the crucial features hindering the adoption of EVs is the relative range of batteries that can reach, for a 75 kWh pack, 500 km (Tesla Model 3). Innolith, a swiss-based start-up, is patenting a 1000 Wh/kg battery that leapfrogs the current 250 Wh/kg Panasonic battery used in Tesla models. The Innolith battery is based on "wet" liquid electrolyte technology for which the organic (and highly flammable) solvent containing the electrolytes has been replaced by an inorganic substance that is more stable and less flammable. The range expected to guarantee is around 1000 km.[122] This technology will also reduce costs by avoiding exotic and expensive materials. Other technologies are under development, such as solid-state storage with which a battery range can reach 800 km. Ultra-fast charging is also being deployed across Europe. For instance, the Ionity network allows to charges at a power of 350 kW, charging a battery in (10 to 15) minutes.

Heavy-Duty Vehicles

- Short and medium hauls can be electrified more easily taking into account that, distribution logistics requires lower battery ranges. In addition, short-haul logistics can more easily manage charging turn-overs, minimising the number of vehicles providing the same level of service. In certain geographies, such as Europe, the electrification potential is partly given by those transport activities that are characterized by short distance classes. In detail, the distance classes that cover the range of (0 to 150) km and (150 to 299) km account for respectively 22% and 20% of the total tonnes-km in 2017.[123] In this regard, DHL is at the forefront in terms of substituting part of its fleet with electric vehicles.[124] In Germany, Deutsche Post DHL Group decided to rely on StreetScooter, which retrofits existing vehicles with electric powertrains. Deutsche Post DHL has three different delivery van models with battery sizes ranging between (20 to 40) kWh and 76 kWh that cover (100 to 200) km and over 200 km, respectively.

- Long-haul transportation requires longer ranges than current batteries can provide, as well as more energy-dense electricity storage on board to reduce the pay-load. In order to boost the electrification of long-haul freight transport, mega-chargers will be needed. Tesla prospects a 30-minute charge able to cover a 600 km range. Nikola Motor is bringing FCEV semi-trucks to market with more than 13,000 trucks on pre-order. There are currently three models available with the last one to be launched for the European market in 2023. The range of those trucks is about (800 to 1200) km versus a standard ICE-truck range of (800 to 1600) km,[125] in

122 Innolith. "Innolith Energy Technology Brings 1000km EV Within Range." *Innolith*. Last modified 2019. https://innolith.com/innolith-energy-technology-brings-1000km-ev-within-range/

123 Eurostat. "Road Freight Transport by Journey Characteristics." Statistics Explained, 2016, http://ec.europa.eu/eurostat/statistics-explained/index.php/Road_freight_transport_by_journey_characteristics

124 DHL."DHL Freight Tests Electric Trucks to Lower its Overland Transport Emissions." Last modified 2017. https://www.logistics.dhl/global-en/home/press/press-archive/2017/dhl-freight-tests-electric-trucks-to-lower-its-overland-transport-emissions.html

125 Nikola Motor. "Nikola Motor." Last modified 2019. https://nikolamotor.com/

geographies where weight and dimension regulations allow them. The technology is mature but the cost is estimated to be double with respect to common diesel vehicles. The sustainability constraint rests on the supply of clean hydrogen. According to Eurostat data, 39% of the tonnes-km recorded in 2017 covers trips with ranges are between 300 km and 999 km, whereas 18% represents the tonnes-km employed to cover hauls of more than 1000 km.[126] On the other hand, you have electric long-haul trucks like the Tesla Semi, with an announced range of 800km, and pre-orders in the range of a few hundred, including giants like UPS reserving 125 units. Scania, a truck manufacturer, expects electric long-haul trucks to be cost competitive with diesel by 2027, and FCEV to be cost competitive by 2047.[127]

- Electric Road Systems (ERS) are mainly catenary-based or inductive rail-based. Siemens has investigated over-head catenary infrastructure (eHighway) and four pilot projects have been launched in Germany, Sweden, the US, and Italy.[128] The benefit of such technology is given by the possibility to reduce the battery size and decoupe the battery range extension challenge. For full decarbonization, ERS technologies can be combined with smaller vehicle batteries, green hydrogen FCEV, or an ICE using advanced biofuels or synthetic fuels.[129] The cost is estimated around 1.5 M€/km for electrification in both directions.[130] The technology based on inductive rails has been tested by a consortium based in Sweden. The project is called eRoadArlanda.[131] Specific trucks are required to get the power supply while moving. The costs are approximately the same as eHighway technology.

Guided Transport Systems

- Hyperloop is an ultra-high-speed ground transportation system technology that has the potential to to shift trips from aviation to surface transport. The train speed can go beyond 1000 km/h. A commercial prototype of Hyperloop does not exist, but numerous companies are working on very ambitious pilot projects, such as Virgin Hyperloop One, Hyperloop Transportation Technologies, TransPod, DGWHyperloop, Hardt Global Mobility, and The Boring Company. The main concept is that a pod is enclosed in a cylindrical vacuum rail and there is a huge compressor able to remove the air and reduce the friction between the train and the tube. The TransPod technology slightly differs from the conventional hyperloop. It moves electromagnetic fields to propel vehicles with stable levitation off the bottom surface, rather than using compressed air. The high cost of hyperloop infrastructure is indeed a barrier, despite feasibility studies under way localised in India, the Middle East, the US and Europe.

126 Innolith. "Innolith Energy Technology Brings 1000km EV Within Range."

127 McKinsey & Company. "Electric Vehicles in Europe: Gearing up for a New Phase." *McKinsey.* Last modified 2019. https://www.mckinsey.com/featured-insights/europe/electric-vehicles-in-europe-gearing-up-for-a-new-phase

128 Bosi, Marco."eHighway @ BreBeMi." *Siemens Mobility.* Published 2018. http://www.brebemi.it/site/wp-content/uploads/2018/09/Marco-Bosi.pdf

129 Hacker, Florian. "Transitioning to zero-emission heavy-duty freight vehicles." *Öko-Institut e.V.* Published 2018. Accessed August 23, 2019. https://theicct.org/sites/default/files/Oeko-Institut_ZEHDV_Brussels.pdf

130 Ibid.

131 eRoadArlanda. "Electrified Roads - A Sustainable Transport Solution of the Future." *eRoadArlanda.* Last modified 2017. https://eroadarlanda.com/

Maritime

- In 2018, MAN Energy Solutions invested 5 M€ in developing an ammonia-fuel engine. The engine could be operational by early 2022. Called the MAN B&W ME-LGIP dual-fuel unit, is uses dual-fuel in order to give more flexibility to ship owners who are concerned about ports' provision of ammonia fuel. Ammonia fuel will be used in combination with liquefied petroleum gas (LPG).[132]

- European Maritime Safety Agency (EMSA) has reported on nine projects that are working on commercial hydrogen FCEV ships.[133] Projects range from small passenger ships operating in Amsterdam, Bristol, Hamburg, and Bergen to ferry operations with refueling capabilities in San Francisco bay. Projects evolved from technical feasibility studies (as in San Francisco) to full operational (for example Hamburg). The above examples all employ PEM fuel cells with hydrogen as the primary fuel source, with power ranging from 12 kW to 120 kW per module (in the latter case, up to 2.5 MW total power).

- The first autonomous electric freighter was commissioned by the Norwegian fertilizer manufacturer Yara International. The projects will cost 27 M€, of which 14 M€ has been funded by the Norwegian Government. The ship will be equipped with a 7.5 to 9 MWh-battery pack. The purpose of the mentioned technology is to shift travel away from short- and medium- range diesel trucks travels. The ship will be fully operational in 2022.[134] Denmark has started operating a fully electric ferry with a range of 22 nautical miles (41 km) between charges.[135]

- Integration of renewable energy sources. Kite-like devices may be used for power generation on land,[136] while towing kites for ship propulsion has been suggested since the 1980s.[137] [138] Compared to other wind power technologies, kites have some advantages: they may operate at higher altitudes where wind speeds are often greater, and they fly in front of the ship and therefore do not take up any deck space.

132 Laursen, Sejer R. "Ship Operation Using LPG and Ammonia As Fuel on MAN B&W Dual Fuel ME-LGIP Engines." *MAN Energy Solutions.* Published 2018. Accessed August 23, 2019. https://nh3fuelassociation.org/wp-content/uploads/2018/12/0900-Ammonia_vision-Rene-Sejer-Laursen-MAN.pdf

133 Tronstad, Tomas, Hanne Høgmoen Åstrand and Gerd Petra Haugom, Lars Langfeldt. "Study on the Use of Fuel Cells in Shipping." *EMSA European Maritime Safety Agency*. Accessed August 23, 2019. www.emsa.europa.eu/news-a-press-centre/external-news/download/4545/2921/23.html (see table A.1)

134 The Beam. "The World's First Electric Autonomous Container Ship To Set Sail In Norway." *CleanTechnica* (blog). August 23, 2018. Accessed August 22, 2019. https://cleantechnica.com/2018/08/23/the-worlds-first-electric-autonomous-container-ship-to-set-sail-in-norway/.

135 E-Ferry, Ærø Kommune and Ærøfærgerne. "Baptism of the e-ferry Ellen." *E-Ferry.* Last modified 2019. Accessed August 23, 2019. http://e-ferryproject.eu/Portals/0/News/Press_release_ENG_Baptism_Ellen.pdf

136 Airseas. "Airseas - To Power with Wind."

137 Traut, Michael et al. "Propulsive Power Contribution of a Kite and a Flettner Rotor on Selected Shipping Routes."

138Fritz, Falko. "Application of an Automated Kite System for Ship Propulsion and Power Generation.

Air

- Solar Impulse was the first solar plane to circumnavigate the globe. The aircraft weight was 1600 kg and it was equipped with four electric engines of 7.4 kW power each. The plane wings were covered with solar panels and the engines were coupled with battery storage. It was the first step towards further improvements in the solar aviation sector. There are several small pilot projects all over the globe, but the potential is limited to passenger travel. The commercial potential is in the reduction of operating costs. Fast advancements would be visible with a boost in solid-state battery technology. The optimal range for this technology is 1000 km and the direct competitors of solar aircrafts are high-speed trains.

- In 2017, ASTM International (a regulatory authority) certified alternative fuels from five conversion processes under the standard ASTM D7566: synthesized paraffinic kerosene (SPK) from the Fischer-Tropsch process (FT-SPK); SPK from hydro-processed esters and fatty acids process (HEFA-SPK) synthetic iso-paraffins (SIP) from hydro-processed fermented sugars (HFS-SIP); SPK from the alcohol-to-jet process (ATJ-SPK), and FT-SPK with increased aromatic content, the so-called synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources (FT-SPK/A). Four types of feedstocks can be used on these conversion processes: oil, sugar, starch, and lignocellulose. Each SAF has a maximum blending ratio that varies between 10% (HFS-SIP) and 50%.[139] Under an economic lens, HEFA-based fuels range between 0.7 $/L to 1.25 $/L, FT process-based range from : 0.9 $/L to 1.96 $/L, and ATJ costs from 1.56 $/L to 2.76 $/L. A conventional jet fuel costs around 0.59 $/L (at USD 76.8/bbl). However, strong sustainability requirements should be enforced to avoid biokerosene having an overall impact on the climate is worse than the fossil alternative.

