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SECURE, CLEAN AND EFFICIENT ENERGY

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Note about contributors:

The deliverable criteria are met by the SENTINEL ICTA-UAB and IASS teams.

WP leader responsible for the deliverable:

Cristina Madrid López (ICTA-UAB)

Contributors:

Nick Martin (ICTA-UAB)

Cristina Madrid López (ICTA-UAB)

Laura Talens Peiró (ICTA-UAB)

Diana Süsser (IASS)

Hannes Gaschnig (IASS)

Johan Lilliestam (IASS)

SENTINEL Internal Reviewer:

Anthony Patt (ETHZ)

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Contents

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

List of figures

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

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List of tables

Acronyms

ABM	agent-based model
AFC	alkaline fuel cell
ARENA	Australian Renewable Energy Agency
BCG	Boston Consulting Group
BEV	battery electric vehicle
BOS	balance of system
CAES	compressed air energy storage
CCS	carbon capture and storage
CHP	combined heat and power
CSP	concentrated solar power
CZTS	copper zinc tin sulphide
DAO	decentralised autonomous organization
DER	distributed energy resources
DG	distributed generation
DLT	distributed ledger technologies
DOE	Department of Energy (United States)
DR	demand response
DSM	demand-side management
DSSC	dye-sensitized solar cell or Grätzel cell
EC	European Commission
EDM	energy demand management
EEG	Erneuerbare-Energien-Gesetz (German Renewable Energy Act)
EEM	evolutionary economics model
ENVIRO	Environmental and Bio-economic Impacts and Constraints
EP	energy poverty
EU	European Union
F8AC	false 8 adaptive cycle
FCEV	fuel cell electric vehicle
FCV	fuel cell vehicle
FP	fuel poverty
GHG	greenhouse gas
GTCC	gas turbine combined cycle
GW	gigawatt
H&C	heating and cooling
HAWT	horizontal-axis wind turbine
HEV	hybrid electric vehicle
HFB	hybrid flow battery
HVDC	high-voltage direct current
IAM	integrated assessment model

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IAMC	Integrated Assessment Modeling Consortium
IAWG	Interagency Working Group
ICGC	integrated coal-gasification combined cycle
IEA	International Energy Agency
IoT	Internet of Things
JGCRI	Joint Global Change Research Institute
JRC	Joint Research Centre (European Union)
KPI	key performance indicator
kWh	kilowatt-hour
LBD	learning by doing
LBR	learning by researching
LCA	life cycle assessment
LED	light-emitting diode
LFR	Linear Fresnel Reflector
LNG	liquefied natural gas
LR	learning rate
LTSET	long-term socio-ecological transitions
MCFC	molten carbonate fuel cell
MLP	multi-level perspective
MuSIASEM	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism
MW	megawatt
NEMESIS	New Econometric Model of Evaluation by Sectoral Interdependency and Supply
NGCC	natural gas combined cycle
NIMBY	not in my back yard
NZEB	nearly zero-energy building
OECD	Organization for Economic Cooperation and Development
OLED	organic light-emitting diode
OSC	organic solar cell
PAFC	phosphoric acid fuel cell
PC	pulverised coal
PEFC	polymer electrolyte fuel cell
PEMFC	proton-exchange membrane fuel cell
PLED	polymer light-emitting diode
PR	progress ratio
PSC	perovskite solar cell
PTES	pumped thermal electricity storage
PV	photovoltaic
QDSSC	quantum-dot sensitized solar cell
QTDIAN	Quantification of Technological Diffusion and Social Constraints
RES	renewable energy source
RFB	redox flow battery

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SCC	social cost of carbon
SDM	system dynamics model
SES	socio-ecological system
SESTM	socio-ecosystem transition management
SET	strategic energy technology
SNM	strategic niche management
SOFC	solid oxide fuel cell
TAM	technology acceptance model
TIS	technological innovation system
TM	transition management
TRL	technology readiness level
TSG	tidal stream generator
V2G	vehicle-to-grid
ZEB	zero-energy building
ZEBRA	Zero Emissions Batteries Research Activity

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Index

Executive summary

In line with its commitments to lower carbon emissions under the Paris Agreement and its own 2030 Climate & Energy Framework, the European Union (EU) has committed to increase the share of renewable energy use–around 15% in 2018–to be at least 32% by 2030. Achieving this will require a major reconfiguration of current energy systems in what could be seen as an example of a socio-technical transition or, more specifically, of an 'energy transition'. The key driver of this transition will be the ***electrification*** of heating and mobility functions. However, owing to the intermittent nature of most renewable energy sources (RES), this will need to be accompanied by the increased ***decentralisation*** and ***digitalisation*** of electricity networks. Existing energy system modelling softwares can simulate the dynamics of many of these processes. Nevertheless, they generally do not adequately capture the social and ecological aspects of the technologies that will drive this transition. Accordingly, the report aims to identify ways that future modelling applications–such as the ENVIRO and QTDIAN modules to be developed within the current project–can be used to address this gap and what information, theories, frameworks and methodologies exist that can guide such processes.

Section 2 reveals that hydropower looks set to be replaced by wind energy as the dominant RES for electricity generation in the EU. Several other technologies, particularly solar photovoltaic and bioenergy, are also predicted to contribute. Changes in the mix of ***energy supply*** technologies is expected to be accompanied by changes at the ***energy demand*** end, most notably via the increased integration of digital technology to form 'smart grid' networks. The functionality of such networks relies heavily on devices that can attenuate electrical energy in order to address the intermittency issues of RES and many technologies, old and new, are available at all scales. Understanding these trends will allow us to identify the energy supply and energy demand technologies that should best be considered within the forthcoming modelling studies.

Similarly, it is recognised that achieving a just and sustainable energy transition will also require changes within society itself. Accordingly, a selection of six key social trends relating to the energy transition are identified. Collectively, these trends suggest that addressing issues of social acceptance, democracy and justice are likely to greatly improve the success of transition processes. An understanding of these trends will allow us to identify the drivers and constraints that apply to modelling processes and data relating to past trends will be used to guide the formulation of specific modelling scenarios.

A number of frameworks and theories that can be used to conceptualise the social processes and processes of technological emergence within broader energy transition processes are discussed in **section 3**. Firstly, the four main theoretical foundations for visualising transitions are identified as the Multi-Level Perspective (MLP), the Technological Innovation System (TIS), Strategic Niche Management (SNM) and Transition Management (TM). All four–and the MLP in particular–can be used to understand how structural changes occur in energy systems and how to guide sustainable energy transition processes. In any case, as these frameworks do not fully represent exchanges between societies and the ecosystem, so-called socio-ecological system (SES) frameworks are also discussed. Lastly, two approaches for quantifying the rates of technological progress and market impact for burgeoning technologies are discussed. Together, it is hoped that this information can be used to conceptualise and predict the myriad potential transition pathways that are to be developed using the ENVIRO and QTDIAN modules. This is perhaps particularly true of the QTDIAN module which specifically aims to use theoretical insights from these sources to guide the formulation of a series of new model toolboxes.

While qualitative methods have tended to dominate the approaches taken to transition theory in the past, **section 4** presents a summary of six existing frameworks and approaches that have found use in the quantitative modelling of energy transitions. The first of these–the use of integrated assessment models (IAMs)–involves the integration of multiple existing quantitative models, is already widely employed to simulate transition scenarios at larger scales and is perhaps the most relevant to the current project. The remaining five model categories are a group of more abstract frameworks and approaches that attempt to model complex systems, behaviours and dynamics, often at finer levels of detail. This includes agent-based models (ABMs)–the most commonly used to date–as well as the broadly classified group of complex systems models, evolutionary economics models, socio-ecological systems models and system dynamics models. Most of these are not able to model the social-cultural, organisational, institutional and political aspects of a system, their interplay, or their feedbacks with the surrounding environment, underlining the need for further development. Nevertheless, the overview of the current status quo in real-world transition modelling provides an understanding of the available options for the development of the ENVIRO and QTDIAN modules. It also provides an element of contextual background to other modelling activities within the SENTINEL project as a whole, particularly those involving ABM and IAM approaches.

The findings of the report will act as the foundation for the development of the ENVIRO and QTDIAN modules that will allow social and ecological factors and impacts to be integrated into the energy system modelling platform of the SENTINEL project. It will also serve to open doors to the continued integration of social and environmental factors into future energy system models by demonstrating the ways in which societal and technological trends can be integrated into energy system modelling projects.

Reading guide

	SOCIO-ECO-TECHNICAL ELEMENTS OF ENERGY TRANSITIONS		
	Technologies	**Social organisation**	**Environmental**
Current trends	**Section 2.1**	**Section 2.2**	
Conceptual frameworks	**Section 3.1** Comparing learning curves with Technology Readiness Levels	**Section 3.2** Defining energy transitions as socio-technological transitions and introducing conceptual frameworks	**Section 3.3** Defining energy transitions from the point of view of the metabolism of socio-ecosystems and introducing relevant frameworks for socio-ecosystem transition
	Section 3.4. Presenting a SENTINEL framework for the assessment of socio-eco-technical transitions		
Modelling	**Section 4**		

1 Introduction

Ongoing increases in the rates of greenhouse gas emissions and a growing awareness of the consequences of global warming and other changes in climate conditions have led to what many are now calling a global 'climate emergency' (Ripple et al., 2019). However, scientists and politicians have been aware of the existence and potential threat of climate change for at least 40 years–the First World Climate Conference was held in Geneva in 1979. Despite this awareness, past initiatives such as the 1997 Kyoto Protocol were not adequately ambitious and did not result in significant reductions in global greenhouse gas emissions. Similarly, although the targets set by the most recent global initiative to halt climate change–the 2015 Paris Agreement–are technically attainable (Schellnhuber et al., 2016), many doubt whether the pledges made under the agreement are stringent enough or if all will indeed be honoured (Dimitrov et al., 2019; Rockström et al., 2017; Rogelj et al., 2016).

It has been argued that key polluters should 'take the lead' on reducing the global emissions of greenhouse gases (Parker et al., 2015), a role that the European Union (EU) has traditionally attempted to undertake (Parker et al., 2017). As part of the EU's ongoing program for addressing its commitments to the Paris Agreement it has pledged to reduce greenhouse gas emissions by at least 40%, compared to 1990 levels, by 2030 (Latvia and the European Commission, 2015). Furthermore, as part of its 2030 Climate & Energy Framework, the EU has also promised to raise the share of renewable energy use within the overall amount of energy consumed to be at least 32% and to attain a 32.5% improvement in energy efficiency when compared to 'business-as-usual' projections (European Commission, 2014).

With these commitments in mind, the EU has updated its energy policy framework to focus on a move away from its reliance on fossil fuels while improving the ways in which energy is managed and used (European Commission, 2019a). So, in addition to increasing the use of energy from renewable sources, the new framework focuses on energy efficiency practices, with emphasis in the energy performance of buildings, on achieving more stringent government regulation of energy sectors and on undertaking a complete modernisation of the EU electricity market itself.

The highest energy demands in the EU come from the transport, residential and industrial sectors (Eurostat, 2020). While many industrial activities and transport via shipping and air are likely to remain locked-in to their use of fossil fuels for now, many activities within the residential and transport sectors could be electrified within relatively short timespans. In fact, coupling a growth in renewable energy generation with increased electrification of heating and mobility functions is seen as a critical pathway to rapidly raising global use levels of renewable energy (Bellocchi et al., 2020; International Energy Agency, 2019a).

Implementing the required changes in energy supply (via maximisation of electricity generation from renewable sources) and in energy demand (via increased electrification of existing functions and application of additional processes that optimise the storage, distribution and use of energy) will require a great deal of technological innovation. However, from a broader perspective, it will also require an understanding of the ways in which these technologies can best be promoted and implemented within the existing system.

In this sense, it is also vital that a second innovation perspective–that of social innovation–is considered. The importance of social factors such as feasibility and acceptance in the field of low carbon transitions has been

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underrepresented in the past as technical research has tended to receive considerably more attention and funding (Overland and Sovacool, 2020). However, it is now accepted that maximising the speed and effectiveness of technological change requires human cooperation and action at all levels and there is a growing awareness that the energy transition should be understood as a socio-technical transition (Pregger et al., 2019). Societies play important roles in these processes by making consumption choices, providing spaces for innovations, building support for policies and so forth. As such, the ability to understand and utilise such mechanisms should be considered as important as the technology itself in transition processes.

In politics and science, the understanding of social feasibility and social acceptance often does not go beyond aspects of affordability and consumer-friendliness. On one hand, many scientific publications speak of a target triangle of economic performance, security of supply, and environmental friendliness (see Buchholz et al., 2012; Frank et al., 2012; Pittel, 2012; Pittel and Lippelt, 2012). Conversely, the German Energy Act ("Energiewirtschaftsgesetz" or EnWG), for example, does not contain any explicit target formulation on social feasibility that would satisfy progressive advocates. Such advocates argue that a lack of distributional and participatory fairness prevents a successful energy transition (see, Hauff *et al.*, 2011; IASS, 2013; Renn, 2015).

Despite the energy transition being constrained and motivated by global environmental change, ecosystem dynamics are largely not included in transition frameworks. This, in turn, has guided the study of socio-ecological transition frameworks (Fischer-Kowalski et al., 2012), which are strongly related to the concepts of social and industrial metabolism with a particular focus on the metabolism of energy systems (Parra et al., 2018).

Accordingly, the following report aims to address the nexus of these three aspects and how they all drive and constrain what we could call a socio-eco-technical transition to a low carbon economy. Knowing that a successful transition would need to be socially, technologically and ecologically feasible, the report first attempts to identify both the status quo and upcoming trends in energy supply and demand technologies. A similar survey is then applied to the social aspects that apply to the diffusion of such technologies. We continue with an introduction to the main frameworks for the study of technological progress, socio-technical transitions and socio-ecological transitions, and a proposal for a socio-eco-technical transition framework. An overview of the modelling tools currently available for simulating such processes follows, alongside a selection of relevant examples.

2 Current trends in the energy transition

- A thorough understanding of the present-day energy system and the key technological and social trends that could influence future directions in the system provides a contextual background of the energy transition in the EU and, hence, of the requirements of the ENVIRO and QTDIAN modules
- The status quo and important trends relating to the technological and social aspects of the energy transition are discussed
- The implications of these trends for the energy modelling to be undertaken within the SENTINEL project are also considered

Overview of technological trends

In 2018, the most popular global sources of energy were oil products (31%), followed by coal (27%) and natural gas (23%). The renewable energy share was estimated to be 14%. Within the EU, oil products (33%) and natural gas (24%) dominate, while the renewable energy share is the third highest at 15%. However, the percentage share of renewable energy is predicted to double or triple by 2040.

In the EU, the renewable energy supply is dominated by bioenergy (60%). The remainder is shared between wind energy (13%), hydropower (12%), ambient heat pumps (5%), solar photovoltaic (PV) (4%), solar thermal (2%) and geothermal (3%). However, hydropower and wind energy dominate electricity production (both 35%), followed by bioenergy (18%) and solar PV (11%). By 2040, wind energy is predicted to rise to over 50%, while hydropower is likely to drop below 20%. The shares of solar PV and bioenergy are expected to rise and lower slightly, respectively. Relative changes are expected among the other technologies, but the four dominant renewable technologies are expected to remain at the forefront for the foreseeable future.

Within these categories, the technological trends in energy supply can be summarised as follows:

For wind turbines, the main areas of evolution are in tower and rotor size, rotor materials and generator mechanisms. Towers have risen from around 20 metres in the 1980s to over 150 metres today largely driven by better rotor blade materials, an area that continues to evolve thanks to advanced composite materials. Meanwhile, the use of two very different types of magnets in generator mechanisms–one of which requires a potentially limited supply of rare earth materials–continues to fuel debate within the industry. Lastly, rapid increases in the use of offshore turbines also look set to continue as various limitations and concerns surrounding onshore facilities may slow their expansion.

While first- and second-generation of PV cells continue to dominate the market, most of the advances in solar PV technology are found in third-generation cells, most notably perovskite cells whose efficiency is expected to soon reach an unprecedented 32%. Concentrated solar power (CSP) uses thermal solar energy to generate electricity, but it is a relatively mature technology with few new developments and its use within the EU appears to be levelling off for now.

Hydrogen fuel cells use stored hydrogen to generate localised electricity. Their use has received increasing levels of interest, especially if the hydrogen gas can be produced via electrolysis–which is a far cleaner process than producing hydrogen from natural gases. Ideally the electrolysis processes themselves would also be powered by renewable energy. Fuel cells–alongside heat pumps that capture energy via ambient temperature differentials, thus improving heating and cooling processes–are mature technologies that can be seen to operate in a space between energy supply and demand.

Other technological trends in energy demand–which encompass elements of overall energy efficiency, changes in the patterns and volumes of electricity demand known as demand response (DR) and improvements in the generation, storage and distribution of electricity known as distributed generation (DG)–can be summarised as follows:

The green building concept involves improvements in the efficiency of all types of energy within buildings throughout their lifetime. Meanwhile, the concept of the smart home is focused on improving energy efficiency within homes–particularly regarding the use of electrical energy–via digital technology. Hardware devices within such a home can enable remote access and control of electricity use, vastly improving the ability to improve energy efficiency.

Perhaps the most important smart home technology, smart meters, report energy use information to utility operators to assist in the operation of wider smart grids. By allowing end-users to buy–and, indeed, sell–energy back and forth with suppliers, the role of consumers in future energy networks could vastly change. As such, smart grids are seen as an entirely new approach to electrical systems, where improvements in the transfer of energy and information between suppliers and users is optimised using digital technology.

The smart grid concept allows the more rapid proliferation of locally generated renewable energy sources known as microgrids. Typically operating at level of a single building, facility or community, a microgrid can then present itself as a single controllable entity within a wider smart grid, generating, selling and buying power as required. Furthermore, the buying and selling or electricity and related services within a smart grid can be facilitated by the use of the secure transaction software technology known as blockchain.

Another vital ingredient in an efficient and renewable-friendly electrical network is the use of energy storage technology. The intermittency that is inherent to most renewable energy sources introduces major reliability factors to current networks. Accordingly, if renewables are to be integrated into electrical systems at wider scales, methods are needed for attenuating and controlling flows of electricity within future networks.

While energy storage is currently dominated by pumped hydro technology at the global and EU scales, many new and old technologies are competing for future market share in this arena. Compressed air energy storage (CAES) is on the rise for large-scale storage applications, particularly within Europe.

Meanwhile, the use of secondary batteries also appears to be increasing dramatically, suggesting that it is the most significant emerging technology at the smaller scale. Other established methodologies include flow batteries, ultracapacitors, flywheels, thermal energy storage and even the use of stationary electric vehicles in what is known as vehicle-to-grid (V2G) exchanges.

Overview of social trends

The transformation of our energy systems will also require deep changes in society itself. It becomes more and more apparent that a just and sustainable energy transition will only be possible with social acceptance and support for the energy transition. From this starting point, we reviewed key social trends relevant to be considered for the implementation of the energy transition. Diverse drivers and barriers of the energy transition are underlying those social trends, and they can highlight essential social aspects of the energy transition and their interdependences that have not been considered in models to date.

We identified six observed social trends defining the energy transitions currently: the transition from consumers to prosumers; changes in social acceptance of renewables and denial of climate change; uneven distribution of winners and losers in the energy transition (employment effects, energy and fuel poverty, community benefits and challenges); citizen empowerment by the digitalisation of energy generation and usage; behavioural change and rising awareness of behavioural rebounds; and transition from individual action to policy action. Those trends represent the growing relevance of social acceptance, democratic structures and justice in the energy transition debate.

Based on those six observed trends, we derived two key implications of how the social trends identified can be used to inform the development of energy modelling: Firstly, they can be used to identify new drivers and constraints that seem relevant for model implementation. Second, data relating to past trends can be used to inform scenario building processes (e.g., to define socio-technical RES potentials).

The SENTINEL toolbox QTDIAN will be informed by the social trends identified. QTDIAN aims to approach some of the following interlinked social aspects, which could be qualitatively and quantitatively integrated into energy models: social technology preferences and acceptance; fields and attitudes regarding social justice, preparedness of the economy, responsibilities/ownership, consumption behaviour, policy support. Furthermore, QTDIAN will use these trends as basis for the development of social storylines and scenarios.

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2.1 Technological trends

- Understanding the current patterns of energy use at the global and EU scales and the predicted directions in renewable energy use helps to contextualise potential energy transitions within the EU
- Investigating the latest technological trends provides further guidance on the hardware that is more likely to be implemented in future energy system configurations and, hence, will need to be considered within the project
- An in-depth overview of key energy supply technologies is given alongside a discussion of energy demand technologies, particularly the emergence of 'smart grids' and the energy storage technologies that are required to operationalise them

2.1.1 Current energy mix

The most recent global energy use data (International Energy Agency, 2019a)–for the year 2018 and shown in Figure 1–suggests that oil products remain the dominant energy supply (31.4%). However, solid fossil fuel in the form of coal is the second most popular source (26.7%), followed by natural gas (22.9%). Global renewable energy use remains low (14.0%), while nuclear energy is far less common (5.0%).

Similar data is available for the 28 EU states across the locally defined categories. The current nomenclature favoured by the EU defines the following six energy source groups: (1) solid fossil fuels (primarily hard coal and brown coal); (2) oil and petroleum products (primarily crude oil); (3) natural gas; (4) nuclear; (5) renewables and biofuels; and (6) wastes (non-renewable) (European Commission, 2019b). The most recent comprehensive data–also from 2018 (Eurostat, 2020)–is shown in Figure 1.

The data suggests that the total energy supply is again dominated by oil and petroleum products (32.8%) and natural gas (24.4%). However, solid fossil fuel use is far lower in the EU (13.6%), renewable energy being the third highest category (15.2%). Nuclear power is comparatively high in the EU (13.0%), while non-renewable wastes–not specifically listed at the global scale–falls far behind (0.9%).

At the energy demand end, transport, buildings and industry are the dominant sectors, consuming very similar shares of the total global demand–28.8%, 31.2% and 29.1%, respectively–as shown in Figure 2. All other sectors are grouped together and occupy the remaining 11.0% of demand. Meanwhile, the EU separates societal energy use into six sectors: (1) industry; (2) transport; (3) residential; (4) services; (5) agriculture and fishing; and (6) others, as shown in Figure 2. Here, the data again indicates that the transport (30.8%), residential (27.2%) and industry (24.6%) sectors dominate energy use, with services (14.5%), agriculture and fishing (2.4%) and the others (0.4%) further behind. Nevertheless, it is notable that the big three sectors represent less of the overall energy demand in the EU–82.5% compared with 89.0% globally–

and that the transport sector is slightly more dominant than the residential and industrial sectors within the EU.

Figure 1 Split of global (left) and EU28 (right) energy supply by energy source in 2018. Source: International Energy Agency (2019a) and Eurostat (2020)

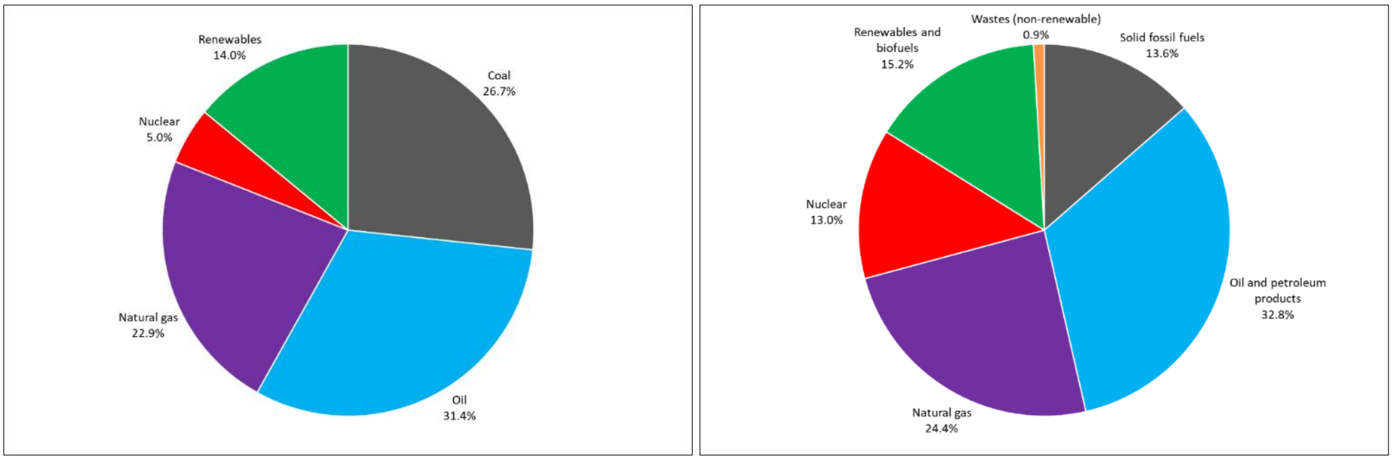
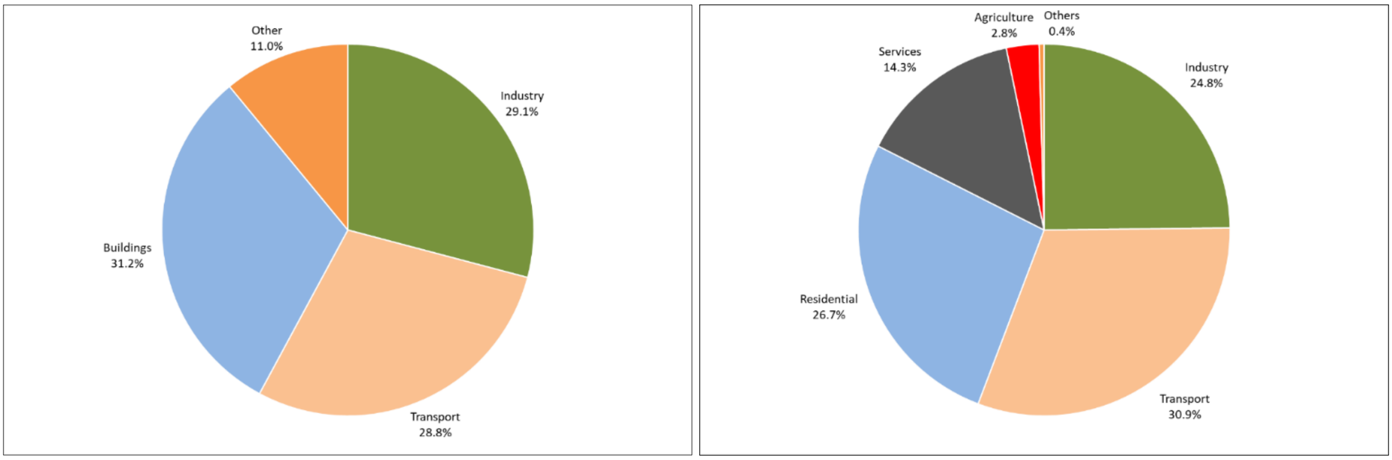


Figure 2 Split of global (left) and EU28 (right) supply by sector in 2018. Source: International Energy Agency (2019a) and Eurostat (2020)



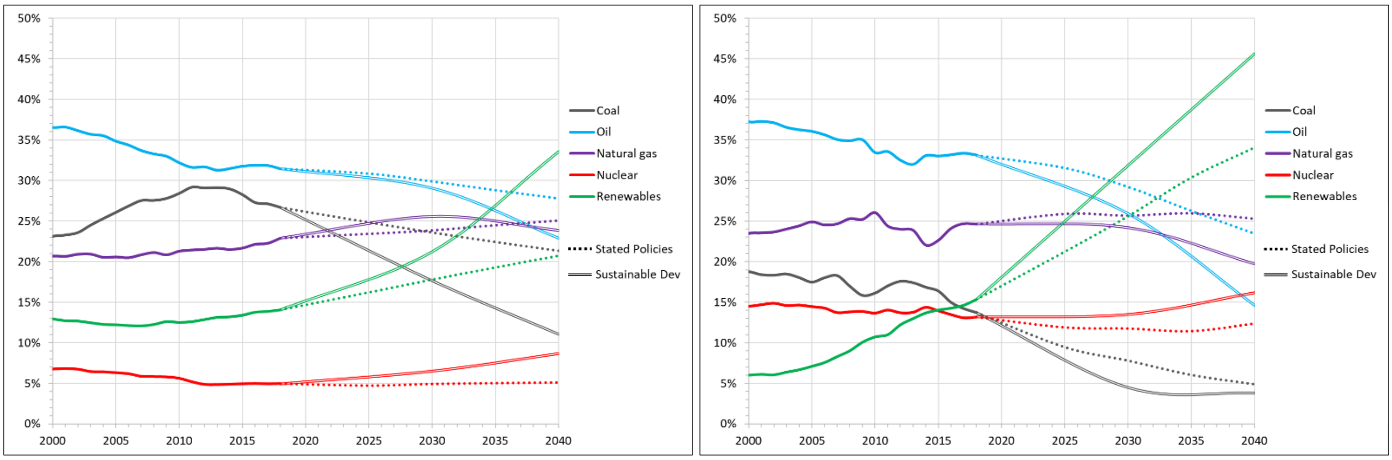
2.1.2 *Renewable energy directions*

Renewable energy sources are being heavily promoted as the key to addressing climate change and their use is expected to increase significantly in the coming decades. In an attempt to quantify these increases, the International Energy Agency (IEA) recently published several projected energy use scenarios as part of its World Energy Outlook 2019 report (International Energy Agency, 2019a). The first of these scenarios–the so-called Stated Policies Scenario–considers all existing government policy frameworks as well as expected future actions in accordance with announced policy positions. The second–known simply as the Sustainable Development Scenario–attempts to imagine a major transformation in the global energy system in response to the potential consequences of climate change.

The projected levels of renewable energy use in accordance with these scenarios, at the global and EU scales, are visualised as extensions to recorded historical data in

Figure 3. The key observation is that renewable energy use is expected to escalate while coal and oil use are expected to fall under both scenarios and across both scales. Comparing the two figures also suggests that the transition to renewable sources is likely to be more pronounced within the EU; even under the Stated Policies Scenario, use levels are predicted to rise from 15.4% in 2018 to 34.1% in 2040 compared to a change of 14.0% to 20.7% at the global scale.

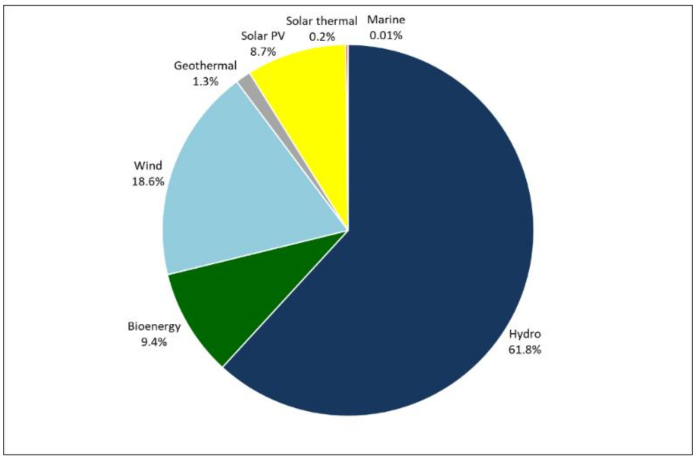
Figure 3 Observed distribution of global (left) and EU28 (right) energy supply by energy source for the period 2000 to 2018. Projected future distributions for the period 2018 to 2040 also shown, in accordance with IEA Stated Policies Scenario and Sustainable Development Scenario. Source: International Energy Agency (2019a, 2019b) and Eurostat (2020)



It is also worth noting that the use of natural gas and nuclear sources are generally not predicted to lower significantly under these scenarios. In fact, both are expected to increase slightly at the global scale to offset the short-term reductions in coal and oil, although the use of natural gas is expected to eventually lower. Within the EU, energy derived from natural gas and nuclear sources are expected to remain at similar levels within the Stated Policies Scenario although, again, natural gas is likely to reduce in time. Meanwhile, much like the global predictions, the use of nuclear energy is expected to rise slightly under the Sustainable Development Scenario to offset reductions in all three fossil fuel categories.

The current mix of renewable energy use within the EU–which forms the focus of this report–is summarised in Figure 4**.** The data suggests that renewable energy supply is currently dominated by biological energy ("bioenergy") sources, which account for some 60.4% of the total renewable energy supply. This is mostly comprised of primary solid biofuels (40.6%), but also includes pure biodiesels (5.7%), pure biogasoline (1.2%) and several others. The bioenergy total also includes two significant energy types derived from waste-to-energy technologies in the form of biogas production (6.9%) and the incineration of renewable municipal waste (4.3%). Renewable energy is also derived from wind energy (13.3%), hydropower (12.2%), ambient heat pumps (5.1%), solar sources–comprising solar photovoltaic or "solar PV" (4.3%) and solar thermal consisting of small-scale collectors and concentrated solar plants or "CSPs" (1.8%)–and geothermal (2.8%) sources.

Figure 4 Split of total renewable energy supply by energy source for all European Union 28 countries in 2018. Source: Eurostat (2020)

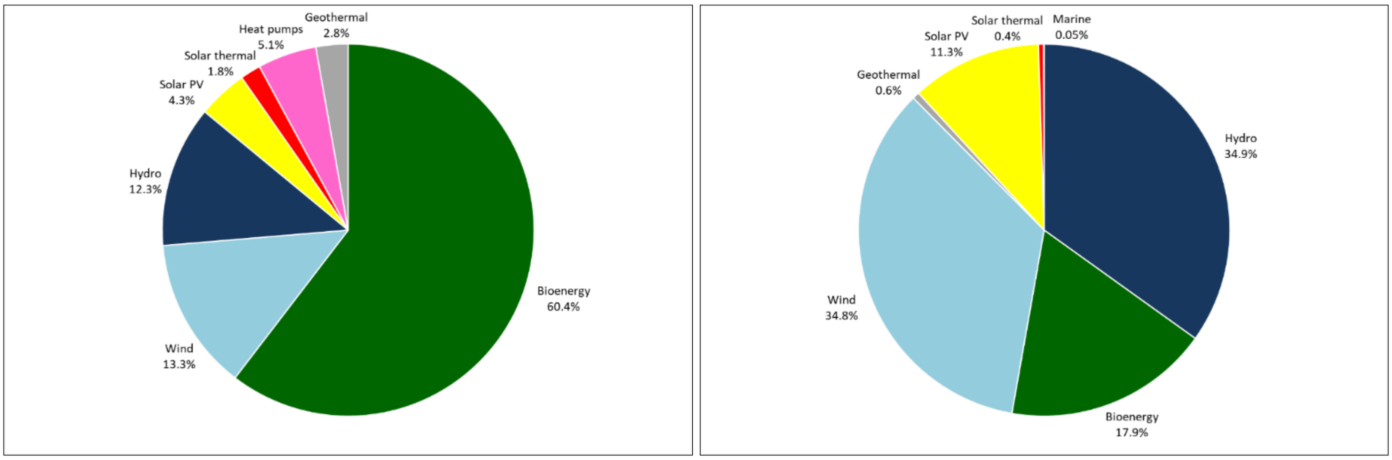


This data is more or less in line with the observed global statistics for total renewable energy use. Available data (International Energy Agency, 2019a) confirms that bioenergy is again the dominant type of renewable energy (67.5%), higher than EU levels largely because of the increased use of traditional biomass sources in developing countries (REN21, 2019a). Hydropower is the next highest category (18.0%)–also above EU levels–while wind and solar energy dominate the remaining 14.6% (BP, 2019).

All of this data confirms the growing role of renewable energy sources–and the distribution of these sources–within the energy spectrum as a whole. However, the rapidly increasing focus on the further electrification of energy systems, particularly in heating and mobility processes, highlights the importance of specifically analysing the current and future use of renewable energy sources within electricity generation processes. With this in mind, the current mix of renewable energy sources used in the generation of global electricity supplies is shown in Figure 5. Note that these sources account for 25.6% of the total electricity supply.

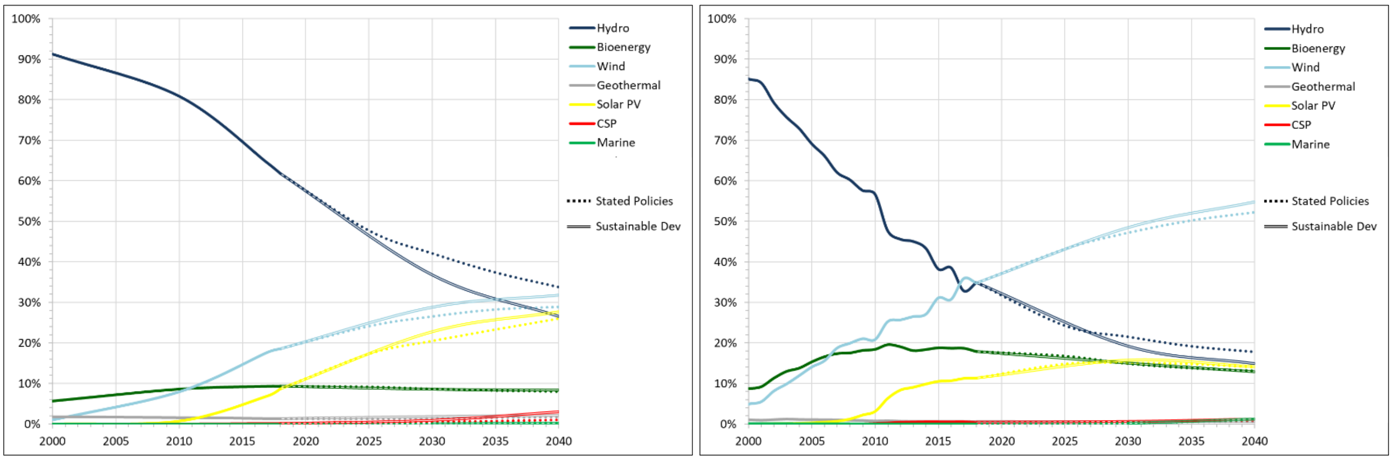
Data for renewable energy sources used to generate electricity within the EU is displayed in Figure 5. Combined, these renewable sources provide 33.2% of the total electricity supply. It is noted that the use of hydropower is much less common in the EU–34.9% compared to 61.8% globally. In its place, the use of wind is significantly higher–34.8% compared to 18.6%. Solar PV and bioenergy sources are also notably higher within the EU. Furthermore, comparison with Figure 5 confirms that wind, hydropower and solar PV are almost exclusively used in electricity generation while–with the exception of CSP plants–solar thermal and geothermal sources are more typically used in heating operations; heat pumps are virtually never used in electricity generation. The greatly reduced proportion of bioenergy in the spectrum of electricity generation confirms that bioenergy is also used extensively to provide heat and fuel energy.

Figure 5 Split of global (left) and EU28 (right) electricity supply derived from renewable energy sources by energy source category in 2018. These sources provide 25.6% and 33.2% of the total electricity supply globally and of the EU-28 countries, respectively. Source: International Energy Agency (2019a) and Eurostat (2020)



Future projections based on the Stated Policies Scenario and Sustainable Development Scenario were also calculated for the specific renewable energy categories (International Energy Agency, 2019a). These are visualised as extensions to recorded historical data at the global and EU scales in Figure 6.

Figure 6 Observed distribution of global (left) and EU28 (right) electricity supply derived from renewable energy sources by energy source for the period 2000 to 2018. Projected future distributions for the period 2018 to 2040 also shown, in accordance with IEA Stated Policies Scenario and Sustainable Development Scenario. Source: International Energy Agency (2019a) and Eurostat (2020)



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The most obvious trend in the data is that the share of hydropower is expected to decrease significantly at both scales in the next 20 years. At the global scale, it appears likely that the steadily rising popularity of wind and solar PV will soon allow them to share the majority of the renewable electricity market with the formerly dominant hydropower, which will continue to decrease in popularity. The share of bioenergy use in electricity production is also predicted to level out or decline slightly.

Wind power seems likely to become the overwhelmingly dominant form of renewable energy for electricity generation in the EU. Although not nearly as severe as the reduction in hydropower, the share of bioenergy use is also predicted to decline steadily within the EU. Likewise, while the use of solar PV is expected to rise, its rate of increase is expected to be milder than that of wind power and may even begin to reduce within the next decade or two.

Nevertheless, the remaining three categories–geothermal, marine energy and thermal solar energy in CSP plants–are all expected to continue to rise in popularity, albeit at a much lower level than the four dominant technologies. The share of geothermal energy is not expected to change considerably in the EU, but it is forecast to rise from 1.3% to 1.8% at the global scale by 2040 according to calculations made for the Stated Policies Scenario. The share of electricity derived from CSPs is projected to rise from 0.4% to 0.9% in the EU and from 0.2% to 1.1% globally under this scenario. It is also noted that the IEA seems to assign a higher priority to CSP technologies than others in this group within its Sustainable Development Scenario–its share at the global scale within this scenario rises significantly from 0.2% to 3.1% by 2040. Lastly, marine energy could prove to be the biggest relative mover in the group, rising from a negligible level of 0.05% to 1.1% in the EU and from 0.01% to 0.3% globally by 2040.

2.1.3 Energy supply technologies

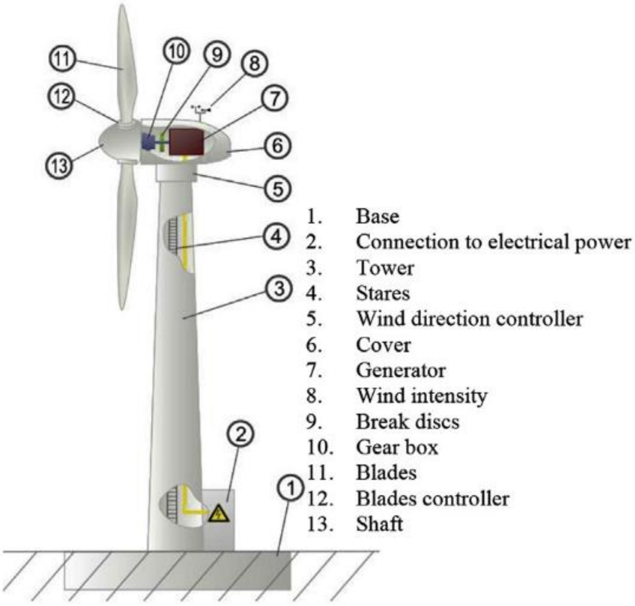
The previous section attempted to identify the current state of affairs with respect to renewable energy sources, and particularly their role within the increased electrification of future energy systems. For now, it appears that wind power, solar PV and bioenergy will continue to be the dominant renewable energy technologies for the foreseeable future, alongside the formerly dominant hydropower, which continues to lose popularity. The latest technological directions in these and other areas of the energy supply field are discussed in the sections that follow.

Wind turbines

Humans have been harnessing the kinetic energy contained within winds for centuries. However, until the middle of the previous century, this energy was solely converted into mechanical energy and used to pump water, grind grains and drive other mechanical devices in a variety of relatively simple applications. Yet, as with many other forms of renewable energy, interest in using wind turbines to generate electrical energy skyrocketed in the wake of the worldwide oil embargo of 1973. Indeed, as the data in Figure 6 demonstrate, wind turbines now look set to overtake hydropower as the leading renewable electricity source, particularly within the EU.

Wind turbines come in many forms and numerous vertical and horizontal approaches have been proposed. Furthermore, they can be situated on land ("onshore" turbines) or within bodies of water ("offshore" turbines). In any case, the most commonly used designs follow the traditional windmill approach of collecting rotational energy along a horizontal axis and, indeed, are known collectively as horizontal-axis wind turbines (HAWTs). By far the most popular of these uses a three-blade design consisting of a high tower anchored to a highly reinforced set of foundations. A nacelle structure atop the tower houses the generator mechanism that converts the rotational energy from the rotors into electricity (see Figure 7).

Figure 7 Parts contained in a horizontal axis wind turbine. Source: Danook et al. (2019)



At the utility scale, a typical modern wind turbine can deliver between one and three megawatts (MW) of power. Individual turbines tend to be installed in arrays known as 'windfarms' which can be as small as 20 or 30 units or, in the world's largest installations, several thousand units. Turbines are expected to complete hundreds of millions of loading cycles, giving them an expected lifespan of around 25 years (Mishnaevsky et al., 2017).

Although wind turbines are now considered to be a mature technology, their design elements continue to evolve, and great scope still exists for further advances. At the broader scale, the main area of evolution is in their size. This includes the diameter of the rotors, the height of tower required to support these rotors and, consequently, the power outputs they are capable of delivering (Serrano-González and Lacal-Arántegui, 2016). Again, while it is commonplace for modern turbines to deliver several MW of power, turbines built in the 1980s were only capable of producing around 50kW, less than 3% of current rates (Blaabjerg and Ionel, 2015). Likewise, rotor diameters and tower heights have risen from 20 or 30 metres in the 1980s to over 150 metres today.

These evolutions are largely due to advances in materials technology that have enabled larger blades to be manufactured that retain the lightness and high stiffness levels required for safe and efficient operation. At present, the rotor blades used in most utility-scale wind turbines are made of plastics reinforced with glass

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fibres known as 'e-fibres'. However, as blade sizes continue to increase, turbine manufacturers are eager to develop advanced composite materials that are stronger, lighter, more resistant to damage and easier to produce. Carbon fibre materials offer many advantages and have been proposed as a viable option but may prove be too expensive for widespread adoption. Accordingly, the use of e-glass/carbon hybrids is thought to offer a suitable compromise. Other high-strength glasses containing basalt and aramid have also been proposed, as well as the use of nanoengineered polymers and composites (Mishnaevsky et al., 2017).