- Airbus has a business line to develop hybrid electric aircraft for commercial service in the not-so-distant future and the Norway airport authority aims for all short-haul flights to be 100% electric by 2040.[140]

139 ICAO, UNDP and GEF. "Sustainable Aviation Fuels Guide." *ICAO.* Last modified 2017. https://www.icao.int/environmental-protection/knowledge-sharing/Docs/Sustainable%20Aviation%20Fuels%20Guide_vf.pdf

140 The Guardian. "Norway aims for all short-haul flights to be 100% electric by 2040." *The Guardian.* Last modified 2018. https://www.theguardian.com/world/2018/jan/18/norway-aims-for-all-short-haul-flights-to-be-100-electric-by-2040

d. Buildings

Lead by: Emanuela Colombo, Niccolò Aste, Claudio Del Pero, Fabrizio Leonforte, Alessandro Miglioli, Politecnico di Milano and Victoria Burrows, World Green Building Council

x. Enabling Conditions: Stakeholders, Assumptions, Key Geographies, and Scaling

Current status and goals

Buildings represent an estimated 36% of global final energy consumption and 39% (28% operations, 11% materials and construction) of global energy-related carbon dioxide emissions.[141] The total building stock is expected to nearly double at a rate of 5.5 billion square meters per year from today's 223 billion square meters to almost 415 billion square meters in 2050.[142]

The current building stock, as well as new building constructions, are asymmetrically distributed among countries. As reported in Figure 8, China still has a larger building sector (in terms of floor area) than North America and Europe and is going to further expand it in the next decades by adding more than 40 billion m^2 to its total stock., second only to Africa. The African continent and India, still have less buildings than North America or Europe, but the total number of floor area additions in the two regions (50 billion m^2 and 30 billion m^2, respectively), is expected to exceed developed countries by 2050 (Figure 8). Further, it is predicted that the African population will double by 2050, reaching 2.5 billion inhabitants.[144] Thus, 700'000 new homes, 310'000 new schools, 85'000 new clinics, as well as additional facilities and infrastructures, are expected to be built within the next 30 years.[145] Negative impacts on social, economic and environmental well-being can be the result of an unsustainable growth of the building sector.

141 GLOBAC, United Nations Environment and International Energy Agency. "Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector." *GLOBAC*. Published 2018. https://globalabc.org/uploads/media/default/0001/01/f64f6de67d55037cd9984cc29308f3609829797a.pdf

142 GLOBAC. "Towards zero-emission efficient and resilient buildings - Global Status Report 2016." *GLOBAC*. https://www.globalabc.org/bundles/app/pdf/GABC%20Global%20Status%20Report%20V09%20november.pdf

143 IEA. "Transition to Sustainable Buildings: Strategies and Opportunities to 2050." *IEA*, Paris, 2013. https://doi.org/10.1787/9789264202955-en

144 United Nations. "Population." *United Nations*. Accessed August 22, 2019. https://www.un.org/en/sections/issues-depth/population/

145 Benimana, Christian. "La Nuova Generazione di Architetti e Designers Africani." (talk, Rwanda, TEDGlobal) https://www.ted.com/talks/christian_benimana_the_next_generation_of_african_architects_and_designers/transcript?language=it#t-173330

146 GLOBAC, United Nations Environment and International Energy Agency. "Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector."

FIGURE 7. Evolution of Building Stock Between 2010 and 2050[143]

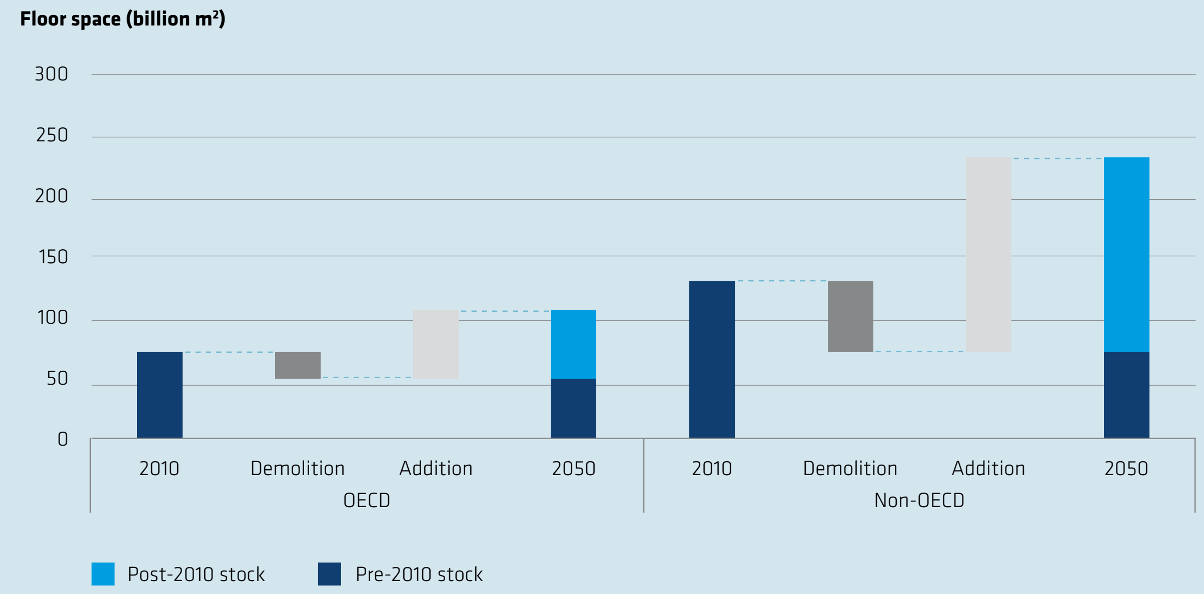
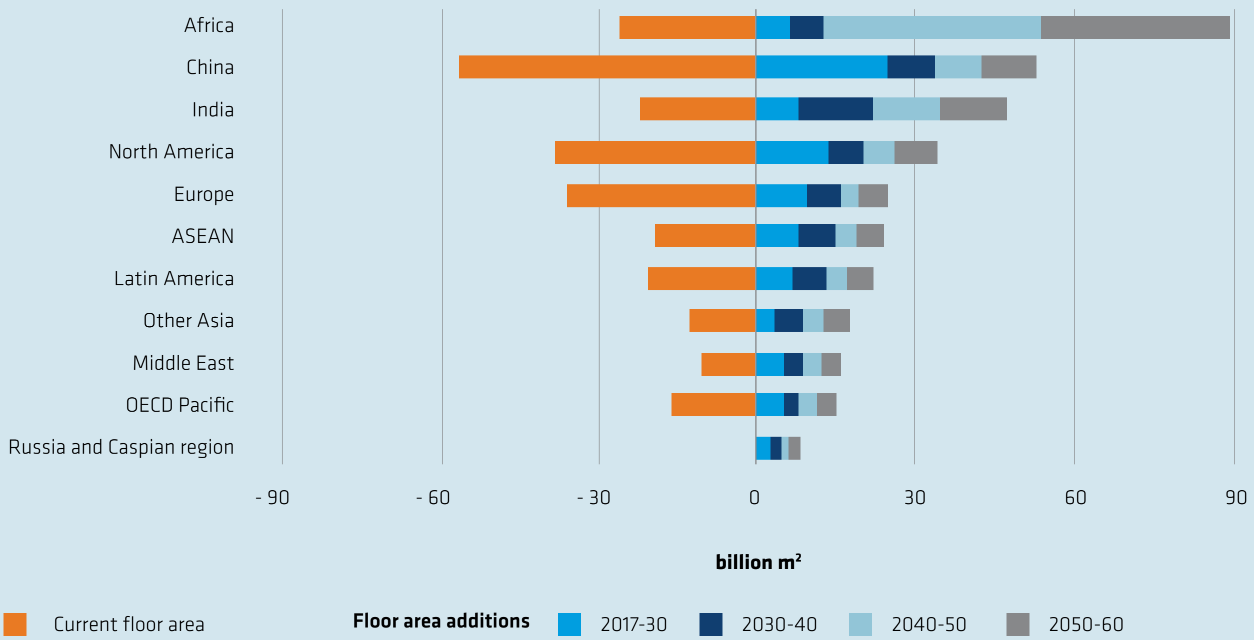


FIGURE 8. Floor Area Additions to 2060 by Key Regions[146]



Growing population and income levels in emerging economies and developing countries represent the main driver for building stock increases, implicating an estimated increase of energy demand in building equal to 50% by 2050 if no action is taken.[147] Even with energy efficiency measures taken, the trend of a rising building energy demand is predicted to continue, especially in OECD countries.

Between 2010-2017, the increase in energy demand (+5%) was lower than the increase in floor area (+17%). Electricity (+15%) and renewable energy sources (+14%) contributed more to the substitution in final energy use of lessÐ efficient coal-based technologies (-8%), than natural gas (+5%) or oil and biomass fuels, which remained almost stable. Natural gas and electricity constitute the main energy source in OECD countries. Non-OECD countries still mainly rely on biomass and coal, while slowly shifting to electricity and gas.

In the current scenario, energy demand and CO_2 emissions are expected to increase by at least 40% by 2050. The non-residential market's ("services sub-sector") energy demand, which is influenced by levels of economic activity, growth in floor area, population profile, building types, age of buildings and climatic conditions, is expected to increase by 1.5% per year, while the residential sub-sector's increase of 0.8% per year is related to change in population, building age and profile, energy prices and consumer behaviours change in.[148]

The goal of total decarbonization of the building sector encompasses the construction of new buildings with zero or almost zero energy consumption from fossil fuels, i.e. zero carbon buildings, and the total renovation of existing building with the same net zero carbon standards.

Current renovation rates account for about 1% of existing building stock each year,[149] while to achieve the 100% zero carbon goal by 2050, it is necessary to ensure a renovation rate higher than 3%.[150] It should be noted that the CO_2 emissions do not only derive from the operation phase.The emissions from material use in buildings, for example, represent almost one third of building-related emissions (e.g. concrete and steel manufacturing requires high amounts of process energy). As buildings become more efficient and the grid decarbonizes, the proportion of embodied carbon (carbon associated with the extraction, transport and manufacturing of materials) increases significantly. By 2050, accounting for all new constructions between 2020-2050, embodied carbon emissions and operational carbon emissions will be roughly equivalent. In this context, the construction industry must radically change its manufacturing processes to abate the increasing embodied energy.

147 Global Alliance for Buildings and Construction. "Towards zero-emission efficient and resilient buildings: Global Status Report 2016."

148 IEA. "Transition to Sustainable Buildings: Strategies and Opportunities to 2050."

149 Global Alliance for Buildings and Construction. "Towards zero-emission efficient and resilient buildings: Global Status Report 2016."