The other highly contested field of research within wind turbine technology involves the generator mechanisms. Traditionally, the relatively slow rotational speeds of rotors have been converted to the faster rates required to produce electricity via a gearbox mechanism. However, so-called direct-drive mechanisms–that can convert the rotation of the rotor directly to electricity at lower rotational speeds via the use of magnets–are now being favoured as they involve fewer moving parts and require less maintenance (Wilburn, 2011). This is seen as a key benefit as turbines are frequently situated in isolated locations.

But, while direct-drive generators have become the norm in new wind turbine constructions, two very different varieties of these generators have emerged based on the type of magnet used in the conversion process. The first uses an electromagnet whereby a magnetic field is created using electrical current through wound copper coils. Meanwhile, the second uses permanent magnets that contain rare earth metals such as neodymium (Nd), praseodymium (Pr), terbium (Tb) and dysprosium (Dy) (Buchholz and Brandenburg, 2018). These magnets are generally more efficient than electromagnets but are significantly more expensive.

Moreover, the global supply of the rare earth elements used in permanent magnet generators, and of neodymium and dysprosium in particular, could become an issue in the future. This is especially true as the vast majority of these metals are mined in China where the government has previously employed export quotas. Unsurprisingly, European turbine manufacturers have tended to employ electrically-excited generators while Chinese manufacturers strongly favour the use of permanent magnets (Serrano-González and Lacal-Arántegui, 2016). In any case, it is worth noting that rare earth supply could become a resource scarcity issue within the wind turbine industry in the future, particularly for producers outside of China.

It is also worth noting that wind turbines–and onshore wind farms, in particular–have attracted some controversy in the past as a result of uncertainties about their potential social and environmental impacts. This has included general discourse regarding the impacts of large-scale wind farms on societal harmony and lifestyles within smaller rural communities (Borch, 2018), specific health impacts relating to the electromagnetic fields, shadow flicker and noise generated by wind farms (Knopper et al., 2014; Onakpoya et al., 2015), aesthetic impacts (Klæboe and Sundfør, 2016; Oosterlaken, 2014) and the physical impacts on local species, particularly larger birds (Vasilakis et al., 2016). A shortage of suitable land-based locations could also constrain the future propagation of onshore wind farms (Dupont et al., 2018; Yamani Douzi Sorkhabi et al., 2016).

In 2019, 95.5% of global wind energy capacity was from onshore wind turbine installations (GWEC, 2020); the remaining 4.5% was contained in offshore turbines. In the EU–which contains 27.4% of total global capacity–onshore turbines are less dominant and represent 88.5% of installed capacity against 11.5% for offshore (WindEurope, 2020). At both scales, the perceived limitations of onshore wind farms appear to have contributed to a significant increase in the use of offshore wind turbine technology in recent years. At the global scale, 10.2% of new installed capacity in 2019 was from offshore turbines. The use of offshore wind turbines is becoming considerably more widespread within the EU, where they represented 27.5% of the new capacity in 2019. Moreover, the capacity share of offshore wind turbines in the EU is expected to rise to almost 40% by 2030 (WindEurope, 2017).

Harvesting wind energy in offshore locations is thought to be generally advantageous to using onshore locations for several reasons (Myhr et al., 2014). Firstly, coastal and open sea locations generally receive higher winds. The potential environmental damages caused by their installation and operation are generally considered to be lower. Being more 'out of sight and out of mind', levels of political and public resistance also tend to be far lower. Finally, in theory, far more potential sites exist in offshore locations.

Conversely, the key constraints to developing offshore wind turbine facilities have historically been related to higher costs and technical limitations. However, the kilowatt-hour (kWh) price estimates for potential UK offshore developments have dropped by a third since 2017 and two-thirds since 2015 (Vaughan, 2019). This considerable decrease is sure to drastically increase the economic viability and attractiveness of future investment in offshore infrastructure.

The vast majority of current offshore wind turbines are installed in shallow water settings; in 2012, the average depth of water was a mere 22 metres (Athanasia and Genachte, 2013). This represents the key technical constraint to offshore wind energy in that it greatly restricts the number of suitable sites for future developments. In order to address this limitation, recent research has focused on operationalising turbines in 'deep offshore' waters where depths are in excess of 50 metres. But, while initial studies tended to favour the implementation of sturdier bottom-fixed structures (Pérez-Collazo et al., 2015), the use of such options does not appear to be practical in deeper waters.

Accordingly, floating wind turbines are now being seen as the superior option for opening large areas of open seas to wind energy generation. Although the turbine structures are allowed to float on the water's surface, they are fixed to a single location on the ocean floor and are not moveable in nature. While tethering turbines such that they can withstand heavy winds, waves and tidal movements requires relatively complex infrastructure to be assembled, turbines can be placed in depths of several hundred metres. At present, only a small number of floating wind turbine farms exist in Scotland and Japan. However, many large-scale research and development projects are currently in operation in Europe and the United States (US) and the technology is predicted to become cost-competitive by the end of the decade (GWEC, 2018).

Third-generation photovoltaic cells

The original, first-generation of photovoltaic (PV) cell technology utilises a single layer of crystalline silicon, wafer-based cells. Owing to the fragile nature of these cells, they are generally encased in several millimetres of glass, making them heavy, difficult to manufacture and limited in their scope of applications.

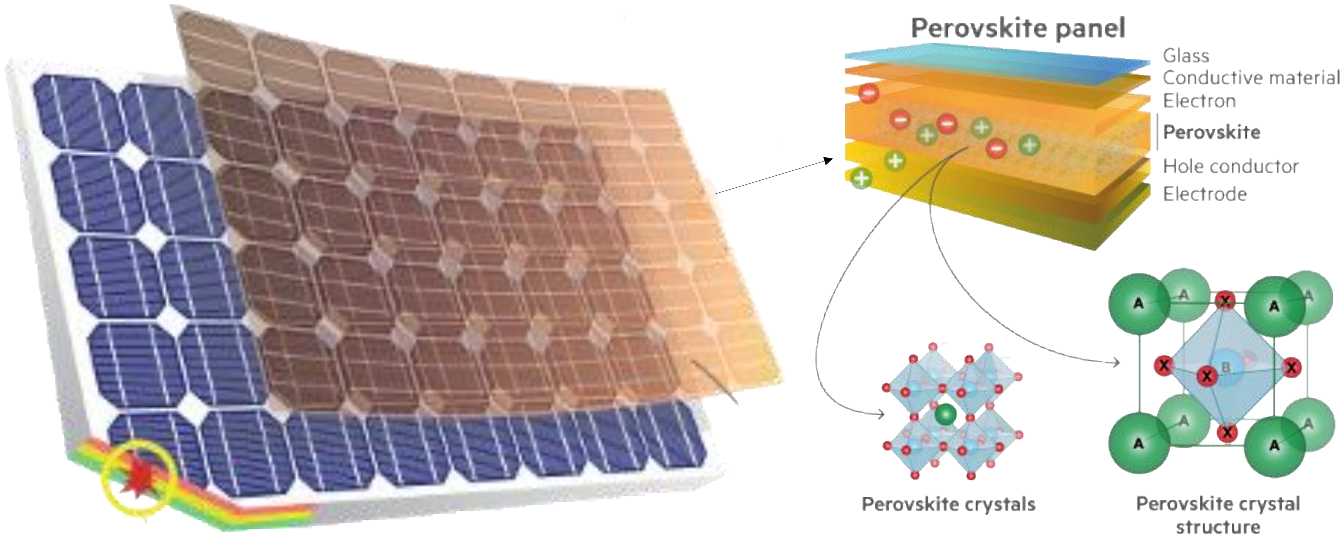
The second-generation of PV technology allowed a so-called 'thin-film' of cells to be arranged on substrate surfaces to form far lighter and more flexible sheets. This greatly improved the range of applications that could utilise PV cells although, until recently, such cells could not rival the solar conversion efficiencies offered by the first-generation technology. In any case, the efficiency rates of both of these technologies are, at best, around 25% for first-generation and 20% for second-generation cells (Ananthakumar et al., 2019).

Production of PV cells is still dominated by these two technologies. However, while still largely at the research and development stage, the next wave of third-generation photovoltaic cell technologies is emerging, with the aim of improving overall efficiency and reducing costs while maintaining the simplicity and versatility of thin film cells.

Many unique approaches are contained within this third generation of technologies. This includes the dye-sensitized solar cell (DSSC), or 'Grätzel cell', where an organic dye is used to absorb light energy, much like chlorophyll in plants. DSSCs are capable of high efficiency levels but concerns have been raised regarding their stability in extreme temperatures and higher manufacturing costs. Another alternative, the quantum-dot sensitized solar cell (QDSSC), offers higher efficiencies and greater stability than DSSC using 'quantum dots'–extremely small semiconductor particles–as the absorbing material. Although QDSSC has shown promising technical characteristics, some concerns remain about potential toxicity and stability issues and further research to address these issues is required (Pan et al., 2018). Conversely, copper zinc tin sulphide solar (CZTS) cells were specifically designed to provide a non-toxic product made from cheap and earth-abundant materials, albeit with lower efficiency levels than other technologies (Ito, 2015).

However, the third-generation technology receiving the most attention in recent years is the perovskite solar cell (PSC) (Mora-Seró, 2018) (see Figure 8). Although, strictly speaking, the word perovskite refers to a specific compound–calcium titanate ($CaTiO_3$)–the term is used here in reference to a group of compounds that share a similar crystal structure. These so-called 'perovskite structured' compounds act as the light-absorbers in a PSC.

Figure 8 Perovskite crystal structure within a perovskite solar PV panel. Source: Modified from Hook (2018)



The upswing in the commercial appeal of PSC technology is largely due to the fact that they are relatively inexpensive and simple to produce and recent research has resulted in dramatic increases in observed efficiencies (Green et al., 2014). In fact, efficiencies of 28% have been achieved in recent PSC research, and efficiencies of up to 32% are predicted (Hossain et al., 2019), confirming that they can be more than competitive with first generation cells in this regard. Add to this chemical stability, potential transparency, the ability to be printed on any number of flexible surfaces and functionality in low-light conditions and PSC technology can be seen to offer a very attractive list of benefits (Fakharuddin et al., 2017).

The ability to easily and cheaply produce solar cells is a key element in their prospects as a viable future renewable energy technology. In this regard, organic solar cell (OSC) technology is also attracting attention in recent years. OSC is especially attractive because of its low production costs and environmental impacts, high flexibility and the ease of printing OSCs over large areas. Traditionally, the major disadvantage of OSC technology has been far lower solar conversion efficiency; the maximum rate in 2013 was still barely 10% (You et al., 2013). However, recent advancements have resulted in far more competitive efficiencies of around 17% (Meng et al., 2018). Ultimately, the attractiveness of OSCs still hinges on the balance between cost, printability and efficiency.

Concentrated solar power

Concentrated solar power (CSP) is a form of thermal solar energy generation whereby sunlight is focused towards a common location allowing very high levels of heat energy to accumulate at a single point. As with other thermal power stations–e.g., coal, gas, nuclear or geothermal–a heat engine is then used to convert the collected heat to mechanical energy and, finally, electricity.

The most common type of CSP is the parabolic-trough collector (see Figure 9). Indeed, parabolic-trough plants dominate the global distribution of CSP plants (Zhang et al., 2013). As they name suggests, they are comprised of parabola-shaped mirrored troughs with a receiver tube of flowing fluid travelling along the focal point of the parabola to collect heat (Barlev et al., 2011). Higher efficiencies and better energy storage capabilities have seen a sharp rise in the popularity of solar towers, the second most common CSP technology. In fact, they now represent around half of the world's new CSP plant constructions (REN21, 2019a).

Solar tower operations use a large array of heliostat reflectors, each focusing sunlight towards a single, central collection point within an elevated tower. The third most common CSP type, Linear Fresnel Reflectors (LFRs), are similar to parabolic troughs in that they focus solar heat into a local receiver tube. However, LFRs utilise complex arrays of flat mirrors to direct incoming sunlight. Although LFR use is thought to be more cost-effective, it is generally considered to be a low efficiency technology (Abbas et al., 2013). As such, pending further research, interest in LFRs remains low when compared with parabolic-trough and power towers.

At present, all large-scale CSP plants (with capacities above 50 MW) in the EU are located within Spain and use parabolic-trough technology. These plants represent 94% of installed capacity within the EU (National Renewable Energy Laboratory, 2019) and approximately 42% of global capacity (REN21, 2019a). Several smaller towers, representing a further 4.4% of EU capacity, are in operation in Spain, France, Italy, Greece, Germany and Denmark. Three Linear Fresnel Reflector plants operate in France, Italy and Spain and represent the final 1.7% of EU installed capacity.

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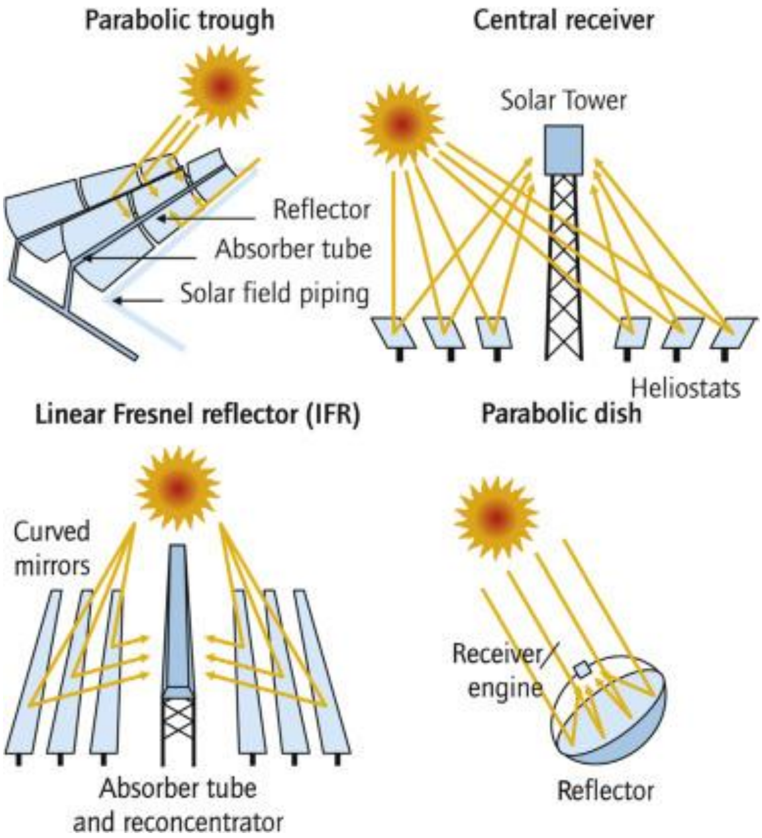
Figure 9 Types of available concentrated solar power technologies. Source: Fuqiang et al. (2017)



CSP is seen as a relatively mature technology and many new plants are planned worldwide, particularly outside of Europe. And, although the investment feasibility of CSP projects is generally limited to sunnier regions, the technology is of particular interest to developing countries with increasing energy demands and high levels of solar radiation.

Marine energy

The constant movement of the vast global volumes of ocean water offer a vast and largely untapped source of renewable energy. Various approaches now exist that seek to harness this potential in the form of tidal and wave energy technologies, although most are yet to make it beyond the conceptual or demonstration stages. Nevertheless, research continues to produce encouraging results, suggesting that this is a field of renewable energy research with considerable potential (Uihlein and Magagna, 2016).

The most obvious benefit of utilising tidal energy is that the high reliability of tidal cycles effectively eliminates the intermittency issues inherent in other forms of renewable energy generation such as wind and solar. The most established of these methods is known broadly as tidal range technology and generates energy using the potential energy difference between the high and low levels within a tidal cycle. During the

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peak, 'high tide' period some form of mechanical restriction is applied such that the level is maintained within a given location. The most common of these is to apply a moveable barrage, much like a dam. Then, when outside water levels recede, energy can be generated by driving the higher water levels within the storage space through turbines, much as energy is generated in a hydropower dam. Although this is by no means a new practice–the Rance Tidal Power Station was completed in France in 1966–only a handful of such structures are in operation. However, even if their functionality is more or less limited to areas with large tidal differences, their potential is still recognised in many locations (O'Doherty et al., 2018).

The most promising new approach to tidal energy is that of the tidal stream generator (TSG). Here, the tidal energy is accessed directly in open bodies of water using underwater turbines in horizontal or vertical configurations. Unlike tidal range approaches, this method does not require the construction of large infrastructure and is, hence, far cheaper, less resource intensive and less disruptive to local ecosystems. As they are best driven by higher velocity flows, such devices are ideally situated where some form of natural restriction causes incoming and receding tidal flows to be faster than in more open locations. A single tidal stream turbine was in operation in the UK from 2008 to 2019, although no facilities are currently in operation. However, a number of technologies and projects are currently in development.

Although less inherently predictable than tidal energy, wave energy is also increasingly being investigated as a potential marine energy source. Wave energy collectors aim to exploit the kinetic energy of wave motions using a variety of different approaches. In fact, over 1000 patents have been filed for a range of available technologies (Greaves, 2018).

Wave energy technologies can be broadly classified according to the methodology employed. Oscillating water columns are partially submerged objects with a volume of air trapped within it. Incoming wave actions generate energy by forcing his air through a turbine. Hinged contour devices involve two or more individual parts which move around each other in some pattern as waves pass by. This relative motion is then used to generate energy. Buoyant moored devices are relatively simple devices where the motion of a floating device bobbing on the surface is converted to energy. Finally, overtopping devices generate energy by forcing water that flows through an open inlet to flow through a turbine beneath.

In both hemispheres, the highest levels of wave energy occur at locations with between 40 and 60 degrees of latitude and these are seen as the most suitable locations for collecting wave energy (López et al., 2013). Accordingly, a growing number of 'wave farms'–where multiple wave energy devices are installed–have been or are being constructed in and around these zones, particularly in the UK, Portugal, the US and Australia. In any case, wave power remains a niche technology and even the world's largest wave farms are only capable of delivering between 5 and 20 MW of power.

Biogas

Biogas is a combustible mixture of gases–primarily methane and carbon dioxide, but often also containing traces of hydrogen sulphide, water and siloxanes–formed by the anaerobic digestion of organic matter. Gases produced at biogas plants are typically converted to electricity, heat or a combination of both using onsite gas-fired engines and it is thought that the split between these two uses is currently more or less even within the EU. Furthermore, carbon dioxide and trace gases can also be removed from biogas to produce

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biomethane which can be used as a vehicle fuel or be transferred to the local natural gas grid. This is said to represent around 7% of the current biogas production in the EU (Scarlat et al., 2018).

The EU is the current world leader in the field of biogas production and produces around half of the global supply. Although the growth rate in overall biogas capacity in the EU appears to have peaked around 2007, the total number of biogas plants in the EU rose from 6,227 in 2009 to 17,783 in 2017. This suggests that the ongoing steady increases in capacity are now driven by smaller plants, many of which are used to digest agricultural plant substrates, the dominant type of biogas facility in the EU (71%) (Banja et al., 2019). Other common types are those that digest sewage sludge (16%) and landfill waste (9%).

So, while fuels derived from biological sources still dominate the statistics for renewable energy in the EU (see Figure 4) the biggest gains within the group of bioenergy sources in the past ten years has been from biogas. Indeed, while the share of renewable energy attributed to biologically sourced fuels has dropped from 59.2% in 2008 to 50.0% in 2007, the share for biogas has risen from 4.5% to 7.2%. This suggests that, although biogas production is a mature technology with a limited scope for further technical advances, it is the ongoing quiet achiever in the world of bioenergy and may well continue to expand its share in the renewable energy mix.

Hydrogen–fuel cells

Originally invented in 1838, the fuel cell is a theoretically simple device that creates electrical energy from a fuel source and an oxidising agent via a pair of redox chemical reactions (O'Hayre et al., 2016). The fuel–most commonly hydrogen–is first split into positive ions and electrons at an anode in the presence of a catalyst. The ions then flow from the anode towards a cathode via an electrolyte compound that runs between them. At the cathode, an oxidising agent–most commonly oxygen–reacts with the ions, also in the presence of a catalyst, to form a waste product, in this example water. Most importantly, the electrons released in the initial reaction generate direct current (DC) electrical energy.

Individual fuel cells are not capable of producing large amounts of power. Consequently, in order to produce usable amounts, many smaller units are typically combined in a multi-cell setup. And, while almost all fuel cells use hydrogen and oxygen as the fuel and oxidising agent, respectively, different fuel cell technologies, capable of producing different levels of power, are distinguished by the electrolyte used as well as their typical operating temperatures.

Smaller-scale units tend to operate at lower temperatures. The most common commercially available examples of these technologies include the well-established alkaline fuel cell (AFC) and the proton-exchange membrane fuel cell (PEMFC), both of which typically operate below 80°C, and the phosphoric acid fuel cell (PAFC), which operates at around 200°C (Badwal et al., 2014). Working examples of these technologies have produced power outputs as high as 200-500 kW, although typical applications tend to be far smaller.

Conversely, larger-scale 'high-temperature' units, operating at temperatures well over 600°C, are able to produce far higher power outputs. The solid oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) have both proven capable of delivering up to 2MW of power, although designers have predicted that units of up to 100MW are possible (Smithsonian Institution, 2017).

At present, the dominant uses of fuel cell technology are localised power supply and transportation. Stationary fuel cells are already used in a variety of industrial, commercial and residential settings as sources both primary and backup power supplies. Owing to the simplicity and reliability they are especially useful in remote locations. Indeed, alkaline fuel cells provided energy and water to the Apollo spacecraft in the 1960s. Installing fuel cells within post-transition renewable energy power grids has also been identified as a potential solution to the intermittency issues that are inherent to wind and solar energy (Ehteshami and Chan, 2014; Heilek et al., 2014).

Fuel cell vehicles (FCVs), predominantly cars and buses, are already in use. Although their market penetration has been limited to date, Hyundai, Toyota and Honda all have fuel cell-powered models currently in production. Likewise, although only around 100 buses are in use globally, fuel cell buses are capable of far higher fuel economies than either diesel or natural gas-powered equivalents. Fuel cells are theoretically capable of efficiently powering many other types of vehicle, from motorcycles, boats and trains, and even jet engines for aviation (Hamacher, 2014). Nevertheless, it is noted that the global availability of platinum–the most common catalyst in FCV cells–has been highlighted as a potential future constraint (Stephens et al., 2016).

Hydrogen–electrolysis

While the operation of a fuel cell itself does not produce harmful emissions–only electricity and water–it does require hydrogen as a fuel. This is problematic as raw hydrogen is predominantly still produced using processes that utilise fossil fuels in the form of natural gas (48%), oil (30%) and coal (18%), all of which produce sizeable volumes of greenhouse gas emissions (Chouhan et al., 2016). The remaining 4% of hydrogen is produced using the far cleaner process of electrolysis, where electrical energy is applied to water to produce hydrogen and oxygen. As such, it can be seen as the reverse of the fuel cell process and equally devoid of harmful emissions.

Accordingly, if the electricity used in this process is derived from renewable sources, electrolysis and the use of hydrogen represents a promising gateway to an array of new possibilities in renewable energy use. Aside from the many functions offered by powering fuel cells, cleanly-produced hydrogen–or 'green hydrogen'–can be combusted directly for use as a heat source in a variety of industrial applications, particularly those that require very high heat levels (Wilkes et al., 2019). Large-scale electrolysis plants are yet to become operational, although several high-profile demonstrations projects are currently in development, particularly in Europe.

Heat pumps

Although not directly related to electricity generation processes, heat pumps are another form of energy-capturing technology making recent headway in the renewable energy sector. They take advantage of the often-small amounts of ambient heat that already exist around us in a variety forms and sources and convert them into useable heat. As these pieces of heat are generally not hot enough to be used directly as heat sources, a heat pump uses external electrical energy to amplify the heat differential to a temperature that is useable for space heating applications, particularly in residential and commercial buildings (Urchueguia, 2016).

The concept of the heat pump is a very mature technology; the idea was first proposed by Lord Kelvin in 1852. In fact, many other common devices that use external energy to move heat from one place to another, such as air conditioners and refrigerators, operate in much the same way using what is known as the vapour-compression refrigeration cycle. First, heat is removed from one location–the "source"–by transferring it into a transfer medium or "refrigerant" within a pipe. The refrigerant is then mechanically compressed, raising its heat and pressure. This pressure increase also helps to transfer it to a second location in the pipe network. Here the temperature of the heated refrigerant drops as it transfers its heat to a cooler space that requires heating–the "sink". The cooler, but still pressurised, refrigerant is then allowed to expand and is moved back to the source location to begin the cycle again.

So, while an additional amount of external energy is required for their operation, the net energy gains from a heat pump can be significant. Certainly, heat pumps use less energy to produce a given amount of heat than the direct use of electrical or fossil fuel energy in, for example, electric furnaces or radiant heaters. It is here that the benefits of heat pumps are best demonstrated, and these benefits are even more pronounced when they are powered by electricity from renewable sources.

The sources of heat used in heat pump setups are generally air and water, although any temperature differential could theoretically be used to drive a heat pump cycle, and heat from such things as sewage, industrial waste and flue gas have been used. Large scale heat pump applications tend to operate on geothermal energy whereby heat from the earth–typically within groundwater, but also within heated streams and other bodies of water, or the earth itself–is used to provide heated water to local networks. In fact, it is estimated that around 70% of the world's geothermal energy consumption is via heat pump applications (DiPippo and Renner, 2014).

The heat pump market within the EU is currently dominated by small-scale air-based applications and this is likely to remain the case for the foreseeable future in light of increasing legislation on energy efficient heaters and buildings (Urchueguia, 2016). While the geothermal share has stagnated at around 10% in recent years, a growing interest in the use of large-scale heat pumps, where geothermal sources are more prevalent, is predicted to bolster future levels of use. This would seem to be largely driven by the attractiveness of using large-scale heat pumps for district heating and industrial applications (Paardekooper et al., 2018).

2.1.4 Energy demand technologies

Energy demand management (EDM), or demand-side management (DSM), are general terms used to describe all activities and technologies concerned with the streamlining and minimising of energy use after it has been produced by energy supply activities. Collectively, these elements can be divided into three general types. The first two of these focus on the reduction and alteration of the demands themselves, while the third relates to the management of available energy supplies within networks at different scales. All three elements are often implemented simultaneously, particularly in modern electricity networks.

Firstly, ***energy efficiency*** encompasses methods of reducing demands by lowering the amount of energy needed to undertake a task. Elements contained within this group do not address the tasks or patterns of energy use themselves. Rather, they seek to find more efficient pathways for completing energy-related

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activities. This is usually achieved via technological innovations in energy-using machines, appliances or other devices or by implementing holistic design approaches specifically aimed at maximising efficiency in a system.

Secondly, ***demand response (DR)*** refers to changes in the patterns and volumes of demand that result from changes in consumer behaviour, generally within electricity networks. DR mechanisms are typically the result of time-dependent pricing structures and other financial incentives applied by energy suppliers (Paterakis et al., 2017), but may also be influenced by other technical information or signals (Nolan and O'Malley, 2015). Traditionally this has involved simple incentives such as reduced charges during off-peak periods. However, technological advances in power metering, communication and control within networks, have resulted in a far wider range of options for creating more reliable and efficient networks (Deng et al., 2015; Siano, 2014).

Lastly, the term ***distributed generation (DG)*** is used to describe the many ways in which energy can be generated, stored and distributed at the local scale in order to improve the reliability, efficiency and cost-effectiveness of localised energy supplies. Collectively, infrastructure components within a distributed generation system are known as distributed energy resources (DER). Although the term is often assumed to solely refer to devices that produce localised sources of electrical energy, renewable or otherwise (Mokhtari et al., 2017), it can also be expanded to include other infrastructure that assists in the smarter use of this energy, or energy entering from a wider energy grid, such as local energy storage devices (Funabashi, 2016).

The energy systems of the future are likely to be driven by three factors: decarbonisation, electrification, decentralisation and digitalisation (Andoni et al., 2019; Brilliantova and Thurner, 2019). Understandably, energy supply technologies tend to be centred on the decarbonisation of energy sources, mostly via the increased use of renewable sources of electricity. However, emerging technologies within the areas of energy distribution and consumption are attempting to address all three of these factors in a variety of intersecting ways. Again, this is occurring predominantly within the field of electrical networks, but other technological advances are occurring, particularly with respect to thermal heat. An overview of the key technological directions being taken within the energy demand field is provided in the sections that follow.

Green buildings

As the increased electrification of the energy system has become a priority in the race to reduce carbon emissions, the key emerging technologies within the field of energy demand tend to focus on changes within the electricity sector. This will become evident in the sections that follow. However, regardless of the available sources of energy, at a more fundamental level the green building concept attempts to minimise environmental impacts incurred during the construction–and sometimes demolition–processes and, subsequently, during the ongoing daily operation of a building. Assessment of these impacts typically considers greenhouse gas (GHG) emissions, air and water pollution, land and resource use and waste production, although other factors may also be considered.

Around 80% of the GHG emissions produced during a building's lifetime occur within its operational phase (Jadhav, 2016a). Accordingly, green building design processes tend to have a strong focus on maximising the net energy efficiency observed in buildings during their day-to-day activities (Kubba, 2017). This is principally achieved by optimising thermal processes, appliance and fixture selection, and through the use of on-site renewable energy sources and storage devices.

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Optimal temperatures within a building are achieved by the management of heating and cooling processes. Meanwhile, appropriate ventilation is needed to circulate and refresh the air within the building. In green buildings, these processes are optimised in several ways. Firstly, passive architectural design elements involving the sizing and alignments of walls, rooms and windows can improve access to sunlight and air flow and retention of heat energy. Similarly, use of high thermal mass materials in walls and floors can be used to store thermal energy in order to regulate building temperatures (Hu and He, 2018). The third mechanism is that of insulation. Minimising unwanted heat flows into or out of a building is a vital part of regulating overall building temperatures and the highest and lowest sections of a building–attics, roofs, basements, ground-level floors, and so on–are often highlighted as particularly sensitive areas. However, many buildings also lose significant amounts of heat energy through poor quality glass and special, low-emissivity coatings are now being used to restrict heat radiation through glass windows and doors (Jadhav, 2016b). Finally, heat being expelled from the building in wastewater and ventilated air can be reused to heat incoming water and air as part of an energy recovery process (Kibert, 2016).

Overall energy consumption within a building can also be greatly reduced via the use of energy efficient appliances, fixtures and lighting. A range of ecolabel systems are now in worldwide operation that allow prospective buyers to assess the energy efficiency ratings of many types of consumer appliances. A variety of low-energy lighting options are also now available. This includes the still-dominant older fluorescent lighting technologies and the relatively new solid-state lighting–including semiconductor light-emitting diodes (LED), organic light-emitting diodes (OLED) and polymer light-emitting diodes (PLED)–all of which offer efficiencies well in excess of the traditional electrical filament lights. Furthermore, new styles of power fixtures can now restrict the small amounts of lost energy drained by appliances in stand-by mode (Jadhav, 2016c) Lastly, much like thermal flows, passive solutions implemented in the building design stage can allow greater passage of sunlight into a building, reducing the need for powered lights during daylight hours.

Small-scale onsite renewable energy sources are also often integrated into green buildings. At present, this most commonly involves solar PV and wind turbine devices for electricity generation, and solar thermal devices and air-based heat pumps for heating. The terms zero-energy building (ZEB) and nearly zero-energy building (NZEB) are now being used to describe buildings where all, or nearly all, of the ongoing energy demands of a building–typically also being minimised by a combination of energy efficiency measures–can be satisfied using only renewable sources (Berardi, 2018).

Smart homes

Much like green buildings, the concept of the smart home is primarily related to the optimisation of site-specific energy use. However, the growing field of technology that surrounds them has much wider implications for addressing efficiency issues at broader scales. In its most general sense, a smart home is one where users and utility providers can access and control the functionality of domestic systems using some form of digital network technology (Hargreaves and Wilson, 2017). The ability of using network connections to access heating and lighting systems and a wide array of other Internet of Things (IoT) or 'smart' devices and appliances introduces myriad possibilities for understanding and enhancing home energy efficiency.

Smart home technologies include all such sensors, monitors, meters, interfaces, appliances and devices within the home that can be networked in ways that enable access and control from both local and remote

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locations. Sensors and monitors are typically used to report environmental factors such as temperature, humidity, light levels or motion. So-called 'smart meters' can also be used to report energy use information back to utility operators to assist in the operation of wider 'smart grids'. Control functionality is provided using software interfaces on devices such as smartphones, tablets, laptops and other devices or via permanent hardware interfaces within the home. Many appliances and devices can also make automatic adjustments based on real-time environmental or energy network information. Appliances and devices already being operated within such networks include heating and lighting systems, refrigerators, hot water boilers and radiators, windows and curtains, electric car chargers and washing machines. A thorough overview of the latest developments in smart home technologies can be found in Lobaccaro *et al* (2016).

The promotion of smart home technology was on the EU's list of 10 priority actions within the 2015 version of its Strategic Energy Technology (SET) Plan (European Commission, 2015) and smart technologies continue to be highlighted within the latest publications (European Commission, 2018, 2017). At the broader scale, in 2009 the EU also planned to have 80% of consumers equipped with electricity smart meters by 2020 in an attempt to streamline the functionality of the region's electricity networks (European Commission, 2012, 2009). And, although progress has been slower than expected–recent predictions suggest that around 40% of consumers will have meters installed by 2020 (Tractebel Impact, 2019)–significant percentages have been achieved in many countries and the rollout is set to continue. In any case, the push for smart metering is predicted to stimulate the further dissemination of smart appliances and other smart home technologies within the European market (Serrenho and Bertoldi, 2019).

Even if smart home technology is still in its infancy, it has already unquestionably demonstrated its ability to employ technology as a tool for monitoring and controlling electrical energy efficiency at the household-level. Furthermore, as domestic consumers represent the end-use node in any energy distribution system, the ability of the smart home to interact with energy suppliers and fellow users in real time makes them a fundamental building block (DECC/OFGEM, 2011) in what is arguably the most important trend in energy demand technology today: the smart grid.

Smart grids

The concept of the smart grid is a blanket and somewhat loosely-defined term (Salman, 2017a) used to describe more holistic, symbiotic and technologically advanced approaches to the generation, transmission, distribution, storage and consumption of energy within electrical networks. While the name implies the increased use of digital technology–and this is certainly the key element–the term ultimately refers to electrical grids that encompass advances in all three elements of energy demand management (Siano, 2014).

The smart grid represents the next generation in electricity network technology by implementing decentralised grids where significant improvements in the reliability, security, profitability and flexibility of networks can be achieved while increasing overall efficiency and, hence, reducing carbon emissions (Deng et al., 2015). A simplified summary of the differences between current, conventional electricity networks and smart grids is shown in Table 1.

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Table 1 Comparison of current electrical networks and smart grids. Source: Salman (2017b) and Keyhani (2019)

	Current networks	Smart grids
Communications	None or one-way between power companies, generally not in real time	Two-way, in real time
Interaction with customers/users	Limited to large energy users	Extensive
Metering	Electromechanical	Digital, enabling real-time pricing and metering
Operation and maintenance	Manual checks	Remote monitoring and diagnostics, time-based maintenance
Power generation	Centralised	Centralised and distributed, significant use of renewable resources and energy storage
Power flow control	Limited	Comprehensive, automated
Reliability	Prone to failures and cascading outages	Proactive protection prevents outages before they start
Restoration after disturbances	Manual	Decentralised self-healing
Network topology	Generally radial with one-way power flow	Network with multiple power flow pathways

In essence, the smart grid is a new approach to electrical systems, one where improvements in the transfer of information, and of electricity itself, between suppliers and users is optimised using digital technology. Firstly, the increased ability of energy utility operators to monitor energy flows in real time–particularly via the use of smart meters–has greatly enhanced the capacity to plan and regulate networks (Borlase et al., 2018). In a traditional network, the price of electricity has tended to be fixed by suppliers. Even when small demand response measures are offered, such as slightly reduced prices during off-peak hours of the day, electricity charges tend to remain more or less constant for months at a time. Moreover, operators are not able to assess or control system loads in real time, particularly during peak load periods, and typically need to rely on auxiliary equipment during these times, equipment that is subsequently left idle during off-peak periods (Keyhani, 2019). Predictability issues of this kind are exacerbated further when less predictable sources such as wind and solar are introduced into the system.

Conversely, in a smart grid equipped with smart meters, detailed network usage data allows energy suppliers to monitor system behaviour and develop their short- and long-term responses accordingly. They are also able to attenuate consumer demand on the system by varying the cost of energy via so-called 'real-time pricing'. Informing the consumer of the price of electricity in real time allows them to make incentive-based

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decisions regarding their power use. It also allows smart appliances to optimise energy consumption within buildings, particularly for nonessential activities that can be undertaken when prices are lower.

The second critical factor driving the development of smart grids is the growing proliferation of locally generated renewable energy which can be sold to other users or fed back into wider networks (Lobaccaro et al., 2016). In traditional networks, most of the energy is obtained from large, centralised sources. Distributed generation sources such as solar PV and fuel cells were generally only used as backup or auxiliary supplies for their owners and not part of the grid proper (Kabalci and Kabalci, 2019). However, generating and supplying energy from multiple decentralised locations can greatly reduce transmission distances and improve the quality, reliability and cost of supply (Rihan, 2019).

Furthermore, real-time pricing schemes provide incentives for energy users to install distributed generation infrastructure of their own in order to become both energy consumers and producers–so-called 'prosumers'–and the economic incentives provided by selling locally-generated electricity is predicted to appeal to a wide range of both residential and commercial users (Keyhani, 2019). In this way, the smart grid concept is seen to actively foster the decentralisation of electricity networks and the foundation of smaller regional sub-units of energy users, producers, distributors and sellers. The conceptualisation of these regional clusters, or 'micro grids', is discussed further in the section.

The heart of the smart grid concept, therefore, lies in the optimisation of the bidirectional exchange of energy and information between producers and consumers, thus transforming end-users from passive to active participants in the functioning of electrical networks (Salman, 2017b). However, various other technologies are also employed to streamline the operation of the network and increase efficiency at the local scale. This includes all smart devices and elements within smart homes than enhance the functionality of smart grids at wider scales (Collotta and Pau, 2015).

Microgrids

The sub-modules that form the skeleton of a smart grid are known as microgrids. These small, regional clusters of distributed generation devices–typically at the level of a single building, industrial facility or community (Detroja, 2016)–undertake the specialised tasks required to operationalise smart grids at the local scale. By consolidating a group of renewable energy sources, storage devices, the associated converters and transformers, and the local users themselves, a microgrid can operate and present itself as a single controllable entity within a wider smart grid. This decentralisation of electricity networks makes the microgrid a key driving force in implementing the smart grid concept. And, the increased tangibility and local benefits that microgrids offer would seem to provide further incentives for making this transition a reality (Bifaretti et al., 2017).

The possibility of generating revenue as an electricity 'prosumer' is perhaps the most obvious motivation for individuals, businesses and communities to create local microgrids. Although installing the required infrastructure can require substantial amounts of initial investment, the relatively simple nature of small capacity systems means that they can be installed quickly and integrated seamlessly within existing networks without major compatibility issues (Rihan, 2019). Furthermore, future capacity additions or other changes can usually be easily implemented. Either way, the revenue earned from selling energy back to a wider network generally compensates for infrastructure investments within relatively short periods of time (Stadler et al., 2016).

A typical microgrid can operate in one of two modes (Deng et al., 2015; Keyhani, 2019). The most common of these involves full integration with the larger power grid system. External electricity and electricity generated within the microgrid–usually via solar PV, wind turbines, fuel cells or combined heat and power (CHP) devices–can then be traded using a smart meter device. Microgrids can also operate as isolated islands capable of satisfying all local energy demands using local sources. Operating in this mode is far simpler when energy storage devices (see section 2.1.5) are implemented within the microgrid in order for energy stocks to be accumulated and regulated efficiently within the system over time. Indeed, such devices are vital for anything but the smallest systems. While most microgrids are designed to operate in both modes, as required, entirely isolated microgrids are increasingly being considered as electrical network solutions in remote and inaccessible locations, particularly in developing nations (Rihan, 2019).

Blockchains

A further technology that could prove instrumental in optimising and promoting the functionality of smart grids, microgrids and smart homes is that of blockchains, or distributed ledger technologies (DLT). Implementing decentralised smart grids introduces levels of market complexity–particularly with respect to the bidirectional flow of energy and funds–that the existing centralised electrical networks are not equipped to manage (Brilliantova and Thurner, 2019). The sheer number of potential actors and activities means that future networks will require a decentralised, robust and reliable trading model capable of administering the high volumes of energy and funds flowing within them (Miglani et al., 2020).

The blockchain concept, originally developed as a secure ledger system for managing transactions of the Bitcoin cryptocurrency, enables transactions made between two or more parties to be digitally recorded and stored within peer-to-peer (P2P) networks without the need for a central managing authority. Evolving lists of transaction records are encrypted such that they are permanent and unalterable, thus providing accountability and security to both parties while removing the need for the involvement of third parties or authorities (Andoni et al., 2019). Their decentralised nature also means that they are far less susceptible to hacking or data loss and, in the absence of external administrators, no fees or commissions are paid. Market interference from utility companies is also minimised, assuring fairer market conditions (Andoni et al., 2017).

Blockchains are already being used for a range of financial payment operations and are finding a growing number of uses in a variety of other areas such as copyright and patent management, supply chain tracking and electronic voting. And, by offering security and accountability via a decentralised mechanism, the use of blockchains in administering energy-related transactions is now seen as one of the most promising future applications of the technology (Di Silvestre et al., 2020; Grewal-Carr and Stephen, 2016).

Another selling point for adopting blockchain technology within the energy sector is its range of potential applications. Blockchains have already been identified as an ideal mechanism for streamlining large transactions at the wholesale trading level. However, perhaps their greatest potential lies in their ability to simplify medium- and low-level prosumer sales and simpler trades at the local level (Mengelkamp et al., 2018). Indeed, their suitability for in microgrid operation is a recurring theme in the literature.

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In any case, like most smart applications within the energy sector, the use of blockchains requires the prior installation of smart meters. Again, smart meters record the movements of electricity within the network–particularly at the household or building level–in order to provide data on energy use and on transfers between users and back to the network grid itself. The connections between meters, and the flow of data between them, provides the information exchange required to operationalise blockchain transactions (Zhu et al., 2020).

Although the rollout of smart meters is relatively advanced within the EU and other locations, their full integration is required for the full capabilities of blockchain technology to be realised. As such, current blockchain usage within the energy sector is mostly limited to cryptocurrency payments for the charging of electric vehicles (Brilliantova and Thurner, 2019). In line with the ongoing installation of smart meters, the next step is likely to be the use of so-called smart contracts for medium- and low-level prosumer sales (Ahl et al., 2020). Here, terms of supply and pricing are prearranged between users and utility operators in order to allow real-time exchanges of energy and funds within grids via blockchains. Eventually, the use of large-scale, complex blockchains that encompass entire networks–known as decentralised autonomous organizations (DAOs)–are predicted to come into operation.

2.1.5 Energy storage technologies

Intermittency factors, inherent in most renewable energy sources, have the potential to introduce major reliability issues to current networks. In fact, it has been estimated that even a 20% increase in renewables use could significantly destabilise many existing networks (Gür, 2018). Accordingly, any future attempts to decarbonise energy networks must also include methods for regulating supplies such that they are at least as reliable as energy derived using existing methods. The widespread integration of energy storage technology appears to be the best option for achieving these outcomes.

Most modern applications of the concept of energy storage are within electricity networks. Here, excess electrical energy is converted into a secondary form of energy–typically when it is unneeded or inexpensive–such that it can be reconverted back to electricity at a later time when demands are higher. Again, such mechanisms are vital for contending with the intermittent energy supplies derived from renewable sources. However, storage technology can also act to balance energy loads within networks in real time, which is vital to the efficient functioning of smart grids (Wagner, 2014). At smaller scales, energy storage devices are often used to store locally generated renewable energy within buildings or microgrids. Outside of electrical networks, thermal energy is also stored as part of efficient heating and cooling systems.

It is generally assumed that a combination of technologies operating at different scales will be required to perform the range of energy storage tasks required to optimise the operation of future smart grids (Javed et al., 2020; Zame et al., 2018). Accordingly, a range of energy storage technologies exist, each of which offer their own physical and operational characteristics. These can be characterised by the amounts of energy they can store, the rates of power they can deliver, and the timeframes required to convert and discharge electricity. Values of specific energy and specific power–the energy and power characteristics per unit of mass or volume–are also often discussed as they be decisive practical considerations. Other environmental, resource scarcity, geographic and cost aspects determine the advantages and disadvantages inherent in each energy storage option.

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The most common current methods fall broadly into one of two categories. The first involves large-scale electromechanical devices that use potential energy to store higher volumes of energy that is accessed in longer timeframes. This includes pumped hydro and compressed air technologies. The second category involves smaller-scale devices that use electrochemical energy (e.g., batteries), electromagnetic energy (e.g., ultracapacitors) and electromechanical energy in the form of kinetic energy (e.g., flywheels) to store and release smaller volumes of energy within shorter timeframes. The use of thermal storage technologies also occurs at multiple scales.

Data for currently operating energy storage infrastructure is available in the Global Energy Storage Database (U.S. Department of Energy, 2020). A summary of this data–in terms of the percentage of total power capacity assigned to each category–is provided in Table 2. Values are shown for all global infrastructure and for infrastructure within EU-28 countries. In order to estimate future directions for each category, percentage breakdowns are also given for in-progress developments. This includes all projects that have been announced, contracted or are currently under construction.

Table 2 Summary of operational and in-progress energy storage infrastructure (February 2020). Source: U.S. Department of Energy (2020)

Technology	**Global**		**EU-28**	
	Operational	**In-progress**	**Operational**	**In-progress**
TOTAL [MW]	173,943	16,681	50,998	2,031
Pumped hydro [%]	96.6	78.0	94.9	64.2
Compressed air [%]	0.4	5.4	0.6	26.4
Secondary batteries [%]	1.0	9.8	0.5	8.6
Flow batteries [%]	< 0.1	1.4	< 0.1	0.1
Metal air batteries [%]	-	0.1	-	-
Ultracapacitors [%]	< 0.1	< 0.1	< 0.1	0.1
Flywheels [%]	0.5	0.3	1.7	< 0.1
Thermal energy [%]	1.4	5.0	2.3	0.5

The data indicates that the implementation of energy storage is currently dominated by pumped hydro infrastructure. However, it also suggests that the use of CAES is on the rise for large-scale storage applications, particularly within Europe. The use of secondary batteries also appears to be increasing dramatically, suggesting that it is the most significant emerging technology at the smaller scale. The use of

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flow batteries is also rising, particularly in larger-scale applications, but there appear to be no significant improvements in the use of metal air batteries, ultracapacitors and flywheels. The global use of thermal energy storage is rising, although this does not appear to be being mirrored within Europe at present.

Pumped hydro

The concept of storing large volumes of water such that it can be used to produce electricity when required is nothing new; hydroelectric dams have been in existence since the 1890s (Koch, 2002). Strictly speaking, these dams represent the world's largest man-made sources of available stored energy. However, their importance is in their ability to store large amounts of potential energy for extended periods. Pumped hydro facilities borrow many of the theoretical fundamentals of hydroelectric dams, albeit at smaller geographical scales and with the purpose of converting electricity back and forth at smaller timescales.

Two bodies of water are required to operate such a facility. Firstly, a lower reservoir or open body of water provides a reliable source of water. Electrical energy from a grid is used to pump water from this source to an upper reservoir when energy is cheaper or more available. Electricity can then be recreated when required by allowing water to flow, under gravity, from the upper reservoir back through a turbine generator near the lower reservoir or water source (Díaz-González et al., 2016). Conversion and discharge timescales can be as low as a few hours and efficiencies of between 70 and 85% are generally achieved. The world's highest-rated energy storage facility–the Bath County station in Virginia–outputs over 3GW of power. In fact, the top 140 energy storage facilities are pumped hydro plants, all of which are capable of producing in excess of 400MW of power. A typical pumped hydro plant layout is shown in Figure 10.

Figure 10 The Geesthacht pumped hydro storage plant in Germany. Photo credit: Vattenfall AB

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Aside from their high power capacities, the main advantage of such plants is their relatively cheap and easy mode of operation, which involves no significant ongoing emissions or resource scarcity issues. Their projected lifespans are very long and daily operation costs are low. However, their high setup costs and potential geographic or land availability issues may limit their use in some situations (Wagner, 2014). Nevertheless, many new projects are in progress (see Table 2), suggesting that pumped hydro will continue to be a dominant energy storage option for larger-scale applications.

Compressed air

Much like pumped hydro storage, compressed air energy storage (CAES) relies on a relatively simple electromechanical process to store electrical energy, typically at the utility scale. In this case, excess electricity is used to operate compressors that push high-pressure air into large underground aquifers, caverns and other rock formations, or into tanks or pipes in smaller-scale operations. When required, this air can then be released through turbine generators to produce new electricity.

Unlike pumped hydro, CAES is a relatively undeveloped technology; only one currently operational plant–the Kraftwerk Huntorf in Germany–can release over 300MW of power. However, this seems likely to change in the coming years as many new installations are planned (see Table 2), including two plants in the US and one in Northern Ireland, all capable of releasing over 300MW.

As with pumped hydro, the key advantages to CAES lie in their simplicity and low environmental impacts. Furthermore, as large-scale plants make use of naturally-occurring geological spaces, installation costs per watt are typically much lower than for other technologies (Gür, 2018). Conversely, this requirement greatly reduces the number of possible sites, at least for large-scale operations. Turnaround timescales for CAES operations are also relatively long and are generally measured in hours or days, while expected efficiencies are no higher than 70%. In any case, CAES appears to represent a key technology in the future of energy storage and, according to the Global Energy Storage Database data (U.S. Department of Energy, 2020), more overall capacity is in progress (903MW) than is already installed (724MW). This represents the second highest growth rate according to this ratio, only surpassed by flow batteries (discussed later in the section).

Secondary batteries

The use of rechargeable or 'secondary' batteries is perhaps the most significant of the currently available energy storage options. For many years, the high cost per unit of energy of these batteries was seen as a limiting factor to their widespread implementation. However, in recent years, substantial cost reductions–around 45% between 2012 and 2018–have resulted in dramatic changes in the prospects of secondary battery implementation at both local and utility scales. Indeed, in the latest World Energy Outlook report (International Energy Agency, 2019a), battery use is predicted to be the fastest growing energy storage resource over the next 20 years, rising in capacity by a factor of 40 by 2040. Aside from the ongoing reductions in cost, the widespread availability, modularity and ease of construction of battery setups has made them an increasingly attractive choice in many energy storage applications.

Several secondary battery technologies have been proposed over the years. The distribution of the most common of these within current energy storage projects, and projects that are in development, are shown in Table 3. Again, values are provided for all global infrastructure and for infrastructure solely within EU-28 countries. The data clearly shows that lithium-ion technology is the most commonly implemented type of secondary battery at present and that they are overwhelmingly the most popular choice for projects that are currently in progress. It is also significant that the total power capacity data for in-progress projects–which includes projects that are announced, contracted or are currently under construction–are roughly on par with operational projects. This suggests a very rapid rise in the use of secondary batteries for energy storage operations worldwide.

Table 3 Summary of operational and in-progress secondary battery infrastructure (February 2020). Source: U.S. Department of Energy (2020)

Technology	**Global**		**EU-28**	
	Operational	**In-progress**	**Operational**	**In-progress**
TOTAL [MW]	1,661	1,630	262	175
Lithium-ion [%]	80.6	98.3	82.0	97.3
Sodium-ion [%]	0.1	< 0.1	< 0.1	-
Lead-acid [%]	5.3	1.3	0.8	-
Nickel-cadmium [%]	1.8	0.1	1.1	-
Sodium-sulfur [%]	11.4	-	14.4	-
Sodium-nickel-chloride (ZEBRA) [%]	0.9	0.3	1.6	2.7
Other nickel [%]	< 0.1	-	-	-
Zinc-manganese-dioxide [%]	-	< 0.1	-	-

The emergence of the lithium-ion battery as the battery of choice in energy storage applications is for good reason. They possess excellent energy density and power-to-energy ratios, discharge and recharge within short timeframes, operate simply and reliably at safe temperatures and require relatively little maintenance. While once slightly restrained by the burden of high setup costs, the popularity of lithium-ion technology has been significantly boosted in recent years by rapid reductions in price and by equally impressive improvements in their energy density characteristics (Nayak et al., 2018). And, while other second battery types have proven capable of delivering better returns, lithium-ion installations are still capable of delivering

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more than adequate round-trip efficiencies of between 70 and 80% for most applications (Schimpe et al., 2018).

It should also be noted that the dominance observed in the field of energy storage is part of a larger wave of popularity currently being enjoyed by lithium-ion battery technology in general. For several years it has also been the favoured battery type for portable electronic devices and electric vehicles, among other things, further highlighting the momentum and dominance of the technology within a variety of global markets. This has caused many to begin to investigate the potential that dramatic increases in demand for lithium could have on its global supply reserves and, indeed, on future price variations. Cobalt and nickel are also vital to the creation of lithium-ion batteries and have been identified as further potential sources of future production bottlenecks (Delucchi et al., 2014).

A lithium-ion battery used within an electrical grid is expected to have a lifespan of between seven and 10 years (Smith et al., 2017). As such, suitable replacement and disposal strategies need to be in place when implementing long-term energy storage projects involving lithium-ion components. Here, improvements in recycling processes–known to be undeveloped at present–could provide economically and ecologically beneficial solutions that also address the resource-scarcity issues surrounding lithium, cobalt and nickel. To date, investigations in this area have tended to neglect options for lithium itself in favour of cobalt, nickel and copper, simply because of its lower market value. However, easily accessible lithium could become scarce by 2050 and recycling processes capable of recovering the majority of lithium from batteries is likely to be needed to sustain supplies into the second half of the century (Hanisch et al., 2015).

Although the spread of lithium-ion batteries looks set to continue, scarcity issues, potential environmental impacts–predominantly related to copper and aluminium extraction rather than lithium (Notter et al., 2010; Stamp et al., 2012)–and the possibility of thermal runaway incidents, such as those that affected air travel in recent years (Zubi et al., 2018), have also fuelled research into safer alternatives. The most promising immediate replacements involve sodium-ion batteries (Li et al., 2018), which are technologically very similar but far less burdened by resource constraints. What's more, life cycle assessment (LCA) findings suggest that sodium-ion cell production is less damaging to the environment (Peters et al., 2016). In any case, sodium-ion batteries are still incapable of comparable lifespans, and this restriction would need to be overcome for them to pose any serious threat to the dominance of lithium-ion cells.

Two formerly prominent older technologies–lead-acid and nickel-cadmium batteries–have fallen notably out of favour. Lead-acid batteries, still extremely common in automobile ignition systems and other settings, were never likely to be adopted in the long-term due to their poor energy density, high operation and maintenance costs, temperature sensitivity, relatively poor reliability, long charge times and, perhaps most notably, their reliance on hazardous lead (Zubi et al., 2018). Similarly, nickel-cadmium batteries, which rely on another hazardous substance in cadmium, also suffer from energy density limitations and are susceptible to the 'memory effect', where voltage drops occur during use as a result of past recharging patterns.

Once popular in larger-scale applications, particularly in Japan, sodium-sulfur batteries also seem to have lost their appeal. However, they may still prove to be a viable solution in certain applications. The key materials in their design, sodium and sulfur, are both inexpensive and readily available (Gür, 2018), energy densities are high and they can deliver high efficiencies–typically around 90%–throughout a high number of

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life cycles (Ould Amrouche et al., 2016). Nevertheless, as they operate at temperatures of approximately 350°C, they are less practical for safe use in household settings.

Another sodium-based technology–sodium-nickel-chloride or Zero Emissions Batteries Research Activity (ZEBRA) batteries–operate at similarly high temperatures. However, they are considered safer and easier to maintain than sodium-sulfur batteries, while still achieving high efficiencies and long life cycle expectancies (Chamberlain et al., 2017). ZEBRA batteries are perhaps best suited to larger storage plant scenarios but are also being considered for their potential in electric vehicle applications. Although their use remains low at the utility level, a small number of newer plants are in development.

Flow batteries

A very different type of battery–the flow battery–has also been discussed as a suitable energy storage option, particularly for larger-scale applications for electrical utility and industrial users (Wang et al., 2013). Unlike conventional secondary batteries, where energy inside a charged battery is stored within the unit's *electrodes*, energy inside a flow battery is stored within electroactive chemicals dissolved into liquid *electrolytes* (Salman, 2017c). Excess electrical energy is used to charge the batteries by generating these chemicals–and, hence, chemical energy–within an electrolyte solution using a pair of electrodes and a second electrolyte solution as part of an electrochemical reactor cell setup. The energy-rich solution is then stored within an external tank until needed, when the same reactor can be used to convert chemical energy back to electricity (Badwal et al., 2014).

Two general types of flow battery exist. In a redox flow battery (RFB) both electrolyte solutions are kept within tanks and pumped into the reactor when in operation. Table 4 displays the distribution of flow batteries at the global and EU scales and clearly demonstrates that the vanadium-redox version is the most dominant form, accounting for over half of the globally operational flow battery capacity and a high proportion of the projects now in progress. Vanadium redox batteries also account for most existing and in-progress EU capacity, although it is noted that the use of flow batteries is substantially lower within the EU.

The other type of flow battery is the hybrid flow battery (HFB). Here, one solution remains in the reactor at all times and the second solution is pumped through its side of the reactor during operation. The most common type of HFB is the zinc-bromine version which, although used in around 43% of the currently installed flow battery capacity, appears to be losing its popularity to vanadium redox batteries.

While the total capacity of in-progress flow batteries cannot hope to compete with secondary batteries (refer Table 3), the rate of growth is substantially higher; over three times as much capacity is in progress compared to current installations. Although flow batteries are more complex than conventional secondary batteries in many ways, they are capable of fast response times and have relatively high efficiencies of between 75 and 85% (Skyllas-Kazacos et al., 2011). Furthermore, as the solutions used within them are very stable and do not degrade over time, flow batteries are theoretically capable of achieving very long lifecycles. So, although they tend to have higher upfront costs, they may be a cheaper option in the long run for long-life applications (Ding et al., 2013). New developments in organic redox flow battery technologies may also result in cheaper and less environmentally hazardous alternatives, although more research is required (Zhao et al., 2020).

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Table 4 Summary of operational and in-progress flow battery infrastructure (February 2020). Source: U.S. Department of Energy (2020)

Technology	**Global**		**EU-28**	
	Operational	**In-progress**	**Operational**	**In-progress**
TOTAL [MW]	75	241	1	3
Vanadium redox [%]	56.5	88.3	93.8	100.0
Zinc-iron redox [%]	0.3	1.3	6.3	-
Zinc-bromine hybrid [%]	43.0	10.4	-	-
Hydrogen-bromine hybrid [%]	0.1	-	-	-
Zinc-nickel-oxide hybrid [%]	0.1	-	-	-

Perhaps the biggest advantage of flow batteries is in their flexibility. In a conventional secondary battery, the amount of energy stored and the power that can be delivered are inextricably tied to the volume of the battery and, thus, to each other. So, to increase the power available from a lithium-ion battery you would typically need to build a larger unit capable of carrying more energy. In flow batteries, however, the energy capacity is defined by the volume of the electrolyte storage tanks, while the power output is derived from the surface area of the electrodes used in the reactor unit. This allows engineers to effectively 'decouple' the two concepts and design flow battery modules with the electrode and tank configurations that suit the requirements of individual plants (Gür, 2018).

This can be advantageous considering the fact that flow batteries tend to have lower energy densities. Lithium-ion batteries, for example, have higher energy densities, but tend to weigh more and are less suited to stacking. Meanwhile, flow batteries can be stored in modular stacks (refer Figure 11) capable of delivering the required power outputs while occupying similar footprints to comparable lithium-ion batteries (Skyllas-Kazacos et al., 2011). Again, although lithium-ion batteries dominate the present-day battery market, the ratio of in-progress capacity (241MW) to operational capacity (75MW) for flow batteries marks it as having the highest growth rate of all categories presented here. This suggests that flow batteries will continue to be an attractive option in many applications.

Ultracapacitors

Ultracapacitors–alternatively known as supercapacitors–work in a similar fashion to batteries. However, rather than using chemical energy as a storage agent, they utilise the electrostatic energy that results from the physical charge separation between two electrodes. As no chemicals are involved, the process is highly reversible and is theoretically capable of undertaking an unlimited number of cycles. Energy efficiency is also very high and values of over 90% are generally achieved. The main downside of using ultracapacitors lies in their inability to contain their charge for long periods of time and most devices lose around 10% of their energy per day (Chamberlain et al., 2017). As such, they are often used in places where electrical energy is exchanged relatively quickly, and they are particularly common in railway applications. However, it is hoped that they may find more electrical network applications in the future, particularly in conjunction with batteries in hybrid storage systems (Ould Amrouche et al., 2016).

Figure 11 Typical flow battery installation showing three rows of stacked cells. Photo credit: Redflow Limited

Flywheels

Like ultracapacitors, flywheels are used in energy storage applications that require fast charge and discharge rates over short or medium periods of time (Gür, 2018). In the case of flywheels, the energy is stored as kinetic energy within a large rotating cylinder that is coupled to an electrical conversion device that acts as both a motor and generator (Akinyele and Rayudu, 2014). As a motor, incoming electrical energy is used to drive the wheel, increasing its rotational speed. When energy is required, the converter can act as a generator by applying torque to the rotating cylinder, slowing the wheel and producing electricity (Wagner, 2014).

The amount of energy stored within a moving flywheel has a linear relationship to its mass and the square of its rotational velocity. Hence, steel is often used in low-speed flywheels, which operate at speeds of up to 10,000 revolutions per minute (rpm), while high-speed flywheels operating at up to 100,000 rpm tend to incorporate lighter and more efficient composite materials. However, the superior performance offered by high-speed versions comes at a price and they can cost up to five times that of a low-speed equivalent (Arani et al., 2017).

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While flywheels are normally not capable of achieving high levels of energy density, their key characteristics as energy storage devices are in their abilities to charge and discharge energy at very high rates and, hence, to accumulate and deliver very high levels of power over relatively short periods of time. As such, they are ideal as a 'rapid-response' form of storage, best suited to grid-level power quality applications relating to power smoothing, frequency regulation and general stability improvement. However, flywheels have also been implemented specifically to support the integration of renewable energy sources.

Flywheels possess several other important advantages over other energy storage technologies, mostly relating to their relatively simple nature. They are generally very predictable, reliable and require very little ongoing maintenance (Mousavi G et al., 2017). Likewise, they are designed to have very long life cycles and a well-engineered unit could theoretically continue to operate indefinitely. So, even if the cost of an installed device is high–up to 40% more than an equivalent battery-based installation–this can be compensated over time. The physical nature of their operation also means that net emissions are very low, making them one of the most environmentally friendly of the current energy storage options.

Efficiency levels in flywheel installations also tend to be high, and efficiencies of between 80 and 90% are typical. However, these levels can drop significantly over time as a result of frictional forces during dissipation; losses can lower efficiencies to below 80% after a few hours and down to 50% if outputting power for 24 hours (Ibrahim et al., 2008). Similarly, their low energy density characteristics mean that massive flywheels would be required in order to deliver sustained amounts of energy. This reiterates the fact that flywheels are really only viable for use within minutes or, at most, one or two hours. However, while not the most cutting-edge of the available energy storage options, flywheel projects continue to be implemented and the technology is likely to play a role in future electricity networks.

Thermal energy storage

Thermal energy storage devices operate by storing a heated or cooled medium within an insulated enclosure such that it can be used for heating, cooling and power generation at a later time. Installations are categorised into three very distinct functional categories. The first two, both already in widespread use, perform utility operations that offer slight variations in the standard pathways of energy storage devices. A third category, still in its infancy, uses thermal energy to regulate electricity flows within networks in much the same way as other energy storage technologies.

The most common type of thermal energy storage currently in use involves the intermediate storage of heat collected in concentrated solar power (CSP) power plants prior to its conversion to electricity (refer Table 5). Here, the intermittency of solar energy is addressed more directly by storing the raw heat generated in CSP processes within large tanks at the plant itself. This heat can be converted directly to electricity and provided to the grid as required. Storage periods are usually less than eight or nine hours, but very high efficiencies–up to 98%–are reported (González-Roubaud et al., 2017).

The most common medium used to store heat in these plants are so-called molten salts–typically mixtures of sodium and potassium nitrates–which offer good thermal properties at low cost. Heat stored in these salts is converted to steam and used in generators when needed. The only other medium in current operation is steam, which is used for storing heat *and* driving generators without the need for an additional heat transfer process.

Table 5 Summary of operational and in-progress thermal energy storage infrastructure (February 2020). Source: U.S. Department of Energy (2020)

Technology		**Global**		**EU-28**	
		Operational	**In-progress**	**Operational**	**In-progress**
TOTAL [MW]		2,432	831	1,154	10
Heat storage in solar thermal electricity production	Molten salt	84.0	94.5	95.7	-
	Steam	7.3	1.1	3.9	86.5
Time-shifted electrical cooling	Chilled water	5.6	-	< 0.1	-
	Ice	3.0	4.3	0.4	-
Time-shifted electrical heating		0.1	-	-	-
Pumped thermal electricity storage		-	0.2	-	13.5

The second category includes technologies that act to 'time-shift' the electricity used in heating and cooling operations. Motivated by price incentives and a desire for more efficient temperature-control processes, these systems use a thermal storage medium that can be heated or cooled during off-peak periods, when electricity is cheaper and more readily available, only to be used at a later time (Kalaiselvam and Parameshwaran, 2014). The most common application is in cooling (refer Table 5), where reserves of cold water or ice are created and stored at night then used during the day in building air conditioning systems.

Applications of this kind are conceptually very similar to conventional energy storage technologies that seek to smooth demands on the electricity network while offering the advantages of demand response mechanisms. However, in these cases, the energy used is not intended to be reconverted to electricity. Rather, the changed thermal properties of the storage media are used directly for their intended purpose at the local scale.

Conversely, the final category–pumped thermal electricity storage (PTES)–operates in precisely the same manner as conventional energy storage technologies in that heat is simply used as the storage method for converting and reconverting electrical energy within grid networks. Various technical methodologies have been proposed, all of which involve relatively simple and well-established engineering theory and, potentially, existing equipment (Benato and Stoppato, 2018).

PTES is seen as a potential competitor to large-scale options such as pumped hydro, CAES or flow batteries and is seen as being comparable in cost and projected lifespan, but with considerably less geographic,

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resource or environmental constraints. However, low efficiency levels–expected to be between 40 and 50% using existing methods–remain a key barrier. This could be overcome by advancing research into this technology. Indeed, the only plant of this type currently in development–the Isentropic PTES demonstration plant in the United Kingdom–is endeavouring to address this and other limitations in the hope that PTES could become a viable large-scale option in the future.

While the overall percentage of in-progress projects (831MW) to operational projects (2432MW) is not as high as flow and secondary batteries or CAES, thermal energy storage installations appear likely to remain an active player in the spectrum of energy storage options. However, it is notable that very few projects are in progress within Europe; aside from the Isentropic PTES demonstration plant, only a single 9MW steam-based storage at a CSP plant in France is planned. This is likely to change if further CSP plants come online or if PTES is further embraced. For now at least, it appears that Europe is tending towards alternative technologies for its general energy storage applications.

Vehicle-to-grid

Another novel idea in the ongoing development of the nexus between energy storage and smart grid technologies is the vehicle-to-grid (V2G) concept. Considering the fact that the average electric vehicle is not being driven approximately 95% of the time, it has been proposed that their batteries could be used as grid-connected energy storage devices during these downtime periods (Mwasilu et al., 2014). Using smart technology, owners could choose to sell electricity within their vehicles by either returning it outright or throttling their recharge rates during times of elevated network demand (Tan et al., 2016).

Although most electric vehicles use lithium-ion batteries–with efficiencies of around 90%–the actual efficiencies obtained using V2G are likely to be much lower. Various losses within the power electronics components undertaking the AC to DC conversion within a vehicle (Apostolaki-Iosifidou et al., 2017), and significant decreases related to higher and lower ambient temperatures, mean that expected efficiencies from using V2G are probably more likely to be between 53 and 70% (Apostolaki-Iosifidou et al., 2018; Shirazi and Sachs, 2018).

Concerns have also been raised that more frequent and somewhat random charging and discharging of lithium-ion batteries could reduce their battery life and, hence, offset the financial and environmental benefits of taking part in V2G programs. However, Uddin et al. (2017) found that battery degradation could actually be reduced by participating in smart grid schemes that optimise vehicle battery use as part of its operations. Although still in its early stages of development, V2G technology could offer another innovative pathway for stabilising electricity networks and allowing greater infiltration of renewable energy sources while offering demand response incentives to energy users.

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2.2 Social trends

- Understanding social trends helps us to identify the social drivers and barriers that underlie the energy transition in the EU and that should be considered in energy models
- A thorough literature review revealed six social trends currently defining energy transitions

The energy transition induces not only a long-term structural change in energy systems, but also a reconfiguration of current spatial patterns of economic and social activity (Bridge et al., 2013; Fast, 2013). The relevance of the social dimensions of the energy transition continues to increase as there is a trend in the debate from pure economic and technical feasibility elements towards social feasibility, social justice and social tipping points and so on. The energy transition should be seen as a socio-political-technical challenge, one which involves different processes such as the acceptance of place changes, the planning of renewable energy projects, the adoption of technologies and decision-making about energy policies.

The aim of this section, then, is to identify key social trends underlying the energy transition in the EU, trends which are rather non-linear and have the potential to be disruptive when embraced by larger sections of society. As social trends, societal developments emerge from general megatrends and energy transition-specific structures and processes which can have impacts on the energy production and consumption/demand. The six ***key issues*** in the field of social trends are as follows:

- Transition from consumers to prosumers;
- Changes in social acceptance of renewables and denial of climate change;
- Uneven distribution of winners and losers in the energy transition;
    - Employment effects
    - Energy and fuel poverty
    - Community benefits and challenges
- Citizen empowerment by the digitalisation of energy generation and usage;
- Behavioural change and rising awareness of behavioural rebounds; and
- Transition from individual action to policy action.

Each country within the EU might be differently affected by such trends at different times, given the differences of national energy systems and their geographical and political contexts. Nevertheless, understanding these trends can support developing strategies and instruments to meet energy policy goals at EU, national, regional and local levels.

While most of the scientific and non-scientific reports and articles regarding megatrends and trends in the energy transition are focussed on technological trends, it is also possible to identify specific trends with social implications. Table 6 provides an overview of the main trends identified along with their link to a set of specific themes. These trends will be discussed in relation to the six ***key issues*** in the sections that follow.

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Table 6 Summary of identified social trends in the energy transition based on past trends studies

Observed social trend	Theme(s)	Source(s)
Benefits spreading unevenly **"In the EU, the number of renewable energy jobs reached 1.4 million in 2017 and is expected to increase, with the creation of up to 1.5 million net jobs by 2030. […] [but] while the fossil fuel sector provided jobs for 30 million people globally in 2017, it is set to lose 8.6 million jobs by 2050."** **"Social contestation grows as lower incomes struggle with the transition"**	#benefits #jobs #energy poverty	European Political Strategy Centre, 2018
Energy demand transformed as responsible consumerism kicks in **"technological progress will not relieve consumers of their responsibility to make sustainable choices"**	#responsible consumerism	European Political Strategy Centre, 2018
Digital driving the energy revolution **"The growing involvement of digital platforms is driving the development of new services and apps that serve to optimise society's energy consumption, cut costs and reduce carbon footprint. […] As such, digitalisation is giving rise to a new generation of empowered consumers, able to control their energy consumption in real time – e.g., shifting demand to times of cheaper prices. […] sharp growth in 'mobility as a service', as car-sharing and ride-hailing apps grow in popularity"**	#digitalisation #sharing economy	European Political Strategy Centre, 2018
Electrification rhymes with democratisation… as well as fragmentation **"millions of consumers around the world are now able to produce their own electricity"; "the ownership structure for renewables is more diverse"**	#prosumers #ownership	European Political Strategy Centre, 2018
Energy is getting smarter **virtual power plant actively involving citizens: "a marketplace for people with solar panels and batteries to sell the power they generate to the grid"**	#digitalisation	Clean Energy Canada, 2018
Energy blockchain and IoT **"The lack of centralisation in blockchain leaves it as ideal for eliminating the middlemen of electricity suppliers. It reduces energy inequality and inefficiency and empowers consumers to buy and sell energy from other consumers directly."; "With the correct applications, devices can autonomously buy and sell energy at the optimal times, optimise energy system settings in a real-time context and monitor and analyse performance of energy-consuming devices."**	#digitalisation #blockchain	Ellsmoor, 2018
New technologies and business models empower the consumer **"IoT and AI enable demand side management, decreasing consumers' costs by improving energy efficiency and preventing energy waste"; "Aggregators enable distributed technologies (RE plants, storage) to participate in the energy market"; "Platform based model promote Peer to Peer trading, offering a market place for distributed generation"; "By promoting P2P trading and though emerging cryptocurrencies, blockchain incentivises growth in decentralised generation"**	#smarthomes #virtualpowerplants #blockchain	IRENA, 2018
Digitalisation of energy and transport systems are becoming smarter and better networked	#sharing economy #smart homes	Buck, Graf and Graichen, 2019

"The sharing economy enables consumers to use cars and bikes with unprecedented convenience. Smart home systems optimise the use of rooftop solar installations, heating systems, battery storage, and electric vehicle charging and thereby help integrate renewables into the power grid."		
Demographic and economic change in rural areas: many regions must cope with ageing and shrinking populations and face shifting economic opportunities **"Yet with the spread of wind and solar power generation and the production of renewable gases, the energy transition will offer new economic opportunities for rural areas, especially those whose solar and wind potentials are high. At the same time, the energy transition will also exacerbate existing rural challenges such as the downsizing of coal-fired power production and the loss of well-paid jobs in the coal-mining industry. Additionally, new wind onshore installations in some parts of Europe face local opposition due to concerns about landscape disfigurement."**	#benefits #jobs #acceptance	Buck, Graf and Graichen, 2019
Decentralisation: small-scale solutions enable but also require proactive energy consumers **"So-called prosumers directly consume the energy they produce. And thanks to digitalisation, distributed electricity demand applications such as electric cars or heat pumps can be used as resources to integrate variable and decentralised wind and solar electricity production"**	#prosumers #digitalisation	Buck, Graf and Graichen, 2019
Decentralised supply is the future **"The trend is towards smart grids that connect producers, consumers, storage facilities, and network structures,"**	#decentralisation #digitalisation	Federal Ministry of Education and Research, 2020
Blockchain technology **"These peer-to-peer networks are helping customers to effectively trade energy with ease. This can be used by energy companies themselves, or even by private individuals."**	#digitalisation #blockchain	McFadden, 2019
The age of storage and decentralised grids **"Energy storage is also likely to shape decentralised grids driven by consumer energy decisions such as rooftop solar and behind-the-meter batteries."**	#decentralisation #prosumers	Bhattar, 2020
Accessibility for private households **"New generation distributed energy resources such as solar panels or wind energy generators can be used in private households and help consumers gain more control over their energy usage. These devices can be installed in houses, and even in apartment buildings. Therefore, users can generate as much energy as they want and sell residual to energy suppliers."**	#prosumers #digitalisation	PV Europe, 2020
Blockchain-based solutions **"Blockchain infrastructure is built to eliminate the middleman, which benefits solar energy consumers. It does not only make renewable energy cheaper and more accessible but can also allow individual households to control their energy consumption without overpaying for public services."**	#blockchain #digitalisation	PV Europe, 2020

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2.2.1 Transition from consumers to prosumers

#prosumers #decentralisation #ownership #community energy

As discussed in section 2.1.4, the energy transition has given rise to a new generation of agents as active producers of renewable electricity. Around the globe, energy initiatives, energy communes, energy cooperatives, energy communities and energy islands are stamping out this new ground. What they all have in common is that renewable energy technologies function as actors that set social dynamics in a specific place in motion, and cause the development of a community or social structure of common interest around it (Lowe and Feldman, 2008; Süsser et al., 2017). Consequently, people become both the consumers and producers–so-called prosumers–of electricity. This change from pure energy consumers to prosumers is a clear trend of the energy transition.

More diverse and democratic ownership structures for renewables are, thus, being formed based on the decentralisation of energy production. For example, German citizens own roughly one third of the country's renewable electricity capacity and these people can play an initiating, enabling and supportive role in driving the energy transition (e.g., Süsser, Döring and Ratter, 2017). Local people detect occasions, develop prospects, raise social awareness for opportunities, gather support and transform innovation into a business (Feldman, 2014; Süsser et al., 2017; Tanimoto, 2012) by making use of locally grounded social, cultural and economic capital in a creative and adaptive way (Feldman and Kogler, 2010). The engagement of different agents depends on different aspects, such as their acceptance of new energy infrastructures, their decisions to adopt new technologies and services, their investment choices, and expected and experienced benefits (Rogers et al., 2008; Süsser and Kannen, 2017; Walker et al., 2014; Walker and Cass, 2007).

Community renewables and citizen energy emerged as a grassroots-led innovation concept that creates socially acceptable and contextualised bottom-up solutions for sustainable energy generation (Hargreaves et al., 2013; Seyfang and Smith, 2007; Walker and Cass, 2007). Communities became actors who identify, evaluate and make use of opportunities for innovation and entrepreneurship in renewable energy. Because such grassroots innovations and entrepreneurship are driven by not only a single person, they must be rather considered as a 'collective achievement' (Tanimoto, 2012; Van de Ven, 1993). Community energy can, therefore, support distributional justice (fair outcomes) and procedural justice (fair process) (Walker and Devine-Wright, 2008).

Even though not all community-energy projects aim for energy autarky, across Europe, local electricity autarky could largely be possible (Tröndle et al., 2019). At a municipal level, around 75% of the European population lives in areas that are supplied with enough renewable electricity when considering autarky. Enhanced cooperation between municipalities and regions could relieve local pressures on land (Tröndle et al., 2019). Possibilities for self-sufficient energy plans exist, thus offering strong local empowerment opportunities for many citizens.

On a technical level, decentralised renewable energy production and supply need decentralised and networked infrastructures, which potentially engage humans at new levels. The 'one-way street' of energy distribution is replaced by more decentralised and bidirectional structures on low, medium, and high voltage level (Buck et al., 2019). Distributed electricity demand applications–such as electric cars or heat pumps–can be used as resources to integrate variable and decentralised wind and solar electricity production into the energy system. Thus, citizens become empowered in terms of local energy production and become an essential part of the energy supply, making issues of social acceptance even more important.

Moreover, the degree of decentralisation is interlinked with the degree of participation. From a social perspective, decentralisation is not only about minimising the transition costs but also about the democratisation of energy supply through citizen participation. Positive side-effects are a growing democratic control of the supply and the facilitation of general democratic innovation (Bauknecht et al., 2020). The impacts that technological decentralisation can have on three forms of participation–procedural, representative democratic and financial (individual and collective)–are shown in Table 7.

Table 7 The impacts of technological decentralisation on three forms of participation. Source: Bauknecht et al. (2020)

	Procedural participation (A)	**Representative democratic participation (B)**	**Financial participation (individual and collective) (C)**
Connectivity (1)	More people affected by increasing number of power plants connected to distribution grid, which can reduce acceptance. More possibilities for procedural participation, not necessarily more or "better" participation processes.	Democratic control of state-owned companies does not depend on decentralisation. Increasing decentralised connectivity enables more politically adopted local energy concepts and re-municipalisation/new foundations of local utilities.	Liberalisation and EEG allow citizens to invest in decentralised plants; wider distribution of property/profits follow to a certain extent. Decentralisation enables a broader range of participation. Broader financial participation does not guarantee a more equal distribution of profits among all citizens.
Proximity (2)	The effects of decentralised connectivity and proximity are closely related. Both can increase participation options, but can also increase the demand that the participation regimes need to fulfil	Shift of potential democratic control to lower levels, but opportunities for democratic control can vary in a decentralised system.	Financial participation by citizens is in principle not related to proximity, but proximity can increase willingness to invest.
Flexibility (3)	Decisions on decentralised flexibility options often made by individuals or companies. Whether citizens are included in the planning procedures depends on the owners/planners.	Representatives can influence development of decentralised flexibility through local utilities or energy concepts. Many decentralised flexibility options do not lend themselves to public ownership or democratic control.	Investment in flexibility options becomes more attractive for financial reasons in the context of self-consumption. Decentralised flexibility enables active market participation of a larger number of actors.

Controllability (4)	Local balancing of supply and demand can be part of energy concepts in which citizens might participate. Local balancing is not a necessity for local development of generation capacities or storage systems.	Decentralised controllability could enable local markets, facilitate local energy concepts and support municipal utilities and therefore facilitate democratic participation on a local level.	Decentralisation may trigger financial participation because it is economically attractive. Willingness to invest may increase if electricity can be produced "on-site" or if there are real-time local electricity products.

European countries have undertaken many different measures to support renewable-energy development. While market-based auction systems generally favour the bigger market players, fixed feed-in-tariffs tend to favour individually- and municipality-owned energy projects. In this sense, Germany will soon experience the next phase of renewable energy regulation. The German Renewable Energy Act (EEG) was introduced in 2000 and guaranteed a fixed feed-in-tariff for renewable energy systems over 20 years (Bundesministerium für Wirtschaft und Energie, 2000). In the period 2021 to 2030 a growing number of plants are predicted to fall out of the EEG (see Figure 12) as they were installed in the period of 2000 to 2009. The result will be a new situation–a post-EEG-era–that is yet to be properly regulated (Lenck, 2020). The new renewable auction schemes are generally perceived to favour larger companies and leave municipalities behind. However, the continued use of existing infrastructure is also relevant: law should support households in maintaining the usage of existing, still functioning PV that was financed by the EEG, adding battery storage, or even repowering their rooftops and, thus, facilitating the growth of installed capacity.

To summarise, the local empowerment of citizens and communities as prosumers is a clear trend within the local energy transition and it has implications for the many questions about where renewable energy infrastructures should be built. The potential of accounting for different structures and dynamics of energy generation, such as community energy, need to be further explored in energy models. This trend is also highly linked to the acceptance of renewable infrastructure at the local scale.

2.2.2 Changes in social acceptance of renewables and denial of climate change

#acceptance

Social acceptance is of increasing relevance in scientific, public and political debates. According to Steward Fast: "As renewable energy production has increased so has the reporting of conflicts (and of success stories) over placement and organisation of wind, solar, biomass, hydro, and other facilities [...]" (Fast, 2013). As such, the topic of social acceptance is not new to the energy transition and particularly not to renewables. However, as installed RES capacities are predicted to continue to grow in Europe (see Figure 6), social acceptance would seem to be more important than ever. RES are required to compete with existing technologies that have long been accepted and, therefore, sustainability transition researchers try to explain how the energy transition can be accelerated in the way societal functions are fulfilled (see, e.g., Victor, Geels and Sharpe, 2019; Köhler et al., 2019).

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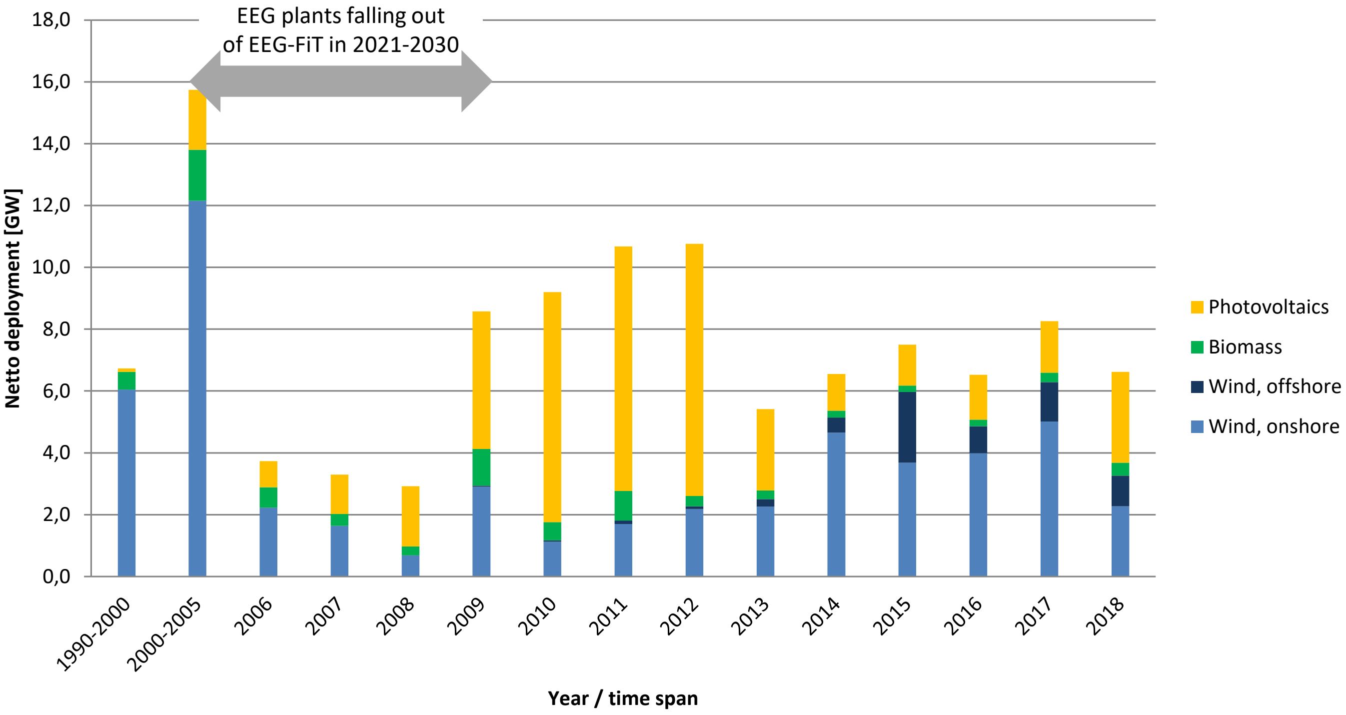
Figure 12 Renewable energy plants that were installed between 2000 and 2009 and will fall out of the Renewable Energy Act of Germany between 2021 and 2030. Source: own approximation, based on data of Gokarakonda et al. (2018)



The energy transition has not remained unquestioned in the population and is contested in a variety of cases. Generally said, people "are motivated to seek, stay in, protect and improve places that are meaningful to them" (Manzo and Perkins, 2016:347). Indeed, the term NIMBY–Not In My Back Yard–is often used to describe the discrepancy between people's openness to new technologies and their opposition to its implementation in locations where it will affect them as individuals (for a review see Burningham, Barnett and Thrush, 2006). Perhaps a good example lies in the discussions surrounding onshore wind energy in some parts of Europe. As stated in Table 6, rural areas may face local opposition due to issues of societal harmony, health impacts, aesthetic impacts and physical impacts on local species.

In Germany, approval for the energy transition remains high. However, its implementation is becoming increasingly criticised. While 90% of the population support the energy transition within Germany, 47% assess its implementation as poor–an increase of 14% from the previous year (Setton, 2019). Most of these people perceive the energy transition as being expensive and unfair. Moreover, the share of citizens that experience the transition as costly, chaotic, unfair, elitist and poorly implemented grew substantially between 2017 and 2018 (Setton, 2019).

Such issues of support or rejection are embedded in local places and communities. Place meanings and attachments (Devine-Wright, 2011; Devine-Wright and Howes, 2010; Manzo and Perkins, 2006) as well as trustworthy locally embedded entrepreneurs (Süsser et al., 2017; Walker et al., 2010) are essential for the acceptance of, and participation in, RES projects. In particular, social and emotional dimensions engendering place attachment were found to be of vital importance when it comes to developing social acceptance and trust in the context of local changes induced by RES technologies (Devine-Wright and Howes, 2010).

The active participation of citizens in the planning process and the distribution of community benefits can also increase the acceptance of technological development. As people and communities are to become the active agents, local energy transition should be implemented by, in and for local places and communities (Süsser et al., 2017). Financial support mechanisms, a more localised and participatory development process and opportunities for local ownership can increase awareness and acceptance (Rogers et al., 2008; Süsser and Kannen, 2017; Walker et al., 2014; Walker and Cass, 2007). Furthermore, a fair process and distribution of community benefits are known to impact the acceptance of projects (Cowell et al., 2011; Gross, 2007; Walker et al., 2014).

However, almost every movement has and provokes an anti-movement. In the climate change debate this includes climate change denier groups who contribute to lowering group-internal acceptance of the energy transition. The denial of scientific data is not a new phenomenon but in the field of climate change it is attributable to specific groups within science, politics, industry, media and the public (Björnberg et al., 2017). Doubts and denial about climate change emerge from the need of trusting scientists and their conclusions in a complex, long-term and non-observable phenomenon. Therefore, misinformation among the public is widespread, while denial decreases many individuals' engagement in climate action (Jylhä, 2017).

In recent years, the movement of climate deniers has gained momentum, even at the political level. The right and rightest wing of conservatives are fuelling doubts and denial of climate change (Götze and Joeres, 2020; Björnberg *et al.*, 2017), and right-wing populism has grown significantly in the last decade in Europe (see Table 13). Not only has the criticism of climate science driven the deniers' movement, it is also driven by distributional impacts, especially by those people who perceive being left behind (Stephens, 2020). But a clear trend for the future is not predictable as arbitrary factors play a role. The movement could lose its momentum, if climate change is more and more observable and perceivable. According to climate scientists the established rule of 'weather is not climate' needs modification as the warming trend can now be perceived in every day's weather at the global scale (Sippel et al., 2020).