150 Laski, Jonathan and Victoria Burrows. "From Thousands to Billions - Coordinated Action Towards 100% Net Zero Carbon Buildings by 2050." *World Green Building Council.* Accessed August 23, 2019. https://www.worldgbc.org/sites/default/files/From%20Thousands%20To%20Billions%20WorldGBC%20report_FINAL%20issue%20310517.compressed.pdf

151 IRENA. "Global Energy Transformation. A roadmap to 2050." *IRENA.* Published 2019. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Apr/IRENA_Global_Energy_Transformation_2019.pdf

152 Architecture 2030. "New Buildings: Embodied Carbon." Architecture 2030. 2030 https://architecture2030.org/new-buildings-embodied/

153 IEA. "The Future of Cooling. Opportunities for Energy-Efficient Air Cooling." *IEA.* Last modified 2019. Accessed August 23, 2019. https://www.iea.org/futureofcooling/

FIGURE 9. Buildings Energy Consumption (left)[151] and Total Carbon Emissions of Buildings in 2050, accounting all new constructions from 2020 to 2050 (right)[152]

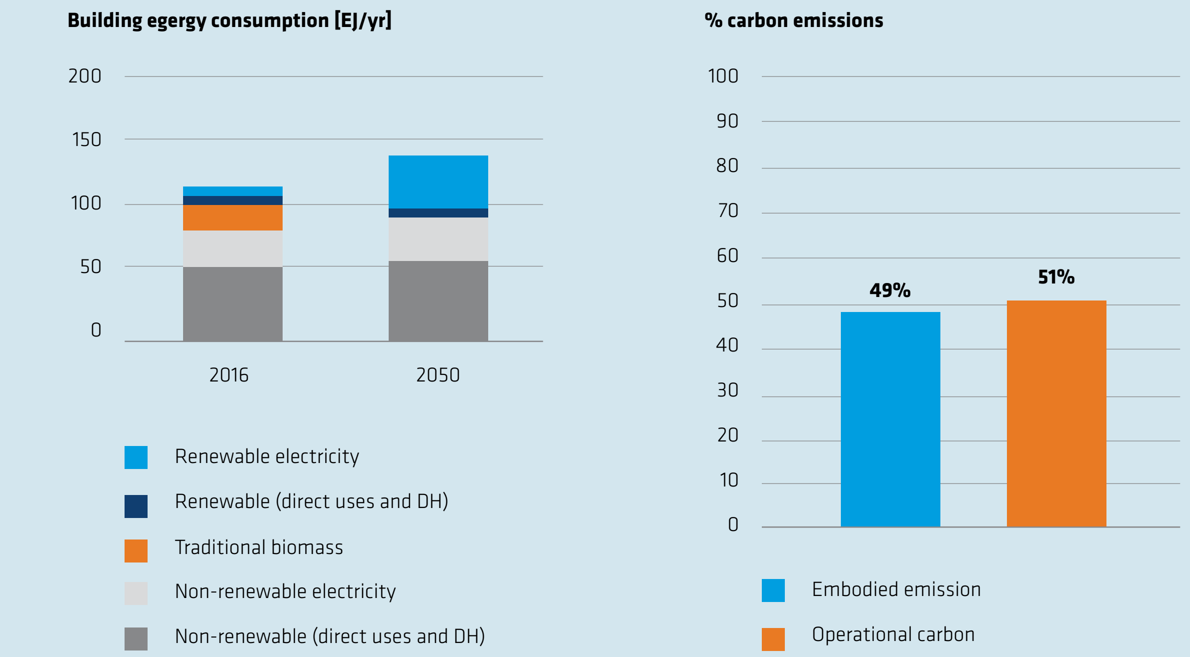
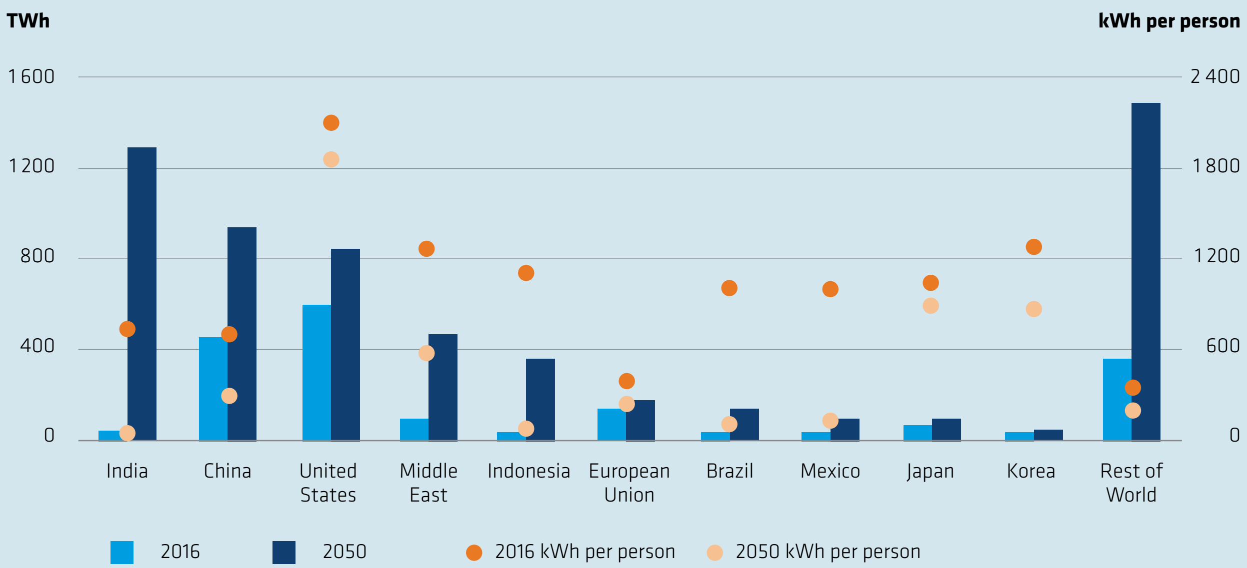


FIGURE 10. World Air Conditioning Energy Consumption Growth[153]



In such a scenario, the role of settlement design is particularly multifaceted and challenging when minimising energy consumption for cooling. This is a very critical issue and needs to be highlighted, as energy consumption for cooling has been growing steeply, and – according to the IEA – will continue to rise in the face of climate change and growing per-capita income.

Pathways and priorities

In order to achieve complete decarbonization within the buildings sector, it is necessary to transform buildings from inefficient energy consumers into net zero carbon buildings. These highly energy-efficient buildings will receive all remaining operational energy use from renewable energy, by means of on-site and off-site production. This new paradigm must be applied not only to new buildings, but also to existing buildings, which must be subjected to deep-renovation. This will bring about multiple co-benefits to society, including lower energy costs, more comfortable and healthy internal conditions, energy security, and resilience against climate change impacts.

Therefore, in order to achieve total decarbonization, the electrification of the building sector, supplied by renewable energy sources, is necessary. IRENA projects that 68% of the buildings' expected energy demand in 2050 will be covered by electricity.[154] Almost the total amount of such electricity must be provided by on-site or nearby renewables, which must be integrated in the building/district design. In parallel, precise rules and guidelines on the impact of embodied energy from different technologies and materials must be disseminated to support designers, builders, and decision makers.

Furthermore, different approaches must be set for different countries. Electrification of buildings implies the availability of reliable grids. Establishing a robust framework in middle- and low-income countries is fundamental to fulfil the objective. Using a combination of readily available technologies and approaches, and performance-based design metrics for net zero carbon buildings, can be achieved today. The best-practice approach, using energy as efficiently as possible and meeting the energy needs by renewable energy supplies, can be adopted and applied as a philosophy to net zero carbon in new and existing buildings across countries with diverse applications. This will result in different combinations of solutions that are appropriate for a specific context, whilst enabling buildings that are fit for purpose, future-proofed and resilient to climate change effects.

Moreover, in order to achieve the overall decarbonization of the building sector, the energy consumption due to fuel use for cooking must be reduced. In such regard, traditional uses of bioenergy would be phased out, replaced with energy technologies such as modern cookstoves, electric cooking, and LPG. This will also help to significantly reduce the 3.3 million premature deaths annually due to indoor air pollution.[155] Energy efficiency improvements, such as induction cooking technology, also help to diminish growing electricity demand for electric cooking, which by 2050 should be 3 times more than today. At present, around 1 billion households use oil or natural gas for cooking. The efficiency of smooth-top electric hot plates approaches 75% while induction plates are the highest energy performing products (around 90%), as changing magnetic fields generate heat through the cookware directly.

154 IRENA. "Global Energy Transformation. A roadmap to 2050."

155 IEA. "Perspectives for the Clean Energy Transition - The Critical Role of Buildings." *IEA*. Last modified 2019. https://www.iea.org/publications/reports/PerspectivesfortheCleanEnergyTransition/

Of course, achieving decarbonization by 2050 will require a substantial and rapid shift towards investment in clean energy technologies. In 2017, the share of overall clean energy investment, covering both low-carbon energy supply and energy efficiency, was only 32%, relative to 51% for fossil fuel investment. The share of clean energy in the global energy investment would need to increase substantially to achieve 70% by the mid-2030s. By contrast, the share of fossil fuel investment is expected to fall to just over 10% by 2050. The share of high-efficiency district energy networks in total investment remains relatively stable at around 15% in 2050 (compared to 17% in 2015).[156]

A suggested pathway to address decarbonization is the following:

- Set appropriate targets on carbon emissions and energy performances of buildings, for different time milestones from 2020 to 2050, with advanced trajectories for new and existing buildings;
- Increase R&D activities related to innovative low-emission, durable, repairable, recyclable materials and construction techniques;
- Reduce energy demand and material use, maximise refurbishment of existing buildings, establish performance based metrics and requirements for monitoring and disclosure;
- Define a set of best available technical solutions and their application methodologies to reach the target at country level, differentiating approaches for existing and new buildings and for different regional conditions;
- Implement policies, fiscal/energy incentives and mechanisms, enforce requirements through authorities.

The key issues to which the policies/actions must aim in order to reach the objectives established are the following:[157]

- *Ensuring energy efficient buildings*
  a) Ramp up deep renovation of the existing building stock; fostering renovation activities requires a balance between creating tools that stimulate the financial market for energy renovations, and defining mandatory requirements for better energy performance.
  b) Boost the market uptake of nearly zero-carbon (ready) buildings; encourage buildings to have the lowest possible carbon emission with any remaining compensated with on-site/nearby renewables, and optimised for a future decarbonized energy grid.
  c) Upskill the construction sector; training and qualification for the property developers, designers, and workforce are needed to build competence and awareness of innovative solutions and integrated design.
  d) Phase out inefficient technologies; inefficient solutions (e.g. gas/oil boilers, window air conditioners, etc.) must be quickly substituted, guiding building owners/designers towards more efficient and renewable choices.
  e) Sanctions for transgressors; economic sanctions must be inflicted to those who do not respect regulations and accomplishments.

156 Ibid.

157 Bean, Frances, Maarten De Groote and Jonathan Volt. "Opening the door to smart buildings - Driving the Transition with EU Directives." *BPIE* (2017). http://bpie.eu/publication/opening-the-door-to-smart-buildings/

- *Increase dynamic operability*
  f) Empower all consumers with smart meters; all consumers must be able to have a smart meter, dynamic pricing contracts for their energy supply, as well as access to the grid.
  g) Optimise buildings with automation and controls; the performance of a building and its technical systems should be controlled and monitored in a way that is easy-to-use, informative and empowers the owner or occupants.
  h) Increase load matching; load profiles of buildings must match as much as possible with the generation profile of renewables (especially solar energy), by means of demand side management and energy storage.