Political activism towards climate change mitigation is also growing and stands in opposition to climate change denial. The *Fridays for Future*-movement, a protest of pupils and students against climate change, developed in only a few months from a local initiative to a global movement with Greta Thunberg as its seed crystal (Wikipedia, 2020a). Present hot spots for the movement are industrialised continents like North America, Australia and Europe. However, the movement's development seems dynamic. Meanwhile other sister initiatives have joined the movement, namely Artists for Future, Change for Future, Entrepreneurs for Future, Parents for Future and Scientists for Future (Wikipedia, 2020b) indicating a broader support exceeding the initial group of young students. The probability that it will gain further momentum and political impact are high considering the fact that climate change and its negative impacts are becoming more and more observable and measurable.

Table 13 Populism in Europe in 2018 indicated by share of votes for populist parties in European national elections in 2008 and 2018, structured from highest to lowest increase between 2008 and 2018. Source: Statista (2019)

EU Country	2008	2018	Difference
Italy	8,3%	50,0%	41,7%
Greece	17,0%	54,6%	37,6%
Czechia	12,8%	49,6%	36,8%
Slovakia	11,7%	34,3%	22,6%
Hungary	43,7%	65,1%	21,4%
Poland	32,1%	51,2%	19,1%
Spain	3,8%	21,2%	17,4%
France	13,8%	27,1%	13,3%
Finland	12,9%	24,8%	11,9%
Germany	10,3%	22,0%	11,7%
Sweden	8,8%	18,6%	9,8%
Ireland	8,0%	17,7%	9,7%
EU average	**11,0%**	**18,7%**	**7,7%**
Denmark	13,9%	21,1%	7,2%
Romania	3,2%	10,0%	6,8%
Estonia	26,1%	32,9%	6,8%
Bulgaria	26,0%	32,7%	6,7%
Croatia	1,8%	6,5%	4,7%
Cyprus	31,1%	35,4%	4,3%
Lithuania	29,0%	32,8%	3,8%
Luxembourg	1,9%	4,9%	3,0%
Slovenia	5,4%	8,2%	2,8%
Portugal	8,3%	9,4%	1,0%
Latvia	7,0%	6,9%	-0,2%
Netherlands	22,5%	22,2%	-0,3%
United Kingdom	2,2%	1,8%	-0,4%
Austria	28,2%	26,0%	-2,2%
Belgium	16,0%	4,9%	-11,1%

Overall, the developing split between climate deniers and the global climate movement is a trend which has the potential to influence the acceptance of renewable energy expansion. It expresses the relevance for considering local places of the energy transition, and understanding people’s attitudes, expectations and fears to counteract a complete hold of the energy transition.

2.2.3 Uneven distribution of winners and losers in the energy transition

#energyjustice #energyjobs #energypoverty #communitybenefits

Many issues surround the potential of energy transition processes to create unfair distributions in the internal and external costs and benefits, risks and chances among populations at all spatial scales (global, continental, national and regional/local).

Previous research has predicted the challenges for implementing justice within energy transition processes at the global scale. Taconet et al. (2020) find that climate change will increase inequalities between countries in two ways: “On the one hand, rising temperatures from greenhouse gas accumulation cause impacts that fall more heavily on low-income countries. On the other hand, the costs of mitigating climate change through reduced emissions could slow down the economic catch-up of poor countries.”

Meanwhile, Goldthau et al. (2019) translate the conflict over justice into a scenario-based winner-loser perspective. They compare four optimistic and pessimistic geopolitical scenarios regarding mitigation efforts and collaboration of nations (big green deal, technology breakthrough, dirty nationalism, muddling on), and conclude that “abating carbon will create losers” and that “falling fossil-fuel demand” must be dealt with reference to a country’s development stage, as not all can rely on the same financial background to compensate its losers (Goldthau et al., 2019:31).

In this regard, Eicke et al. (2019) provide three recommendations:

- Address the global dimension of just transition;
- Promote integrated low-carbon tech transfer mechanisms; and
- Shift financial flows to increase ambition.

Aside from these global and continental challenges, energy justice at the national level also warrants consideration. Sovacool *et al.* (2019), for instance, analysed four European case studies (nuclear power in France, smart meters in Great Britain, electric vehicles in Norway and solar PV panels in Germany) using a mixed method approach. They found 44 collective injustices on three spatial scales (micro, meso, and macro level), as shown in Table 8.

Finally, justice challenges can also materialise at the regional and local level and the following sections investigate employment effects, energy poverty, and community benefits as major topics within the winner-loser debate from a subnational perspective.

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Employment effects

#energyjobs

The relative number of jobs in the RES industry compared to those in the coal, gas and nuclear industries provides an important criterion for assessing the welfare impacts of the energy transition. Accordingly, a range of studies such as Duscha *et al.* (2014), IRENA (2018) or Buck, Graf and Graichen (2019) analysed the gross impact (direct and indirect jobs created) and net impact (including substitutional and budget effects). Others attempted to provide advice for negatively affected regions–for example, Oei *et al.* (2020) investigated localised implications of the German coal-phase out.

Table 8 Summary of spatial scales of injustices for four low-carbon transitions. Source: Sovacool et al. (2019)

Case study	Micro scale injustices	Meso scale injustices	Macro scale injustices
French nuclear power	(1) Water consumption, (2) nuclear waste streams, (3) community health, (4) depressed property values, (5) interference with wine making, (6) social peripheralization and marginalisation	(1) Safety, reliability and national accidents, (2) interference with the development of national low carbon innovations	(1) Accident risks to neighbouring countries and beyond, (2) environmental impacts of uranium mining, (3) political impacts of uranium mining, (4) nuclear exports, (5) interference with other European transitions
British smart meters	(7) Exclusion of rural areas, (8) exclusion of those living in social housing blocks, (9) rising household energy prices, (10) negative impacts on vulnerable groups, (11) added stress for families	(3) Loss of jobs, (4) higher national energy prices, (5) the environmental impacts of the smart meter roll out	(6) reliance on raw materials from unstable regions, (7) hazardous waste streams
Norwegian electric vehicles	(12) Increased car use leading to congestion, (13) pollution, (14) parking problems, (15) avoidance of walking/cycling, and (16) lack of infrastructure in rural areas	(6) Diversion of taxes from public transport, (7) Expansion of roads into environmentally sensitive areas, (8) Greenwashing of national policy	(8) Poor labour conditions foreign resource extraction, (9) hazardous waste streams, (10) exporting of dirty cars
German solar panels	(17) Exclusionary nature of the feed-in tariff, (18) local closure of German coal mines (19) Loss of solar manufacturing jobs	(9) Threatening centralised energy supply models, (10) stigmatising future solar investment and the loss of German solar manufacturing (11) poor employment conditions or standards at German manufacturers	(11) Erosion of markets for electricity in Poland and the Czech Republic, (12) disruption of global fossil fuel industries, (13) extraction of raw materials and waste flows, (14) poor working conditions at overseas solar manufacturers

In general, the gross number of RES jobs is growing. In 2017, around 10.3 million jobs existed within the industry across all RES technologies, an increase of approximately 50% since 2012. Solar photovoltaic

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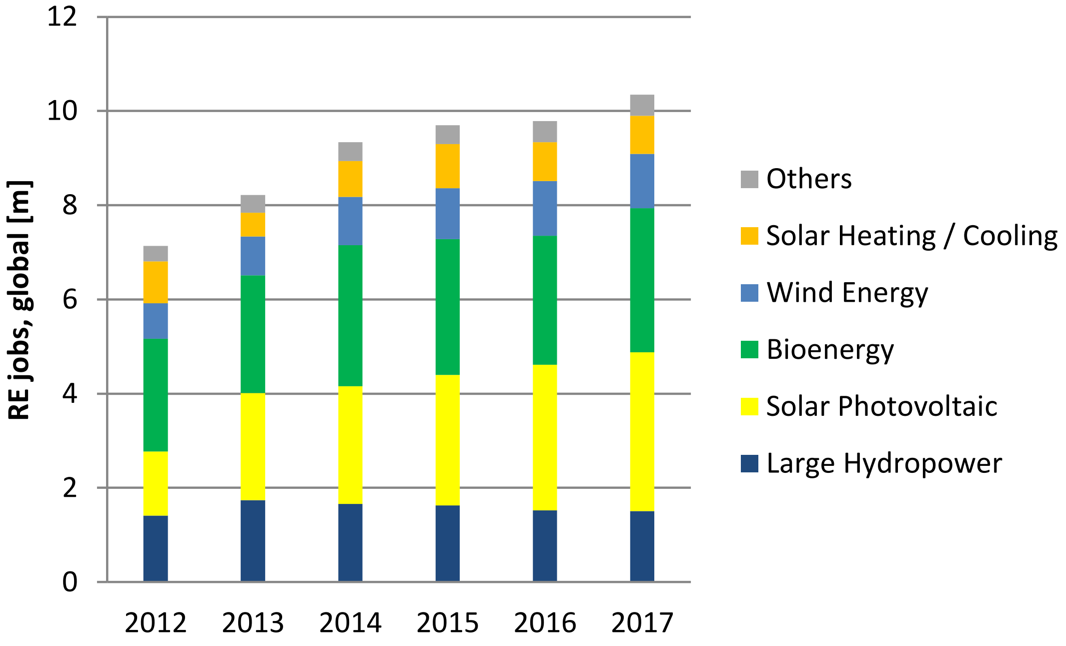
contributes the highest share with nearly 3.4 million jobs (see Figure 14). While the global trend indicates a steady growth, the national situation can be less obvious. Although the RES industry is growing in Europe, employment fluctuations on national levels are still visible (EurObserv'ER, 2019a, 2019b).

Figure 14 Global renewable energy employment by technology in 2012-2017 worldwide. Source: own figure based on IRENA (2018)



Additionally, the observation of longer time periods reveals that significant fluctuations in employment may occur at the national level. For example, in Germany, the renewables industry has experienced years of continuous growth, but also subsequent years of decline because of a RES source specific mixture of social, economic and political influences. The national solar PV industry suffered a major breakdown starting in 2012/2013 (Tampubolon et al., 2018) especially due to the Chinese PV-dumping policy and a belated reaction of the EU in terms of its anti-dumping policy. At present, the national wind industry struggles due to an increasing number of lawsuits against installed and planned plants (Quentin, 2019).

From a purely financial perspective, the net employment effect shows a positive trend as RES technologies become cost-effective. Duscha *et al.* (2014) estimate that seven million jobs will be created by the energy transition by 2030 if RES technologies reach a 30% share of the gross final energy demand. Depending on background assumptions of the corresponding New Econometric Model of Evaluation by Sectoral Interdependency and Supply (NEMESIS) projection model, and under additional growth rates, even more jobs could be created by 2050 (see Table 9).

Table 9 Renewable energy targets and projections on key macroeconomic indicators for 2030 and 2050. Source: Duscha et al. (2014)

		Renewable energy share of gross final energy demand			
		30%		**35%**	
		2030	**2050**	**2030**	**2050**
Total RES deployment	*[TWh/a]*	3,600	5,400	4,100	5,600
Share in gross final energy demand	*[%]*	30%	59%	35%	62%
Gross value added	*[bn €$_{2010}$/a]*	100/92	166/160	122/120	165/164
Gross employment	*[1,000 jobs]*	1,700/1,600	2,200	2,100	2,200/2,300
Net GDP (NEMESIS)	*[%]*	0.4/0.3	0.3	0.8	0.5/0.7
Net employment	*[1,000 jobs]*	700	300/700	1,500	600/1,400

The phase-out of nuclear and coal-fired power plants will come with demographic and economic challenges, especially in rural areas. The loss of these plants means the loss of well-paid jobs. What's more, employees of these plants are not guaranteed to easily find work in the RES industry and not necessarily in or near their current places of residence. Therefore, plant shutdowns come with many challenges for the workers and other residents of affected regions (Buck et al., 2019) and these areas are distributed unevenly across Europe (see Figure 15).

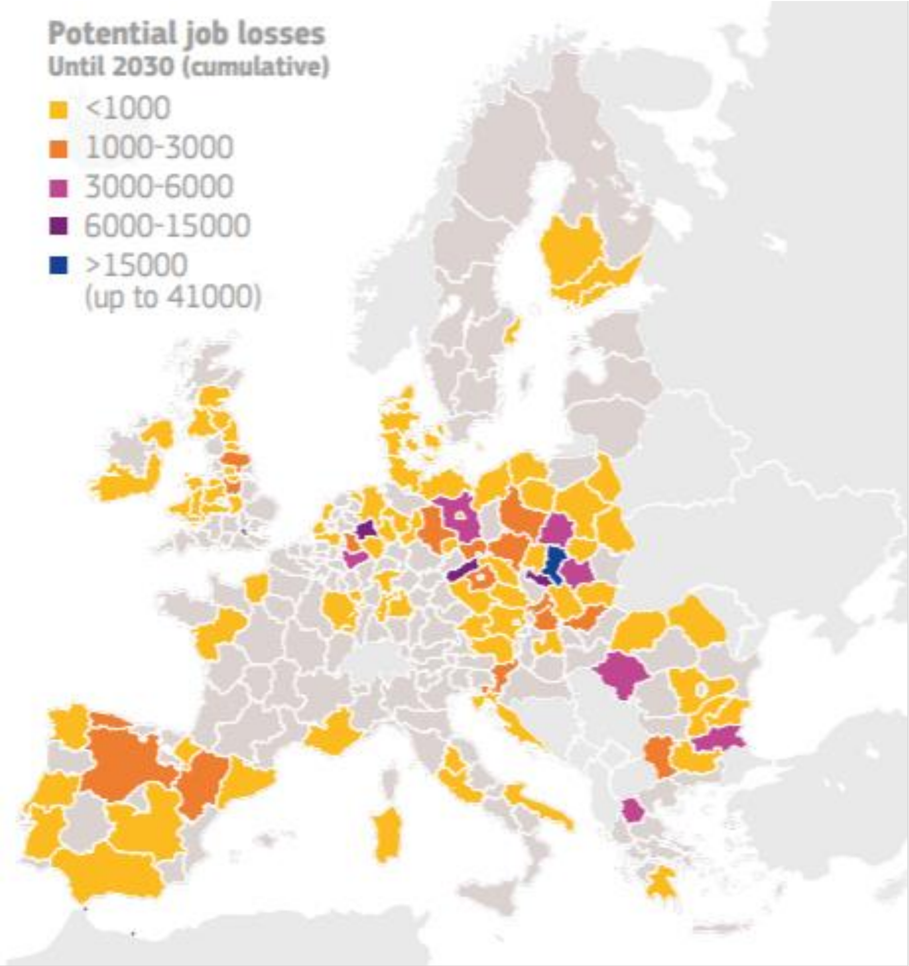
Oei *et al.* (2020) find evidence that German coal-regions face different intensities of negative effects and will be affected harder in cases of an early phase-out. However, they also state that these challenges can be overcome through either migration flows into other regions or via a strengthening of local welfare. If employees are supported with targeted labour market and social policy, they could potentially develop new market niches within the regions such as post-coal tourism or RES and refurbishment jobs.

Energy and fuel poverty

#energypoverty #fuelpoverty

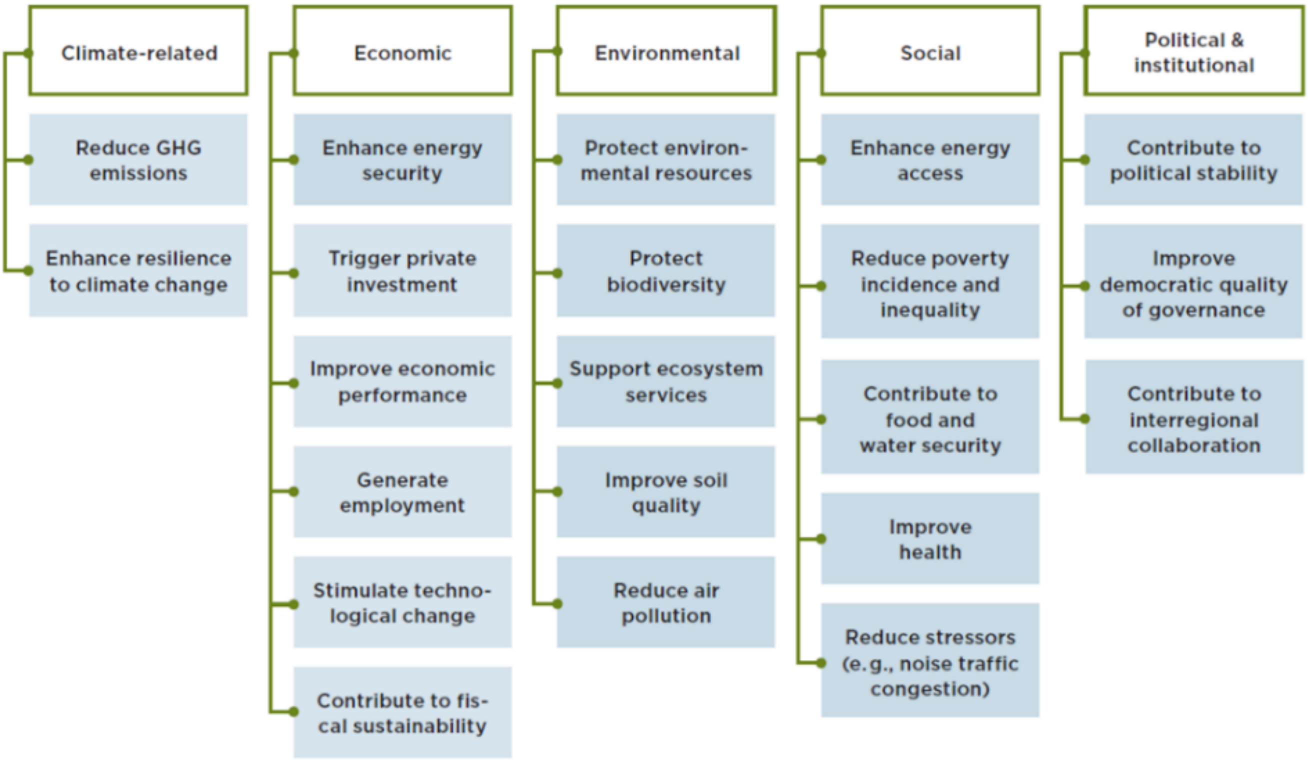
The scientific literature distinguishes two concepts of energy-related poverty: energy poverty and fuel poverty. Energy poverty (EP) traditionally tackles insufficient energy supplies in developing countries due to a lack of physical energy infrastructure and other common challenges such as corruption. In comparison, fuel poverty (FP) is defined as a situation in which households are lacking heating and/or cooling–or other essential services such as electricity or hot water–even though they have access to the physical infrastructure (Castaño-Rosa et al., 2019). In such cases, it is more the financial status of the household in a developing, emerging, or industrialised country that limits the supply with energy by the utility company, or the affordability of other energy resources such as gasoline or processed food supplies. In any case, the two definitions are often used interchangeably, even within the scientific literature.

Figure 15 Potential job losses in the coal industry in Europe until 2030. Source: European Political Strategy Centre (2018)



The use of RES spread in developing and emerging countries not only because of its potential to mitigate climate change but because of positive side-effects like energy poverty reductions. Such co-benefits of a transition towards sustainable energy future can be clustered into climate-related, economic, environmental, social, political and institutional benefits (see Helgenberger and Jänicke (2017) and Figure 16). Many of these findings improve the energy access, security or enhance the income of households directly or indirectly, or reduce expenses for other goods, leading to a reduced risk of falling into energy and fuel poverty.

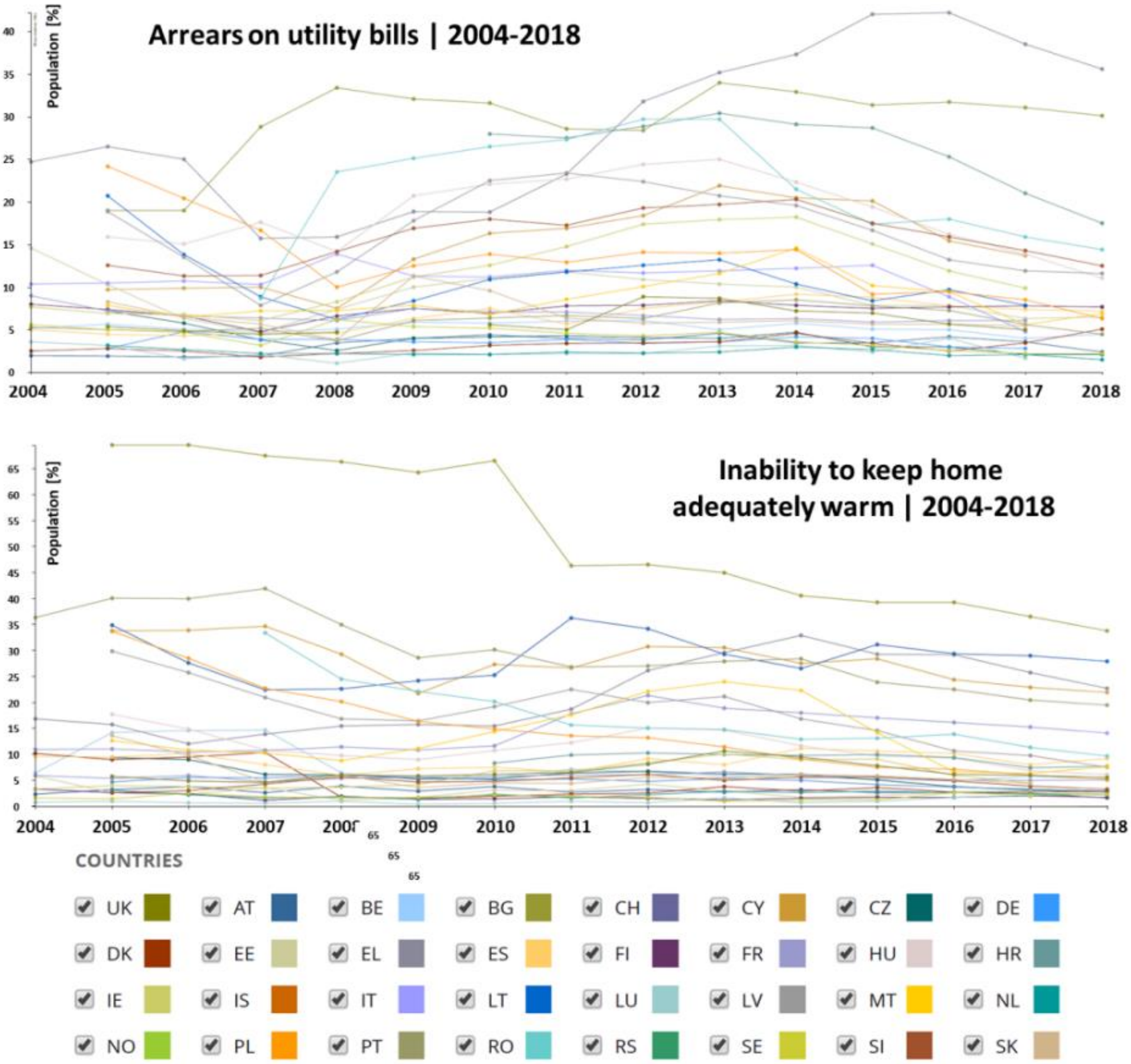
Figure 16 Categories of co-benefits of a sustainable energy transition. Source: Helgenberger and Jänicke (2017), under licence CC-BY-SA



In Europe, those experiencing fuel poverty represent a significant share of the population. While physical energy infrastructures are established in all European countries and are widely available, even in rural areas, many households still have financial difficulties covering their electricity and heating bills. Around 2010, approximately 8% of all EU households reported being in arrears with their utility bills within the past 12 months, while approximately 12% of households could not keep their homes adequately warm due to financial shortcomings. At the time, this share was highest in Portugal where 35% of households had financial problems paying for heating and Bulgaria experienced the highest share of households who could not pay their electricity bills (32%). South-eastern countries particularly suffered from above-average fuel poverty shares (Thomson and Snell, 2013). The EU has consequently launched the EU Energy Poverty Observatory that collects and presents data for different indicators (European Commission, 2020a), and current data indicates that fuel poverty is still high in many member states.

While overall levels of fuel poverty in the EU are declining, it remains an issue considering different energy sources in different countries (Figure 17). For electricity, a country-based comparison with longitudinal data from the EU Energy Poverty Observatory reveals that the share of affected population has remained low (less than 10% of the population share) with slight fluctuations in member states with high average income like Luxembourg, Germany, France, UK, Austria and the Scandinavian countries. A significant decrease can be observed in some Eastern Europe countries like Poland, Estonia, Croatia, and Lithuania. However, a temporal or remaining increase of electricity poverty was also visible in countries like Greece, Latvia, Romania and Cyprus (European Commission, 2020b).

Figure 17 Trends in fuel poverty indicators in the EU in 2004-2018. Source: European Commission (2020b, 2020c)



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For heating, fuel poverty has remained low in most EU countries, especially those with high average income. In some cases, the share has declined significantly, especially in Eastern European countries like Poland, Bulgaria and Romania. Only Greece has suffered a major increase in heating poverty (European Commission, 2020c). Significant increases of fuel poverty for heating and electricity may have occurred in countries that were struck hard by the last financial crisis.

The need for energy justice is an ongoing trend in Europe and demands for answers to tackling fuel poverty are increasing. Primc and Slabe-Erker (2020) differentiate between energy policy options that directly try to diminish social conflicts and classical, social policy that reacts to fuel poverty as a sub-form of poverty in common. They summarise their suggestions in four paths for different national situations:

- Path I fuel poverty is "characterised by a combination of non-high household income and energy policy" while energy prices play only a minor role. Here, liberalisation and privatisation of the energy sector can reduce energy poverty by rising household income. But only if income increases are not outpaced by price increases.
- In Path II fuel poverty, high energy prices and energy policy (irrespective of household income) leads to energy poverty. In such cases, social policy like social welfare payments or direct payments of energy bills would be appropriate.
- In Path III and IV fuel poverty, countries are characterised by the absence of energy poverty as average income is high. Here, governments can either prevent it with social policy (as in the Netherlands), or energy policy that keeps energy prices low (as in Belgium, France, Austria and the UK) or both.

In general, Primc and Slabe-Erker (2020) consider countries with above-average fuel poverty to be in a trapped situation. They also warn policymakers of the dangers of downplaying fuel poverty as merely another form of poverty; it comes with both side-effects for the natural environment and health risks for humans, both of which are not necessarily true for other forms of poverty.

Community benefits and challenges

#communitybenefits

The community benefits of local renewable-energy projects are of increasing interest–especially in relation to wind farm projects–because of their potential to increase local acceptability, mitigate conflicts around projects and enhance opportunities for regional development (Centre for Sustainable Energy, 2009; Cowell et al., 2011; Munday et al., 2011; Süsser and Kannen, 2017; Walker et al., 2014; Wolsink, 2006).

The six common categories of such benefits are: community ownership (some form of shares), community benefit fund (money provided by the developer), in-kind benefits (enhancement to local infrastructure, facilities and environment), local contracting (local employment during construction and operation), environmental mitigation and enhancement, and involvement in the development process (form of connection activity) (see Cass, Walker and Devine-Wright, 2010; Cowell, Bristow and Munday, 2011; Munday, Bristow and Cowell, 2011; Bristow, Cowell and Munday, 2012).

A strong focus has, thereby, been devoted to regional added-value, such as local tax incomes, incomes of companies and long-term employment due to renewables (Hirschl et al., 2010; Prognos, 2015; Agentur für Erneuerbare Energien, 2015). However, while community benefits such as payments to communities have received a significant amount of attention (e.g., Munday, Bristow and Cowell, 2011; Baxter, Morzaria and Hirsch, 2013; Walker, Wiersma and Bailey, 2014), interactions with social and environmental benefits have gained less attention.

Beyond these benefits, renewable-energy projects may also induce negative impacts and challenges to places and communities. In this regard, some studies have found negative environmental impacts, social conflicts and difficulties in project development (Aitken, 2010; Baxter et al., 2013; Rogers et al., 2008).

Therefore, trade-offs between the benefits and challenges of community-based energy projects often need to be made. Süsser and Kannen (2017) undertook a comprehensive analysis of environmental, social, economic, technical, planning and political benefits and challenges induced by a case-study communal renewable-energy project and identified five trade-offs of environmental, social, economic, planning, technical and political aspects:

- Environmental impacts are socially acceptable, but this depends on technologies and community benefits generated;
- Community renewables swing between social enhancement and social splitting;
- Economic benefits and challenges emerge at individual, community, regional, and superregional levels;
- Continued political support and social and technical innovation are needed for sustaining community renewables; and
- Community renewables hold the potential to enable a sustainable regional development.

There are also indications that public perceptions, attitudes and the acceptance of renewables change throughout the planning and development process (Aitken, 2010; Devine-Wright, 2011; Wolsink, 2006), which might be caused by differences between expected and experienced outcomes of RES projects. Thus, it must be carefully considered how community benefits are portrayed and perceived (Walker et al., 2014) and which disadvantageous impacts emerge and how these are perceived.

2.2.4 Citizen empowerment by digitalisation

#smarthomes #virtualpowerplants #blockchain #sharingeconomy

Elements of digitalisation in energy systems via smart technology–as discussed in section 2.1.4–are seen as both disruptive innovations and as key enablers of sector-coupled, renewable energy systems (Buck et al., 2019). Such innovations empower citizens as smart energy consumers and often enable them to become energy providers. As such, these technologies could democratise energy markets by amplifying the number of market actors and lead to the ideal of perfect competition. Leis (2019) calls such a scenario of intensified intra- and inter-fuel competition ’hyper-competitiveness’. Therefore, it is not surprising that the EC expects the amount of smart homes to grow tenfold by 2021 from approximately 9 to 81 million (European Political Strategy Centre, 2018).

Smart applications have primary and secondary benefits but also risks and barriers that determine the pace of their diffusion. Typical examples of the benefits of smart homes are energy savings, convenience and controllability, financial benefits and savings, while commonly discussed risks and barriers include issues of

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privacy, security, technical reliability and usability (Sovacool and Furszyfer Del Rio, 2020). The acceptance and, consequently, the use of new technologies is likely to depend on an individual weighing up the advantages and disadvantages to them personally (Richard et al., 2018). Therefore, the successful roll-out of smart devices into society comes with uncertainty, can be demand-side or supply-side driven, and potentially needs significant political support.

In summary, digitalisation offers new possibilities across societies and economies. However, while technologies such as shared mobility and smart homes could make our daily lives easier, some technologies and devices still require wider acceptance within society.

2.2.5 Behaviour change and rising awareness of behavioural rebounds

#behaviouralchange #reboundeffects

Much of the debate on climate action surrounds levels of so-called "pro-environmental behaviour": "behaviour that harms the environment as little as possible, or even benefits the environment" (Steg and Vlek, 2009:209). From electricity use and home heating to washing, many activities influence a household's levels of energy consumption.

While environmental awareness among citizens is high–and continues to increase–in industrialised countries, openness to behavioural changes and sufficiency-based lifestyles are still relatively uncommon (Toulouse et al., 2017). In science, behavioural changes are often not seen as a loss in welfare but as a gain in wellbeing and satisfaction (Samadi et al., 2017), as beneficial lifestyle innovation (Göllinger, 2012), and the 'holy grail' of sustainability (Morrissey et al., 2016). Reasons why those framings are not automatically incorporated in society can be explained by attitudes towards energy use, the dominant social paradigm, or the fear of loss and marginalisation.

Energy consumption practices among Europeans are slowly changing. Nevertheless, it is not changing across all sectors at a speed that is compatible with a successful energy transition. In the EU-28, the electricity consumption per capita has slightly increased between 2000 and 2016. While the EU-15 countries show a minimal trend towards a reduction–at least since the financial crisis–the trend among new member states (NM-13) is for increased energy use, even if the average EU-15 citizen consumes 1.6 times more energy than a citizen in NM-13 countries (Tsemekidi Tzeiranaki et al., 2018). Thus, the trend represents a "catching up" process among the NM-13 countries in Eastern Europe to its western partners in terms of income and wealth.

It is worth noting that the declining energy demands resulting from more efficient electrical and thermal appliances are offset by the rising number of appliances per capita. Since 1990, the specific demand of white goods, space cooling and heating technologies has decreased by up to 40%. But, at the same time, the overall energy consumption of electrical appliances per capita has increased in the EU by 40% and cooling demand has increased by a staggering 700%. Thus, the overall electricity consumption per capita has remained virtually unchanged. Only the heating demand has fallen by around 25 % (EEA (2019). Furthermore, sector-coupling and electrification are expected to increase electricity use and its peak demand levels. New electricity consumers in the heating and mobility sector, especially those utilising heat pumps and e-mobility options, substitute fuel-based technologies (Buck et al., 2019).

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As a result, energy savings per device has not contributed significantly to current European energy transitions and more consciousness for behavioural change in consumption seems necessary. In social sustainability research, the study of lifestyle changes contributing to an overall reduction of energy consumption is referred to as the sustainability strategy of energy sufficiency (e.g., Göllinger, 2012; Brischke *et al.*, 2016; Samadi *et al.*, 2017), which is closely related to the postgrowth or degrowth paradigm (Samadi et al., 2017).

To summarise, individual behaviours and consumption choices do currently have a significant impact on energy consumption. It remains to be seen to what extent energy targets will rely on these, and to what extent they are played off behavioural rebounds. Behavioural aspects could be especially of relevance in the context of energy models in the building sector.

2.2.6 Transition from individual action to policy action

#responsibleconsumerism #energyinvestment #policyaction

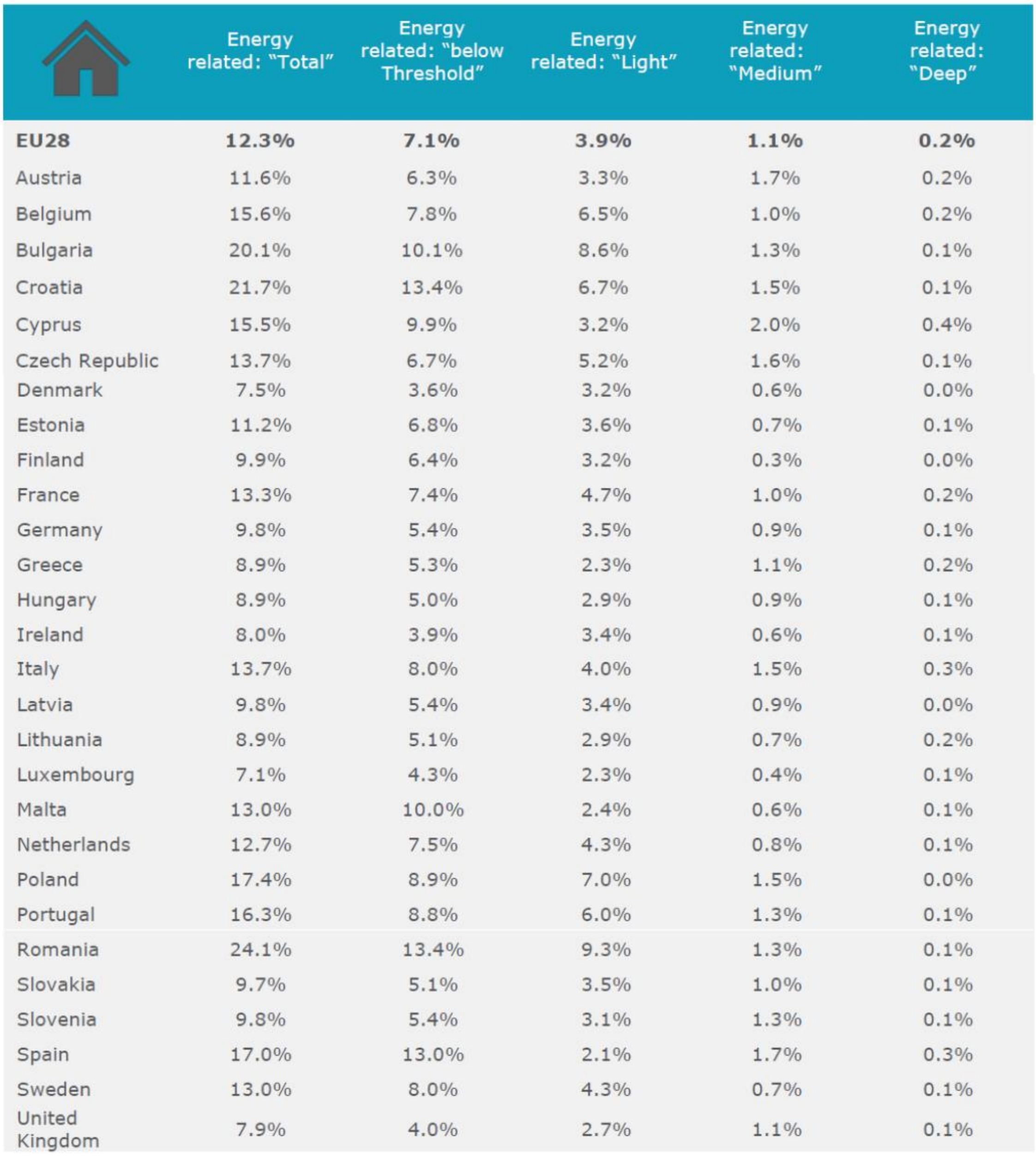
Much of the climate action debate was–and still is–about the importance of personal choices to reduce emissions, minimise resource use and save energy. The discussion is often focused on the relative importance of different measures with low, medium, and high impact on the individual CO_2 footprint (for an overview of options compare (e.g., Wynes and Nicholas, 2018). However, there is also a perceived trend towards a growing demand for actions by politicians and the economy to act on climate change. Individual behaviour and consumption changes can reduce human's environmental footprint, but the environmental impacts at an individual level are relatively limited. As such, wider changes across the economy are required in terms of resource use and production patterns.

Global movements call for climate action by governments. The *Fridays for Future* movement, for example, demands a policy that tackles climate change (Wikipedia, 2020c), and global divestment organisations call upon cities, corporations, banks and insurance companies to "get[ting] rid of stocks, bonds, or investment funds that are unethical or morally ambiguous" (Fossil Free Divestment, 2020).

Individual consumption choices and regulations and incentives in the energy field have often been influenced by each other. In Europe, for example, the sales of electronic household appliances with high energy efficiency have risen quickly due to stricter regulations and changes in purchasing behaviour. As a result, the average energy consumption rates of refrigerators, washing machines and tumble dryers have fallen by around 25% between 2004 and 2015 (Michel et al., 2016).

The refurbishment rate of residential and non-residential buildings in Europe is close to 1% per year (Belgium Ipsos and Navigant, 2019). Within EU-28 countries, 12.3% of residential buildings have been refurbished in some way between 2012 and 2016, meaning a refurbishment rate of around 2.5% per year. The annual rates differ for EU member states between 1.4 and 4.8%. In any case, only 0.2% of the 12.3% of residential buildings received a 'deep' renovation. Refurbishments are classified as 'deep' when more than 60% of the prior primary energy demand was saved. Most energy refurbishments lead to savings of the primary energy consumption of less than 3% and, therefore, are classified as 'below threshold' (see Figure 28). As a consequence, most of the refurbishments undertaken in the EU do not significantly contribute to a reduction in the energy consumption of buildings (see Figure 18).

Figure 18 Energy-related renovation in residential buildings in the EU for the period 2012 to 2016. Source: Belgium Ipsos and Navigant (2019)



	Energy related: "Total"	Energy related: "below Threshold"	Energy related: "Light"	Energy related: "Medium"	Energy related: "Deep"
EU28	**12.3%**	**7.1%**	**3.9%**	**1.1%**	**0.2%**
Austria	11.6%	6.3%	3.3%	1.7%	0.2%
Belgium	15.6%	7.8%	6.5%	1.0%	0.2%
Bulgaria	20.1%	10.1%	8.6%	1.3%	0.1%
Croatia	21.7%	13.4%	6.7%	1.5%	0.1%
Cyprus	15.5%	9.9%	3.2%	2.0%	0.4%
Czech Republic	13.7%	6.7%	5.2%	1.6%	0.1%
Denmark	7.5%	3.6%	3.2%	0.6%	0.0%
Estonia	11.2%	6.8%	3.6%	0.7%	0.1%
Finland	9.9%	6.4%	3.2%	0.3%	0.0%
France	13.3%	7.4%	4.7%	1.0%	0.2%
Germany	9.8%	5.4%	3.5%	0.9%	0.1%
Greece	8.9%	5.3%	2.3%	1.1%	0.2%
Hungary	8.9%	5.0%	2.9%	0.9%	0.1%
Ireland	8.0%	3.9%	3.4%	0.6%	0.1%
Italy	13.7%	8.0%	4.0%	1.5%	0.3%
Latvia	9.8%	5.4%	3.4%	0.9%	0.0%
Lithuania	8.9%	5.1%	2.9%	0.7%	0.2%
Luxembourg	7.1%	4.3%	2.3%	0.4%	0.1%
Malta	13.0%	10.0%	2.4%	0.6%	0.1%
Netherlands	12.7%	7.5%	4.3%	0.8%	0.1%
Poland	17.4%	8.9%	7.0%	1.5%	0.0%
Portugal	16.3%	8.8%	6.0%	1.3%	0.1%
Romania	24.1%	13.4%	9.3%	1.3%	0.1%
Slovakia	9.7%	5.1%	3.5%	1.0%	0.1%
Slovenia	9.8%	5.4%	3.1%	1.3%	0.1%
Spain	17.0%	13.0%	2.1%	1.7%	0.3%
Sweden	13.0%	8.0%	4.3%	0.7%	0.1%
United Kingdom	7.9%	4.0%	2.7%	1.1%	0.1%

A global trend towards electrification and higher energy efficiency in the mobility sector is emerging, but the cumulative number of cars sold remains small. The market for electro-mobility has been growing steadily since 2012 and 1.2 million electric vehicles were sold in 2017, with demand mainly coming from China, Europe and United States (see Figure 19). Additionally, many countries–and especially cities–have begun to understand mobility transitions not only in terms of fuel substitutions, but as a shift in the modal split

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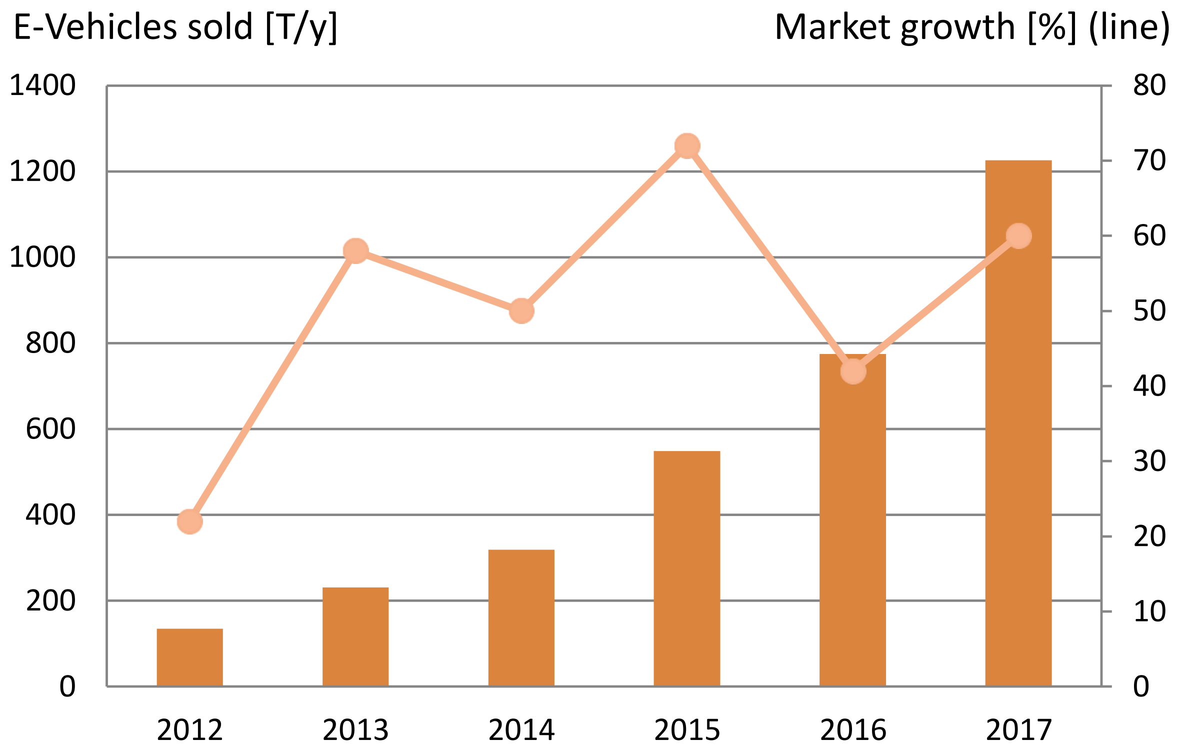
towards public and active transportation (European Commission, 2016). The sharing economy, for example, changes the ways in which mobility is provided and consumed, and enables consumers to use cars and bicycles with unprecedented convenience (Buck et al., 2019). The current trend of shared modes of transportation is expected to continue to grow rapidly (Osztovits et al., 2015).