- *Establishing energy-system responsiveness*
  i) Allow and encourage occupants to generate and self-consume renewable energy; consumers should be able to generate, consume and store (electrical or thermal) their own energy, minimizing the amount exchanged between the grid and heat networks;
  j) Make dynamic pricing contracts available for all consumers; all consumers should be able to have dynamic pricing contracts for their energy supply and network tariffs.
  k) Enable aggregation services; aggregators should be able, on behalf of consumers, to combine the flexibility from multiple buildings for sale, purchase or auction in energy and (where relevant) capacity markets.
  l) Enable synergies between smart buildings and electric vehicles; smart charging avoids costly spikes in power demand and electric vehicles can act as storages to deliver valuable services to the electricity system.

The strategy must be structured according to the following aspects:
- Different building stock: New buildings / existing buildings;
- Different stakeholders: Policy makers, investors, utilities, building owners;
- Different time scale: 2020, 2030, 2040, 2050;
- Opportunities to achieve solutions at scale, not relying solely on a building-by-building approach.

The precise strategy to adopt must always be tailored according to the different boundary conditions. There is no common solution that can be effectively applied to every context (different climates, regional peculiarities, different user's awareness and behaviour, different financial and economic scenarios, etc.).

The fundamental assumptions that are necessary to reach the before-mentioned objectives are the following:
- 80-100% renewable energy sector in 2050;
- Decarbonization of construction materials industry;
- Worldwide diffusion of clean-cooking technologies.

The key policy actions and strategies to enable a faster energy transition in buildings are summarized in Table 5..

TABLE 5. Building Sector Actions

ACTION AREA	NEAR-TERM ACTIONS TO 2025	LONG-TERM AMBITIONS TO 2050
Whole buildings	Implement and enforce mandatory building energy codes, striving for near-zero energy and net-zero emissions in new constructions in the coming decade. Work with stakeholders to set clear energy performance targets for existing buildings.	Establish advanced building energy codes with mandatory performance standards (e.g. near-zero energy or better). Set minimum energy performance levels for existing buildings and work with industry to increase availability of energy-efficient and low-carbon measures at affordable prices.
Building envelopes	Require high energy performance envelope components and measures, including air sealing, insulation, insulating and low emissivity windows and cool roofs. Provide incentives for deep energy renovation of existing building shells.	Achieve high efficiency building envelopes at negative life-cycle cost and mandate energy performance standards for envelope components. Work with industry to deliver non-invasive and whole-building retrofit packages.
Space heating	Provide incentives for solar thermal and heat pump technologies. Improve heat distribution and controls. Mandate minimally condensing boiler technology for fossil fuel equipment. Set targets for MEPS (Minimum energy performance standards) above 100%. Support development of integrated, high efficiency district systems.	Mandate MEPS above 150% for stand-alone heating equipment in new construction. The use of electric resistance heaters as main heat source must be allowed just when other more efficient alternatives are not feasible. Prevent expansion of fossil fuel heating and pursue strategy to shift demand to high efficiency and integrated energy solutions with net zero emissions.
Space cooling	Set MEPS of 350% efficiency or higher. Improve thermal distribution and controls. Work with air conditioning manufacturers to identify R&D needs to deliver higher efficiencies. Promote the use of waste heat from cooling for heating and hot water demand.	Pursue low-cost solar cooling technologies and set MEPS above 400%. Pursue high efficiency and renewable district cooling where appropriate. Mandate use of waste heat from large-scale cooling for heating and hot water use on-site or via district systems.

contiues >

ACTION AREA	NEAR-TERM ACTIONS TO 2025	LONG-TERM AMBITIONS TO 2050
Water heating	Encourage heat pump water heaters. Continue R&D on low-cost solar thermal. Support adoption of demand-side response measures.	Mandate MEPS of 150% efficiency for electric equipment. Achieve affordable thermal storage and low cost solar thermal systems (for low-income countries only).
Appliances	Expand and update MEPS to cover all major appliances and set energy performance requirements for networked devices.	Set MEPS above or higher than current best available technologies and enact MEPS for small plug-loads.
Lighting	Ban incandescent and halogen light bulbs. Establish MEPS above 65 lm/W lighting by 2025 and encourage the uptake of light-emitting diode (LED) technology.	Implement MEPS above 120 lm/W for all new lighting. Work with manufacturers to ensure product reliability and higher efficiencies.
Building controls	Encourage smart sensors and intelligent building energy management systems. Work with industry to enable demand-side response solutions.	Require energy management systems for large commercial buildings, and intelligent controls for all major heating and cooling equipment in buildings.

xi. Key technologies

The technological issue in the building sector is much less stringent than in the transportation and industry sectors, since efficient solutions are already available (although some R&D efforts on new materials are still needed). The decarbonization of the building sector can be reached by addressing proper strategies, according to the following main priorities:[158 159]

1. Maximize the buildings' energy efficiency first, through passive solutions: all the passive technologies and design strategies to reduce the thermal energy demand (i.e. energy needed by the building envelope), for heating and cooling in buildings, have to be put into practice before any other measure to ensure comfortable conditions with the minimum possible amount of energy. In countries with large heating loads, advanced insulation and proper architectural choices are pivotal to reduce thermal losses. In hot climates, where cooling loads are set to increase substantially, the reductions can be achieved through low-cost and local material components, such as cool roofs and shading systems. Heat flows can be better managed, preferably through natural ventilation, or mechanical

158 De Groote Maarten and Mariangiola Fabbri. "Smart Buildings in a Decarbonized Energy System - 10 Principles to Deliver Real Benefits for Europe's Citizens." *BPIE* (2016). Published 2016. Accessed August 23, 2019. http://bpie.eu/wp-content/uploads/2016/11/BPIE-10-principles-final.pdf

159 UN-Habitat. "Sustainable Building Design for Tropical Climates." *UN-Habitat* (2015).

ventilation systems that manage airflow and reduce unnecessary energy demand for cooling. In mixed climates, with both space heating and cooling loads, the multiplicity of seasonal constraints requires solutions which address both. For example, low-emissivity windows can reflect solar radiation during the summer to minimise heat gain, as well as reflect radiative heat from the inside during winter to minimise heat loss.

2. Adopt high-efficiency technical systems and advanced control/management strategies: the second priority is the phasing out inefficient boilers, using conventional fuel and low-carbon systems, such as heat pumps and district heating. It must be coupled with the introduction of control/management strategies. This can be as simple as programming gradual power ramp-up before building occupants wake in the morning, or using more complex tools such as artificial intelligence in building energy management systems to manage and mitigate peak electricity load profiles.

3. Maximize on-site or nearby renewable energy production and self-consumption to completely cover or exceed the total energy demand of each building and minimizing the energy exchange with the grid (thus stimulating energy management, storage and exchange at district level). In order to maximize the on-site or nearby renewable energy generation, policies need to be established that move beyond net metering ("NEM successor structures") to compensate for load matching through dynamic pricing.

Although widespread solutions and common practices to reach new zero-energy and zero-carbon buildings are already available, their systemic and synergistic integration to obtain optimal results is still difficult to reach. In addition, the retrofit of existing buildings is more complex, due to the large diversity of buildings and application contexts among countries and regions. To ensure that the most suitable design strategies and technologies are properly coupled and applied in each context, further efforts must be taken to support decision making processes and the design phases for retrofit and new constructions.

In addition, under a district-wide approach, thermal networks and advanced electrical grids for smart districts/cities play a key role in the decarbonization; they enable the interconnections of distributed energy resources (renewables, combined heat and power generators, etc.), storage systems and loads (electrical and thermal), they balance supply and demand locally, creating a Multi-Energy System (MES).

Such MESs increase the overall efficiency of a district or a group of buildings, by allowing waste heat recovery for heating, cooling and domestic hot water applications, and optimal local dispatching of both thermal energy and electricity.

Innovative thermal and electrical multi-energy systems must be designed with the aim to integrate multiple renewable energy sources (i.e. photovoltaics and geothermal energy), energy storage technologies (i.e. sensible thermal storages, batteries), and different types of thermal and electrical loads (space heating, space cooling, domestic hot water preparation, appliances, electric vehicles, etc.).

Such MES can represent a key solution not only for new urbanization, but also for the energy retrofit of existing buildings (e.g. by distributing groundwater to existing buildings, thus enabling the substitution of fossil-fuel boilers with high-efficiency water-to-water heat pumps).

In parallel, there is a pressing need to efficiently manage the local energy distribution to avoid or minimize the electrical system's overload. This brings along considerable advantages, such as:

- Significant reduction of the impact on the grid from electric renewable energy sources;
- Minimization of the peak electricity demand due to the electrification of the building and transportation sector.

Each technological option, suitable for reaching the 2050 target, should be evaluated in its whole and life cycle value. Selected strategies should consider the co-benefits and trade-offs of technical, socio-economic and environmental implications, including changes on internal comfort conditions, energy consumption, grid loads, peak demand, and supply chains.

The following key technologies can be identified for the achievement of expected results.[160] [161]

- Low embodied-carbon materials and envelope technologies; efficient, low-carbon and easily-recyclable/ reusable key solutions must be applied, such as: high-performance selective glazing, opaque materials with high thermal insulation and mass, solar reflective materials, etc. Further, low-carbon materials (those with the lowest embodied energy) must be used. Thus, local and natural materials are preferable.

- Photovoltaic (PV) and photovoltaic/thermal (PVT); solar energy is the most widespread renewable energy source that can be easily exploited in urban areas. It can be converted into electricity, (with photovoltaic technology) or into electricity and thermal energy (by means of photovoltaic/thermal technology). In relatively cold climates, the improvements in thermal insulation of buildings is decreasing the heating demand, while the cooling demand is constantly increasing. Fortunately, PV and PVT technologies, integrated in the building envelope's surfaces, are able to cover a significant fraction of the yearly total energy demand for heating, cooling and Domestic Hot Water (DHW) preparation in several climatic contexts. In temperate and warm climates, their annual electricity production easily overcomes the buildings' electricity demand. In addition, these technologies are reliable, easy to integrate into buildings, and affordable (in several countries PV electricity reached the grid parity). The annual installed PV capacity, expected in 2050, must be higher than 300 GW/y to make a substantial contribution to decarbonization. In developing countries, a high penetration of PV/PVT is also encouraged for the development of microgrids. However, a massive integration of PV/PVT technologies requires an adequate building design to maximize the available surfaces for their installation (e.g. high-rise buildings should be limited).

- Solar thermal for DHW production (in low-income countries only); it is a consolidated and affordable technology, which can be convenient in regions where solar radiation is abundant, space heating is absent and other solutions are less feasible (too expensive, no reliable electricity grid, no availability of clean fuels, etc.) This technology is a viable solution in small buildings, where the costs for water piping and its installation do not exceed the costs of solar PV coupled with water heaters based on vapour-compression technology.

160 De Groote Maarten and Mariangiola Fabbri. "Smart Buildings in a Decarbonized Energy System."

161 IRENA. "Global Energy Transformation, a Roadmap to 2050."

- Heat pumps; at present they can be considered the most versatile and high-efficiency solution for space heating, cooling and DHW preparation. A heat pump has the potential to deliver significantly more energy than it requires to run, by exchanging thermal energy with the air, ground, water bodies and sources of waste heat. Electrically driven heat pumps can easily deliver three to five units of energy for every one unit of electricity consumed. Heat pumps can be synergistically integrated with PV ad PVT technologies, obtaining solar assisted heat pump systems. Moreover, when used with appropriate control measures and thermal storages (e.g., thermal mass, water tanks), heat pumps can help to balance the electrical system by shifting load away from peak periods. Heat pump sizes range from small capacities (less than 1 kW, for a single-room application) to several MW (to serve large buildings/districts); in the latter case, they are effectively connected to district heating/cooling systems, and also increase flexibility by using thermal storage capacities and waste heat.

- Energy management systems (EMS) with demand side management (DSM capabilities; Building automation and controls coupled with smart metering allow buildings to react to the occupants' needs (user response) and to external signals (grid response); the energy use of the building should be continuously optimized, by ensuring that the energy is used only when and where necessary and that all technical building systems are properly integrated. Moreover, all consumers should be allowed to feed the electricity they generate, but do not use, into the grid and/or to participate in demand-response activities. This will also enable synergies between smart buildings and electric vehicles. Cloud-based EMS must be preferred since they coordinate multiple buildings and ease the application of district/city-scale management strategies.

- Energy storage technologies at building and district scale; the share of energy being stored or used immediately/locally needs to be maximized. This means encouraging energy storage possibilities in buildings and districts. For example, in urban areas, energy that was generated but not used by one building can be stored or used by another nearby building. Improvements in energy storage systems have so far been limited due to high price (especially for electrical storage), however economies of scale are leading to significantly reduced costs. Sensible thermal energy storages are already competitive and are particularly interesting when coupled with heat pumps and solar technologies, since they significantly increase the renewables' self-consumption with low investment costs.

- Passive cooling technologies to replace or integrate with chillers in hot climates; the increasing demand of cooling, especially in hot climates, is a key issue which needs to be addressed, not just with high-efficiency chillers. Where possible, several low-energy/passive technologies can be effectively applied, such as indirect evaporative cooling systems in hot and dry climates, ceiling fans and/or night ventilation to limit the need of active cooling in all climates. Such solutions are particularly significant in developing countries, where the combined application with a proper climate-responsive building design can avoid the presence of an active cooling system.

On top of all, an effort in integrated buildings/districts design is required: design approaches that integrate passive (building fabric, natural ventilation, daylight etc.) and active (heating, ventilation, cooling, etc.) systems, and optimize the synergistic performance of technologies must be improved.

However, expected problems or barriers to overcome could be present, as listed hereafter, together with stakeholders' main actions in order to achieve objectives.

TABLE 6. Challenges and Solutions to Barriers

EXPECTED PROBLEMS OR BARRIERS TO OVERCOME	STAKEHOLDERS' MAIN ACTIONS
a) Low retrofit rate of existing buildings. If the current retrofit rate (typically 1%/year) of existing buildings is not increased, expected decarbonization objectives cannot be reached in 2050.	Policies and subsidies that favor the retrofit of existing buildings rather than new constructions are absolutely necessary. In addition, all barriers to the development of new business models must be removed (i.e. ban on credit-transfer from tenants to investors etc.), to significantly increase private investments in energy retrofit.
b) Building electrification-related problems. The huge increase of non-programmable renewables, electric heat pumps and induction cooktops can cause grid overload and electricity dispatching issues; proper load matching strategies must be put in practice at building/district level.	Regulations and measures obstructing self-consumption, such as specific additional taxes or levies, should be lifted and administrative procedures to allow self-consumption should be user-friendly. Energy Performance Certificates (EPCs) should consider the building's capacity to consume self-produced renewable energy. Consumers must have the ability to benefit from flexible demand services, otherwise smart business models will not be developed.
c) Overload due to deep vehicles electrification. The deep and quick penetration of electric vehicles' charging stations in urban areas can cause grid overload or increase electricity price in some periods, thus limiting the electrification of the building sector.	Local governments are uniquely positioned to advance district energy systems in their various capacities: as planners and regulators, as facilitators of finance, as role models and advocates, as large consumers of energy, and as providers of infrastructure and services. A regulatory framework is urgently needed to define charging strategies of EV in urban areas.
d) Performance/environmental problems in key emerging technologies. In some cases, new technologies could present both environmental drawbacks (e.g. electrochemical batteries with high environmental impact in manufacturing and decommission phases) and performance problems (e.g. limited actual performances of air-source heat pumps in critical climatic conditions).	Policy makers should develop strategic frameworks to create adequate market conditions for low-carbon technologies and guide building owners/designers in making the correct choices. Adequate information on performance/ environmental features of each technology must be mandatory disseminated by components' manufacturers. A clear framework for embodied energy/GHGs assessment on a building's life cycle must be defined, in order to compare various scenarios by different environmental professionals.

contiues >

EXPECTED PROBLEMS OR BARRIERS TO OVERCOME	STAKEHOLDERS' MAIN ACTIONS
e) Lack of skills in design and integration of key technologies. Professionals do not adequately integrate a climate-responsive design, which can limit the benefits obtainable with key technologies.	Training and capacity building activities must be adequately promoted, as well as the development of specific DSS (decision support system) or design-aid tools to strongly increase the application of climate-responsive and integrated building design. Standardized permitting processes and streamlined software for design will also be helpful in reducing costs.
f) Performance gap and rebound effect problems in new or retrofitted buildings. The possibility to have energy services at low or zero cost typically induces wasteful behaviors in end-users and misuse of technologies, reducing the expected benefits in terms of savings.	Consumers equipped with smart meters should have access to their real-time consumption data to enable monitoring of actual energy use and should be given the opportunity to grant access to third parties. Energy management systems must also send warnings/ suggestions in case of energy overconsumption or wrong behaviors. Information campaigns should be launched to empower user awareness about correct behaviour in system management.

xii. Case Studies

Representative examples of low carbon districts/buildings for specific climatic contexts (i.e. cold and hot) are described below.


Schlierberg Solar Estate, Freiburg, Germany[162][163][164]

"Am Schlierberg" in Freiburg is one of the first solar and energy-plus housing estates in the world. The housing development was built in 1997 and has been acting as a trend-setting pilot project for solar building and clean energy living ever since.

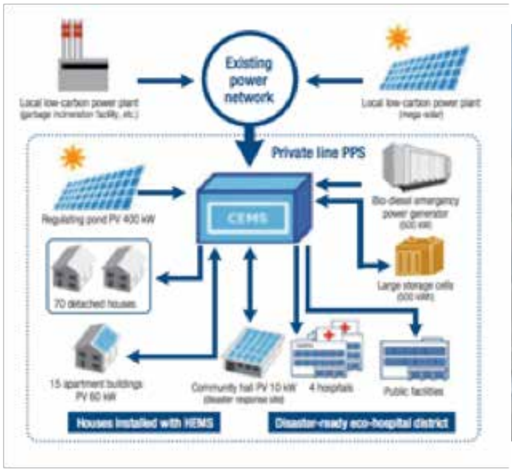
The solar installation consists of 445 kWp grid-connected PV and string inverters mounted underneath the roof deck. The total annual solar electricity production is 420,000 kWh. The housing development was designed to assure optimum efficiency. Therefore, unobstructed solar radiation on the roofs throughout the year, summer shade, and winter sun on the southern façades were taken into account, and all south facing roofs were covered with horizontal area PV modules. This, together with the energy efficient building design, allows for 2 million kWh primary energy savings per year. Any excess generated electricity, which is not used by the residents, is fed into the public grid in return for a feed-in compensation, covered under the German National Renewable Energy Acts' feed-in tariff. Heat energy is generated by a local network of solar hot water evacuated-tubes, which are located on the "Sonnenschiff", a 125 m service block. Any additional energy required during the winter months is provided by a local combined heat and power plant, fueled by wood chips and natural gas.The building's low energy demand derives from a group of measures, such as the building design in compliance with the passive house standard, the high insulation standard, the average U-value for the building envelope (0.28 W/m^{2}K), and efficient ventilation heat recovery. Additionally, the complex uses electricity-saving appliances and energy conservation practices.

The project's aim is to apply German Passive House and Plus Energy House directives, as well as show sustainable construction principles through material selection, appliance choice, energy consumption, transportation options, and construction method. The project shows how the complex relation between a building's location, orientation, layout, use, energy production and consumption can create a positive impact by generating energy and feeding it into the grid.

162 UN-Habitat "Energy and Resource Efficient Urban Neighborhood Design Principles in Tropical Countries - A Practitioner's Guidebook." UN-Habitat (2018).

163 PV Upscale. " Solarsiedlung am Schlierberg, Freiburg (Breisgau), Germany." *PV Upscale.* Accessed August 22, 2019. http://www.pvupscale.org/IMG/pdf/Schlierberg.pdf

164 Department of Indoor Environmental and Building Services Engineering. "Solar Settlement Freiburg, Germany." *Czech Technical University in Prague.* Accessed August 22, 2019. http://tzb.fsv.cvut.cz/projects/resset/files/resset-germany.pdf



Higashimatsushima City, Smart Eco-Town, Japan[165]

In the aftermath of the 2011 earthquake and tsunami, the Japanese city of Higashimatsushima experienced the worst flood damages of all cities in Miyagi prefecture. To establish a more sustainable and resilient energy infrastructure, the city of Higashimatsushima set a goal to become a net zero energy city by 2022. The plan includes the creation of an experimental 85-home microgrid community, supplied by solar, wind, and biodiesel technologies, along with large-scale energy storage.

The community consists of 70 detached, single-family homes and 15 multifamily apartment buildings. The energy needs of the micro community will be met by solar (470 kW) and bio-diesel (500 kW) energy systems, and 500 kWh of energy storage to meet the entire town's energy need of three days.

The town's electrical grid infrastructure is developed and owned by the city, which operates as a regulated monopoly. By having its own distribution system, the city will get an electricity supply contract with either the regional utility or renewable energy independent power producers (IPPs), and distribute electricity to all 85 households.

The city will further apply a Community Energy Management System (CEMS). It will allow the city to monitor electricity consumption and generation data via individual smart meters, manage the energy storage system during peak-demands, and bill customers. During emergencies, the system will start the biodiesel generator to help control and balance the energy needs usually provided by solar and energy storage. This microgrid community is a joint project with the city of Higashimatsushima and Sekisui House, Japan's leading housing developer, who received research funding from the Ministry of Environment.

165 Born from Disaster: Japan Establishes First Microgrid Community, Junko Movellan 2015, *Sekisuihouse*. "Promoting Net-Zero-Energy Housing." Sekisuihouse (2015). https://www.sekisuihouse.co.jp/english/sr/datail/__icsFiles/afieldfile/2015/08/19/P21-P52.pdf

Enerpos, Reunion Islands[166 167]

ENERPOS (French acronym for POSitive ENERgy), a two-storey university building, is located in a tropical climate. The building is split into two parallel wings and separated by a vegetated patio, with a total gross floor area of 739 m².