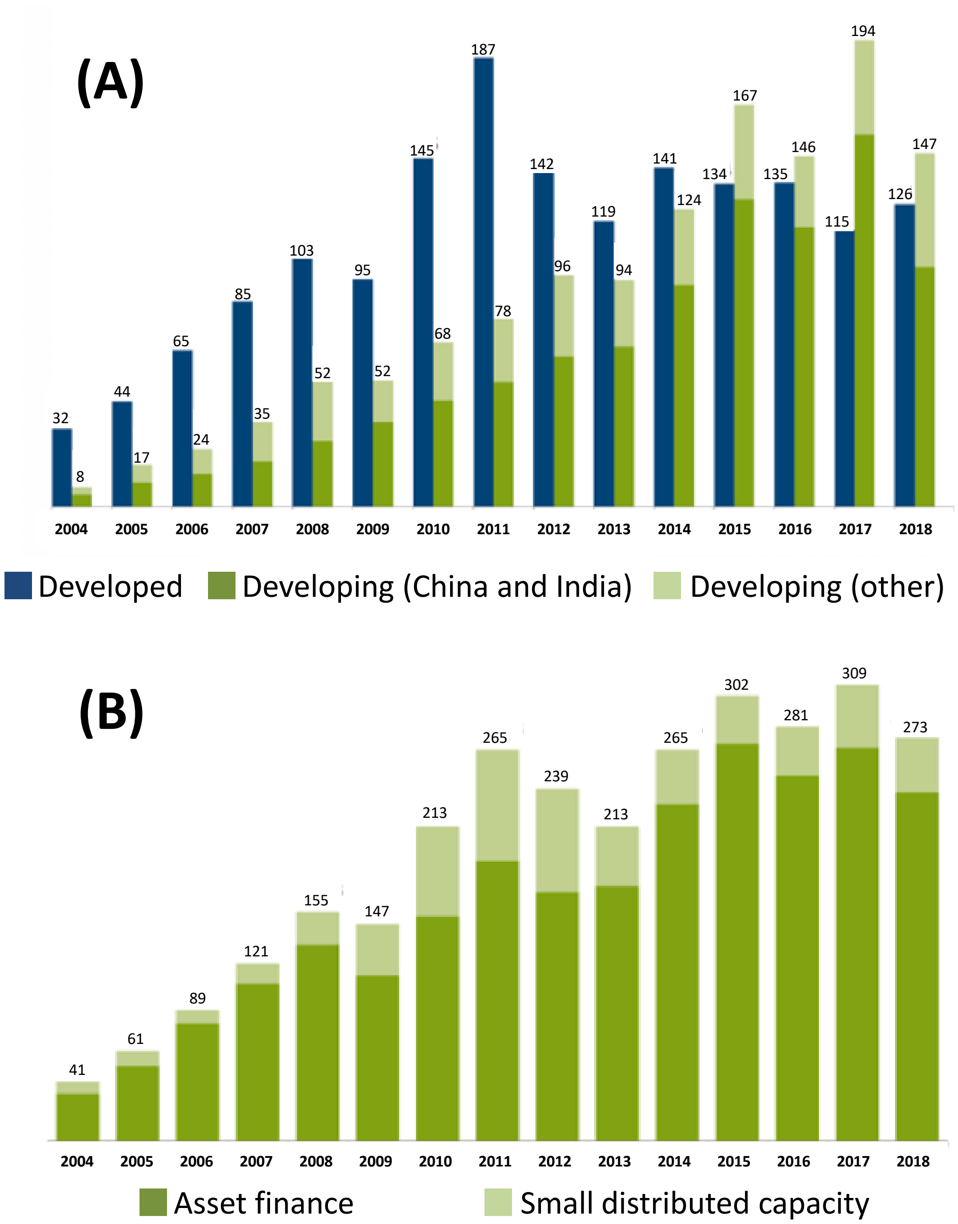
Figure 19 Global passenger electric vehicle market, 2012-2017. Source: own figure, based on REN21 (2019b)



For both individual and corporate investments, green investments are growing in the energy sector. According to Leis (2019), *"[…] environmental consciousness is shaping consumer reactions, investor appetite and government response",* and observable developments are in line with this assumption. Since 2004, investments in RES have more than quadrupled in developed and developing countries worldwide, although the majority of contributions come from the financial assets of utility companies and a minority from small distributed capacities. In recent years, however, rates of investment have stagnated (see Figure 20).

Participation in green investment schemes tends to be driven by different factors. In the period 2000 to 2009, a first rise in interest in RES technology was measurable by investors and the public, initiated by political programs building upon rising climate change concerns. By that time, specific investment costs were high for all emerging RES technologies such as wind, solar and biomass. By 2010, the trend had dissipated, caused largely by the slow economic growth after the financial crisis, falling fossil-fuel prices and new political pressure on RES due to perceived high costs resulting in subsidy reductions. However, RES investment costs continued to fall and are now competitive with many fossil fuels. As a result, many energy systems are slowly adopting to RES needs by, for example, expanding grids or adding storage options (Frankfurt School-UNEP Centre/BNEF, 2019).

Figure 20 Annual investment in renewable energy capacity by country type (A) and investor type (B), 2004 to 2018 ($billion). Source: Frankfurt School-UNEP Centre/BNEF (2019)



The overall trend from individual action to wider policy action underlines the importance of governmental action on the implementation of changes in consumption patterns, and demand for policies that can drive the required economic decarbonisation. For the energy modelling, it implies the importance of policies for changing production and consumption patterns, and accelerating investments that drive the energy transition.

2.3 Implications of technological and social trends for the SENTINEL project

- A selection of the most-relevant technologies will need to be made while developing ENVIRO and QTDIAN modules and each technology is likely to present different challenges and result in different outcomes
- A list of issues and questions relating to the real-world challenges of implementing new technologies, and the challenges that could occur while attempting to model these processes, are presented
- Utilising the outcomes of the social trend analysis will also present various challenges, particularly regarding the implementation of social drivers and constraints and in the formulation of scenarios
- A list of issues and questions that could guide these processes is also provided

The inventory of trends discussed in the previous sections, while not exhaustive, is suitably complete for providing several useful inputs to the ongoing SENTINEL project. Above all, it provides an overview of the wide range of options at hand. Different combinations of technological and social innovation pathways will result in very different configurations of future energy systems. What's more, further consideration of each of these two elements is likely to provide its own share of challenges that will need to be addressed within future energy modelling processes.

2.3.1 The use of technological trends in energy modelling

The overview of current directions in technology introduced above provides an indication of the wide range of options available to decision makers in the definition of energy transition strategies. The selection of one technology or another could result in very different energy transition pathways with very different environmental and social impacts. This also applies to the modelling of imagined scenarios, where different technological preferences are certain to result in a range of different environmental and social outcomes. A short discussion of some of the challenges that could be encountered while integrating the observed trends into the QTDIAN and ENVIRO modules of the project are discussed below.

Challenges in energy transition processes

Firstly, the potential real-world challenges of integrating the available supply and demand technologies further into the socio-technical regime need to be considered.

- **Readiness levels of technologies and required time of development:** In order for a burgeoning or underutilised technology to achieve widespread implementation it must have reached a suitable level of 'maturity' (see section 3.1.1). Is the technology sufficiently developed and ready to enter large-scale production? If so, are production facilities ready and able to manufacture the required hardware? Are there any related issues or restrictions regarding installation? Is data available–such as learning and experience curves (see section 3.1.2)–that could indicate potential development, cost and implementation timelines?
- **Personnel availability:** Likewise, levels of implementation may be limited by human factors. Are particular skills or levels of expertise required to manufacture or install hardware? If so, are a suitable number of qualified workers available? Are there geographical elements to staff availability? If training of new staff is required, how long is this likely to take? What prerequisites do new staff require?
- **Resource availability:** Growth in a technology may also be subject to bottlenecks relating to resource availability. Do manufacturing processes require the input of limited resources? Are the prices of these resources likely to fluctuate? Are substitutes available or likely to be developed?
- **Environmental impacts:** Quantifying the burden that each technology places on local and global ecosystems is a central element of the proposed ENVIRO module. The biophysical constraints arising from the manufacture, installation, operation and disposal of all elements of a proposed activity should be considered in line with the principles of life-cycle assessment (LCA). This typically includes consideration of elements such as energy, raw materials and water as inputs and air and water pollutants, wastewater, material waste and land degradation as outputs. Are some technologies significantly more or less impactful than others? In what ways? How are different impacts to be compared? Are some impacts more tolerable than others?
- **Areas of application in energy systems:** All supply and demand technologies are designed to undertake the same function. While many technologies compete to undertake the same function in the energy system–e.g., secondary and flow batteries–other technologies operate at entirely different scales to one another–e.g., pumped hydro and ultracapacitors. Furthermore, synergies exist between the various functions such that a rise in integration in one technology may necessitate an increase in capacity at another level of the system. So, for instance, a rise in wind energy capacity would require more large- and local-scale energy storage devices to be implemented in a suitable configuration.
- **Other economic issues:** As always, the attractiveness or likelihood of integration of a product is heavily influenced by economic considerations. Are some applications cheaper or more efficient than others? Do they require less maintenance? Are transport or installation costs lower? Are lifespans known and reliable?
- **Other physical issues:** Lastly, several physical factors could also affect the implementation of different supply and demand technologies at the end-user level. Are some more convenient or user-friendly than others? Are some physically smaller or less visually intrusive? For example, a given

energy storage device would seem far more likely to be implemented if it is small, easy to install, modular in design and aesthetically appealing. It is acknowledged that several such issues may occupy a space between the technical aspects of a technology and the personal and political issues more related to social trends.

Challenges in modelling

Secondly, challenges exist for those attempting to model these processes.

- **Choice of approach:** Many approaches are available for simulating the various aspects of transition processes (see section 4.2). The choice of approach is likely to be guided primarily by the particular aspect of the process that is being investigated and at what scale is most appropriate for doing this. It will also be influenced by the input and output parameters that are of most interest. Also, what amount of detail required? What question or issue are you trying to address? Is the model quantitative or more conceptual? Do you wish to optimise a system within a given set of constraints or determine outcome pathways from given inputs? What simulation times are acceptable? How many different scenarios do you wish to test?
- **Choice of limiting factors:** The factors that limit and influence transition processes provide the majority of the conceptual and quantitative foundations of transition models. It follows that many of the challenges in energy transition processes listed above will guide the choice of model approach and, subsequently, provide many of the inputs–as raw data and as relationships between parameters–into the model.
- **Data availability and reliability:** Models can only be created and used where suitable data exists and the quality of model outputs are strongly linked to the quality of the data inputs. Hence, the existence of readily available data of good quality is a key factor in the creation of robust and reliable models. The modelling of energy transitions is likely to rely on a significant amount of technical data from the electricity industry, from pre-existing energy modelling applications or other sources such as LCA databases, all of which is assumed to be relatively easy to obtain. However, for new or underutilised niche technologies this is not always be the case and data may be limited or be of poor quality. Furthermore, many of the inputs for modelling of this kind–particularly when defining response relationships or connections between parameters–take the form of assumptions. As such, data availability and reliability issues are often an issue in the models used to simulate transition processes.

2.3.2 *The use of social trends in energy modelling*

The social trends identified in the preceding sections can be used to inform the development of energy modelling in two ways. Firstly, they can be used to identify new drivers and constraints that seem relevant for model implementation. Second, data relating to past trends can be used to inform scenario building processes, e.g., define socio-technical RES potentials.

New drivers and constraints in models

Social trends are closely linked to many of the key questions relating to the energy transition and the analysis of trends can highlight many relevant social aspects of the energy transition that have not been considered in models to date. The underlying reasons behind trends can often point to barriers and drivers of change that can be relevant for understanding technological diffusion. Depending on the research questions, it might be relevant to adapt the model logic and corresponding structures according to social drivers and constraints. Further research within SENTINEL should consider how and to what extent the following social aspects could be qualitatively and quantitatively integrated into energy models:

- **Social technology preferences and acceptance:** How do different RES sources and their impacts (e.g., on landscapes) influence the attitudes in the population and affect the degree of opposition? Can different deployment strategies (e.g., maximum tolerable RES density, maximum local deployment pace) reduce opposition and support local energy transitions?
- **Fields and attitudes regarding social justice:** Who profits from and who is burdened by the energy transition? How do local job gains and losses impact the energy transition? How does energy/fuel poverty impact the acceptance and overall pace of the energy transition? What impact would specific social policy strategies (e.g., maximum tolerable electricity price) have on the transition?
- **Preparedness of the economy:** How does the acceptance of or resistance against the energy transition in the economy effect the diffusion? How are (local) economies prepared for the needs of the energy transition?
- **Responsibilities/ownership:** How do prosumers and community energy groups accelerate the energy transition? Should we think nationally or at a continental level? How do these options influence the common energy targets?
- **Consumption behaviour:** How do individual consumption patterns influence each other and what impact does that have on energy savings? Would energy sufficiency be a viable option?
- **Policy support:** What are best practice policies for the expansion of RES grids and storages? What are policies supporting a just transition?

The implementation of such aspects is particularly relevant if parameters are closely connected to the research question, and if their consideration may have a high impact on the results. As the current document is a collection of relevant social aspects, it could serve as a background document for further investigation. It also has significant amount of overlap with the findings of modellers analysing the next ambitious steps in the integration of social aspects in energy models (e.g., Pfenninger et al., 2014; Trutnevyte et al., 2019).

Basis for scenario development

If the parameters corresponding to a particular social trend are included in a model, the past data relating to that trend can be used for scenario development. Therefore, it is important to differentiate between a social trend consisting of a set of parameters that have a coupled direction and logic of development, and a single mathematical trend of one parameter. The extrapolation of one or several past parameter trends can serve to build trend scenarios.

However, simply using the extrapolated trend of a parameter will not be sufficient. Future development always comes with uncertainty. So, for robust analysis of explorative and normative scenarios, trend scenarios should be complemented with sensitivity analyses that represent incremental path shifts or disruptive events. Such variation can be plausibly explained by different narratives. Thus, the current document can serve as a basis for data of mathematical trend extrapolation and development of social storylines.

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3 Conceptual frameworks

- An understanding of the current technological progress, social-technical theories and approaches towards socio-eco-technical transitions provides an overview of the available options of the theoretical and technical development of the ENVIRO and QTDIAN modules
- Discussion of two tools to assess the maturity of new technologies reveals that learning and experience curves are a more robust method than technology readiness levels
- A group of four sustainability transition frameworks are discussed and implications drawn for modelling energy transitions
- Including the concept of socio-ecosystem metabolism could connect ecosystems with socio-technical systems to form the theory of the socio-eco-technical transition

Overview

The maturity of technologies plays an important role in the definition of future energy scenarios. Learning and experience curves are a more robust method than the technology readiness levels (TRLs). One-factor learning curves are available for many of the renewable energy technologies, especially onshore wind power and solar photovoltaics. The latest advances focus on the development of two factor models where both the learning by doing and learning by researching are included, and its implementation in energy system models.

We introduce four main theoretical foundations for conceptualising socio-technical transition processes: the Multi-Level Perspective (MLP), the Technological Innovation System (TIS), Strategic Niche Management (SNM) and Transition Management (TM). Those theories are useful to be applied in the context of the energy transition in order to better understand how structural change in the energy systems comes about, and to make the energy transitions happen and navigate developments towards sustainable energy systems.

Different transition theories can provide a holistic structure and explanations of change for important system dimensions including micro, meso and macro level and their influencing elements. Thus, they can be applied for developing model scenarios and parameters. The QTDIAN toolbox uses the Multi-Level Perspective as a theoretical foundation for developing narratives of social future storylines and the influence of different parameters for change within.

In addition to these frameworks–which do not fully represent exchanges between societies and ecosystem–so-called socio-ecological system (SES) frameworks are also discussed. These highlight the biophysical exchange between society and the ecosystem, the contribution of the exchange to social stability, the impacts of the exchange on the ecosystem and the relationship between social and ecosystems. Three such frameworks are reviewed here: Long-Term Socio-Ecological Transitions (LTSET), the False 8 Adaptive Cycle (F8AC) and Socio-Ecosystem Transition Management (SESTM). Combining the dynamics between society, the environment and technology, a framework for the assessment of energy transitions from a socio-eco-technical point of view is offered.

Modelling tools are rooted in conceptual models and narratives. As part of the exercise of defining the conceptual roots for QTIDIAN and ENVIRO, this chapter provides an overview of conceptual approaches for the assessment of the role that innovations in technology and social practices play in the energy transitions. We first review options for quantifying and predicting technological progress and social acceptance of technologies, including conceptualisations such as technology readiness levels (TRLs) and learning and experience curves. A discussion of frameworks from the field of *socio-technical transitions* follows. We review frameworks that explain the dynamics that determine generalised technological changes within society. The interactions between socio-economic systems–in which energy systems are embedded–and ecological systems are discussed as part of a summary of *socio-ecological transitions*. These frameworks explain how and why the socio-technical system impacts the environment. After these surveys we conclude with the definition of the conceptual framework used in SENTINEL for the assessment of social and environmental constraints to sustainable energy transitions.

3.1 Understanding technological progress

- Examining the maturity levels of technologies plays an important role in the definition of future energy scenarios
- Investigation found that learning and experience curves are a more robust method than technology readiness levels and that, while one-factor learning curves are available for many renewable energy technologies, data for two-factor models are still relatively undeveloped

As previously mentioned, technological innovations are one of the strategies expected to contribute to the energy transition. New energy supply and demand technologies are often expensive at the point of their market introduction. However, they typically become cheaper over time as the result of technological learning. In order to model the shift from fossil fuel to low-carbon fuels and renewable energy sources, an assessment of the maturity of new technologies becomes more imperative. Here, two possible tools to define the maturity of a technology–the ***technology readiness level (TRL)*** scale and ***learning and experience curves***–are detailed.

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3.1.1 Technology readiness levels

The TRL scale is a widely used scale for assessing the "maturity" of a technology. Originally developed by NASA and the US Department of Defense in the 1970s, it has since been adapted by the European Cooperation for Space Standardization (ECSS) (ISO, 2013) as a way to monitor early technology initiatives in space system hardware and programs (Jamier et al., 2018).

The EU research framework program Horizon 2020 subsequently adopted the TRL scale to measure technology maturity and guide research, development and innovation within the EU. Moreover, TRL levels are used by many specific energy-related organisations such as the US Department of Energy (DOE), the Australian Renewable Energy Agency (ARENA), the Government of Canada and the Organization for Economic Cooperation and Development (OECD) (De Rose et al., 2017).

Despite some differences, most existing TRL scales look very much the same. The scale itself ranges from the lowest level ("TRL 1"), where only the most basic principles of a new technology have been observed, to the highest level ("TRL 9") for fully proven and operational technologies. Table 10 shows the TRL scaled used for the evaluation of the Horizon2020 project proposals.

Table 10 TRL scale used by Horizon2020 for the eligibility assessment of projects

TRL	Description of TRL
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment
6	Technology demonstrated in relevant environment
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment

In 2017, the EC's Joint Research Centre (JRC) developed a study aimed as assessing the use of TRLs in the energy field in Europe (De Rose et al., 2017). The study was mainly based on desk research and complemented by surveys and a validating workshop where stakeholders gave feedback on a draft guidance document with TRL definitions which were further discussed to reach consensus. According to the outcomes of the workshop, TRLs are generally used to indicate status with respect to technological development, mainly centred on the performance and manufacturing approach. However, as illustrated in Table 12, TRLs can also be used to assess non-technological parameters, including standardisation, economic analysis (market, costs and business), sustainability, risk analysis and simulation and numerical models.

As a first step, the report assessed the TRL of a series of renewable energies, including solar photovoltaics, concentrated solar power (CSP), hydropower, wind energy, renewable heating and cooling (H&C), geothermal energy, renewable alternative fuels, ocean energy, bioenergy (biological pathway), and bioenergy (thermochemical pathway). The outcome of the analysis is presented in Table 11.

Table 11. Technology Readiness Level (TRL) for technology and non-technology topics of ten renewable technologies. Source: De Rose et al. (2017)

	Technology Readiness Level (TRL)								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Stable performance				☼✳✖🟦♦◆	🟫△▲				
Expected performance					☼✳✖🟦	△▲◆			
Manufacturing approach		◇				☼✳✖	🟦△▲♦◆		
Standardisation						✖◇	✳🟦△▲	☼♦	
Market, costs and business	🟫	🟫	🟫◇♦	🟫	🟫	☼🟫	🟫	△▲	
Sustainability	♦	🟦♦	♦	♦	✖△♦◆	▲	◇		
Risk Analysis	◆	✳	◇♦	🟫					
Simulation/numerical models		✳🟫✖◇🟦△▲◆	♦						

☼	Solar photovoltaic (PV)	◇	Ocean energy
✳	Concentrated solar power (CSP)	△	Bioenergy (biological)
🟫	Geothermal	▲	Bioenergy (thermochemical)
🟦	Hydropower	♦	Renewable heating and cooling
✖	Wind power	◆	Renewable alternative fuels

The findings showed that levels between TRL4 and TRL8 are typical for issues more related to the technical parameters as performance, manufacturing and standardisation. For most renewables, TRLs are low for economic analysis, risk analysis and simulation and numerical modelling issues. The authors suggest that the results illustrated in the table shall be considered as indicative rather that a precise estimate, particularly in light of some of the shortcomings of the assessment, which can be summarised as follows:

- For CSP (✳) and geothermal (🟫), site conditions which influence the specific engineering practice, and dimension of the installation were difficult to reflect in the assessment.
- For hydropower (🟦) and wind (✖), the stakeholders highlighted the need to consider the physical system separately from the software tools.
- Renewable heat and cooling (♦) were not a technological sector but an application of three different types of technologies: geothermal, solar and biomass.
- The geothermal (🟫) sector included electricity, in addition to heat and cooling, which uses different technological infrastructure. It also entails many different stages as site identification, surface

exploration, deep exploration, tests/field models/evaluation, plant/field engineering, and plant construction/installation/management. Each of these stages can be at different TRL levels, as reflected in Table 11.

- The renewable alternative biofuels (◆) included artificial photosynthesis, metal fuels and other potential unknown technologies for alternative fuel production. Thus, the TRLs presented in the table are only considered indicative.
- Similarly, ocean energy (◇) was assessed as a general concept rather than focusing on a specific technology due to the diverse technologies for producing energy from wave and tidal current, including new ocean energy technology such as ocean thermal energy conversion, currents, salinity gradient-based technologies and others that have not yet emerged.
- For the assessment of the bioenergy (biological pathway) (▲) and bioenergy (thermochemical pathway) (▲), the focus was in both the technologies for conversion and the cultivation of feedstocks.

The study concluded that there remains a lack of common understanding around the concept of TRL and that further guiding principles are needed. Furthermore, technology development follows different paths which depends on individualities at the interface with environment, manufacturing readiness, testing and validation steps. A list of trends identified for each of the TRL defined, as described in Table 12, was given to homogenise technology readiness levels.

In summary, TRLs are still predominantly only used when describing project proposals for funding applications or for reviewing project proposals within funding calls. Some participants of the study of De Rose reported that they are also used for internal and external communication and, to a lesser extent, as a planning or decision-making tool. Indeed, from the interviewed stakeholders, only research institutes indicated the use of the TRL as a planning tool. 30% of the research institute stakeholders used TRL as planning tools on a regular basis while the other research institutes and industrial companies with research departments reported the use of other tools for planning tasks. This is because they do not consider the TRL scale as an efficient Key Performance Indicator (KPI) for most planning tools.

3.1.2 Learning and experience curves

Economic scaling is widely applied in production cost analyses in order to account for typically lower investment costs of larger plants or devices. In similar fashion, learning and experience curves reflect how gaining experience in the manufacturing of a product leads to lower costs of production (Louwen and Lacerda, 2020). Berglund and Söderholm (2006) consider experience curves as the single most important driver for defining the cost of energy supply and demand technologies and thus shape the future energy configuration.

The concept of the learning curve dates back to the 19th century when Herman Ebbinghaus illustrated the process of memorising lists of words as an exponential process where the effort of learning increases progressively (Ebbinghaus, 1885). Later, Wright (1936) found that unit labour costs in airframe manufacturing decline at a constant rate with each doubling of cumulative production. Wright's learning curve was expanded by the Boston Consulting Group (BCG) to describe unit cost of a product across a whole industry, rather than within a single company, and called this concept the experience curve to distinguish it from the previous learning curve. Their definition included the effects of learning-by-doing and learning-by-researching, scale and investment (Louwen and Lacerda, 2020). Nevertheless, in the following section both terms are used indistinctively.

Table 12. Common trends of Technology Readiness Level (TRL). Source: De Rose et al. (2017)

TRL	Description of the TRL	Common trends identified in (De Rose et al. 2017).
1	Basic principles observed	☐ Identification of the new concept ☐ Identification of the integration of the concept ☐ dentification of expected barriers Identification of applications ☐ Identification of materials and technologies based on theoretical fundamentals/literature data ☐ Preliminary evaluation of potential benefits of the concept over the existing ones
2	Technology concept formulated	☐ Enhanced knowledge of technologies, materials and interfaces is acquired ☐ New concept is investigated and refined ☐ First evaluation about the feasibility is performed ☐ Initial numerical knowledge ☐ Qualitative description of interactions between technologies ☐ Definition of the prototyping approach and preliminary technical specifications for laboratory test
3	Experimental proof of concept	☐ First laboratory scale prototype (proof-of-concept) or numerical model realized ☐ Testing at laboratory level of the innovative technological element (being material, sub-component, software tool, …), but not the whole integrated system ☐ Key parameters characterizing the technology (or the fuel) are identified ☐ Verification of the proof of concept through simulation tools and cross-validation with literature data (if applicable).
4	Technology validated in lab	☐ (Reduced scale) prototype developed and integrated with complementing sub-systems at laboratory level Validation of the new technology through enhanced numerical analysis (if applicable). ☐ Key Performance Indicators are measurable ☐ The prototype shows repeatable/stable performance (either TRL4 or TRL5, depending on the technology)
5	Technology validated in relevant environment	☐ Integration of components with supporting elements and auxiliaries in the (large scale) prototype ☐ Robustness is proven in the (simulated) relevant working environment ☐ The prototype shows repeatable/stable performance (either TRL4 or TRL5, depending on the technology) ☐ The process is reliable, and the performances match the expectations (either TRL5 or TRL6, depending on the technology) ☐ Other relevant parameters concerning scale-up, environmental, regulatory and socio-economic issues are defined and qualitatively assessed
6	Technology demonstrated in relevant environment	☐ Demonstration in relevant environment of the technology fine-tuned to a variety of operating conditions ☐ The process is reliable, and the performances match the expectations (either TRL5 or TRL6, depending on the technology) ☐ Interoperability with other connected technologies is demonstrated ☐ Manufacturing approach is defined (either TRL6 or TRL7, depending on the technology) ☐ Environmental, regulatory and socio-economic issues are addressed
7	System prototype demonstration in operational environment	☐ (Full scale) pre-commercial system is demonstrated in operational environment. ☐ Compliancy with relevant environment conditions, authorization issues, local / national standards is guaranteed, at least for the demo site ☐ The integration of upstream and downstream technologies has been verified and validated. ☐ Manufacturing approach is defined (either TRL6 or TRL7, depending on the technology)
8	System complete and qualified	☐ Technology experimented in deployment conditions (i.e. real world) and has proven its functioning in its final form. ☐ Manufacturing process is stable enough for entering a low-rate production. ☐ Training and maintenance documentation are completed. ☐ Integration at system level is completed and mature. ☐ Full compliance with obligations, certifications and standards of the addressed markets
9	Actual system proven in operational environment	☐ Technology proven fully operational and ready for commercialization ☐ Full production chain is in place and all materials are available ☐ System optimized for full rate production

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Typically, the experience curve of a technology is defined using either the progress ratio (PR) or the learning rate (LR). PR represents the cost decline (expressed as a ratio) for each doubling of cumulative production. Production costs can be estimated as a power-law function of cumulative production, as represented in equation (1):

$$\mathrm{Ccum_i} = \mathrm{C_{0,i}} \times (\mathrm{Pcum_i})^{\mathrm{b_i}} \quad (1)$$

where, $\mathrm{Ccum_i}$ = price or costs of technology i at $\mathrm{Pcum_i}$; $\mathrm{C_{0,i}}$ = price or costs of the first unit produced; $\mathrm{Pcum_i}$ = cumulative production; $\mathrm{b_i}$ = learning parameter of technology i.

By applying the logarithmic function, a linear experience curve can be plotted with $\mathrm{b_i}$ as the slope parameter and log $\mathrm{C_{0,i}}$ as the price or cost axis intercept, as shown in equation (2):

$$\log(\mathrm{Ccum_i}) = \log(\mathrm{C_{0,i}}) + \mathrm{b_i} \times \log(\mathrm{Pcum_i}) \quad (2)$$

A technology-specific progress ratio ($\mathrm{PR_i}$), expressed as a percentage, can be calculated as the rate at which the price or costs of a technology decrease with each doubling of cumulative production, as illustrated in equation (3):

$$\mathrm{PR_i} = 2^{\mathrm{b_i}} \quad (3)$$

Meanwhile, the learning rate ($\mathrm{LR_i}$), illustrating the percentage at which costs decline after each doubling of cumulative production, can be calculated using equation (4):

$$\mathrm{LR_i} = 1 - \mathrm{PR_i} = 1 - 2^{\mathrm{bi}} \quad (4)$$

That is, as an example, a PR of 80% will result in a LR of 20%. Here, a LR of 20% implies that the cost falls by 20% for every doubling of cumulative production. As learning occurs, the learning ratio increases more rapidly and the cost is bound to fall more rapidly (Karali et al., 2015).

Figure 21 provides an example of an experience curve for solar PV modules. The plot on the left shows the empirical data collected on a normal, linear scale while the plot on the right illustrates data on a double-logarithmic scale. In this case the learning rate is estimated to be 23.9%, meaning that the price of PV modules declines 23.9% for every doubling of cumulative production. Accordingly, learning effects reduce costs and enable the technology to succeed in a broader range of applications. Figure 22 shows how the global installation of solar panels increased as the price of solar panels progressively dropped between 1975 and 2015 (O'Connor, 2016).

Figure 21 Variations in the price of solar panels and global solar panel installations from 1975 to 2015. Source: O'Connor (2016)

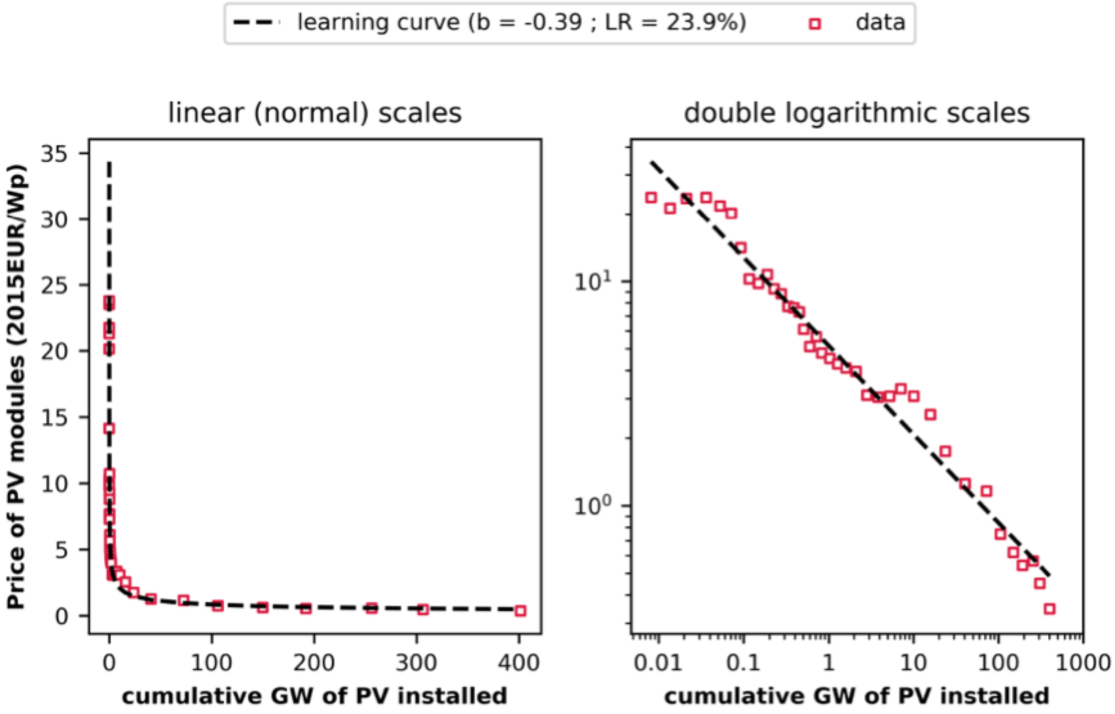
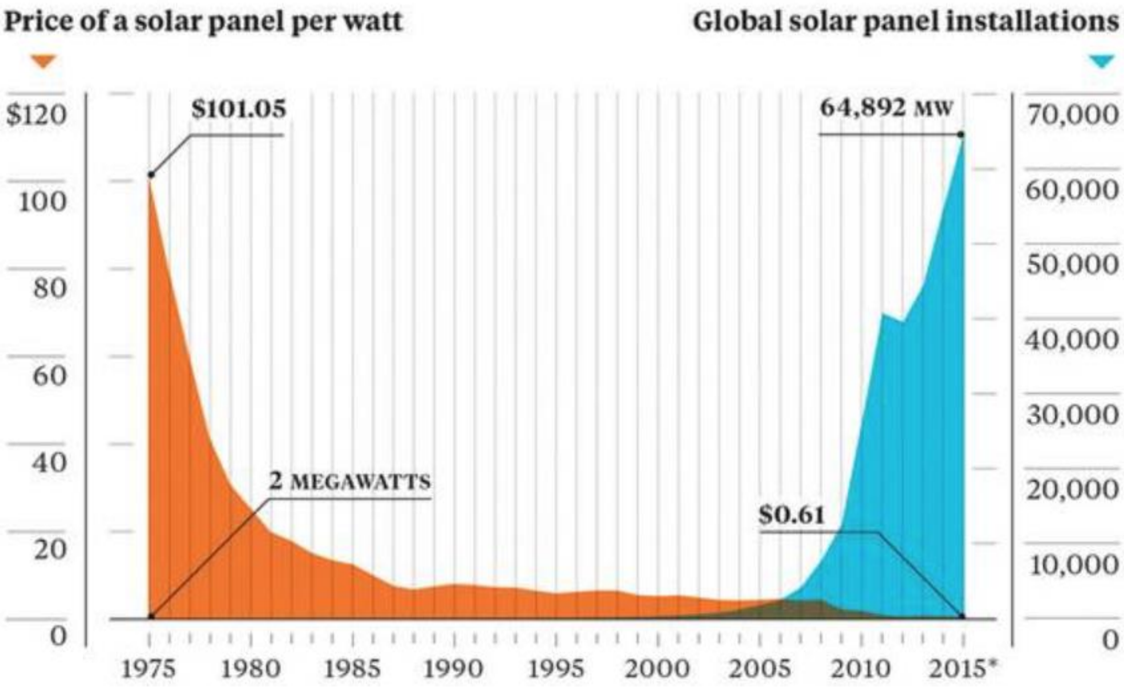


Figure 22 Example of experience curves on two scales: normal, linear scales (left) and double logarithmic or log-log scales (right). Source: Louwen et al. (2019)



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The rates at which production costs decline are technology dependent and even vary for identical technologies depending on the time period and the geographical system boundary (i.e., the country or region), as well as by policies (Weiss et al., 2010). Furthermore, currency exchange rates can generate additional differences of learning rate calculations (Lilliestam et al., 2020). For instance, the 2011-2016 learning rate for solar PV based on Chinese yuan is 37% while the rates based on the Euro and the Japanese yen are estimated as 28% and 21%, respectively. Thus, in this case the learning rate of solar PV fluctuates by up to 16%.

Technological learning is the result of a combination of various mechanisms such as learning-by-doing, economies of scale, technological innovation or factor substitution in manufacturing (Weiss et al., 2010). However, while experience curves describe the observed empirical trend of decreasing unit costs, they provide little to no insight into the underlying mechanisms driving these cost reductions.

Yeh and Rubin (2012) listed aspects considered by multi-factor learning models which include learning by research (LBR) phenomena in addition to the learning by doing (LBD) aspects observed in manufacturing by Wright (1936). LBR includes the spending in research and development, knowledge spillovers, increased capital investment, economies-of-scale, changes in input prices, labour costs, efficiency improvements and other public policies (Rubin et al., 2015). Studies using multi-factor models report lower learning rates compared to studies based on one factor models. Among these multi-factor models, the 'two-factor learning curve' considers–in addition to the cumulative production ($\mathrm{Pcum_i}$) or installed capacity–the cumulative expenditure for research and development ($\mathrm{Rcum_i}$) as a key driver of cost reductions (Jamasb and Köhler, 2007). Taking the one model factor expressed in equation (2) as a baseline, equation (5) illustrates a two-factor model which includes the 'learning by research' parameter, b_r:

$$\log\left(\mathrm{Ccum_i}\right) = \log\left(\mathrm{C_{0,i}}\right) + \mathrm{b_i} \times \log(\mathrm{Pcum_i}) + \mathrm{b_r} \times \log(\mathrm{Rcum_{ri}}) \quad (5)$$

Some authors have suggested dividing plants into multiple components or sub-sections to enable learning rates to be considered at a component-based level (Ferioli et al., 2009; Rubin et al., 2007). This approach is useful for complex technologies, where components are at different stages of maturity and, thus, the cost of new components will decline faster than that of a more mature component. For example, Rubin et al. (2007) analysed the learning rates of power plants with carbon capture and storage by dividing systems into a power plant boiler, conventional air pollution control system and carbon capture unit. Equation (6) illustrates the 'component-based learning curve' equation for a one-factor learning model (Yeh and Rubin, 2012). The lack of systematic data for validation and use impedes the development of multi-factor models of technological change.

$$\mathrm{Ccum_i} = \sum_{i=1}^{n} \mathrm{C_{0,i}} \times (\mathrm{Pcum_i})^{\mathrm{b_i}} \quad (6)$$

where n = number of technology components or sub-systems; i = individual cost components of a given technology; $C_{0,i}$ = specific cost of component n of the first unit produced; b_i = learning parameter for the technology component n.

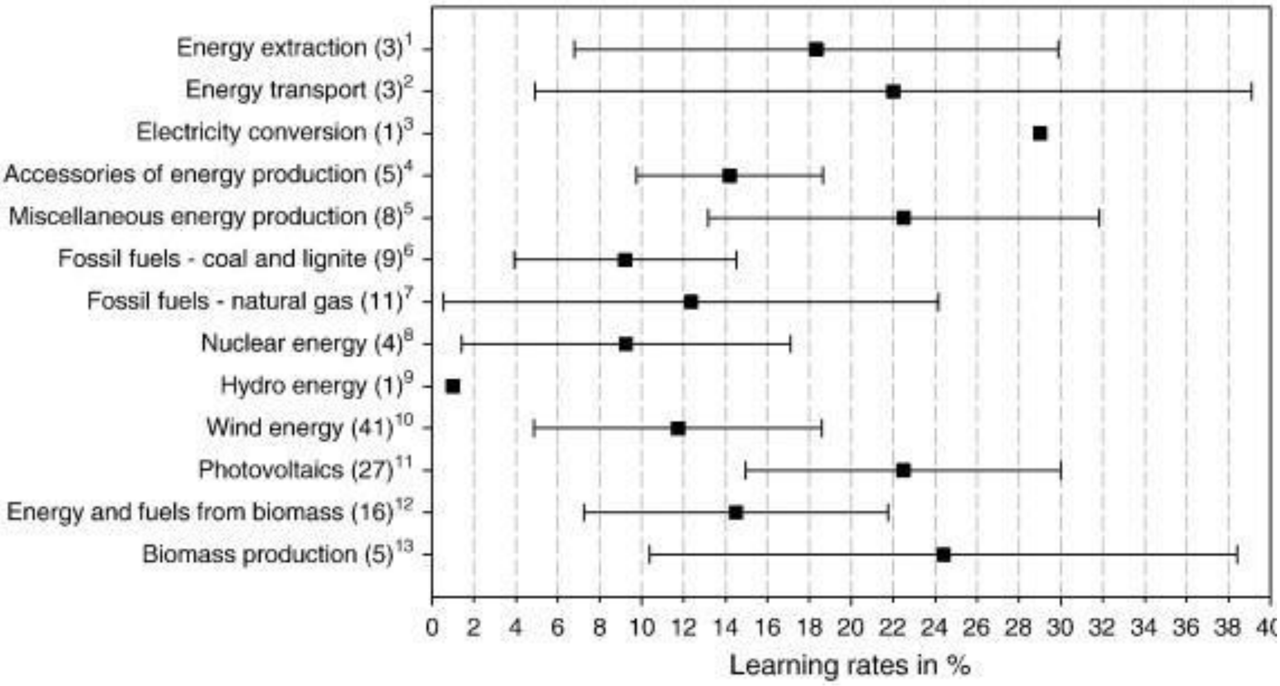
Experience curves are increasingly being applied to establish efficient energy technology policies and to forecast technology diffusion and technological change in energy and greenhouse gas (GHG) emission models. In the context of renewable energies, the experience curve approach is now being widely applied to renewable and conventional energy supply technologies.

Weiss et al. (2010) provided a comprehensive overview of experience curve studies on energy supply and energy demand technologies. Their study compiled a table of experience curve analyses available which served to generate a frequency histogram of learning rates for energy supply and energy demand technologies. Average learning rates and associated uncertainty intervals were generated in aggregate and for individual technologies and technology clusters. Figure 23 shows the average learning rates for 13 individual supply technologies and technology clusters, using data from Junginger et al. (2013), Kahouli-Brahmi (2008) and McDonald and Schrattenholzer (2001). The numbers in parentheses indicate the sample size, which varies from a single study for high-voltage direct current converter (HVDC) stations and hydro energy, to 41 studies for solar PV. Learning rates were mainly given as a range interval together with their associated uncertainty figures which have been estimated based on the standard deviation of the data taken from the studies, except for those with one single value represented in Figure 49 as single points. Among the energy supply technologies assessed, it is worth noting that wind energy and photovoltaics were by far the technologies with greater number of studies providing learning rates. Overall, the average learning rates of energy supply technologies was 16±9%. Unfortunately, comparisons of all the energy supply technologies displayed in Figure 23 are not possible as the theoretical framework used for the analysis is only consistent for a limited number of energy supply technologies.

In addition to those for energy supply technologies, Figure 24 shows a range of values of learning curves and their associated uncertainty for 15 energy demand technologies (Weiss et al., 2010). Again, the number of studies is provided in brackets and, in most cases, does not exceed six. This provides an indication of the low level of data availability. For some technologies, the variation in learning rates was not significant, probably due to limited technical changes over time. Good examples here include Ford model T and refrigerators whose learning rates span short periods of time. Other technologies, such as washing machines and lamp ballasts, enjoyed longer lifespans and have experienced great technological progress over the past century.

Variations of learning rates between technologies varied to some extent due to differences in performance measures applied by individual studies. For example, the use of either absolute prices, specific prices, or unit costs as the dependent variable can cause variations, as can the use of cumulative capacity or cumulative production referring to different geographical system boundaries as the independent variable. In summary, energy demand technologies became cheaper at an average learning rate of 18±9%, thereby showing rates of cost decline similar to energy supply technologies and manufacturing in general. The learning rates for energy demand technologies were roughly normally distributed; the mean was therefore a good representation of the data sample.

Figure 23 Average learning rates and associated uncertainty intervals for individual energy supply technologies and technology clusters. Source: Weiss et al. (2010)

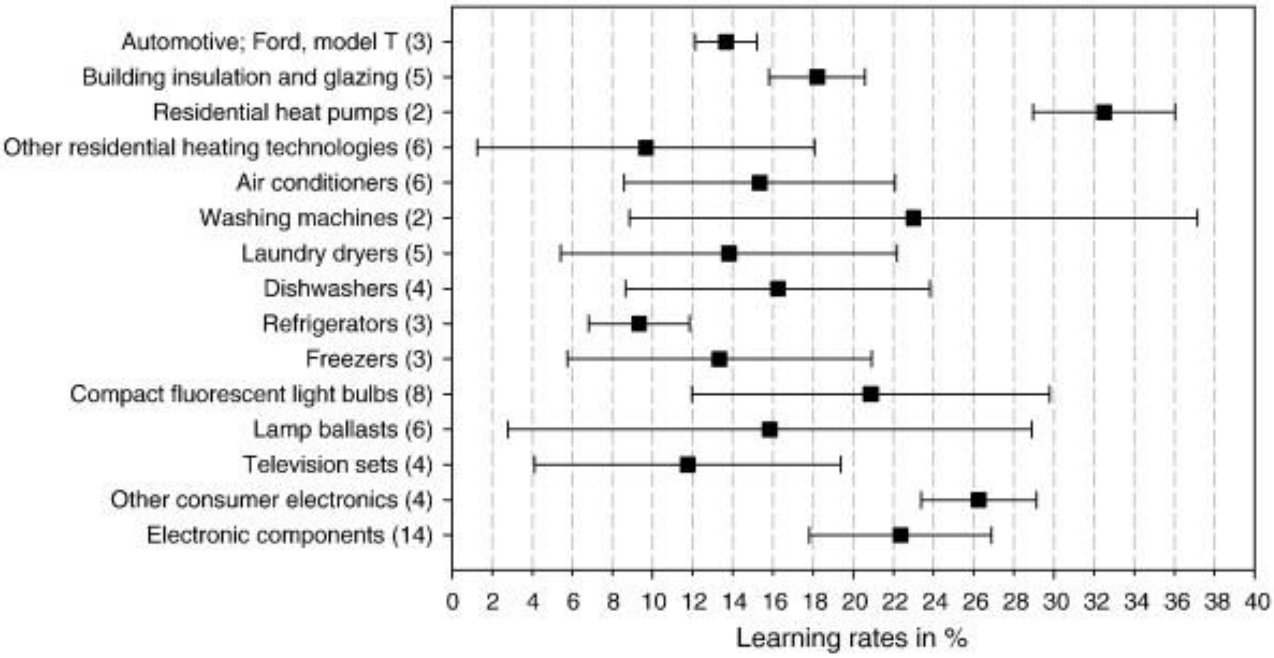


[1]including oil extraction, coal production for electric utilities, and crude oil production at well; [2]including submarine HVDC (high-voltage direct current) cables, on-shore and offshore pipelines; [3]including HVDC converter stations; [4]including flue gas desulphurisation and selective catalytic reduction; [5]including retail gasoline processing, electric power production, LNG (liquefied natural gas) production, fluid petroleum cracking, bitumen production from non-conventional oil and oil sands; [6]including coal, supercritical coal, pulverised coal and lignite power plants, as well as pulverised coal boilers; [7]including gas turbines and gas turbine combined cycle (GTCC) power plants; [8]including nuclear power plants; [9]including hydropower plants; [10]including wind power plants and components thereof; [11]including solar modules, panels, and entire solar photovoltaic systems; [12]including bio-ethanol, biogas, biodiesel, and electricity from biomass; and [13]including production of corn, sugar cane, rapeseed, as well as logistic chains for forest wood chips.

Rubin et al. (2015) reviewed learning rates for the cost of 11 electricity supply technologies. The paper summarised values of learning rates using a one factor model based on LBD, and a two-factor model which also considers the effect of LBR. Among all the technologies assessed, solar photovoltaic and wind energy were those with the largest number of studies, as also noted by Weiss et al. (2010). In general, all the energy sources showed a trend of declining unit capital cost (or cost of electricity generation) with increasing installed capacity or generation over the time periods studied. The reported learning rates vary considerably as result of the use of diverse databases; thus, no single estimate of a technology learning rate could be considered sound.

The variation in learning rates could not readily be explained by factors such as time span, geographical scope or other parameters. Overall, although prices declined according to cost for the one-factor model learning curves, in some cases they were affected by market structure, subsidies, high market demand and monopolies, among other factors. In the two-factor learning curve models, where both LBD and LBR rates were given, the cost for production was significantly reduced by the investment in research and development. As such, the influence of LBR was considered greater than that of LBD. However, the number of two-factor models is unfortunately limited by to the limited availability of research and development spending data for specific technologies. Table 13 summarises the LBD and the LBR rates given in the study.

Figure 24 Average learning rates and associated uncertainty intervals for individual energy demand technologies and technology clusters. Source: Weiss et al. (2010)



Experience curves were also investigated as part of the H2020 REFLEX project. The project analysed and evaluated development towards a low-carbon energy system with a focus on flexibility options in the EU until the year 2050, and to support a better integration of renewable energy sources. Table 14 displays the one-factor learning rates of some of the energy technologies revised within the project. As illustrated, the values of the learning rates generally fall between 10% to 21%, with the exception of onshore wind whose learning rate is about 6%. Errors in the learning rate range from very low (0.6% for hybrid electric vehicle (HEV) battery packs) to very high (5.9% for power to hydrogen).

The REFLEX project also investigated the use of learning curves in various energy models. Figure 25 illustrates an overview of the technical implementation of endogenous and exogeneous experience curves in energy-system models (Louwen and Lacerda, 2020). The blue boxes are for the model functions, the white boxes represent model-produced data, while the grey boxes with the dotted frame illustrate external data sources.

The figure demonstrates endogenous implementation by including the outcomes of equation (4) directly into the modelling code. In such cases, energy models need to include the required data for the development of the cumulative production in the model. Data is then transferred into the experience curve function. Technology costs are then calculated, feedback looped, and applied in the energy model.

Table 13 One-model and two-model learning rates for diverse electricity generation. Values reflect model estimates which were projected based on different assumptions. Source: Rubin et al. (2015)

	One-factor learning model (LBD)			**Two-factor learning model (LBD + LBR)**					**Years covered**
	Studies	**LBD range**	**LBD mean**	**Studies**	**LBD range**	**LBD mean**	**LBR range**	**LBR mean**	
Solar PV	13	10-47%	23%	3	14-32%	18%	10-14.3%	12%	1959-2011
Hydroelectric	1	1.4	1.4%	1	0.5-11.4%	6%	2.6-20.6%	11.6%	1980-2001
Wind									
Onshore	12	-11% to 32%	12%	6	3.1-13.1%	9.6%	10-26.8%	16.5%	1979-2010
Offshore	2	5-19%	12%	1	1%	1	4.9%	4.9%	1985-2001
Biomass									
Power generation	2	0-24%	11%	0	-		-		1976-2005
Biomass production	3	20-45%	32%	0	-		-		1985-2001
Coal									
Pulverised coal (PC)	4	5.6-12%	8.3%	0	-		-		1902-2006
Pulverised coal (PC) + carbon capture and storage (CCS)	2	1.1-9.9%		0	-		-		projections
Integrated coal-gasification combined cycle (ICGC)	2	2.5-16%		0	-		-		projections
Integrated coal-gasification combined cycle (ICGC) + carbon capture and storage (CCS)	2	2.5-20%		0	-		-		projections
Natural gas									
Natural gas combined cycle (NGCC)	5	-11% to 34%	14%	1	0.7-2.2%	1.4%	2.4-17.7%	10%	1980-1998
Gas turbine	11	10-22%	15%	0	-		-		1958-2001
Natural gas combined cycle (NGCC) + carbon capture and storage (CCS)	1	2-7%		0	-				projections
Nuclear	4	<0- 6%		0	-		-		1972-1996

Alternative routes of the endogenous implementation of experience curves are illustrated via the blue dotted arrows. Some of the characteristics hampering endogenous implementation were the mathematics and optimisation approach of the model. In other cases, the increasing complexity of the model makes the interpretation of the model results more difficult (Junginger et al., 2013).

Table 14 Learning rates and their errors of some of the energy technologies assessed within the H2020 project 'REFLEX'. Source: Louwen et al. (2019, 2018)

Energy technologies	Learning rate (one-factor)	Error	Cumulative unit	Functional unit
Solar				
Modules	21.4%	0.8%	MW installed	Wp
*Balance of system (BOS)**	12.9%	1.7%	MW installed	Wp
Systems	18.6%	1.0%	MW installed	Wp
Wind				
Onshore	5.9%	1.3%	GW installed	MW
Offshore	10.3%	3.3%	GW installed	MW
Coal + carbon capture and storage (CCS)	2.1%		MW installed	kW
Natural gas + carbon capture and storage (CCS)	2.2%		MW installed	kW
Polymer Electrolyte Fuel cell (PEFC) – micro combined heat and power (CHP)	19.3%	1.6%	Units sold	kW
Transport				
Battery electric vehicle (BEV) battery packs	15.2%	2.9%	GWh sold	kWh
Hybrid electric vehicle (HEV) battery packs	10.8%	0.6%	GWh sold	kWh
Fuel cell electric vehicle (FCEV) stacks	18.0%	1.7%	GWh sold	kWh
Heat pumps	10.0%		Units sold	kW
Power to hydrogen (H_2)	17.7%	5.3%	GW installed	kW

Wp = watt peak; *BOS includes wiring, switches, a mounting system, inverters for converting direct current (DC) to alternating current (AC), a battery bank and battery charger (US Department of Energy, 2006).

In the exogenous implementation route, the model only provides the year for which the technology costs should be calculated, while external data is used to define the cumulative production over time. This then needs to be converted into the right units before being implemented into the experience curve function (Louwen and Lacerda, 2020). To summarise, the exogenous technological change was only time dependent while the endogenous technological improvements could be influenced in several ways from past, present, and/or future expected policies and prices (Gillingham et al., 2008).

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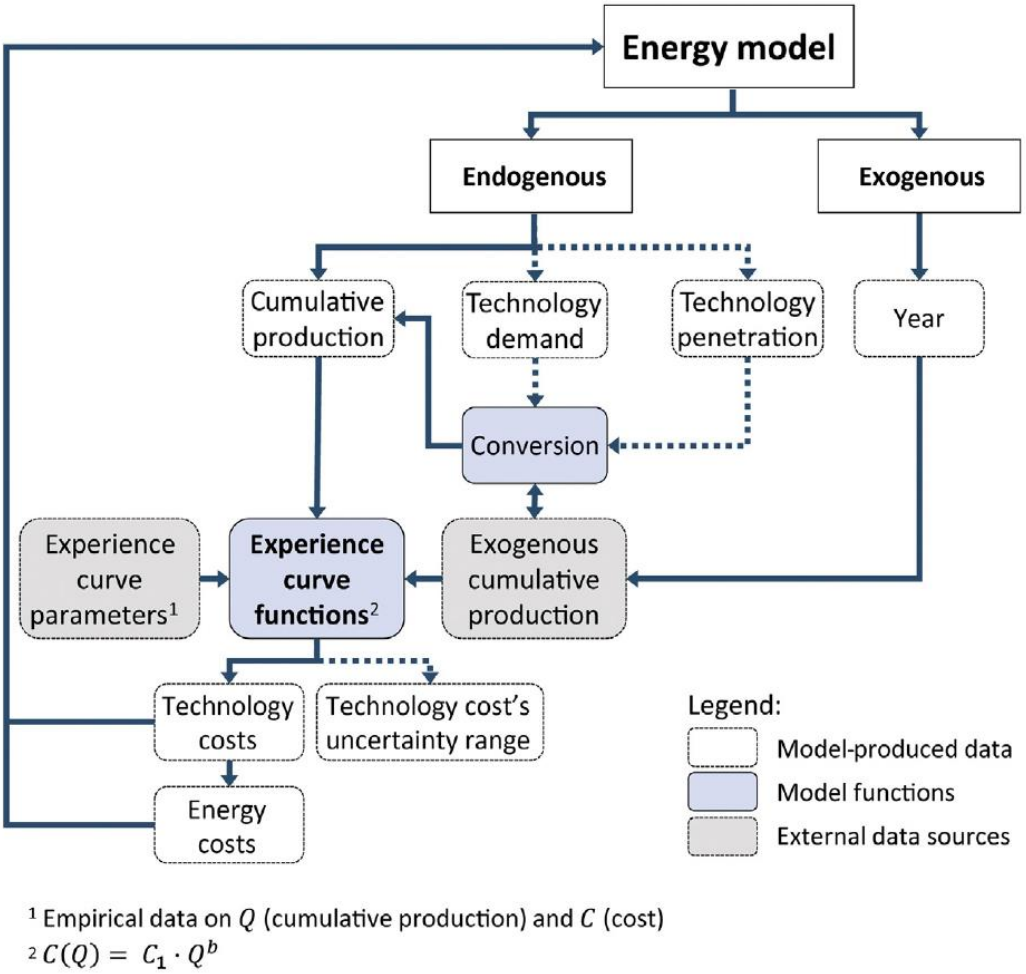
Figure 25 Overview of possible endogenous and exogenous experience curve implementation routes in energy system model. Source: Louwen and Lacerda (2020)



3.1.3 *Summary of measuring technological progress*

Quantifying the maturity of energy technologies is vital if one wishes to understand and predict possible future energy scenarios, particularly in the case of renewable energy technologies. Here, two available methods–technology readiness levels (TRLs) and learning/experience curves–have been considered. TRLs have previously been adopted as a way to identify technology maturity in the evaluation of Horizon 2020 project proposals by the EC, while the EC's Joint Research Centre (JRC) has undertaken efforts to define a common trend for assigning TRLs in energy technologies. Nevertheless, many technology specifications exist that limit their widespread application (De Rose et al., 2017).

Learning or experience curves, however, appear to be a more robust method. Discussions surrounding their use have progressed from one-factor models to multiple-factor models as technology cost affected by LBD and LBR factors, as well as economies of scales and other factors (Rubin et al., 2015). Other lines of discussion suggest that several components within energy technologies have different costs which result in diverse learning curves (Louwen and Lacerda, 2020). Thus, at present, data requirements limit the use of learning curves to one-factor models.

Learning curves have also been implemented in energy system models via endogenous and exogenous learning. The exogenous implementation seems the most convenient of the two, as technological change is only time dependent. However endogenous implementation can be undertaken if the mathematical layout of the model, computation time and the ability of models to produce the needed input parameters are controlled.

3.2 Understanding socio-technical transitions

- Sustainability theories help to better understand the ways that structural change in energy systems comes about, and to navigate developments towards sustainable energy systems
- Knowledge of the different transition theories can provide insights for developing model design, scenarios and parameters
- The four main theoretical foundations for conceptualising socio-technical transition processes and their application in the context of the energy transition are discussed

Sustainability transition research is a vast growing field of research, which is motivated by the fact that many environmental challenges, such as climate change and loss of biodiversity, imply large societal challenges (Köhler et al., 2019). 'Sustainability transition' studies demand a shift from fixing existing systems towards the creation of completely new socio-technical systems. According to Holtz *et al.* (2015:42), two central agendas of transitions research are "(1) scientific progress: to better understand how structural change of large-scale complex societal systems comes about; and (2) impact: to make particular societal transitions happen and navigate developments towards sustainability".

However, changing is not as easy as it may sound: societies are often locked-in their historically and experientially established way of acting or functioning, such as behavioural patterns and routines (Süsser et al., 2019). To overcome such path dependencies, we need to "understand the multi-dimensional interactions between impulses for radical change" (Köhler *et al.*, 2019:3).

Sustainability transitions are complex and long-term processes, involving interaction between different system elements–namely technologies, user practices, cultural meanings, infrastructures, policies, industry structures, and supply and distribution chains–and changes in elements and dimensions. Diverse agents and social groups are the engine of transitions, which are characterised by their own values, norms, capitals and so forth.

But what makes sustainability transitions specific? Firstly, they are 'purpose'-driven, or goal-oriented (Geels et al., 2017; Smith et al., 2005), because they address environmental and social problems. Secondly, those solutions that are able to tackle such problems, might be, however, not the ones that generate the highest cost-benefit ratio (Geels, 2011). In contrast, actions of different groups affected are also guided by established beliefs, conflicting values, competing interests etc. (Geels et al., 2017). Thirdly, it's not only about the technical solution but often also about changes in user practices, cultural discourses, and broader political changes (Geels et al., 2017). The fourth characteristic is that sustainability transition requires complex negotiations and compromises between multiple objectives and constraints (Geels et al., 2017). For example, there are complementary assets and resources between innovators, who invent environmental innovations, and large firms, which can potentially accelerate innovations by adopting them (Geels, 2011).

To better understand the ways in which transitions occur, different phases can be distinguished. These phases are generally assumed to progress in an S-shaped pattern (Rotmans et al., 2001):

- A ***predevelopment phase*** of dynamic equilibrium where the status quo does not visibly change;
- A ***take-off phase*** where the process of change gets under way because the state of the system begins to shift;
- A ***breakthrough phase*** where visible structural changes take place through an accumulation of socio-cultural, economic, ecological and institutional changes that react to each other. During the acceleration phase, there are collective learning processes, diffusion and embedding processes; and
- A ***stabilisation phase*** where the speed of social change decreases and a new dynamic equilibrium is reached.

Furthermore, alternative transition pathways have been described in the literature with emphases on different dimensions and characterised by different actors and their (inter)actions (e.g., Smith, Stirling and Berkhout, 2005; Geels *et al.*, 2016). Berkhout, Smith and Stirling (2005) distinguish between purposive transition, endogenous renewal, reorientation of trajectories and emergent transformation while Geels and Schot (2007) differentiate between substitution, transformation, reconfiguration and de-alignment and re-alignment (see section 3.2.1). Research has also highlighted the fact that transitions change elements and dimensions throughout the course of time (Köhler et al., 2019). As such, pathways are not thought to be static but highly dynamic, and this can include switches from one transition pathway to another.

The energy transition can be understood as an example of a socio-technical transition (e.g., Geels *et al.*, 2017; Pregger *et al.*, 2019). Considering the urgency of responding to climate change, the energy system requires rapid and deep change and recent research in sustainability transitions is attempting to investigate essential aspects of this transition. Specific areas of interest include the breakthrough and large-scale diffusion of energy technologies, interactions between multiple technologies (e.g., V2G) and different systems as whole, the ways in which energy transitions can be accelerated and the understanding of social processes and tipping points (Köhler et al., 2019).

While much research focuses on the transition towards new socio-technical systems, an important new topic is the destabilisation, decline, and phase-out of existing systems and regimes (Köhler *et al.*, 2019; Turnheim and Geels, 2012; Kungl and Geels, 2018). For example, the study of energy transitions is beginning to

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investigate locations that will be affected by the coal-phase out and how new energy futures can be approached in order to avoid 'societal collapses' (e.g., Oei *et al.*, 2020).

In a recent review, Köhler *et al.* (2019) identified the four main theoretical foundations of sustainability transitions: the ***Multi-Level Perspective (MLP)***, the ***Technological Innovation System (TIS)***, ***Strategic Niche Management (SNM)*** and ***Transition Management (TM)***. All four take a "systemic perspective to capture co-evolutionary complexity and key phenomena such as path-dependency, emergence and non-linear dynamics" (Köhler *et al.*, 2019:4) and combine ideas from evolutionary economics, system innovation theory, complexity science, the sociology of innovation, institutional theory, and governance studies.

It is noted, however, that these theoretical foundations focus on different phases of the transition process, different system elements and characteristics and, thus, have their own strengths and limitations. In particular, the MLP provides a widely accepted general framework for understanding transition processes as a whole, while the remaining frameworks tend to be more concerned with analysing and improving transition processes.

Nevertheless, there are strong interlinkages between the theories that will become apparent by studying the different transition theories. The following sections aim to provide an overview of the different analytical frameworks available, their applications, and their implications for modelling socio-technical transitions.

3.2.1 The Multi-Level Perspective

By far the most commonly discussed and utilised framework is the ***Multi-Level Perspective (MLP)*** (Rip and Kemp, 1998; Geels, 2002; Smith and Stirling, 2010). It has been used extensively for understanding and describing socio-technical transitions by framing them as a dynamic system whereby activities interact across three distinct levels (see Figure 26)

The ***socio-technical regime*** occupies the meso-level at the centre of the framework and represents the current, shared cognitive routines within society. In other words, this level describes the current dominant practices and institutions in the fields of technology, science, markets, industry, policy and culture. Changes within this level are what fundamentally constitute a 'transition' itself and these transitions occur as a result of interactions with developments at the micro- and macro-levels.

The ***socio-technical landscape*** occupies the macro-level of the framework and represents the general, ever-changing contextual developments within the global society. Operating above the regime, activities at this level represent the broader and deep-seated patterns in cultural behaviour, macro-economics and macro-politics. Examples could include societal consumer trends and exogenous shocks. Exogenous shocks are conceived as abrupt events of any kind–such as industrial accidents and natural hazards–that introduce radical system changes and lead to an altered or changed path (Süsser *et al.*, 2019; Victor, Geels and Sharpe, 2019).

Niche-innovations occupy the micro-level of the framework and represent new and/or underutilised technologies or social practices that seek to become part of the regime. The system's capability to generate such new ideas through interactions of–and multifarious reshaping of–relations among the elements on the so-called regime level is called emergence (Süsser *et al.*, 2019). While the term is more often used to describe physically tangible examples of technological advancements in science or engineering, it can also refer to

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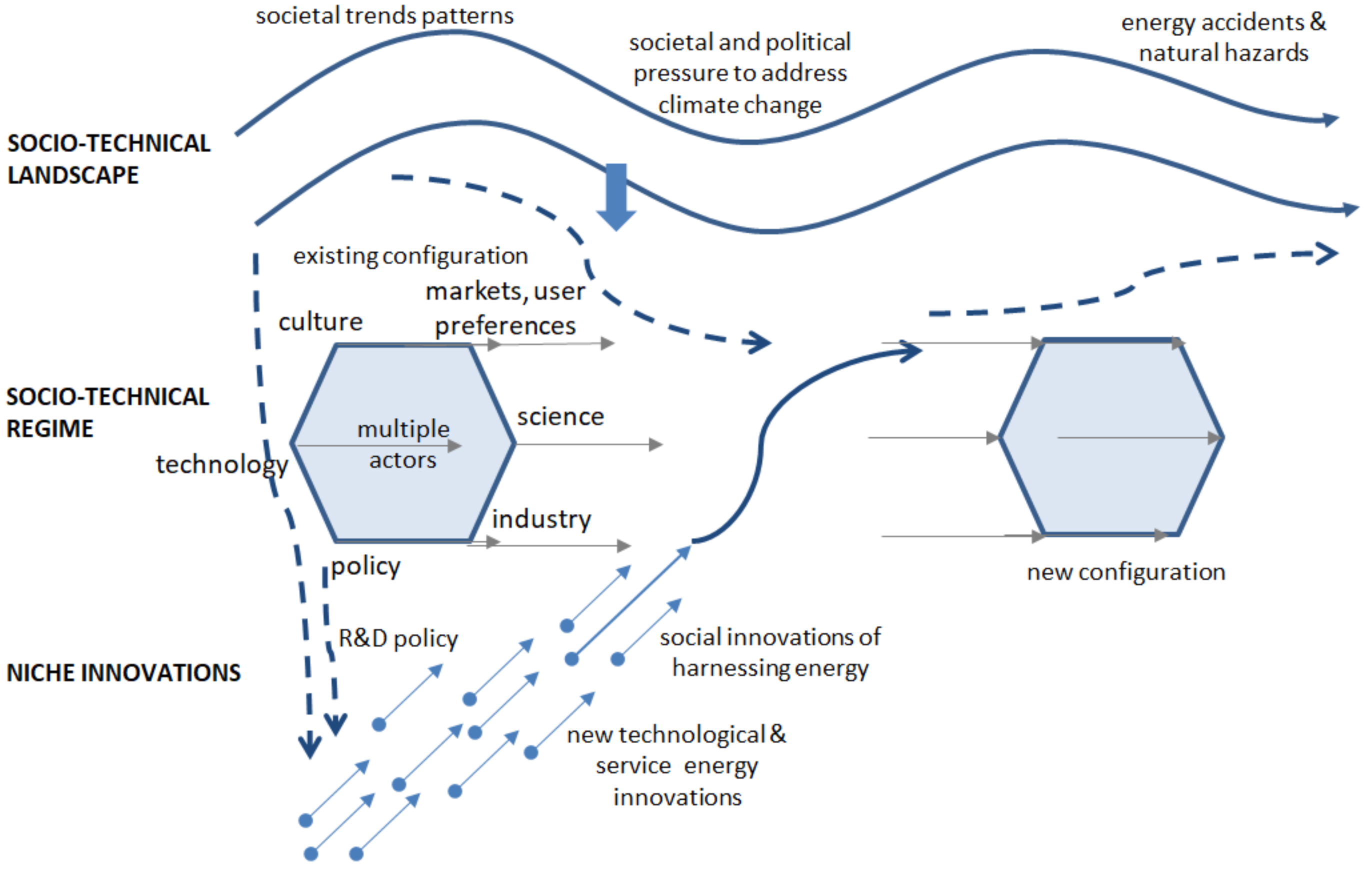
developments in the less tangible aspects of society. For example, new socio-political ideologies, management practices or social norms could also be considered types of niche-innovations in certain contexts. Niche-innovations are further classified as being either *competitive* where they aim to replace an existing technology or practice, or *symbiotic* where they can be adopted into or enhance an existing technology or practice.

Figure 26 Sustainable energy transitions within the framework of the Multi-Level Perspective. These transitions can be thought of as a change from the existing configuration towards a new configuration with greater inclusion of renewable energy sources. While some renewable energy technologies are well developed and in use, increasing the use of these and other renewable energy sources are considered to represent niche-innovation pathways within this framework. Source: Adapted from Geels and Schot (2007)



While socio-technical transitions can occur via any number of complex pathways, they are typically triggered by changes at the landscape level. These, in turn, create pressure at the regime level. This destabilisation creates windows of opportunity for niche-innovations to become included in a changing regime. The resulting regime changes represent ***socio-technical transitions***.

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Research has also highlighted the importance of interactions between multiples technologies that may emerge out of a niche, and between multiple regimes (Raven and Verbong, 2009). Raven and Verbong (2009) identified competition, symbiosis, integration and spill-over as main typologies for multi-regime interactions.

Energy transitions within the MLP

In order to analyse energy transitions using the MLP framework, it is necessary to define the three levels of the MLP within this context.

As always, the ***socio-technical landscape*** level is represented by the wider patterns of cultural behaviour, macro-economics and macro-politics within the global society. If we understand institutions as a set of formal and informal rules that organise a society (Ostrom, 1990), the socio-technical landscape is formed by those institutions that regulate relations between agents at the macro scale (e.g., the EU Framework Directives). In the case of energy transitions within the EU, the 2050 Energy Strategy and its long-term goal of reducing greenhouse gas (GHG) emissions by 80-95% (compared to 1990 levels) affects activities within the current EU socio-technical landscape. Likewise, the landscape is continuously influenced by the general paradigm of the "Low Carbon Economy".

The ***socio-technical regime*** level is defined by the actual patterns of energy supply and use. However, it also includes their associated technologies (e.g., well-established technologies like hydropower or cutting-edge technologies like perovskite solar panels) and strategies (e.g., energy mix scenarios).

The social functions of energy supply and their supply patterns are influenced by several factors. For example, functions can be defined according to the sources of energy used for carrier generation or by the technologies used in the generation, distribution and storage functions of each of these carriers.

In the context of sustainable energy transitions, the ***niche-innovations*** level is represented by those innovations that bring about change in the patterns of energy supply and/or demand. These innovations can come in different forms. Typically, they are seen as new technologies relating to the renewable energy that would need to gain greater prominence in the overall 'energy mix' at the regime level in the future. This would include undeveloped technologies that are yet to achieve full-scale implementation. However, for the sake of visualising the desired transitions, it also includes those existing renewable energy technologies that, while fully developed and operational, could be considered 'underutilised' within the current energy system. In this sense, innovations in social practices that result in higher levels of adoption and diffusion of renewable energy in the regime (e.g., more environmentally conscious political or management processes, new social norms) can also be considered to act as strategic innovations within a transition pathway.

Potential transition pathways

Using this general structure, Geels and Schot (2007) also identified four broad pathways in which a transition can occur:

Transformation commences when moderate landscape pressure occurs, and niche-innovations are not yet developed to accommodate the required changes. Actors within the regime then respond by modifying the direction of the regime and stimulate innovation activities. In time, a number of symbiotic niche-innovations will be brought online to implement the required transition.

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De-alignment and re-alignment occur when a large and sudden change in the landscape causes erosion and de-alignment of the regime. If niche-innovations are not immediately sufficient, multiple innovations may develop in an attempt to address the situation. Eventually, one of these innovations will prevail, leading to a final re-alignment in the regime.

Technological substitution is also triggered by a large and sudden change in the landscape. However, in this case, niche innovations are sufficiently developed to address the pressures felt within the regime. Nevertheless, these innovations may not be able to break through if the regime remains stable and entrenched in its existing configuration. A further 'shock' in the landscape is needed in order to create sufficient pressure within the regime and allow the niche-innovation to become integrated within a new regime.

Reconfiguration involves small changes in the regime by niche-innovations that are gradually integrated to address specific local problems. Such changes are generally symbiotic in nature and are adopted as add-on or component replacements to existing technologies. Over time, ongoing landscape pressures and a sequence of innovations result in a major reconfiguration at the regime level.

It is worth noting that real-life transitions are often highly complex and cannot easily be classified using only one of these broad pathways. They may occur as a sequence of these pathways or involve crossovers between pathways within an overall transition process.

As with all transitions within the MLP framework, the sustainable energy transition is a reaction to changes in the existing ***socio-technical landscape*** (Geels and Kemp, 2007). Geels and Schot (2007) defined five general types of change that can occur at the landscape level according to the frequency, amplitude, speed and scope of these changes. Of these five types–regular, hyperturbulence, specific shock, disruptive and avalanche–climate change was identified as being a ***disruptive*** type of change. This means that the change is infrequent (low frequency), severe (high amplitude), slow (low speed) and does not directly affect all aspects of the system (low scope).

Examples of these disruptive changes can already be observed at the present-day landscape level. These include the physical impacts of climate change (e.g., global warming, extreme weather events, sea-level rise or landscape morphology), increased levels of public awareness and concern for these and future impacts, and changes in the global macro-policies with respect to climate change (e.g., Paris Agreement, other national climate policies and intergovernmental coalitions).

Accordingly, the previous landscape of disregarded carbon lock-in faced with the situation of climate change is forcing the ***socio-technical regime*** towards a new configuration that reduces polluting emissions. This, in turn, creates windows of opportunity for various new or underutilised innovations in the form of renewable energy sources or social practices that encourage their use at the ***niche-innovations*** level. In the years that follow, these sources of energy and social practices interact and 'compete' for positions within new configurations of the regime.

This process–of moving from a configuration of dominant energy sources towards a series of more sustainable future configurations–is the essence of the concept of sustainable energy transitions. A simplified version of this process overlaid onto the generalised framework of the MLP is shown in Figure 26.

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Lastly, Geels and Schot (2007) found that disruptive situations such as climate change typically result in transitions within the ***transformation*** or ***reconfiguration*** typologies. Moreover, these changes can occur as part of a sequence or a coevolution of these two types, often commencing via predominantly *symbiotic* innovations within a transformation pathway and later incorporating the more *competitive* innovations that typify a reconfiguration pathway.

Past applications of MLP to energy transitions

The latest trends in energy supply and demand technologies were listed in sections 2.1.3 and 2.1.4, respectively, while the latest energy storage technologies were listed in section 2.1.5. Furthermore, it is acknowledged that many more promising renewable energy technologies are likely to arise in the coming decades. However, despite the ongoing research and investments in these areas, and the increasing levels of concern at the regime level, many energy innovations are yet to be exploited at large scales.

A good example of an innovation undergoing a multi-level transition process is perhaps provided by the development of the wind energy industry in Germany. Here, the niche innovation of industrial wind energy generation first emerged in the 1980s. Against the backdrop of a strong anti-nuclear movement in the 1970s, and a strong environmental movement in the 1980s, renewable energy began to receive attention at the landscape level in the 1990s. Public attention soon turned to alternative ways of generating electricity and the first wave of wind turbines began to spread over Germany.

Because of the strong interest of farmers, entrepreneurs, technicians and customers alike, a modest level of support for renewables created enough space for its development (Jacobsson and Lauber, 2006). Jacobsson and Lauber (2006, p. 271) emphasise four features that were present during this period: "institutional change in the form of a changed energy R&D policy (although only on the margin), the formation of markets (although very small) in the form of protected niches, entry of firms and establishment of some of the elements of an advocacy coalition". The strength of this period lay in the opportunities for experimentation, learning and the formation of visions of a renewable energy future.

It was not until the new millennium that wind energy began to seriously diffuse into the energy market, driven by institutional changes, governmental policies and gained momentum of energy cooperatives. Technical improvements and price drops made wind energy an important pillar of the energy transition for wind-rich countries. Nevertheless, ongoing limitations in social acceptance and ineffective policy changes might be two factors lowering the current speed of diffusion, suggesting that the diffusion of innovations like wind energy is a multi-layered and interactive socio-political-technological process among system elements that can lead to system change.

Dzebo and Nykvist (2017) investigated the heat regime in Sweden, which has also undergone significant changes since the 1970s by gradually replaced oil with renewable energy, mainly via biomass. Using the MLP framework they assessed the degree to which the socio-technical regime in Sweden's heat-energy system is stable and locked-in, and whether there are emerging tensions. While early developments were driven by the oil crises and cheap electricity from nuclear and hydropower sources, the main landscape drivers are currently thought to be climate change, energy efficiency, liberalised planning and low energy demand in new buildings. They also identified interconnectedness with supply-oriented niches such as industrial waste heat, complementarity but increased competition between district heating and electricity through resistive

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heating and heat pumps, and market saturation for new technologies as the three key characteristics of the regime that risk creating tensions and the lock-in of less sustainable practices.

Raven and Verbong (2009) demonstrated the importance of multi-regime interactions in the Netherlands, where bioenergy developed in small niches of farms and industries against the background of the waste regime in the 1970s and early 1980s. In the 1980s, a global oil price collapse, global environmental problems and a rise of neo-liberalism were three landscape developments that put pressure on both the waste and electricity regimes in the nation. While this led to vast improvements in combined heat and power technologies in the electricity regime, many actors also became attracted to development in the waste regime. The boundary crossing between the two regimes led to a symbiotic and even integrative relationship between them in the early 1990s. Additional landscape pressures due to EU legislations and an increasing demand for climate actions further accelerated the mutual development of electricity and waste regimes.

Based on two cases, Raven and Verbong (2009:92) identified key patterns in the way boundary crossing innovations develop: (1) innovations are initially framed and developed against the backdrop of a single regime; (2) landscape dynamics create high expectations about the application of innovative practices against the backdrop of another regime; (3) institutional problems prevent rapid diffusion to other regimes; (4) restructuring through institutional adaptation, or rule changes, enables diffusion to other regimes; (5) diffusion not only affects the outcome of the innovation journey but also induces profound changes in the relations between the regimes involved.

Lastly, Geels *et al.* (2017) studied socio-technical dynamics within the German electricity transition and identified drivers of niche momentum and regime tensions, as shown in Table 15.

3.2.2 Technological Innovation Systems

The ***Technological Innovation System (TIS)*** approach (Bergek et al., 2008; Hekkert et al., 2007; Markard et al., 2015) is another important framework used to analyse specific innovation systems resulting in technological change in order to identify key policy issues and set policy goals. The TIS approach studies the emergence of novel innovations and is used to query the speed and direction of innovation and technological change.

Generally, innovation systems as an analytical concept has been applied to different scales: national, regional, sectoral and technological innovation systems (see Carlsson et al. (2002) for an overview). The technology-specific innovation system overlaps with sectoral and regional innovation systems, which are all embedded in national innovation systems (Hekkert et al., 2007). The choice of the level of analysis depends of whether you are, for example, interested in a specific technology, specific cluster of activities, or a specific geographic area (Carlsson et al., 2002).

The TIS approach goes beyond the analysis of structures of innovation systems, and focuses on the dynamics and processes of innovation systems (Bergek et al., 2008; Hekkert et al., 2007). Or in other words, the analysis is on the 'activities' and what is actually 'achieved' in innovation systems.

A TIS is comprised of three structural components: actors, networks, and institutions (Carlsson and Stankiewicz, 1991). *Actors* include firms along the whole value chain, universities and research institutes, public bodies, influential interest organisations, venture capitalists, etc. (Bergek et al., 2008). *Networks* can

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be different kinds of formal and informal networks. While some networks emerge around technological tasks or out of market formats, others follow a political agenda, and influence the institutional context (Bergek et al., 2008). *Institutions* comprise culture, norms, laws, regulations and routines (North, 1994).

Table 15 Drivers of niche momentum and regime tensions. Source: Geels et al. (2017)

	Endogenous niche momentum	Regime tensions
Techno-economic	Price/performance improvements as a result of R&D	Technologies, and network externalities technical failures, disruption of infrastructures, accumulating negative externalities (e.g., CO_2 emissions)
Business	Learning by doing, scale economies, complementary new entrants or incumbents from other sectors are more likely to drive radical innovation than traditional incumbents. Their success may lead to ''innovation races'' when other firms follow a first mover	Shrinking markets, economic difficulties in incumbent industries, loss of confidence in existing technologies and business models, reorientation toward alternatives
Social	Growing support coalitions and constituencies improve available skills, finance, and political clout	Disagreement and fracturing of social networks, defection of key social groups from the regime
Political	Advocacy coalitions lobby for policy changes that support the niche innovation such as subsidies and supportive regulations	Eroding political influence of incumbent industries, declining political support, removal of supportive policies, introduction of disruptive policies
Cultural	Positive discourses and visions attract attention, create cultural enthusiasm, and increase socio-political legitimacy	Negative cultural discourses undermine the legitimacy of existing regimes (e.g., coal and climate change, diesel cars, and air quality)

TIS puts the system dynamics in the centre of analysis to understand innovation processes and to search for system patterns. Varied interaction patterns are also explored by applying new methods such as computer models (Walrave and Raven, 2016a). Because of the diversity of activities happening, Hekkert *et al.* (2007) pointed out to focus on those that influence the development, application, and diffusion of new technological knowledge within the innovation system.

Building on previous research from different disciplines, Bergek *et al.* (2008) developed a scheme to analyse specific innovation systems, as shown in Figure 27. Of the six analytical steps, Bergek *et al.* (2008) described, we focus here on step number 3: the so-named functions. According to the framework Bergek *et al.* (2008), seven ***functions of innovation systems*** influence the development, diffusion and use of a new technology:

- Knowledge development and diffusion (e.g., scientific, technological, production, market, logistics and design knowledge);

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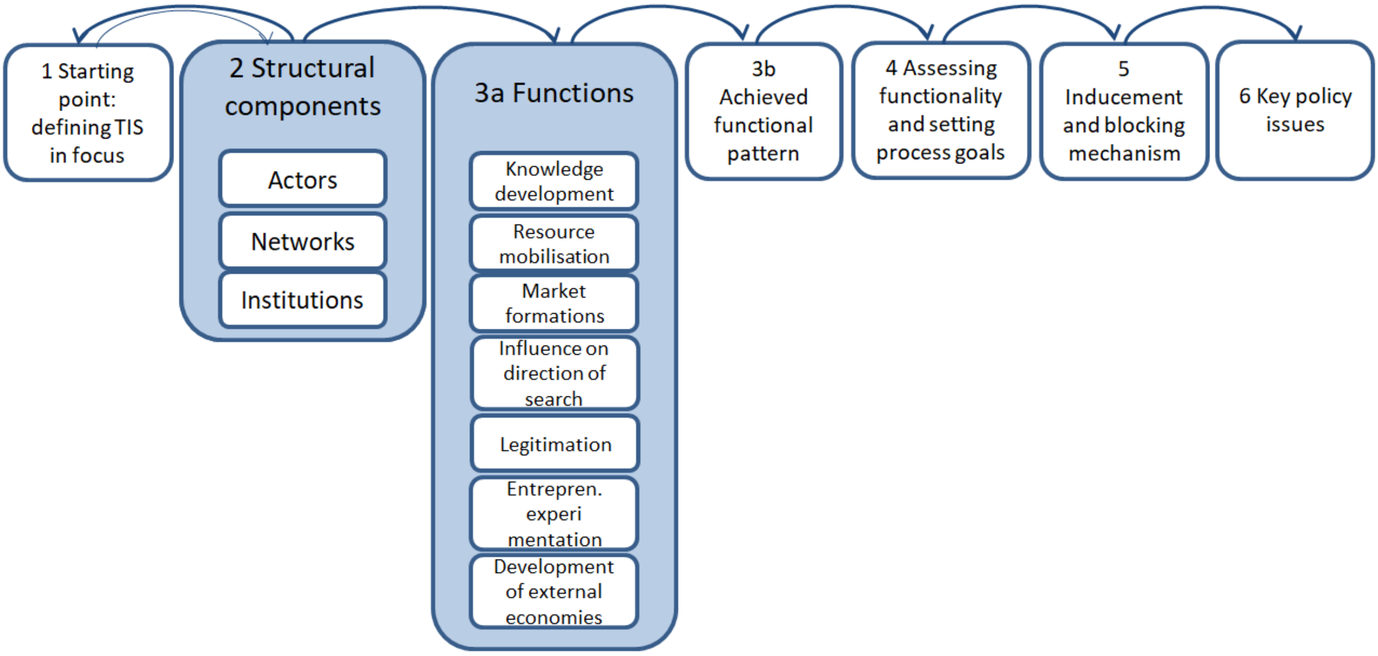
- Influence on the direction of search (e.g., visions, expectations, beliefs);
- Entrepreneurial experimentation (main source of uncertainty reduction)
- Market formation;
- Legitimation (social acceptance and compliance with relevant institutions);
- Resource mobilisation (e.g., competence/human capital, financial capital, complementary assets); and
- Development of positive externalities (e.g., through entry of new firms).

Figure 27 Representation of the TIS scheme of analysis. Source: Adapted from Bergek et al. (2008) and Oltander and Perez Vico (2005)



The description and evaluation of these seven key processes (functions) is the core of operationalisation of the technical innovation system framework (Bergek *et al.,* 2008). By doing so, insights in the dynamics of innovation system can be created, and technological changes be understood.

Examples of and learnings from TIS application in the context of the energy transition

The energy system as a whole can be considered as a technical innovations system, which builds on energy technologies and infrastructures. An interesting starting-point for applying the TIS approach in the context of the energy transition is wind energy. The study by Bergek and Jacobsson (2003) did a comparative analysis between Germany, the Netherlands and Sweden in order to study the emergence of the wind industry. They mapped and investigated the different functions of the TIS. They found four factors that can explain the relative success of the German wind industry: the creation of variety of turbine sizes and designs in an early phase ('entrepreneurial experimentation'), (2) establishment of legitimacy of wind energy ('legitimation'), (3) the employment of advanced market creation policies in a later phase ('market formation'), and (4) the use of industrial policy to favour the domestic industry ('development of external economies'). Beyond, other factors had an influence, such as a range of private investors to enter the wind industry in the early phase, which influenced on 'the direction of search'. The study, thus, could reveal how different processes influenced the development, diffusions and use of wind energy.

3.2.3 Strategic Niche Management

Strategic Niche Management (SNM) (Raven et al., 2016; Rip and Kemp, 1998; Schot and Geels, 2008; Smith and Raven, 2012) is another widely used framework for analysing the emergence and early adoption of radical, new innovations, and socially desirable innovations for meeting long-term sustainability goals. As such, SNM serves to bridge the 'valley of death' between R&D and market diffusion of particular types of innovations and, therefore, to potentially to contribute to socio-technical change (Schot and Geels, 2008).

A core assumption of SNM is that sustainability transitions can be facilitated by creating so-called ***technology niches***. Technology niches are assumed to emerge through 'collective enactment' by a range of different actors, such as developers and firms, users and societal groups, but also governments, which can define the course of direction (Schot and Geels, 2008). Niches function as ***protected spaces*** in which innovations emerge and boost the transition into a new regime. Three properties of effective protection can be distinguished in wider transition processes, which determine successful niche development: ***shielding*** holds back pressures on the path-breaking innovation from mainstream selection environments; ***nurturing*** supports the development of path-breaking innovations with active and passive shielded spaces; and ***empowerment*** makes niche innovations competitive in existing environments/regimes, or favourably change the selection environment (Smith and Raven, 2012). The later would mean that the niche itself becomes a new regime. Shielding, nurturing and empowerment are all three processes that can act at the same time and determine each other; for example, early shielding can push the nurturing of the innovation.

Shielding is a process that minimises selection pressures in the context of multi-dimensional selection environments, namely industry structures, technologies and infrastructures, knowledge base, markets and dominant user practices, public policies and political power, and cultural significance (Smith and Raven, 2012). Given the different environments, Smith and Raven (2012) differentiated between six different logics of the need for protective space: *industrial protection,* e.g., path-breaking innovations do not fit into established industry structures; *technological protection*, e.g., prevailing technical standards and infrastructural requirements favour status-quo; *socio-cognitive protection*, e.g., prevailing paradigmatic and institutionally organised knowledge development; *market protection*, e.g., existing market rules and user routines and preferences favouring current technologies; *political protection*, e.g., existing policies optimised for the status-quo; and *cultural protection:* widespread cultural legitimacy and symbolic representation of existing technologies. Once the innovation is *empowered* and diffuses the market, the need for *protection* falls away.

Nurturing processes are the articulation of expectations, support of networking, and assistance in learning processes. Niche innovations nurture through interactions between:

- Robust (shared by many actors), specific, and high quality (substantiated by ongoing projects) ***expectations*** of actors;
- Broad (plural perspectives) and deep (substantial resource commitments by members) ***social networks***; and
- Broad, multi-dimensional, first and second-order *learning processes* (Rip and Kemp, 1998; Schot and Geels, 2008; Smith and Raven, 2012).

A strong focus is hereby given to internal niche processes, while 'later' research also puts more emphasis on the interactions of niches and their broader environment (Geels and Raven, 2006). MLP emphasises specifically on the importance of linking niches with ongoing processes at regime and landscape levels. Thus, MLP seems to be useful for contextualising SNM (Schot and Geels, 2008).