ENERPOS applies a number of passive design strategies (mainly cross ventilation and sun-shading devices for the envelope) with the use of PV (covering the building's peak demand for cooling) to reduce mismatch losses. The passive design strategies for cooling include the following: a 3 m band of native plants surrounding the building, the north and south orientation of the main façades (which are perpendicular to the thermal breezes that blow during the hot season), the building's natural cross ventilation through its window to wall ratio (WWR) of 30%, and the use of external shading, (which allows for airflow regulation, while also providing protection against sun, cyclones and break-ins). Further, high-performance ceiling fans were installed to guarantee additional air speed during windless days. This allows for a transitional period before the use of active air-conditioning systems become necessary. Another cooling measure was the insulation of the roof with a 10 cm layer of polystyrene (less than 0.5% of the solar radiation comes through the roof).

Due to a proper design, the building's electrical consumption from May 2010 to April 2011 was 9,824 kWh kWh/m^{2}y. The main sources of energy consumption were the electrical outlets (46%), the split system used to cool the two technical rooms (15%), interior lighting (14%), ceiling fans (11%), the exterior lighting (7%) and the lift (7%).

The building's photovoltaic roof covers an area of 350 m^2 and enables the production of about 70'000 kWh/y of electricity. The building is a positive energy building as it produces more electricity than it consumes. ENERPOS, was built in 2008, with gross costs per square foot of about $111 and net costs per floor area of $232. The building shows that with current technologies and a small additional cost, it is possible to build a nearly zero-energy building (nZEB), even in hot climates.

166 Lenoir, Aurelie and Francios Gard. "Tropical NZEB." *High Performing Buildings.* Published 2012. http://www.hpbmagazine.org/attachments/article/11967/12Su-University-of-La-Reunion-ENERPOS-Saint-Pierre-La-Reunion-France.pdf

167 UN-Habitat. "Sustainable Building Design for Tropical Climates." *UN-Habitat* (2015).

Umoji House, Dar es Salaam, Tanzania[168 169]

Umoja House is considered a fitting response to the city of Dar es Salaam and its climate. The company BDP designed the structural and environmental engineering for the building. Today, the British High Commission, the embassies of Germany and the Netherlands, and the European Commission are located in the building.

The building consists of two blocks of office accommodation, which are supported by pilotis, connected by bridges and accessible by a central stair and lift. The buildings' design incorporated considerations to protect the building from negative climate impacts. To prevent overall heat gain, the building has a floating solar roof and external louvres on three of its elevations. The building's orientation is designed in respect of the sun's movement. The longer facades have a north-south orientation, while the shorter facades face east and west to avoid the morning and evening sun. The facades are shaded to counteract increases in indoor temperatures. The building has two main wings with an open central bay linked to corridors and staircases. The site and courtyard are landscaped with local plants and trees which provide cool and comfortable space for public events and reduce the demands for cooling through natural ventilation and the thermal stack effect.

The glazed surfaces in all facades are protected by shading devices. These are comprised of stainless steel screens, which both shade the building and maximize the comfort of the users. In this climate, solar control devices are crucial in order to avoid excessive thermal gains. The Heating, Ventilation and Air Conditioning (HVAC) system is connected to solar collectors and bore hole water. It has a rainwater harvesting system that collects water in the basement, which is used for cleaning the building and for irrigating the grass. Construction materials were sourced locally wherever possible, and supported via local agents and contractors. The total construction cost of the building was £2.5m.

168 Zaha Hadid Architects, Gehry Partners, Foster and Partners, Rafael Moneo and more. *Contemporary Architecture:CA2.* Victoria: The Images Publishing Group Pty Ltd., 2004

169 UN-Habitat. "Sustainable Building Design for Tropical Climates." *UN-Habitat* (2015)

Chapter VII

SECTOR COUPLING

Decarbonization of all these sectors must occur in parallel together with deeper integrations between the sectors. Sector coupling can become one of the most important sources of flexibility in the integrated system and this will allow significant cost reduction of the final products, such as power, heat supply, mobility, production of materials etc. When fully optimized there are additional benefits of an integrated system. From one side of sector coupling, for example the electrification of transport, heating, and industrial production can lead to the scaling up of power generation and storage capacities, and consequently to increased utilization of higher cost resources to satisfy this demand. However, on the other side sector coupling could enable access to low cost flexibility options via this higher range of demand response and energy storage in other forms, which will compensate volatility of variable renewable energy sources.

To achieve carbon neutrality, power sector must be at the core of future energy system as a major energy supplier for all other sectors: generating power for all industrial processes, heat production, and for the synthesis of synthetic fuels and chemical production. Optimal management of the sectors will allow the electricity supply cost to decrease and also lower the cost of products in all the sectors. The benefits of coupling mainly depends on the proportion of energy in the total cost of the products: technologies with highest energy cost component (water electrolyzers, electrical heating) are the most valuable source of flexibility in case of sectors coupling, contrary to technologies with high Capex component, which tend to operate on baseload and increase flexibility demand.

Another valuable impact of sector coupling combined with electrification and transition towards RE based power sector, will be an overall efficiency gain. Electrified energy processes are not simply carbon neutral, but generally more efficient[170], leading to lower primary energy demand

170 Breyer, C., D. Bogdanov, M. Ram and A. Aghahosseini. "Impact of the Transition towards 100% Renewable Energy Systems on Primary and Final Energy Demand." Plenary Lecture. October 2019, 14th SDEWES Conference


OUR FUTURE
OUR PLANET
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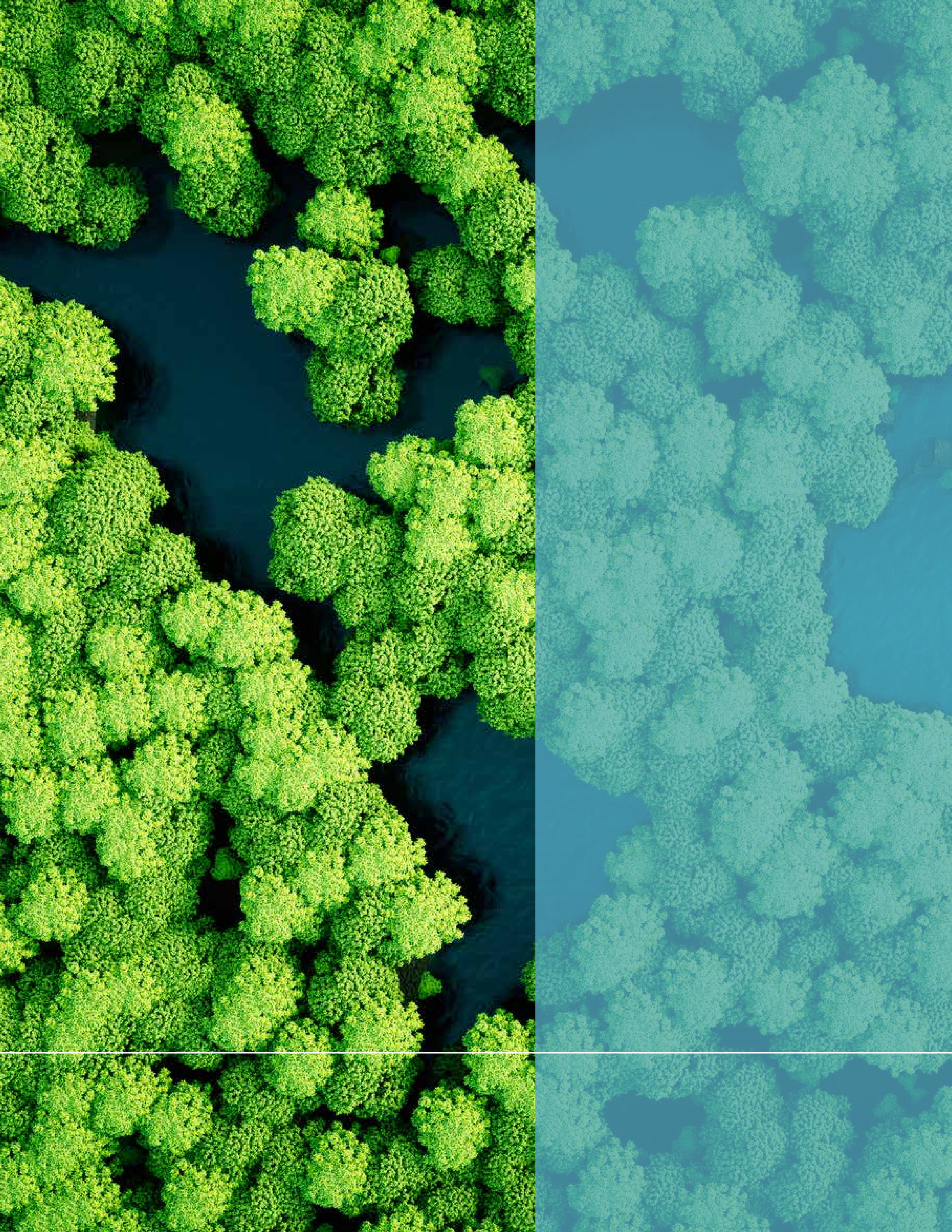
AUSTRALIAN YOUTH
CLIMATE COALITION



Chapter VIII

TOOL KIT ANNEX

Decision Making Tools for decarbonization to 2050 Energy and Integrated Modelling

A. Modelling tools and Resources

Introduction

An informed decision-making process is essential and may be pivotal to support the needed decarbonization pathways that have been highlighted in the document for the power sector, for transport, heavy industry, and buildings. Decarbonization has a lot of consequences within the energy sector and beyond, as it has been proved in the whole document. Based on this consideration it is important to create mention some of the key tools and resources available to design economy-wide Roadmaps.

In 2017, the 2050 Pathways Platforms published the 2050 Pathways Handbook which maps out the starting points for creating such a roadmap. In that report, the authors have articulated the importance of three intertwined elements which are crucial for a comprehensive plan: a narrative, data dashboard, and mathematical model. With these three integrated components, a country can identify its key priorities and create an actionable Roadmap on which it can develop supporting policies to achieve a fair and just transition to zero emissions. This document could serve as a predecessor for the following sections which go into more technical details on defining your modelling approach.

The two pillars of the needed approach

Energy system modelling is widely used to support energy policy and long-term strategic energy planning decisions with insights generated by models. Efforts made so far in developing energy modelling frameworks and linking them with economic models in the European Union (EU) context have been recently reviewed.[171] Energy system models are widely used tools to evaluate the optimal penetration of technologies or to assess potential impacts of specific measures. However, different models can answer different questions: model development, starting from a broad variety of general frameworks, is driven by the intention of the specific purpose and calibrated on the basis of its technological, methodological, and geographical scope. While energy system models approaches are usually based on analytical characterization of the analyzed technologies, economic-wide models mostly rely on empirical datasets derived from Environmentally-Extended Input Output models.[172] Economic-wide models can be generally distinguished into Input-Output and General Equilibrium models. The first is able to evaluate, in an endogenous way, the responses of the economic system to different policies and scenarios without taking consumption into account, while the latter describe the relationship between the primary factors (labour, capital and natural resources such as energy) by using elasticities of substitution.