Niche experimentations are considered as key arenas for nurturing, and the seeds of change (Rip and Kemp, 1998). Niches function here as 'proto-markets', and allow for "experimentation with the co-evolution of technology, user practices, and regulatory structures" (Schot and Geels, 2008). Experimentations are informed by expectations, social networks and learning processes, and enable recursive cycles of interactions between them. Consequently, they generate and shape innovation trajectories (Geels and Raven, 2006). According to the theory, an innovation-specific proto-regime emerges that shields and nurtures the innovation on two different levels: Local-level and global-level niche development processes (see Figure 28). The global-level is the emerging community field, and understood to be carried by projects in local practices, implemented by networks (Geels and Raven, 2006).

Two forms of ***empowerment*** can be distinguished: *fit and confirm empowerment*, which makes "niche innovations competitive within unchanged selection environments" (regimes); or *stretch and transform empowerment, which enables niche innovations to undermine and* "re-structure mainstream selection environments in ways favourable to the niche" (Smith and Raven, 2012:1030). Different actors might seek for the one or the other strategy. To empower niche innovation, it needs a guiding role of government: a so-called socio-technical alignment policy (Kemp *et al.*, 1998). Different narratives for empowerment have been identified as essential for the politics of protective space, according to Smith and Raven (2012:1035):

"(a) positive expectations about the future that justify the niche to wider audiences;

(b) explicit claims for present-day niche friendly institutional reforms; and

(c) statements that re-frame the past to criticise the prevailing regime in ways that emphasise future opportunities for the innovation".

Examples of and learnings from SNM application in the context of the energy transition

In the context of renewable energy innovations, protected spaces supported niche actors, who were willing to invest time and money in developing and nurturing path-breaking innovations. For example, solar photovoltaic cells were initially developed in a 'protective space' of material science programmes in the 1960s, and supporting policies and aid programmes later on (Smith and Raven, 2012). Since the 1990s, solar photovoltaic emerged as nice innovation in the market, supported by technology-specific R&D support schemes. Interestingly, solar PV firms mobilised actors outside the dominating energy regime as initial customers, such as farmers and municipalities (Smith and Raven, 2012).

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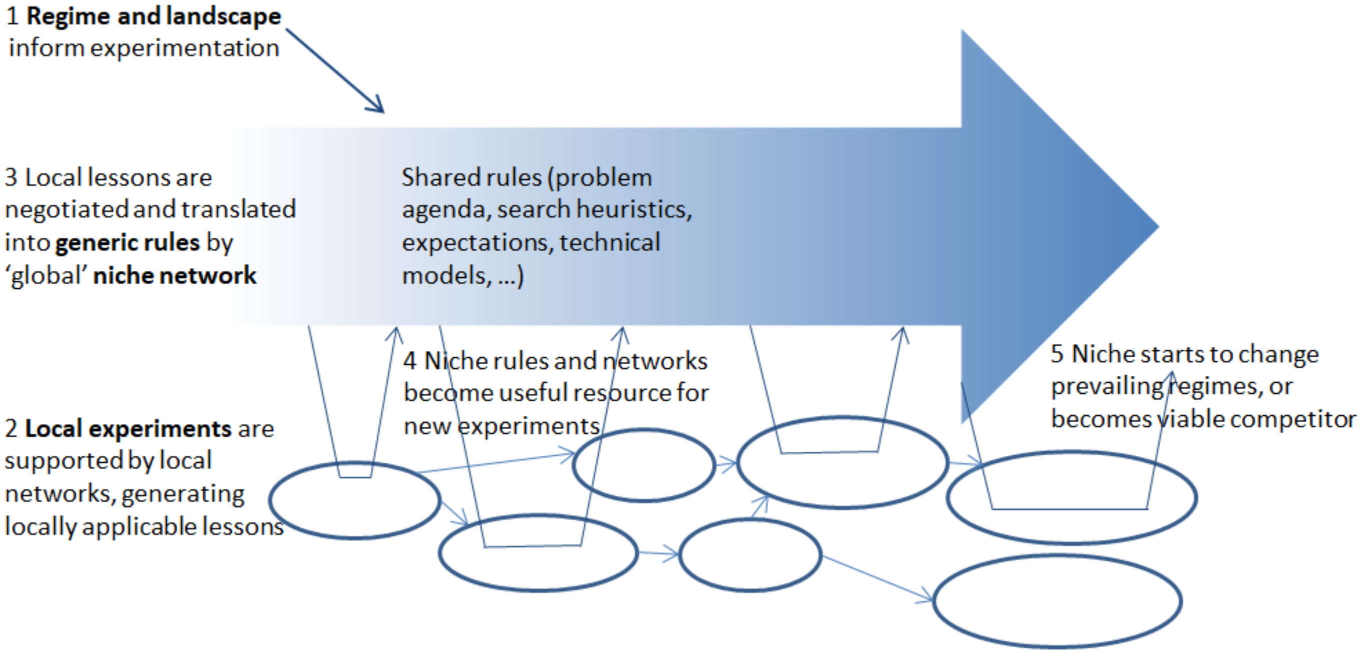
Figure 28 Local-level and global-level niche development processes. Source: Adapted from Smith and Raven (2012) and Geels and Raven (2006)

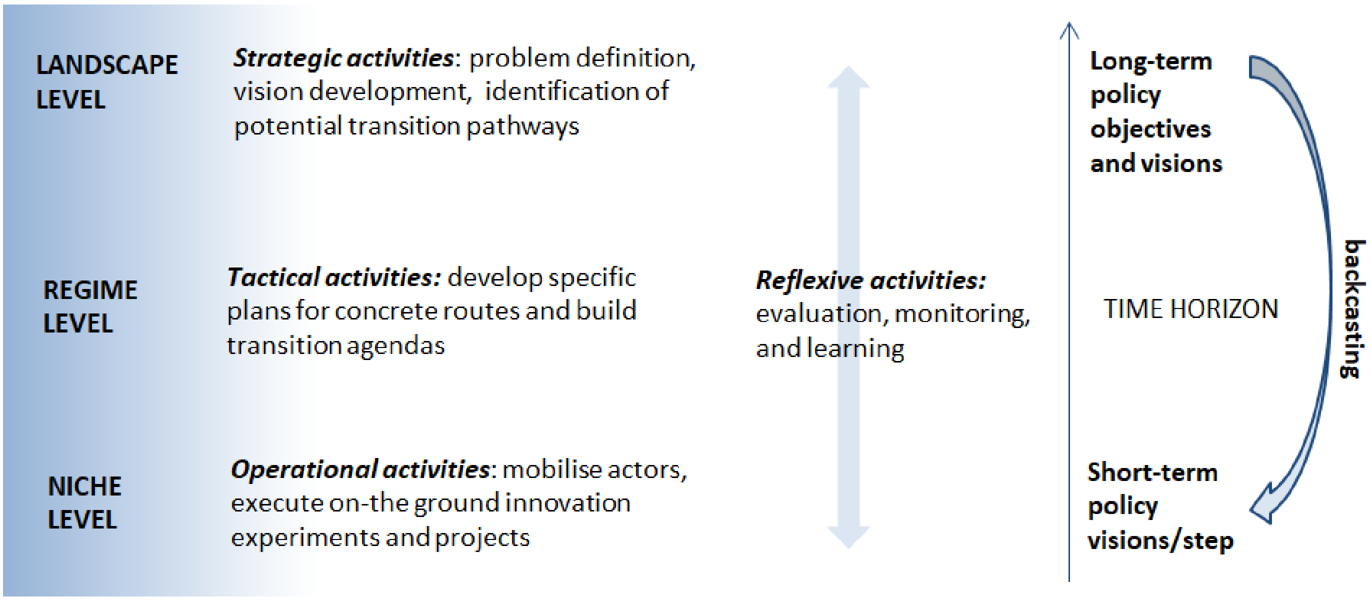


Consequently, grassroots innovations research, as locally anchored niche innovations, has emphasised on the importance of local actors and communities in the energy transition (Seyfang and Smith, 2007). 'Community renewables' have gained increased relevance as grassroots-led innovation concept for providing socially acceptable and contextualised bottom-up solutions for sustainable energy generation (Hargreaves et al., 2013; Seyfang and Smith, 2007; Süsser et al., 2017). 'Community renewables' can be considered as locally anchored networks of local actors, who have/had strong visions and expectations of local energy futures. The regional diffusion of renewable energy technologies has been facilitated by community renewables, and thus, supported local regime shifts. However, it is also important to note that energy policy played an important role in providing 'protected spaces' for the development of local energy cooperatives by providing incentives.

3.2.4 Transition Management

A policy-oriented framework to governing societal problems is offered by ***Transition Management (TM)*** (Loorbach, 2007; Loorbach and Rotmans, 2010; Rotmans et al., 2001). TM can be understood as a deliberative process aiming to influence governance activities to sustainability transition. TM co-evolved from theory and practice and follows a 'learning-by-doing approach' (Loorbach and Rotmans, 2010). According to Loorbach and Rotmans (2010:239), "the very idea behind transition management is to create a societal movement through new coalitions, partnerships and networks around arenas that allow for building up continuous pressure on the political and market arena to safeguard the long-term orientation and goals of the transition process". This implies that different actors from science, policy, civil society and businesses work collaboratively together, and thus facilitate governmental change.

Figure 29 Transition management cycle. Source: Adapted from Loorbach (2004)



Multi-actor governance, *envisioning*, *agenda building* and *experimentation* are the main elements of TM (Loorbach, 2004; Rotmans et al., 2001). Based on those elements and general principles, the transition management cycle was developed as operational model for implementation (Loorbach, 2004; see Figure 29). The cycle consists of four components, or sequential steps, through which policy makers can shape transitions (Loorbach, 2004; Loorbach and Rotmans, 2010; Köhler *et al.*, 2019):

- ***Strategic activities*** in a 'transition arena' aim at problem definition, vision development and the identification of potential transition pathways. Those activities take place at societal/landscape level and have a long-term horizon;
- ***Tactical activities*** develop more specific plans for concrete routes and build agendas and support coalitions for these routes, preferably with investment commitments. System structures, such as institutions, regulation, physical infrastructures, financial infrastructures and alike, are build up or broken down at this subsystem/regime level;
- ***Operational activities*** include on-the ground innovation experiments, demonstration projects and implementation activities, aimed at learning-by-doing, and transition network building. Those activities imply short-term and everyday decisions and action, implemented by actors, who either recreate, restructure or change system structures. Those activities occur at niche level; and

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- ***Reflexive activities*** include the evaluation of projects, monitoring of progress, and drawing of lessons, which should lead to adjustments in visions and the articulation of best practices. Those activities are continuously structured, reframed and dealt with at various levels.

Regarding the emergence of different activities, TM follows a multi-level governance perspective, rooted in fields as multi-level governance and adaptive management (Kemp and Loorbach, 2003).

Differentiation between long-term and short-term policy is essential. TM emphasises the importance of long-term objectives and visions, which function as framework for the back-casting to formalise short-term steps/visions (Rotmans et al., 2001). This approach stands in contrast to the five to ten years typical of current policy.

Examples of and learnings from TM application in the context of the energy transition

TM has been applied at different levels, such as industrial, sectoral, regional, and national level. The Dutch Ministry of Economic Affairs, for example, has used and well documented the application of TM, while there have been also a lot of experimental projects (Loorbach and Rotmans, 2010).

An example of how businesses can make use of the TM approach is provided by the 'roof transition' in the Netherlands (Loorbach and Rotmans, 2010). Led by the firm ESHA, the project brought different actors together–such as technology developers, marketers, policy experts and a toxicologist–to develop a new roof paradigm and vision at a strategic level. After, an Earth Recovery Open Platform has been launched, which was based on the 'transition arena' model, and mobilised different actors. While the different stakeholders engaged in the platform did not question the vision much, it served to design the process for accelerating the roof transition, including new technologies, new rules and regulation, new design and manufacturing tools and practices, and new financial schemes. Within this process, roofs had been reframed as functional areas, on which basis different transition experiments have been set up. Starting from the platform, 'roof transition' has also been adopted by the national government of the Netherlands.

The TM approach seems to be suitable for application in many different processes within the energy transition: for managing the transition of coal mining regions; to guide local participation processes for the implementation of renewable infrastructure; to assist in development of renewable energy futures and local implementation of experiments, and alike. The starting point for each of those cases would be the agreement of a collective energy transition objective, which might be specified with reaching 100% renewable energy in a particular year or limiting to specific CO_2 concentrations. A second step would be the development of renewable energy visions; several might exist to meet the objective. Next, interim objectives need to be formulated to meet the long-term objectives. Then, the objectives would be operationalised by implementing experiments and pilot projects in specific environments. Finally, it would be reflected upon the process.

General lessons have been drawn from TM application in Loorbach and Rotmans (2010): context differs and requires a context-specific approach; selection of frontrunners is necessary if crucial for the transition process; frontrunners play an pivotal role in the transition process, but they must be empowered by providing 'space', resources and support for innovation; transition arenas of different frontrunners function as important, informal networks; close relationships should be built up with regime actors to reduce hold backs; transition processes are complex, and thus, "full of obstacles, barriers and surprises"; substance and process are both equally important for the transition.

3.2.5 Other innovation and acceptance theories

Beyond the transition literature, other theories from the worlds of sociology, economics, geography, communication science and/or psychology exist that relate to the adoption and diffusion of innovations that have been applied within the context of the energy transition.

Diffusion of innovations

Diffusion of innovations (Rogers, 2003) is a well-known theory stemming from communication science and economics. The theory aims to explain how, why and at what rate new innovations−a new idea, object or practice-can spread within a society (Rogers, 2007). Diffusion is a social "process in which an innovation is communicated through certain channels over time among members of a social system" (Rogers, 2003:5). This implies that diffusion is understood as a dynamic process influenced by the social sphere. The concept of diffusion is closely related to that of adoption. Whilst diffusion occurs on the societal level, respectively, adoption of an innovation refers to a process at the individual level.

The theory is based on four analytical categories, which influence the spread of the new innovation:

- The innovation and its characteristics;
- The communication channels through which information is disseminated;
- The time along which the innovation decisions are made; and
- The social system along which the innovation diffuses.

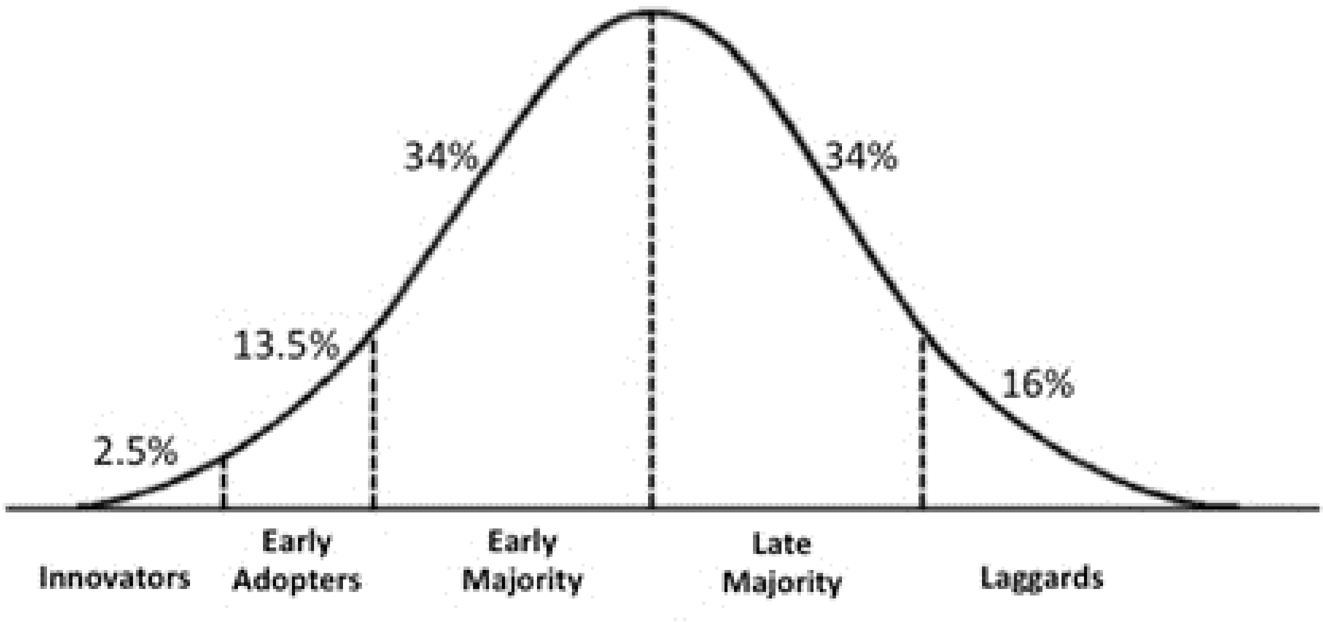
These categories are also seen as analytical elements, which can be identified and studied in every diffusion research study. Additionally, Furthermore, five innovation characteristics influence the individual decision-making about the innovation:

- Relative advantage (evaluation of the innovation);
- Compatibility (perceived consistency of the innovation with existing values,
- Past experiences and needs);
- Complexity (perceived ability to understand the innovation and to use/implement the innovation);
- Trialability (prior experimentation with innovations); and
- Observability (visibility of results of an innovation to others) (Rogers, 2007).

As in the MLP, according to this theory the diffusion of innovations follows an S-shape. Essential is the theory's consideration of adopter categories from innovator, to majority and laggards (see Figure 30).

According to Karakaya, Hidalgo and Nuur (2014), the theory shows a large application potential in the emerging literature on eco-innovations such as renewable-energy technologies; however, its relevance to explain the diffusion of eco-innovations is not known yet. In the context of ABM, the framework has been recognised to provide a suitable and structured framework for investigating how the innovativeness of adopters, social norms and direct communication affect the time and rate of adoption of community renewables (e.g., Süsser, 2016)

Figure 30 Location and distribution of adopter categories in the innovation curve. Source: Rogers (2003)

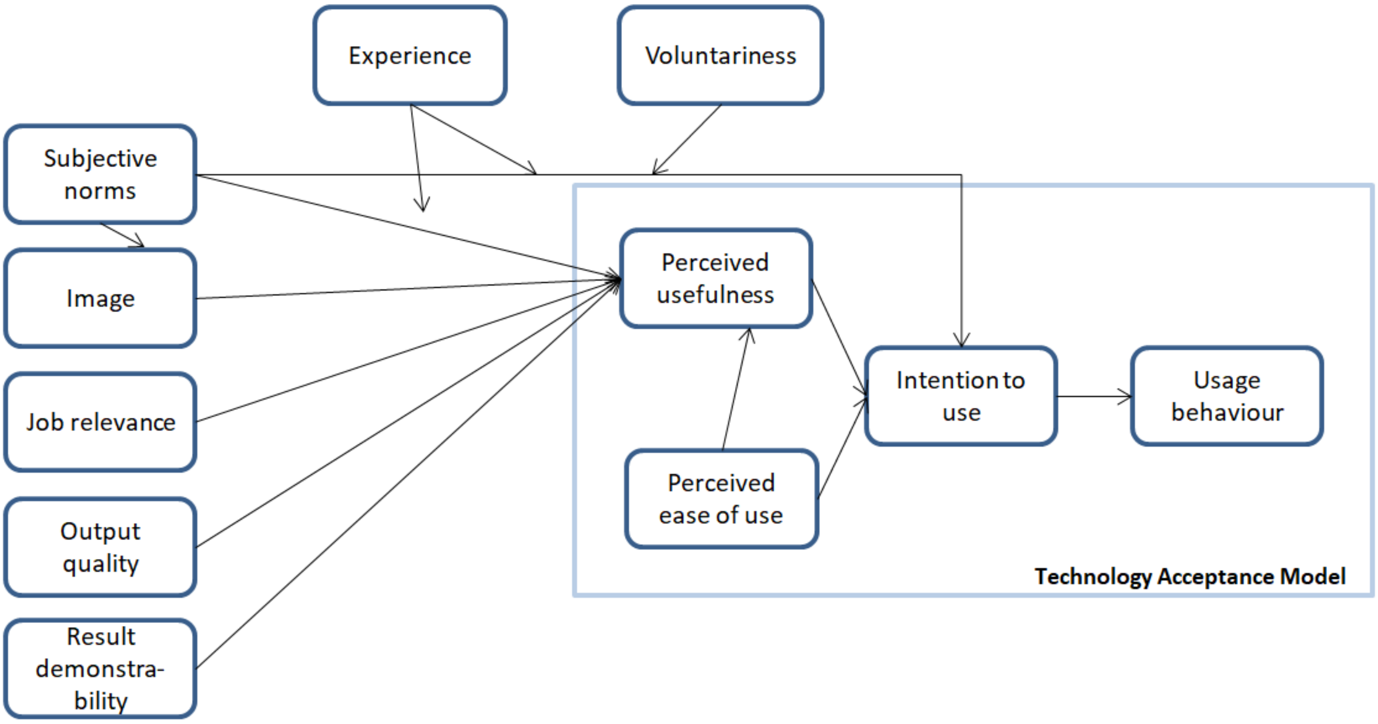


Technology acceptance theories

Diverse acceptance and adoption models have been discussed in the literature (see Taherdoost, 2018 for an overview), e.g., the Technology Acceptance Model (TAM) (see Figure 31), and empirically applied to explain acceptance and adoption behaviour in the real world. A growing amount of literature deals with the role of acceptance/opposition and other social constraints. Technological acceptance theories and empirics provide essential insights about key socio-technological drivers and constraints, such as 'subjective norms' and 'image', and their implications for the speed of technological diffusions. Beliefs, values and norms are not only essential on individual level but can provide implications for social drivers and constraints for the technological diffusion on local, regional, and national level. Thus, technological preferences and acceptance can play an important role for informing future energy scenarios.

Different socio-psychological theories, such as the theory of planned behaviour, have been developed (Ajzen, 2012). The theory has been widely applied in the context of human decision-making (Ajzen, Icek; Fishbein, 2005), and in application- and policy-oriented diffusion models in special (see Schwarz and Ernst, 2009; Kiesling *et al.*, 2011; Süsser, 2016).

Figure 31 The technology acceptance model. Source: Adapted from Venkatesh and Davis (2000)



3.2.6 *Lessons to be learned and implications for energy modelling*

Having discussed different sustainability transition theories, some of the key features and characteristics of transitions that energy models should be able to address can be presented. A selection of these aspects, which have been highlighted in previous research–for example, Geels et al. (2017) and Köhler et al. (2018a)–are summarised in the following sections.

Transition dynamics at and across multi-levels

All four of the discussed frameworks recognise the relevance of three different system levels: micro-level (niche), meso-level (regime), and macro-level (landscape). The multi-level approach has been applied to different case studies, also in the energy field, and revealed to provide a suitable system perspective. Theories focus on different levels: SNM focuses on the emergence of innovations at niche-level; MLP puts its main emphasis on the importance of interactions at regime level. The strength of sustainability transitions might lie in its ability to connect multiple levels, while cantering its perspective to meso-level, with the "central aim [...] to conceptualise and explain how radical changes can occur in the way societal functions are fulfilled" (Köhler *et al.*, 2019:3).

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Nevertheless, in energy modelling a gap is still perceived between energy system models–which mainly represent the macro-level–and agent-based and network models which focus on interactions at the micro-level. This meso-level perspective is missing among the other models within the SENTINEL project. Here, transition theory can potentially provide interesting insights to connect these levels.

Niches as 'protected spaces'

MLP and SNM both recognise the importance of niches as 'protected spaces' for the emergence of new innovations. Literature and case studies on niche innovation underline the importance of developing expectations or visions, spaces for experimentation, forming of social networks and processes of learning.

For energy models, one of the main issues is how to deal with the new innovations that are currently in the niche stage but lack political support, need further development, are not yet commonly known or are perceived from today's point of view as visionary, 'fancy', or without significant potential. Energy production technologies falling in these categories are, for example, floating offshore windfarms on the high seas, airborne onshore windmills, solar panels integrated in streets, installed on lakes or above agricultural land, pressure plates with piezo elements in public surfaces and many more (see section 2.1.3).

Transition theory emphasises on the importance of innovations and the need for spaces to innovate and support to push them towards wider diffusion. How can new emerging technologies be reflected in energy models? And, what might be the impact of new technologies on the transition process? Although the data basis of new technologies is often a weak spot for analysis, models could, for example, integrate these technologies with scenario-based assumptions investigating under which circumstances these technologies would become relevant. The purpose of such activities would be to advise policymakers on whether they should support the development and diffusion of such niche technologies in the area of energy production, storage and distribution.

Beyond technological innovations, social innovations such as community-owned energy projects, and business model innovations such as solar owner as a service, might have an essential influence on the transition. These innovations require the role of specific actors and networks for managing transitions, as outlined in SNM, to be defined.

Landscape pressure

Changes at the landscape level, such as large-scale crises, strong environmental legislations and social movements, have the power to put essential pressure on the regime. Exogenous shocks are largely unexpected but, for example, oil crises or nuclear disasters have led to major changes in energy systems. As with the MLP, TM theory emphasises the importance of the landscape level for change. How can models be able to represent exogeneous shocks? During the writing of the current report, the coronavirus crisis presented a major shock to societies and economies, including the energy sector. While the future impacts remain unknown, it underlines the importance of resilient systems needing to be able to deal with shocks.

Meanwhile, some risk management studies have gathered potentially surprising events for the energy system and its transition with low probability and low predictability but high negative or positive impacts (Kirchner et al., 2016; Krupa and Jones, 2013). Such events with negative effects are called 'black swans', while risks with positive effects for the energy transitions are referred to as 'pink swans' (Kirchner et al., 2016). These elements could be included in models as new scenario elements and for resilience testing. Furthermore, the current crisis could provide an additional opportunity for the energy sectors to transform towards a new system and gradually abandon the old status quo if the correct energy policies and investment choices are adopted now.

Regimes

Regimes are at the centre of most transition theories and are the level where interactions between multiple elements and actors take place. Regime changes occur due to emerging niche innovations and pressures from landscape level. While the MLP considers one regime, there may, in fact, be multiple regimes, as outlined in the SNM literature (Raven, 2007).

For energy models, challenges arise when attempting to depict the main characteristics of energy markets that determine real-world outcome such as different market actors and their behaviour, different degrees of market transparency, liquidity, concentration, different market sizes (national, transnational, European) and different market designs.

Role of multiple actors

The four transition frameworks all emphasise the importance of different actors–such as those from academia, politics, industry, civil society and households–which can be connected in different networks. Different actors may also have different values, norms and cultures that could lead to contestation and disagreement among actors.

Accordingly, one of the main challenges in energy modelling lies in the capability of models to represent different heterogeneous agents and their non-linear behaviour. Moreover, different preferences, beliefs and values of certain technologies and policies may change over time. Thus, models should be able to capture potential changes in social and policy values and norms over time, and/or to reflect them in different scenarios.

Long-term processes of change

It is imperative that transition processes are addressed as long-term processes. This means that they can be characterised by both long-term objectives and visions, and by short-term objectives and activities. Although a typical transition is represented by an S-shape–which reflects changes in the rate of change and other dynamics–other curve forms are also possible depending on the interplay of influence factors and transition models may need to be able to reflect such variations. The transition, moreover, itself underlies uncertainties, and is subject to continued changes of system elements. Thus, the challenge is how to deal and represent unpredictable events and shocks impacting the transition in energy models.

Going beyond single technologies

Transition theories offer the possibility of moving beyond the consideration of single technologies. Nevertheless, many still focus on single technologies even if they also recognise the importance of interactions between multiple technologies for their diffusion. Ideally, energy scenarios should be able to

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reflect interactions between different technologies, and the dynamics of technology changes over time. Another interesting aspect for energy modelling could be the use of different levels of renewables within future energy mixes and the different levels of public acceptability between different theoretical mix scenarios.

Role of policy in shaping transition processes

All four transition theories also emphasise the importance of public policy by shaping the directionality of transitions through environmental regulations, standards, taxes, subsidies and innovation policies. TM stands out in this regard as it is highly policy-oriented and, indeed, was developed within a policy context. Learnings from a socio-technical approach to low-carbon transitions highlights four lessons for low-carbon policy (Geels et al., 2017):

- "Focus on dynamic policy mixes, not isolated or static instruments;
- Analyse politics [and processes of policymaking], in addition to policy;
- Broaden the solution space, beyond supply-side technology and economics (towards behavioural and social drivers and constraints); and
- Actively manage phase-outs, in addition to stimulating innovation".

These four aspects indicate different policy, social and economic aspects that are not extensively represented in current energy models but could be greatly improved in future modelling activities.

3.2.7 Summary of socio-technical transitions

In this section, we introduced four main theoretical foundations of sustainability transitions which are useful to be applied in the context of the energy transition in order to better understand how structural change in the energy systems comes about, and to make the energy transitions happen and navigate developments towards sustainable energy systems.

Different sustainability transition theories can provide a holistic structure and explanations of change for important system dimensions and their influencing elements. A simplified integrated overview of the theories discussed is presented in Figure 32. These aspects can be seen as a checklist for developing more realistic energy models on a qualitative and quantitative level. In the end, all of these elements can be used to provide storylines, model logic and model parameters, as well as an indication of empirical data needs. More work is needed to integrate insights of sustainability transition research and social aspects, more generally, in quantitative modelling to build new energy models that are capable of dealing with the multifaceted challenges of a renewable energy transition (Pfenninger, Hawkes and Keirstead, 2014). The SENTINEL toolbox QTDIAN aims to contribute to closing the present research gap. The MLP has been identified as a promising framework for aiding in the development of scenarios and investigation of key elements influencing transitions and, thus, will be used within the development of the QTDIAN module.

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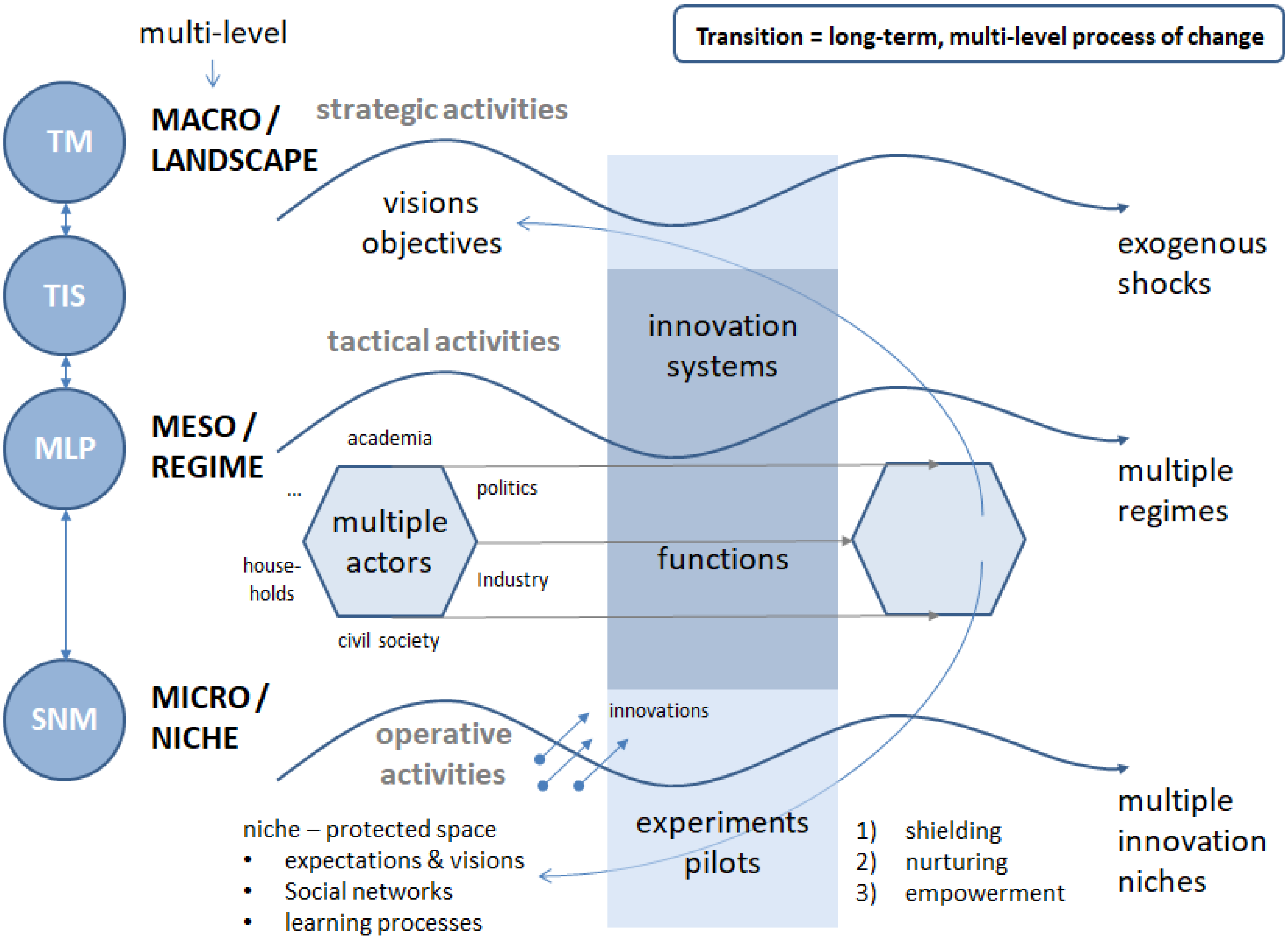
Figure 32 Overview of simplified integration of different sustainability transition research approaches. Source: own figure



3.3 Towards socio-ecological transitions

- Most conceptual frameworks for the study of energy transitions–including those discussed in section 3.2–are techno-centred. However, consideration of the concept of socio-ecosystem metabolism provides a pathway for linking ecosystems with socio-technical systems
- Three established frameworks used to describe socio-ecological transitions are reviewed

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One of the key drivers for transitioning energy systems towards renewable energy sources derives from the impacts that past and current fossil energy system configurations have exerted over ecosystems. The potential for future energy transitions to address these impacts is still discussed using two arguments. The first is that renewables might not be a sufficiently adequate source of energy for the social configuration we have today, due to technical limitations (Shellenberger, 2019). The second argument is that changing energy sources must be accompanied by changes in social structures and dynamics such as those proposed by the degrowth movement (Ernsting, 2015). These two lines of action (technological innovations and social innovations) are the focus of the previous two sections in this chapter. In this section, we add a third dimension to the discussion, that of the change in the relations between the societies and the ecosystems.

3.3.1 Sustainability without the ecosystem?

An overview of the main frameworks considered within sustainability transition research is offered in section 3.2. The frameworks discussed–the MLP, TIS, SNM and TM–form a strong and well-accepted set of conceptualisations that explain how and why technical innovations happen and how they relate to changes in the social order. These technical and social innovations are, in essence, meant to be a way of decreasing the impacts on the environment. However, while Markard et al (2012) attempted to identify the research lines that form the core of sustainability transition studies–as shown in Figure 33–few of these focus on ecosystem dynamics. The only exception is Kauffman's Complex Systems Theory, whose focus in ecosystems is only partial and conditioned to the description of ecosystems as self-organising systems. Hence, Markard's description of sustainability transition studies follows a techno-centric approach that misses an important part of the system's dynamics.

Technological transition studies focus on how technologies and social innovations develop within society and provide valuable information for the design of strategies that work from the social point of view. However, this perspective can be complemented with other frameworks that assess how those strategies influence, and are influenced by, ecosystem dynamics. With this in mind, the following sections summarise several frameworks that focus on the connections between social and ecosystem dynamics.

3.3.2 The metabolism of socio-ecological systems

The need for a more holistic approach to the analysis of the interface between socio-technical systems and ecological systems is illustrated by the popularity gained in the last years of the term socio-ecological system (SES) (Berkes and Folke, 1998a; De Aranzabal et al., 2008; Young et al., 2006). A unique, widely accepted conceptualisation of the SES does not exist (Cumming, 2014). Even if the strong link between human and ecosystem processes is acknowledged, the way in which this relation is defined in analytical terms has been different depending on the aim of the study.

Definitions of SES can be clustered in two groups. The first group (Berkes and Folke, 1998b, 1998a) emphasises the idea that societies are nested within the ecosystems, following the work of theoretical ecologists (Margalef, 1968; Odum, 1971), as shown as approach 'a' in Figure 34. This approach defines sustainability of the SES using the *resilience* capacity of the ecosystem (Folke, 2006) to changes inflicted by the society. The second group describes the ecosystem and the society as two integrated spheres that influence each other. Sustainability is then defined as the ability of the two to undertake *adaptation* to one another (Anderies et al., 2007; Janssen et al., 2007), as shown as approach 'b' in Figure 34.

Figure 33 Core research lines in the field of sustainability transition studies (Markard et al., 2012)

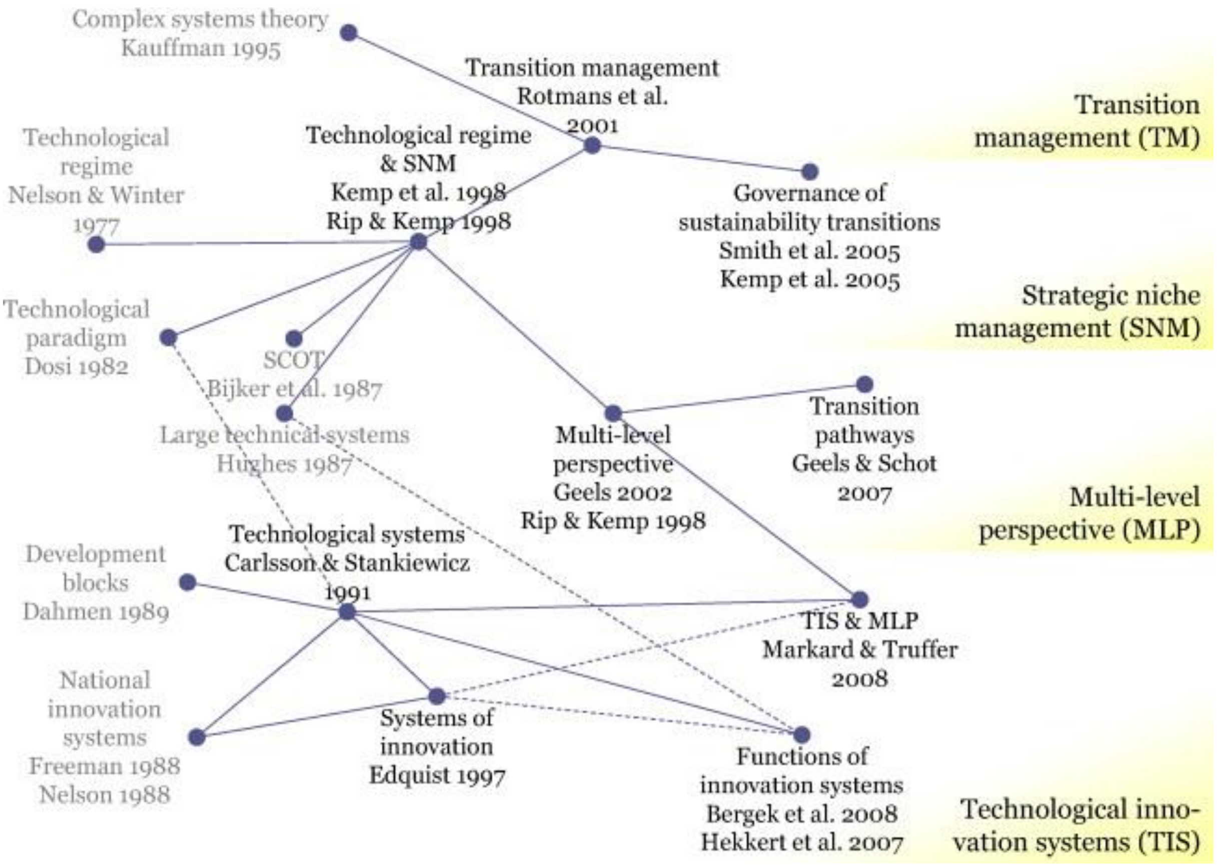
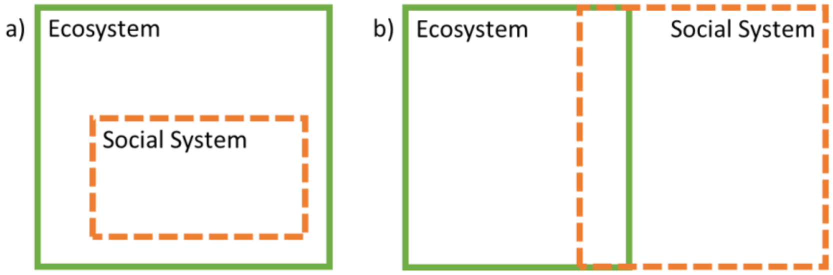


Figure 34 The two approaches in the definition of socio-ecosystems: (a) nested, and (b) interconnected



Both SES definitions include the idea that the ecosystem (or environment) can constraint the social activity. However, the explanation of why is different. In the first case, the ecosystem represents an upper level of

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hierarchical organisation and as such, the ecosystem dynamics influence the social ones (Allen and Starr, 1982; O'Neill et al., 1986). In the second case, the exchange between the ecosystem and the society is limited by the source and sink ability of the ecosystem. This differentiation is particularly important in the modelling of the environmental impacts. Each option provides ground for a different type of model to assess the limitation of a certain energy system configuration. SES representation 'a' will derive in a tree-type model of the energy system and their contributions to the society and the impacts over the environment (Rodríguez-Huerta et al., 2017; Velasco-Fernández et al., 2018). Representation 'b' will derive in a linear type of representation of the energy system in line with life cycle thinking (Hollingsworth et al., 2020; Stamp et al., 2012), for example.

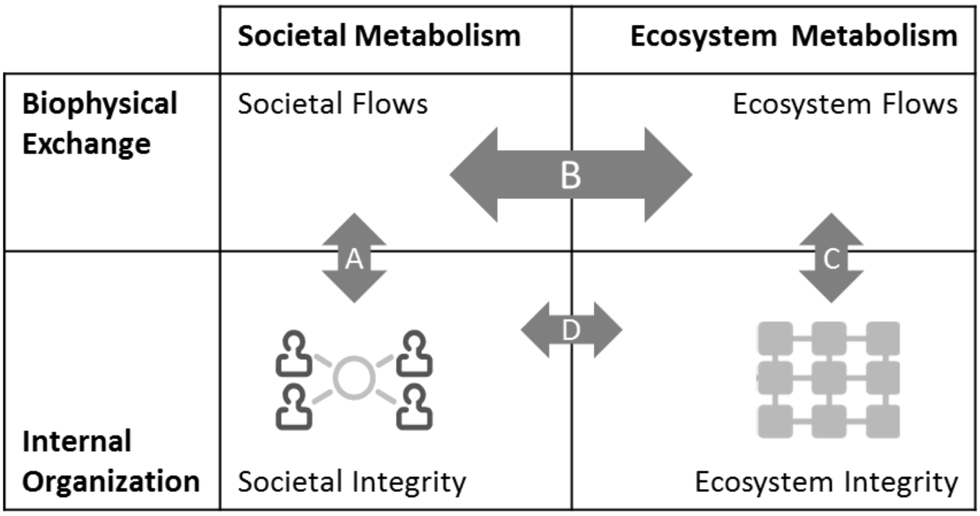
Both definitions of the SES above are integrated in the concept of social metabolism (Fischer-Kowalski, 1998; Gonzalez de Molina and Toledo, 2014), or socio-ecosystem metabolism (Giampietro et al., 2014). Borrowing from the concept of biological metabolism, social metabolism is described as the set of internal and external exchange processes that maintain the stability of the society.

The birth of social metabolism is strongly tied to early energy analysts and derived from the observation of the changes in the use of energy brought by the industrial revolution (Lotka, 1922). Authors who study social energetics are frequently referenced to as the first who studied the metabolism of societies (more detailed explanations can be found in Cleveland (1987), Giampietro and Mayumi (2009) and Martínez Alier (1995)). These early studies focused on the importance that the control over energy (re)sources has for the maintenance of the social dynamics and how a social transition comes with an important change in the use of energy (Harrod and Soddy, 1927; Lotka, 1925; Podolinsky, 1880) and changes in technology that have specific energy requirements (Cottrell, 1956; White, 1943). Nowadays the social metabolism studies may include any energy and material flow that is used by the society (see, for example, Fischer-Kowalski et al. (2011)).

Madrid and Giampietro (2015) define the metabolism of SES according to four different types of relations, as shown in Figure 35. Relation B refers to the exchange of materials and energy between the societies and the ecosystem. Includes processes like water extraction or CO_2 emissions. Relation A studies how those material and energy flows contribute to maintain the stability of the social system. Indicators used here include Euro generated per kilogram of aluminium used, for example. C refers to the relation between emissions and environmental impact. Indicators of CO_2 emissions per kilogram equivalent carbon dioxide (kg ECD). D is the relation between the social and the ecosystem structure. Typical indicators studied here are, for example, population density.

Using this framework, two different types of studies of metabolism can be defined. The first focuses solely on the biophysical exchange and the patterns of resource use and supply and waste emission/absorption, respectively, by the society and the ecosystem (A, B and C in Figure 35, related to SES type 'b' in Figure 34). Other studies compare the use/supply and emission/absorption relationships to the integrity of the societies and ecosystems (A, C and D in Figure 35, related to SES type 'a' in Figure 34). This is the type of studies that assesses socio-ecological transitions. SES transition concepts that are particularly relevant to the current project are introduced in the sections that follow.