171 Müller Berit, Francesco Gardumi and Ludwig Hülk. "Comprehensive Representation of Models for Energy System Analyses: Insights from the Energy Modelling Platform for Europe (EMP-E) 2017." *Energy Strategy Reviews* 21. (2018): 82–87. https://doi.org/10.1016/j.esr.2018.03.006
172 Miller, Ronald.E. and Peter D. Blair. *Input-Output Analysis: Foundations and Extensions.*, ed. Second. Washington DC: Cambridge University Press, 2009.

Taxonomy according to the literature

In view of this, several possible classifications can be found in the literature. Grubb et al. categorize the variety of energy models adopting 6 dimensions, specifically sectoral and geographic extension, level of aggregation, time span, top-down or bottom-up and optimization or simulation.[173] Houracade et al. have tried to condense the complexity of model classification by identifying a 3D space where the axes are technological richness, macro-economic feedback, and micro-economic realism, introducing behavioural complexity of consumers.[174] Hiremath et al. further develop the classification identifying 9 dimensions which further extended the previous ones.[175] The importance covered by the distinguishing between top-down and bottom-up models, have brought Herbst et al. to introduce a further structuring: energy models are primarily distinguished into 2 categories, macro-economic ones and technology rich ones.[176] The first group (top-down) comprehends input-output, econometric, general equilibrium and system dynamics models; the second group (bottom-up) contains partial equilibrium, optimization, simulation and multi-agent models. Müller et al. introduce the model characterization following the first Energy Modelling Platform for Europe meeting: a model matrix has been generated in this occasion limiting categories to three (technology richness, scope and hybridization, geographical focus) in order to provide policymakers with a concise overview. Alongside with this proposal, the importance of surveys and personal interaction between researcher groups has been underlined. This process can provide a continuous space for interaction between modellers and for engagement with actors of the energy sector, relying also on online tools.[177]

State of the art of bottom-up models

Energy modelling has been used to analyse the dynamic nature of energy, taking into consideration the role of new technologies in the contest of an exogenous set of macroeconomic data: technologies are described by technical (installed capacity, use of resources, lifespan, efficiency, availability factor, ect.) and economical (cost of investment, O&M costs, ect.) metrics. Pfenninger et al. delineate four possible paradigms for energy modelling which are:[178]

- Optimization based models: cover the entire energy system with the goal of depicting the evolution of an energy system.
- Simulation based models: provide forecasts of how an energy system could evolve.
- Power system and electricity market models: they cover solely the electricity system utilizing either an optimization or simulation framework.
- Qualitative and mixed-methods scenarios: they rely on qualitative or mixed methods rather than mathematical models.

173 Grubb, Michael, Jae Edmonds, Patrick ten Brink and Michael Morrison. "The Costs of Limiting Fossil-Fuel CO2 Emissions: A Survey and Analysis." *Annual Review of Energy and the Environment* 18. (1993): 397–478. https://doi.org/10.1146/annurev.eg.18.110193.002145

174 Hourcade, Jean-Charles, Mark Jaccard, Chris Bataille and Frederic Ghersi. "Hybrid Modeling: New Answers to Old Challenges Introduction to the Special Issue of The Energy Journal." *The Energy Journal.* 2006. https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI2-1

175 Hiremath, Rahul B., S. Shikh and Nijavalli H. Ravindranath. "Decentralized Energy Planning; Modeling and Application - a Review. *Renewable and Sustainable Energy Review* 11, no. 5, (2007): 729–752. https://doi.org/https://doi.org/10.1016/j.rser.2005.07.005

176 Herbst, Andrea, Felipe Toro, Reitze Felix and Eberhard Jochem. "Introduction to Energy Systems Modelling." *Swiss Journal of Economics and Statistics* 148, (2012): 111–135. https://doi.org/10.1007/bf03399363

177 Müller Berit, Francesco Gardumi and Ludwig Hülk. "Comprehensive Representation of Models for Energy System Analyses."

178 Pfenninger, Stefan, Adam Hawkes and James Keirstead. "Energy systems modeling for twenty-first century energy challenges." *Renewable and Sustainable Energy Reviews* 33, (2014): 74–86. https://doi.org/10.1016/j.rser.2014.02.003

Among optimization models it is worth it to mention MARKAL, TIMES, MESSAGE, PyPSA, Balmorel, PLEXOS and OSeMOSYS which are some commonly used tools for this purpose.. Nevertheless, identifying optimal power system configurations and decarbonization pathways within an integrated energy system still poses challenges. Primarily, despite the recent developments in energy modelling in terms of spatial and temporal resolution and capacity of multiple energy carriers, some issues still must be addressed (i.e. lack of complementary models for the generation of demand profiles). Secondly, energy modelling frameworks commonly consist of technology-rich bottom-up representations of the energy sector alone, whilst policy interventions on the latter entail economic and environmental consequences on the whole set of productive sectors within a national economy.

The role of top-down models

Recent development of richer input-output tables, enhanced by augmented computational power and interest in environmental themes have been a breeding ground for the expansion of Multiregional Input Output Tables (MRIO), which potentially assess the interregional and intersectoral impacts of local technological changes. In particular, such MRIO can be used as input data to both Computational General Equilibrium (CGE) and Input-Output models. The GEM-E3, a multi-regional, multi-sectoral, recursive dynamic computable general equilibrium model, provides details on the macro-economy and its interaction with the environment and the energy system, taking into account also the demand behaviour of economic agents. MRIO databases can be provided as input also to the modelling framework of the World Trade Model (WTM) and the World Trade Model with Bilateral Trade (WTMBT), two versions of a constrained optimization model that situates the standard one-region input-output model within the global context, simulating global production and trading arrangement solely driven by the principle of comparative advantage. [179] [180]

Even if the scope of top-down models is comprehensive, such models are characterised by a high aggregation level: indeed, energy technologies are usually lumped together in one average “energy sector”. For such reasons, this approach should be considered complementary to bottom-up models rather than the opposite, encouraging new methodology to bridge these tools often called “links”, which are increasingly proposed in the recent literature.[181] Rectangular Choice of Technology (RCOT), is also emerging. It introduces technological complexity into the input-output framework, allowing different technologies to produce the same industrial output (i.e. electricity), within the sectoral richness of input-output models.[182] Alongside that, energy system dynamics should be represented with high resolution timesteps which could potentially be modelled throughout dynamic input-output models.[183]

179 Duchin, Faye. “A World Trade Model Based on Comparative Advantage with m Regions, n Goods, and k Factors.” *Economic Systems Research* 17, (2005): 141–162. https://doi.org/10.1080/09535310500114903

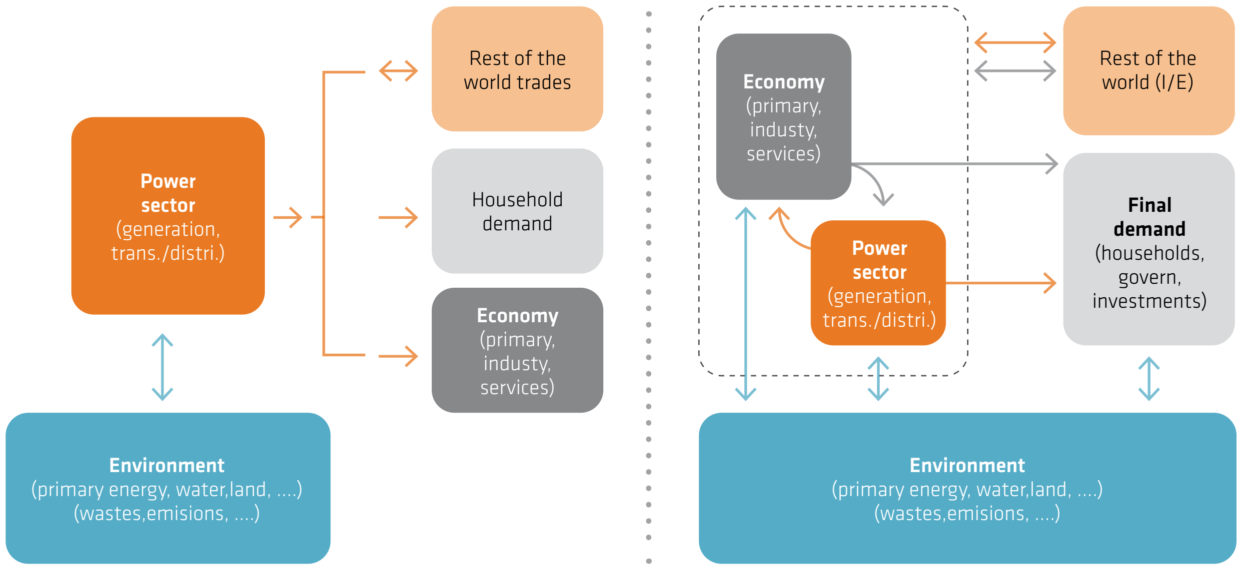
180 Hammer Strømman, Anders and Faye Duchin. A World Trade Model with Bilateral Trade Based on Comparative Advantage.*Economic Systems Research* 18, (2006): 281–297. https://doi.org/10.1080/09535310600844300

181 Brown, Tom W., Tobias Bischof-Niemz, Kornelis Blok, Christian Breyer, Henrik Lund and Brian V. Mathiesen. “Response to ‘Burden of Proof: A Comprehensive Review of the Feasibility of 100% Renewable-Electricity Systems.” *Renewable and Sustainable Energy Reviews.* 92, (2018): 834–847. https://doi.org/10.1016/j.rser.2018.04.113

182 Duchin, Faye and Stephen H. Levine. “The Rectangular Sector-By-Technology Model: Not Every Economy Produces Every Product and Some Products May Rely on Several Technologies Simultaneously. *Journal of Economic Structures* 1, (2012): 1–11. https://doi.org/10.1186/2193-2409-1-3

183 Miller, Ronald.E. and Peter D. Blair. *Input-Output Analysis: Foundations and Extensions.*

FIGURE 11. Traditional Energy Modelling of Power Sector vs Power Sector Integrated into the Input-Output Framework



Scientific research is still in progress to intercept the complexity of the problem of using this tool to represent the electricity production sector, since the needed detailed dynamic and high space and time resolution is difficult to model both in terms of technological description and factor endowment characterization. In this perspective interlinkages between energy and economic models are still widely adopted in form of hard-linking, soft-linking or integration.[184 185]

Interlinking bottom-up and top-down models

In the last decade, the widely recognized relevance of cross-sectoral interlinkages among economic sectors has driven research efforts in deepening joint energy and economic modelling, with a special focus on the integration of bottom-up technology rich energy models with top-down empirical macroeconomic and econometric models.[186] In particular, several attempts have been made on integrating energy systems optimization models (with particular focus on MARKAL and TIMES models) with input-output and CGE models, with the objective to improve feedback loops between energy sector and the rest of the economy, hence providing a more accurate picture of economic and environmental impacts on different energy scenarios.

184 Helgesen, Per Ivar, Arne Lind, Olga Ivanova and Asgeir Tomasgard. "Using a Hybrid Hard-Linked Model to Analyze Reduced Climate Gas Emissions from Transport." *Energy* 156, (2018): 196–212. https://doi.org/10.1016/j.energy.2018.05
185 Helgesen, Per Ivar and Asgeir Tomasgard. "From Linking to Integration of Energy System Models and Computational General Equilibrium Models – Effects on Equilibria and Convergence." Energy 159, (2018): 1218–1233. https://doi.org/https://doi.org/10.1016/j.energy.2018.06.146
186 Bohringer, Christoph and Thomas Rutherford "Combining bottom-up and top-down", Energy Economics, 2008, vol. 30, issue 2, 574-59. https://econpapers.repec.org/article/eeeeneeco/v_3a30_3ay_3a2008_3ai_3a2_3ap_3a574-596.htm6.

Practical examples of interlinkages

Several attempts have been made to link energy and economic models. Some of them are listed below.
In the assessment of the impact of future energy scenarios in UK, the TIMES-Macro model has been disaggregated by linking it with the AMOS UK CGE.[187]

Messner et al. proposed a soft-link between MESSAGE and MACRO models, with the aim to assess the impact of energy supply costs on the national energy production mix in a general equilibrium framework.[188]
Kober et al. linked a macroeconomic model to an energy system model by considering the decreases in consumers' spending due to the introduction of carbon taxes.[189]

Rocco et al. propose a novel approach to soft-link bottom-up OSeMOSYS model and top-down Input-Output model and applied it to assess the economic implication of a change in Egyptian energy mix.[190]
Lombardi et al. provide a comprehensive soft-linking approach to assess the overall impact of technological change in Italian sector of residential cooking through an integration between bottom-up load curve estimation model, technology rich optimization model (Calliope) and Multi-Regional Input Output model.[191]

As part of the EU current policy modelling suite, the TIMES model has been successfully integrated with the GEM-E3 CGE model for assessing the economic and environmental consequences of a variety of energy policies,[192] and similar efforts have been recently made by integrating the TIMES-PanEU model and the NEWAGE CGE model (http://www.reeem.org/).

Backcasting Modeling

In recent years some groups have utilized a "backcasting" approach. This is where instead of projecting the future state of the system based on historical trends, you enter in your desired future state, be it an economic or technological output, and then develop regression formulas based on various input data to reach that state. This methodology results in various scenarios that may help decision makers to understand the options available to them to accomplish the ambitious goal and targets they set in their political fora.

17 Strachan, Neil and Ramachandran Kannan. "Hybrid Modelling of Long-Term Carbon Reduction Scenarios for the UK." *Energy Economics* 30. no. 6, (2008): 2947–2963. https://doi.org/10.1016/j.eneco.2008.04.009
188 Messner, Sabine and Leo Schrattenholzer. "MESSAGE-MACRO: Linking an Energy Supply Model with a Macroeconomic Module and Solving it Iteratively." *Energy* 25. No.3, (2000): 267-282. https://doi.org/10.1016/S0360-5442(99)00063-8
189 Kober, Tom, Philip Summerton, Hector Pollitt, Unnada Chewpreecha, Xiaolin Ren, William Wills, Claudia Octaviano, et al. "Macroeconomic Impacts of Climate Change Mitigation in Latin America: A Cross-Model Comparison." *Energy Economics* 56, (2016): 625–636. https://doi.org/https://doi.org/10.1016/j.eneco.2016.02.002
190 Rocco, Matteo Vincenzo, Yassin Rady and Emanuela Colombo. "Soft-Linking Bottom-Up Energy Models with Top-Down Input-Output Models to Assess the Environmental Impact of Future Energy Scenarios." *Modelling Measurement Control C* 79, (2018): 103–110. https://doi.org/10.18280/mmc-c.790307
191 Lombardi, Francesco, Matteo Vincenzo Rocco and Emanuela Colombo. "A Multi-Layer Energy Modelling Methodology to Assess the Impact of Heat-Electricity Integration Strategies: The Case of the Residential Cooking Sector in Italy." *Energy* 170, (2019): 1249–1260. https://doi.org/10.1016/j.energy.2019.01.004
192 Capros, P., van, D. Regemorter, L. Paroussos, P. Karkatsoulis, C. Fragkiadakis, S. Tsani, I. Charalampidis, T. Revesz. "GEM-E3 Model Documentation - JRC Technical Reports" *European Commission*. Published 2013. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC83177/jrc83177%20(3).pdf

The SDSN's flagship Deep Decarbonization Pathways Project employed this methodology in sixteen national decarbonization reports for the largest emission countries around the world. The results of this exercise provided the technological proof-of-concept to demonstrate the technology options available in specific geographic and political contexts to achieve national decarbonization goals. The project used an open source model, Energy Pathways, based on excel spreadsheets so that the methodology could be adopted by and adapted to local research teams. The results of this project remain relevant and available online at www.deepdecarbionization.org.

Proposed taxonomy: 11 characteristics

The taxonomy proposed by Hiremath proposed 11 dimensions of energy modelling.[193] The relevance of the detailed definition of non-dispatchable renewable energy resource plays a crucial role in modelling energy scenarios and forecasts. Moreover, economic-wide models, which are able to predict direct and indirect consequences, both in terms of environmental and socio-economic impact of energy policies, are usually based on one-year timeframes. The growing sensitivity of governments and consumers on pollutants emission and resource utilization also begs additional energy modelling categorization from this point of view. Therefore, it is suggested that timestep resolution and environmental extension are two further dimensions on which to outline an energy model.

TABLE 7. Energy Modelling Taxonomy

PROPOSED 11 DIMENSIONS OF ENERGY MODELLING
• General and specific purposes • Model structure (internal and external assumptions) • Analytical approach (top-down or bottom-up) • Underlying methodology (optimization, simulation) • Mathematical approach (theoretical structure) • Geographical extension (global, regional, national, local) • Sectoral extension (energy technology richness, comprehensiveness of non-energy sector) • Time horizon (short, medium and long term) • Timestep resolution (minimum time slice considered) • Environmental extension (capability to intercept environmental impacts) • Data requirements

The proposed taxonomy can play the role of a compass for policy-makers which should always have in mind that no perfect model exists and the quality of its output must always be driven by the question that has been preliminary posed.

193 Hiremath, Rahul B., S. Shikh and Nijavalli H. Ravindranath. "Decentralized Energy Planning; Modeling and Application - a Review.."

5 key principles for improving energy planning

The importance of providing clear evidence on energy needs to policymakers does not end with delivering high-quality results. In fact, a few guiding principles should also be adopted in the activity of supporting country governments on strategic energy planning. The Oxford Policy Management, with the support of the UK's Department for International Development (DFID), and in collaboration with several international organizations, has outlined five key principles:[194]

1. National ownership: support synergies between key stakeholders and country-specific energy planners to achieve broad agreement on development strategies.

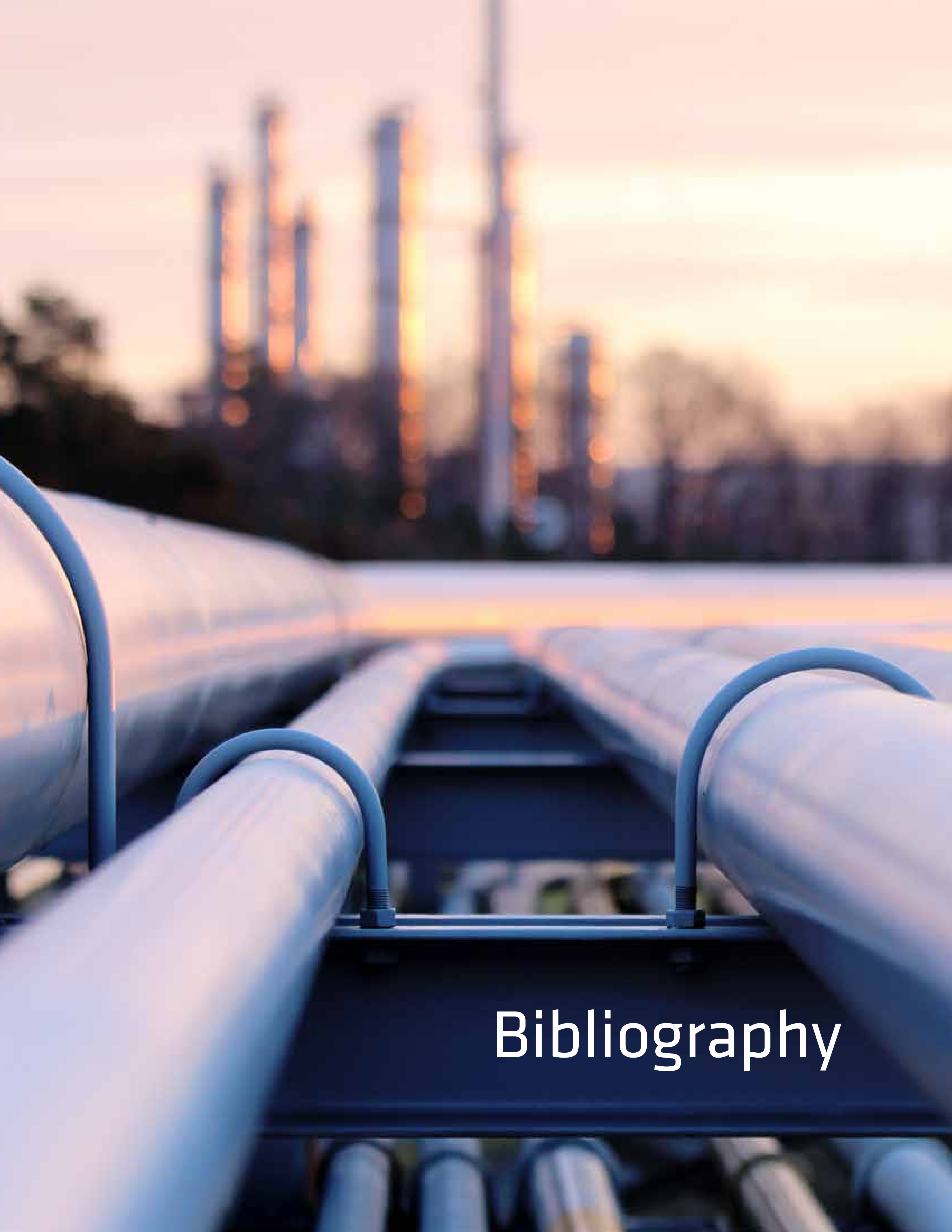
2. Coherence and inclusivity: assist governments in adopting energy strategies which are coherent with country-specific economic, social and environmental objectives.

3. Capacity: sustain governments in capacity building activities, strengthening national institutions capability of incorporating scientific-based evidence in decision making.

4. Robustness: promote the use of models and analysis tools which are based on strong technical and economical foundations and adaptable to the rapidly changing context of energy planning.

5. Transparency and accessibility: encourage the transparency of planning data, design and assumptions to key stakeholders, promoting open access and enhancing reproducibility.

194 Oxford Policy Management, 2019. Key principles for improving the support to strategic energy planning in developing and emerging economies.



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