Figure 35 Relations involved in the metabolism of socio-ecosystems. Adapted from Madrid and Giampietro (2015)



3.3.3 *Long term socio-ecological transitions*

Fischer-Kowalski and Haberl (2013) describe a socio-ecological transition as a process of radical change between one configuration of the relations between societies and their environment and another one, close to system theorists' 'regime shift' (Holling, 2001). This change in configuration is emergent–as opposed to planned or forced–due to the autopoietic nature of the socio-ecosystem (Maturana and Varela, 1980) and it is also unidirectional due to the socio-ecosystems being dissipative (Schneider and Kay, 1994). It is supposed that a SES transition comes as a solution to solve systemic socio-ecological issues (Loorbach and Rotmans, 2010). However, it is not easy to classify a SES within a 'transitional state'. Whether a certain SES is considered to be in one transitional stage or another depends on the spatial-temporal scale considered (Manson, 2008) and the conceptual framework used for the analysis (Binder et al., 2013).

Members of the School of Social Ecology at Alpen-Adria University in Vienna–known as the 'Wien School', Fischer-Kowalski and Weisz (2016)–argue that socio-ecological transitions can also be observed in the long run and at a slow pace (Fischer-Kowalski and Erb, 2016; Haberl et al., 2006). To identify the transition stage that a SES is in–take-off, acceleration or stabilisation–they observe historical emergent changes on the socio-metabolic profile of societies (Krausmann et al., 2016b), thus making the concept of social metabolism central.

This framework focuses on the changes in the metabolic patterns of material and energy exchange at the interface between human and ecosystems in what are known as the 'biophysical structures of the society' (see Figure 36). Even when this approach mostly focuses on flow exchange using Material and Energy Flow Accounting (MEFA), it uses these flows as proxy to assess the impact of the metabolic flows over the ecosystem and society's dynamics (Scheidel and Schaffartzik, 2019).

A substantial change in the metabolic patterns indicates a change of regime. This substantial change is slow in time and can only be observed when the SES is analysed within a wide time extent. According to these

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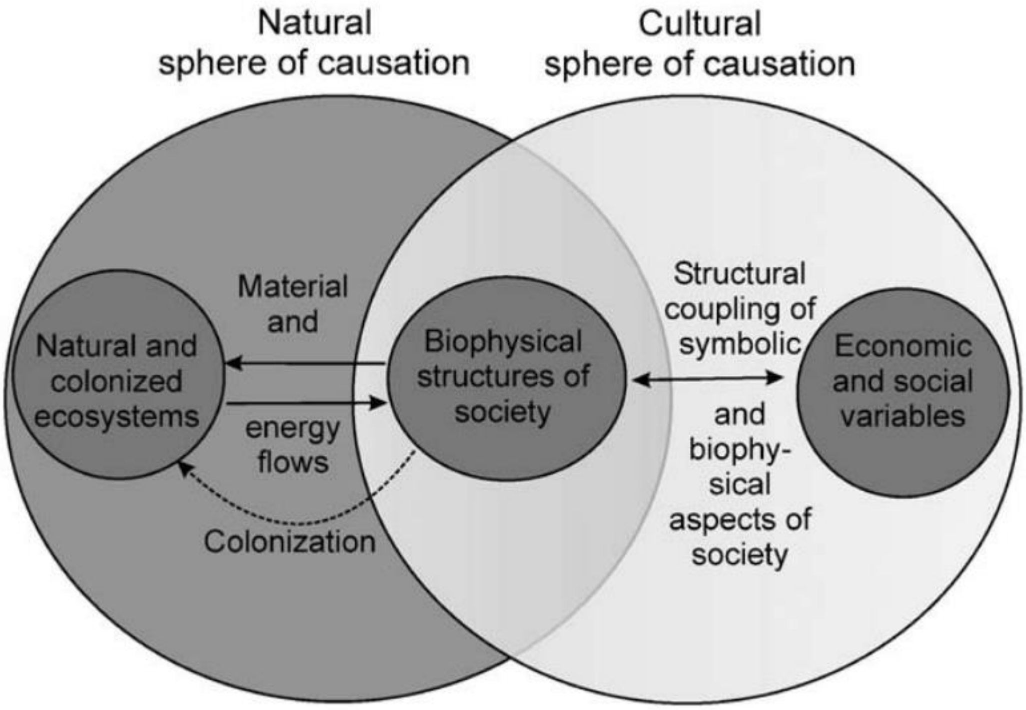
patterns, three long term types of society are distinguished: the hunter-gatherer, the agrarian and the industrial (Haberl et al., 2004).

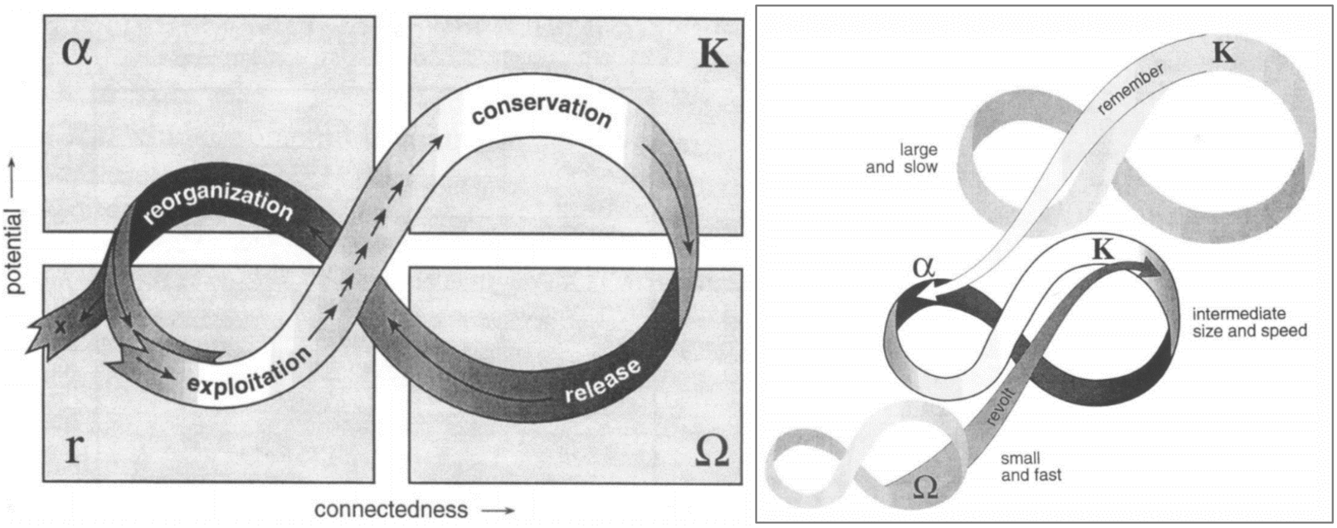
Figure 36 Interaction of the metabolism of societies and ecosystems. Source: Kowalski and Haberl (2007)



The vertical axis in the illustration on the left of Figure 37 represents the potential or socio-ecological wealth of the SES, the higher the wealth, the more options for transition in the future. Meanwhile, the horizontal axis represents the connectedness or controllability. This determines the ability of the system to control the transition process against external disruptors. A third axis, not shown in the figure, covers the resilience or capacity to adapt to unexpected disturbances (including transitions). The figure eight, therefore, is three-dimensional. In Figure 37 an SES moves slowly between the periods of exploitation and conservation and faster between release and reorganisation, while both processes create opportunities for innovation such as new accumulated technological capital in order to deal with system mutations.

Owing to the hierarchical definition of SES used in this framework, the adaptive cycle can be observed at each organisational level, as shown in the illustration on the right of Figure 37. In analytical terms, each level's cycle can be characterised by measuring its process rates (O'Neill et al., 1986). The processes at a certain level act as filters for processes at higher and lower levels in the hierarchy (Giampietro, 1994). In return, the speed of each cycle depends on the speeds of cycles in higher and lower levels of the hierarchy.

Figure 37 The 'false 8' adaptive cycle and its multi-level representation. Source: Gunderson and Holling (2002)



3.3.4 The false 8 socio-ecological adaptive cycle

Gunderson and Holling (2002) outlined another conceptualisation of ecological transitions that has been applied to social and socio-ecological transitions. Better known as 'the false 8', this representation shows four phases of the SES–exploitation (r), conservation (K), release (Ω) and reorganisation (α).

3.3.5 SES transition management

Another framework related to the adaptive cycle described above is the SES transition management proposed by Rotmans et al. (2001). This framework is rooted in the idea that SES transitions are motivated by the need to overcome important structural and multi-level persistent problems. Those problems might be different depending on the level of analysis, a consequence of the multi-level identity expressed by complex hierarchical systems (Allen and Starr, 1982; Pattee, 1973).

Informed by the Multi-Level Perspective (MLP) theory–see section 3.2.1–this approach specifically differentiates between the niche, regime and landscape levels of organisation and relates each of the three transition stages discussed above to each to these levels. In this framework, a transition is given by the changes in the interlevel dynamics of the SES.

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Table 16 Summary of frameworks for the assessment of socio-ecological transitions

School/Framework	Long term socio-ecological transitions	False 8 adaptive cycle	SES transition management
SES definition	Interconnected	Nested	Nested
Transition defined as			Changes in Inter-level dynamics
Metabolism focus	Biophysical exchange, supply/use, emission/sink, social integrity	Contribution to social and ecosystem integrity (social and environmental impacts)	-
Emphasis	Changes in metabolic patterns at the interface	Changes in status of the system (integrity)	Changes in the hierarchical relations motivated by persistent problem
Connection to MLP	-	Multi-level definition with abstract levels	Multi-level definition using same levels.
Examples	(Fischer-Kowalski and Haberl, 2013; Krausmann et al., 2016a)	(Evans, 2008; Holling, 2001)	(Rotmans and Loorbach, 2009)

3.4 Towards the socio-eco-technical modelling of the energy transition

- Combining socio-technical transition theory with elements of socio-ecological theory allows social, ecological and technical aspects to all be considered while analysing the energy transition
- The concept of a socio-eco-technical theoretical framework is presented

Fischer-Kowalski and Rotmans (2009) compared technological transition management with socio-ecological transitions and concluded that the two approaches present important differences in the definition of the analytical scale, the definition of the inter-level relations and the aim of the frameworks. However, they also highlighted the need of finding ways to integrate these two fields. They propose to begin by exploring different conceptualisations of the niche and the regime in socio-ecological transitions. Building upon this challenge, here we define a framework for the assessment of energy transitions with a socio-eco-technical perspective. The proposal uses the framework of metabolism of socio-ecosystems presented in Figure 35 to connect the frameworks for socio-technical transitions and those presented for SES transitions. A scheme of this proposal is presented in Figure 38.

In this proposal, the dynamics of the ecosystem at the micro, meso and macro levels are added to Figure 33. We define ecosystem transitions as a main driver of the socio-technical transition, represented by the cyclic

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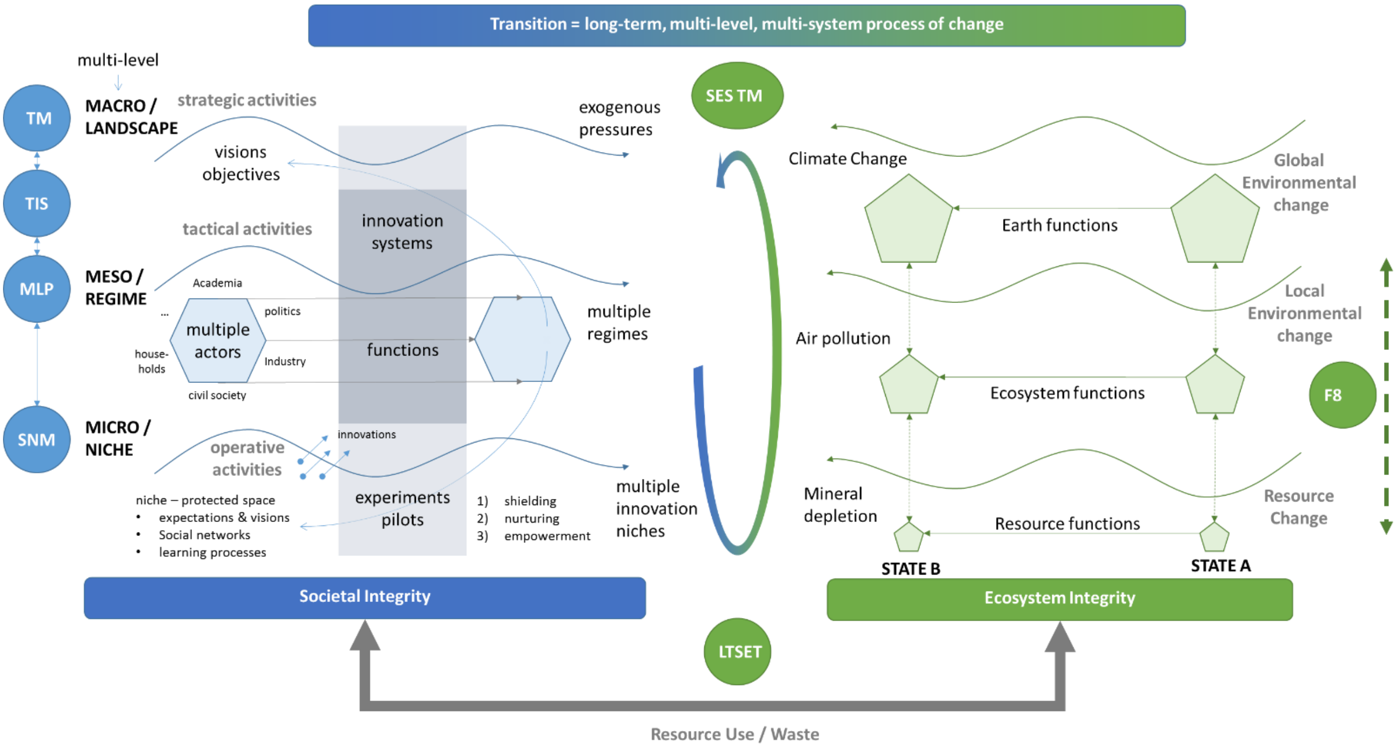
arrow in the middle of the graph. A certain regime results in niches filled by technologies that require the extraction of natural resources or the use of the ecosystem as a sink to succeed. This use of ecosystem capacities at different levels–usually micro and meso–result in global environmental change which, in turn, affects the boundary conditions of the society and can act as sources of exogenous pressure that force a change in the regime. Socio-Ecological Transition Management (SESTM) can be used to frame global environmental change as an exogenous pressure for the socio-technological system.

Figure 38 Overview of integration between socio-technical and socio-ecological transitions. Source: own figure



This organisational representation zooms in to relationship D of the metabolism of socio-ecosystems represented in Figure 36 and has a biophysical counterpart, simplified here by the grey bidirectional arrow at the bottom of the figure. This arrow represents resource use and includes relationships A, B and C in Figure 36, framed here by Long Term Socio-ecological Transitions (LTSET). The false 8 adaptive cycle framework can be used to assess the change in configuration of the ecosystem from state A on the right to state B on the left, while taking into account the nested, multi-level self-organisation of the ecosystem and the environment.

Within the SENTINEL project, the toolbox QTDIAN focuses on providing useful insights about socio-technical constraints and drivers to the modelling suite, whereas ENVIRO focuses on the modelling of the constraints posed by the socio-ecosystem dynamics to the energy transition. The further development of both modules will form the basis of the forthcoming SENTINEL project deliverables 2.2 and 2.3.

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4 Modelling socio-eco-technical transitions

- An understanding of the current status quo in real-world quantitative transition modelling provides an overview of the available options for the development of the ENVIRO and QTDIAN modules
- A general familiarisation with current technologies offers a clearer contextual understanding of other modelling activities within the SENTINEL project, particularly those involving the common-employed ABM and IAM approaches
- A group of six accepted frameworks and approaches are discussed in detail before being compared with a list of six elements previously identified as being key features of a transition modelling tool
- To conclude, simple overviews of the ENVIRO and QTDIAN modules are given that provide preliminary introductions to the modules and stepping-off points for the next stage of the project

Overview

The application of socio-eco-technical transition theory has traditionally taken a qualitative approach and formal quantitative analyses have been relatively limited. However, the growing discipline of transitions modelling is aiming to introduce more quantitative simulation concepts to the field. Nevertheless, the biggest hurdle to be overcome in this regard is the inherent complexity of the systems which are to be modelled, and of the uncertain transitions themselves. Modelling of these systems for more holistic and realistic model results requires consideration of numerous factors including the social-cultural, economic, organisational, institutional, political and technical aspects of the system, their interplay as well as feedbacks to the surrounding environment.

In any case, six potential frameworks and approaches to the modelling of energy transitions have been identified. The first of these–the use of integrated assessment models (IAMs)–involves the integration of multiple existing quantitative models and is already widely employed to simulate transition scenarios. Indeed, one of the most accepted and powerful IAMs–the IMAGE model–has been developed in conjunction with SENTINEL project members within the Utrecht University. In any case, it is acknowledged that IAMs often lack the level of detail required to simulate the more complex low-level aspects of socio-technical systems undergoing transition processes. However, this can be improved by better integration of social elements and progress is already being made to include ecological elements via coupling with life cycle assessment (LCA) outputs.

Conversely, the remaining five model categories are a group of more abstract frameworks and approaches that attempt to model complex systems, behaviours and dynamics, often at finer levels of detail. In particular, the models within this group are generally far more applicable to studying emergence behaviour. The most common of these–agent-based models (ABMs)–are widely used in a variety of applications and, as such, are probably the most likely to find applications in transition modelling in the short term. And, as with IAMs, it is acknowledged that better integration with social and ecological is likely to improve their applicability to transition processes.

Other frameworks and approaches identified and discussed include the broad group of complex systems models, evolutionary economics models, socio-ecological systems models and system dynamics models. It should be noted that many crossovers exist between these groups and many models can belong to more than one of these categories.

The previous sections discussed the various frameworks and other theoretical tools that enable socio-technical transitions to be visualised, most notably the Multi-Level Perspective (Geels and Kemp, 2007). Furthermore, section 3.2.6 provided a detailed discussion of eight conceptual aspects of transitions that energy models should aim to address.

To date, the application of transitions frameworks and other concepts have tended to be dominated by qualitative rather than quantitative case study analyses (Papachristos, 2019) and formal modelling approaches to transition processes have been relatively limited (Walrave and Raven, 2016b). This appears to be changing, however, as many modelling methodologies are emerging as part of a growing field known as transition modelling.

Modelling can provide several advantages for studying socio-technical transitions (Holtz, Alkemade, de Haan, et al., 2015:55). Firstly, they can provide explicit, clear and systematic system representations that induce learning and facilitate communication about the target system. Secondly, modelling allows us to make inferences about dynamics in complex systems and generate emergent phenomena from underlying elements and processes. Lastly, the use of models can facilitate systematic experiments.

Using Halbe et al. (2015) and Holtz, et al. (2015) as a basis, three classes of model use in transition research can be distinguished. Firstly, those used for understanding transition processes. Secondly, models that can be used to provide case-specific policy advice. Lastly, models can also be used to facilitate stakeholder processes.

Regardless of their intended functions, the biggest barriers encountered when modelling transition processes lies in the inherent complexity of the systems which are to be modelled and of the transitions themselves. Papachristos (2017) suggests that social-cultural, economic, organisational, institutional, political and technical aspects, in addition to feedbacks to the surrounding environment, all need to be considered in order to properly simulate changes within a system. Similarly, Foxon (2011) states that the complex evolutions and interactions between ecosystems, technologies, institutions, business strategies and user practices provide the basis for understanding transition processes.

Moreover, Overland and Sovacool (2020) state that social science–which is rooted in deep, qualitative analysis and is often hard to specify in numbers–finds itself in conflict with the clearer and more concrete nature of natural and technical science. As such, current models tend to treat the social dimension of the

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energy transition as an exogenous narrative, meaning that societal assumptions neglect the interaction of societal factors with each other and other social, technical, environmental or economic factors.

Today's energy networks are also becoming more intricate as the result of the ongoing processes of decentralisation discussed in section 2.1.4. Increasing the levels of smaller-scale and community-based actors in energy networks will inevitably lead to a greater number and variety of stakeholders within them. The lower levels of centralised coordination in these networks are likely to create further complexities for prospective modellers (Hansen et al., 2019).

Aside from the volume of elements that need to be addressed within transition models, the complexity of simulating transitions via modelling is further complicated by the highly dynamic nature of the systems in question (STRN, 2010). Most elements contained within transitions models–e.g., social norms, technological trends, government policies or resource prices–are likely to vary in time and often interactively as a result of changes in other elements. Combined, these factors indicate that energy systems are highly complex and non-linear systems that are often very challenging to imitate or predict via modelling practices.

This complexity also implies an interesting perspective of shifting from target models to transition models. Energy models are generally designed as target models "which offer aggregate, goal-oriented techno-economic analyses of different mitigation pathways" (Geels, Berkhout and Van Vuuren, 2016:1). For example, strategic energy system models often start as a target model that searches for a cost-optimal, climate-neutral solution for a given target year. This is often guided by pragmatic reasons, aiming to keep the modelling problem small at first and to add more complexity after the initial problem is solved. In such cases, models are less suitable for answering transition-, pathway- and trend-related research questions, although positive examples demonstrate that such sophisticated models are possible (e.g., Palzer, 2016) and some have proven capable of reflecting social storylines (e.g., Sterchele et al., 2020).

Transition models place a specific emphasis on transition processes. And, although the term has also been used in the context of energy modelling, the understanding of transitions is still predominantly from a techno-economic perspective. Future sustainability transition research may well provide an interesting approach through a "meso level assessments of social groups in relation to radical change in socio-technical systems" (Geels, Berkhout and Van Vuuren, 2016:1).

4.1 Key features of a socio-eco-technical transition modelling tool

- Identifying critical elements of transition processes provides a useful checklist for assessing the suitability of different quantitative modelling methodologies to simulating the energy transition
- Six elements previously identified as being key features of an ideal transition modelling tool are presented

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In addition to the conceptual aspects of transitions that energy models should aim to address–identified in section 3.3.1–Köhler et al. (2018) undertook a more technical analysis of the current status quo in transition modelling and identified six key features of a model that can be used to simulate transitions. Ideally, models employed within the field should be capable of addressing all of the following elements to some degree:

- ***Able to represent non-linear behaviour***

  System changes during a transition tend to occur at constantly varying rates. Perhaps the most common example is the classic 'S-shape' curve pattern where a transition process is initially slow, accelerates as the integration evolves, then slows once again as the new regime becomes stable and ingrained.

- ***Able to represent qualitatively different system states***

  Transitions are not merely increases or decreases in the same set of parameters within a constant set of elements. Rather, they often involve new configurations entirely, implying that system elements can be added, removed or evolve. The rules that govern the interactions that occur between elements are also likely to change.

- ***Able to represent changes in social values and norms***

  Transitions are often strongly influenced by normative changes in value systems within societies, and within other groups of actors, and the modifications to decision making rules that result.

- ***Able to represent diversity and heterogeneity***

  Transitions normally involve an array of diverse actor groups from the social-cultural, economic, organisational, institutional, political and technical arenas. For example, even a simplified energy transition model would include energy producers and consumers, technological researchers and marketers, politicians and government regulators. Furthermore, actors within each of these groups could be expected to have varying skills, preferences and strategies.

- ***Able to represent dynamics at and across different scales***

  Fundamentally, transitions are a dynamic process involving feedbacks between the micro and macro levels within societal systems, often with a meso level in between. These interactions can operate at, for example, different spatial scales (local, regional, national, global), temporal scales (months, years, decades) or within the different levels of institutional, governmental, economic or legal structures. Potentially the most important example in the current context is the representation of scales within the MLP, where the macro, meso and micro scales are represented by the socio-technical landscape, socio-technical regime and niche innovations levels, respectively.

- ***Able to incorporate open processes and uncertainties or contingencies***

  Transitions can sometimes be affected by radical and unpredictable developments such as sudden technological breakthroughs or political changes.

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4.2 Overview of relevant frameworks and approaches

- Determining the current modelling methodologies used in the simulation of transition processes provides an overview of the available technologies that could potentially be employed within the development of the ENVIRO and QTDIAN modules
- Familiarisation with these technologies also allows a clearer contextual understanding of the other modelling activities within the SENTINEL project
- A group of six previously developed frameworks and approaches are identified and discussed

With the aforementioned features in mind, Köhler et al. (2018) went on to categorise and review the available literatures within the field of transition modelling. They found that the methodologies currently being utilised could be categorised using a list of six frameworks and approaches. While each of these can be characterised according to their individual definitions, it is also important to note that significant crossover exists between certain categories and, thus, that many individual modelling practices could be said to belong to more than one category. (spacing 0-6)

The first of these is a very broadly-defined category that includes frameworks that employ existing quantitative models–often in conjunction–to simulate various transition-related outcomes. These models are typically applied to wider-scale applications such as macroeconomic structures or energy networks and are likely to be the most relevant to work to be undertaken within the SENTINEL project. The remaining five categories represent a group of more abstract frameworks and approaches that attempt to model the complex systems, behaviours and dynamics of transition processes at more specific spaces and in finer detail.

4.2.1 Integrated assessment models

As the name suggests, an integrated assessment model (IAM) is one that attempts to incorporate knowledge–usually in the form of pre-existing models–from multiple domains into a single, new modelling framework (Nordhaus, 2013). IAMs attempt to integrate geophysical stocks and flows with economic flows such that the key features of a system and its economy are assessed in conjunction with its interactions with the environment (Wang et al., 2017). Although they have been used in some instances to model other social processes, IAMs are predominantly used in the field of climate change policy (Capellán-Pérez *et al* 2020) and have become a very common approach to assessing mitigation scenarios at the regional, national and global scales.

According to Weyant (2017), two distinct types of IAM exist. And, while both focus on GHG emissions and the processes that cause them, they differ in the way they address climate change impacts. Firstly, *process* IAMs seek to assess specific future projections by quantifying the impacts that are likely to occur as a result of that scenario on the other processes and interactions occurring within the model. That is, they are not used to predict the future so much as paint a more-detailed picture of what the future would look like under certain conditions (van Vuuren et al., 2015). Accordingly, they are useful for providing further information on the physical impacts and economic costs of climate change–and the benefits of emissions reduction–within each sector or sub-region.

Such models are generally composed of three principle building blocks (Gambhir et al., 2019). An energy demand block is used to specify the energy demands within each sector–e.g., the six sectors within the EU, as shown in Figure 2–in each modelled region. Next, an energy system block is used to define the attributes of the energy sources within the model that can be used to meet these demands–e.g., the costs, performance attributes, resource limits and so on for each of the energy sources discussed in section 0. Lastly, a climate block is used to enable environmental damages–e.g., GHG emissions, air and water pollution, land and resource use and waste production–to be calculated.

Process IAMs have become highly influential in informing climate policy debate in recent years (Krey et al., 2019). Indeed, the Intergovernmental Panel on Climate Change (IPCC) have used IAMs to assess mitigation scenarios for over 30 years (Parson and Fisher-Vanden, 1997) and continue to do so (Farmer et al., 2015). More recently, many national governments have relied on IAMs to provide data for formulating their intended nationally determined contributions (INDCs) under the Paris Agreement. It is expected that IAMs will continue to be favoured for undertaking large-scale assessments of this kind in the coming years.

Although many process IAMs have been developed–e.g., see Nikas et al. (2019)–a set of seven well-established global models can clearly be seen to dominate the field. These models are summarised in Table 17. Note that a recursive dynamic model is one where the future is not known and is determined by solving a series of equilibria as the model progresses (Bauer et al., 2015), whereas an intertemporal optimisation model is one where it is assumed that agents have foresight about the future when making decisions. Meanwhile, a general equilibrium model is one that contains a detailed representation of all sectors of the economy, and of the energy technologies within them, and attempts to evaluate the impacts of specific policies within all aspects of the system. This contrasts with partial equilibrium models, which aim to evaluate policies for a specific market or sector by assuming that the remainder of the economy remains constant (e.g., a model that focuses only on finding optimal energy supply scenarios). Models can be run with the aim of finding an optimal solution or by merely simulating interactions as they occur throughout a given time period.

Table 17 also contains quantifications of the levels of representation of various factors within each model. This was done by assessing the composition of each model with respect to each factor using data from the Joint Global Change Research Institute (JGCRI) for GCAM and the Integrated Assessment Modeling Consortium (IAMC) for all other models. A level of low, medium or high was assigned based on the percentage of the parameters included in relation to the total possible number of identified parameters.

The final data demonstrates the wide variety of strengths and weaknesses within each of these models, and that no one model can model all aspects of these systems at the optimum spatial and temporal resolution. Nevertheless, it is noted that the IMAGE model, developed by the PBL Netherlands Environmental Agency in conjunction with SENTINEL project members within the Utrecht University, scores highly in more categories than any of the other models listed. The IMAGE model stands out even further by being the only model that deals with renewable energy sources well, considers land use within its resource use calculations and has an output for inequality as part of its climate change indicator outputs. Accordingly, it appears likely that the IMAGE model will be used as part of the process of modelling energy technology adoption scenarios within the SENTINEL project.

Table 17 Summary of key examples of process integrated assessment models (IAMs). Sources: (IAMC, 2020; JGCRI, 2020; Kriegler et al., 2015)

	IMAGE	MESSAGE-GLOBIUM	AIM-CGE	GCAM	REMIND	WITCH	POLES
Origin	Netherlands	Austria	Japan	US	Germany	Italy	Belgium
Modelling approach	Recursive dynamic	Intertemp optimisation	Recursive dynamic	Recursive dynamic	Intertemp optimisation	Intertemp optimisation	Recursive dynamic
Solution concept	General equilibrium (closed economy)	General equilibrium (closed economy)	General equilibrium (closed economy)	Partial equilibrium (price elastic demand)	General equilibrium (closed economy)	General equilibrium (closed economy)	Partial equilibrium (price elastic demand)
Solution method	Optimisation	Optimisation	Simulation	Simulation	Optimisation	Optimisation	Simulation
Start year	1970	2030	2005	2015	2005	2005	2015
End year	2100	2110	2100	2100	2100	2150	2100
Timestep *[y]*	1-5	5-10	1	5	5	5	1
Spatial regions	26	11	17	32	12	17	66
Levels of representation in the model:							
Socio-economic drivers	Medium	Medium	Medium	Low	Medium	Medium	Low
Economic sectors	High	Medium	High	Medium	Low	Low	Medium
Macro economy	Medium	Medium	Medium	Low	Low	Low	Low
Resource use	High	Medium	Medium	Medium	Medium	Medium	Medium
Land use	Yes	-	-	Yes	-	-	Yes
Technological changes	High	Medium	High	Low	Low	Medium	Medium
Technology substitution	High	High	Medium	High	Low	High	Medium
Energy types	High	High	Low	High	Medium	Low	High
Renewables	High	High	Medium	High	Medium	High	High
Grid and infrastructure	High	Medium	Low	Medium	Medium	Low	High
Energy end-users	High	Low	Low	Medium	Low	Low	Medium
Land-use definition	High	-	High	High	High	Low	Medium
Emissions and impacts	High	High	High	Medium	High	High	Medium
Inequality	Yes	-	-	-	-	-	-

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Of less direct relevance to the study of transitions, the second type of IAM is the *benefit-cost* IAM. Here, rather than assessing the feasibilities of mitigation scenarios using scientific or engineering approaches, these models draw more from the world of ecological economics in order to directly calculate the costs of climate change and of climate change mitigation. This is achieved by deriving the so-called social cost of carbon (SCC), which represents the marginal cost of emitting one additional tonne of carbon dioxide, or equivalent. The SCC is a pivotal concept in the valuation of climate change and, indeed, in the contextualising and implementing of climate policies (Nordhaus, 2017a). By specifying a price of additional carbon dioxide emissions, policymakers can determine if the cost of implementing a new policy or undertaking a certain mitigation action to curb these emissions is economically justified.

As with process IAMs, a dominant group of well-established benefit-cost IAM approaches to determining SCC has emerged. The group includes the DICE model (Nordhaus, 2017b), the FUND model (Waldhoff et al., 2014) and the PAGE model (Hope, 2011). All three have previously been used by the US government's Interagency Working Group (IAWG) to calculate SCC values that inform US climate policy (Rose et al., 2017).

The main criticisms levelled at both types of IAMs are derived from the fact that most social and other qualitative elements are oversimplified within such models (Köhler et al., 2018; Turnheim et al., 2015). While economic, technological and environmental mechanisms are the focus of IAMs, they are generally limited in their ability to represent the institutional, political and social-cultural factors that strongly influence transition mechanisms (van Sluisveld et al., 2020). Similarly, they have a tendency to frame processes of transition as smooth and relatively predictable, neglecting the heterogeneous and dynamic natures of actors between and within sectors and societies (Trutnevyte et al., 2019).

Meanwhile, Edelenbosch et al. (2020) believe that IAMs are too focused on energy supply and that future changes in energy demands–say, in overall watts per capita within a model–are a key and underrepresented factor. Such elements have clear connections to socio-cultural mechanisms, and future IAMs could benefit from an increased focus on the drivers of energy efficiency and demand technologies.

Despite these shortcomings, IAMs are a highly useful and versatile tool for simulating transition processes within large-scale systems and a likely to remain popular to climate change mitigation policy makers (Gambhir et al., 2019). Nevertheless, it is suggested that supplementing IAMs with other modelling and analytical approaches could greatly improve their future functionality (Frank W. Geels et al., 2016). van Sluisveld et al. (2020) propose that transition narratives such as those from the MLP could be used to provide 'analytical bridges' between socio-technical transition studies and IAM, while Hof et al. (2020) showed that transition strategies modelled within two IAMs–IMAGE and WITCH–could be greatly improved using insights from the MLP. Similarly, McDowall (2014) proposes that hybrid approaches incorporating 'dialogues' between models and the MLP could provide useful insights into guiding transition processes. Meanwhile, Trutnevyte et al. (2019) detail three strategies–bridging, iterating and merging–for creating better linkages between IAMs and social processes, as shown in Figure 39.

Enhancing IAM methodologies need not be limited to the integration of socio-technical frameworks and there appears to be a growing interest in integrating life cycle assessment (LCA) methodologies–which provide detailed assessments of the environmental impacts within each stage of the life cycle of a product or process–and IAMs. The studies have tended to focus on the electricity market in an effort to add greater

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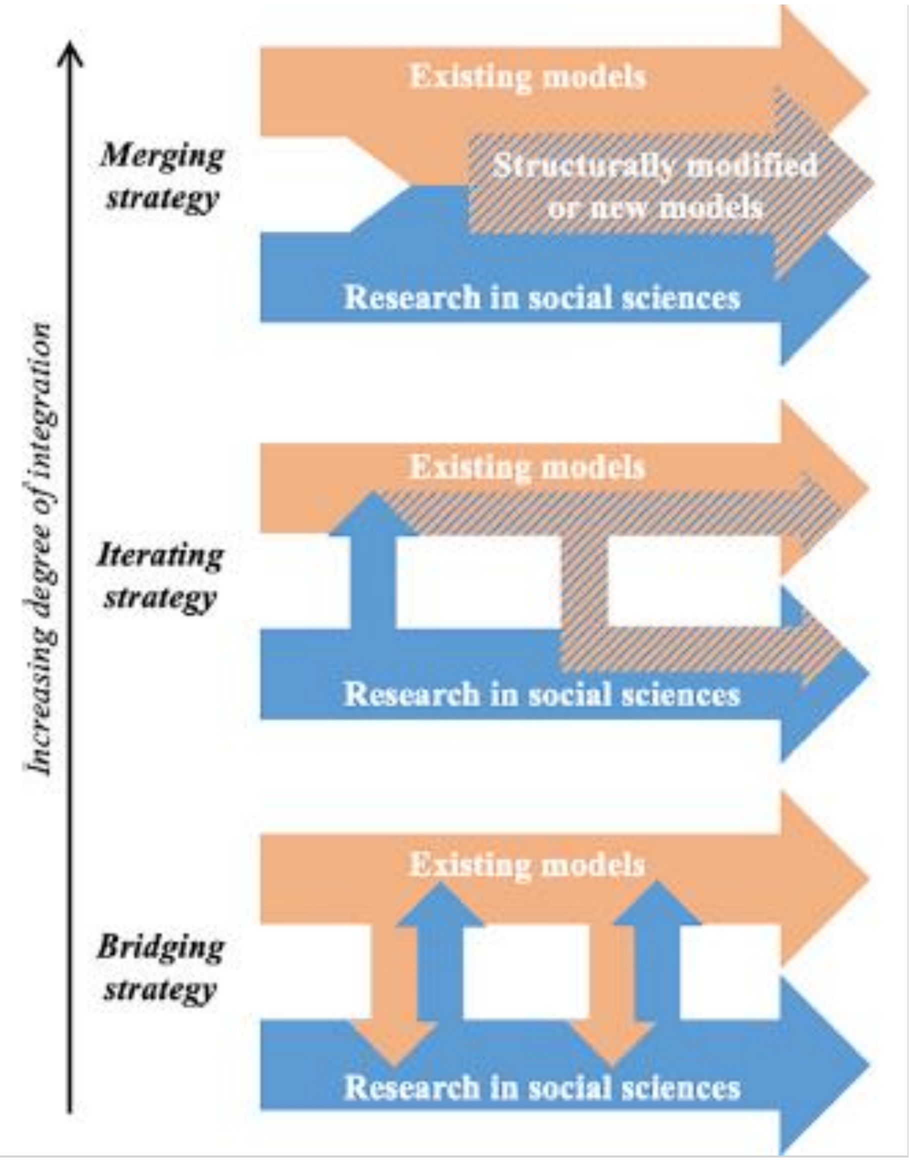
detail of the impacts caused by alternative sources of electricity. As such, many of them could prove to be highly relevant to the development of the ENVIRO model within the SENTINEL project.

Figure 39 Three strategies for linking IAMs with insights from social sciences. Source: Trutnevyte et al. (2019), licence: CC BY-NC-ND



A general framework for implementing LCA functionality into IAMs was proposed by Pauliuk et al. (2017), who added that IAMs could lose their relevance as policy guidance tools without the added detail that LCA integration could bring. Pehl et al. (2017) then used MESSAGE to simulate several transition scenarios for global electricity production that included LCA outputs. A generalised methodology for deriving LCA

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coefficients suitable for use in IAMs was also offered by Arvesen et al. (2018). This approach was then used by Luderer et al. (2019) to perform transition scenario simulations using the IMAGE, MESSAGE-GLOBIOM, GCAM, REMIND and POLES models. Although some limitations and uncertainties were identified, this appears to be a burgeoning field for creating more robust and useful IAMs overall.

4.2.2 Complex systems models

The first of the remaining five categories identified by Köhler et al. (2018) is that of complex systems models. Unlike IAMs, or the categories that follow, the complex systems model is not a well-defined concept, nor does it represent a single model type. Instead, the term is used to represent any highly non-linear model that operates within the scope of complex systems theory.

A complex system is one that contains many diverse components that interact with one another in a non-linear fashion (Rotmans and Loorbach, 2009). The volume of connections and feedback loops contained in such systems mean that behaviours within them are difficult to predict–that is, they are complex. However, as prior states influence future states, there is still some element of predictability via path dependence.

Complex adaptive systems are a type of complex system that contain agents that are capable of changing and learning. As such, the system can adjust over time as a response to variations within it. So, in addition to path dependence, the processes of coevolution, self-organisation and–more importantly–emergence are possible. Common examples of complex adaptive systems include the human brain, animal and human societies, economic markets or the entire biosphere.

Emergence is one of the key concepts within both complex systems theory and transitions theory. It occurs when new and coherent structures, strategies and practices arise within a complex system during a process of self-organisation without the intervention of external intervention or control (Goldstein, 2011). A common example of this concept can be observed in the diffusion of niche innovations into the socio-technical regime within the MLP (see Figure 26). Accordingly, the use of complex systems models within the study of transitions is predominantly focused on emergence phenomena.

4.2.3 Agent-based models

The most common general approach to modelling complex systems is the use of agent-based models (ABMs). An ABM models a system as a collection of autonomous decision-making 'agents'–for example, individual consumers, households or businesses–whose behaviour is defined by a series of simple rules (Bonabeau, 2002). The system as a whole then evolves as the model simulation progresses according to the ongoing decisions–for example, level of consumption or whether to invest in a certain technology–and interactions between the agents within it, allowing predicted outcomes and emergent patterns within groups of individuals to be determined (Goldstone and Janssen, 2005).

The key advantage of using ABMs–and what sets them apart from the broader approach adopted within IAMs–is their ability to deal with heterogeneity within systems (Lamperti et al., 2019). As Sachs et al. (2019) point out, consumer decisions such as energy-related investment tend to be highly variable according to budget, value systems and perceptions about technology, even when individuals are faced with identical

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decision tasks. This highlights the importance of including heterogeneity within energy transition models rather than assuming that all consumers will make the same rational decision at all times.

Including a diversity of well-defined agent types within a system also provides a better representation of the complexities of social interaction and allows important behavioural phenomena such as conformism, status seeking and imitation to be considered (Castro et al., 2020). As such, ABMs allow for the bounded rationality of agents and provide a link between technical analysis and elements of behavioural economics.

The other key element of ABMs in relation to transition modelling is their ability to capture emergence processes. So, an ABM could be used to determine emergent phenomena in spatial or temporal patterns within, say, a market sector or a community of consumers. Accordingly, they are thought to be highly suitable for analysing the emergence of niche innovations within the MLP framework and, hence, for studying energy transition pathways (Hansen et al., 2019).

Another great advantage of ABMs lies in their flexibility. Theoretically, they are capable of representing any system at any level of detail and, hence, are capable of encompassing all of the features of a transition model identified in section 4.1 (Köhler et al., 2018). However, while the architectures of ABM software make the coding of decision rules relatively simple in theory (Zhang and Nuttall, 2011), the construction of a truly representative and detailed ABM is still likely to be a difficult process and models that attempt to include high levels of detail can soon become unmanageable (Sun et al., 2016). Similarly, as the systems they attempt to simulate are complex by definition, ABMs are often difficult to calibrate or validate (Ringler et al., 2016), and less-tangible social or psychological parameters can be difficult to define quantitatively.

Nevertheless, the open-ended nature and flexibility of ABMs means that they can be applied to any number of situations and have been used to model transportation systems, land use, markets and transaction costs, technology diffusion and environmental policy in recent years (Rai and Robinson, 2015). ABMs have been highlighted as being particularly applicable to climate and energy policy (Farmer and Lafond, 2016) and especially to energy demand modelling applications (Rai and Henry, 2016). Such models typically include consumers and energy suppliers as agents operating under certain market structures, but are also likely to include a mixture of other elements such as demand side networks and other infrastructure, new technology types, innovation markets and social networks within their calculations (Holtz, 2011).

To date, the use of ABMs within the energy field has largely been focused on the electricity markets themselves. However, a growing number of models and studies are addressing other energy-related elements, particularly energy transitions. Hansen et al. (2019) offer a literature review involving 62 articles assigned to the categories of electricity market, transitions, consumption dynamics/consumer behaviour, policy and planning, new technologies/innovation and energy system. Likewise, Castro et al. (2020) reviewed a set of 61 climate and energy policy-related ABM studies within the categories of emissions reduction, product and technology diffusion and energy conservation and 23 sub-categories. Ringler et al. (2016) summarise 18 smart grid-related ABMs while Moglia et al. (2017) provide a review of the potential employment of ABM in studying the diffusion of more efficient residential energy demand technologies.

Lastly, it is noted that some are now also proposing that hybrid models combining the benefits of both IAMs and ABMs could provide the next evolution in modelling transitions. Farmer et al. (2015) suggest that the added detail that ABMs provide could result in more robust IAM outputs, particularly in the area of technological transitions, while accepting the challenges associated with the creation of detailed ABMs. Similarly, Lamperti et al. (2019, 2018) detail a so-called 'agent-based integrated assessment model' as a direct hybrid in order to address the shortcomings of the individual approaches.

4.2.4 Evolutionary economics models

Complex systems can also be simulated using frameworks provided by evolutionary economics models (EEMs). Much like an ABM–in fact, EEMs could be considered to be a subset of the ABM approach–an EEM attempts to model variation within a system using the principles of evolutionary biology as an analogue. In particular, EEMs can be used to simulate competition and selection processes that involve populations of agents and competing technologies that could determine, for example, emergence outcomes for new energy supply or demand technologies.

Rather than relying on well-defined rules to define the decisions of agents in a system, in an EEM the processes of change are driven by three of the core concepts from evolution theory, namely variation, selection and differential replication (Safarzyńska et al., 2012). Transitional change is triggered when new innovations lead to an increase in the diversity of technologies within the system–the *variation*. The system then acts to reduce diversity via processes of *selection*. That is, the number of technologies is kept at a certain level via competition; agents must select which technology they prefer, and some will be forced out at the expense of others. It is acknowledged that this selection is largely influenced by imitation processes at the individual and group level–the *differential replication*. As such, the key advantage to using EEMs is seen to be their ability to model the dynamics of social learning within transition processes.

There are clear parallels between the dynamics modelled by an EEM and those described by frameworks such as the MLP–and, indeed, others such as SNM, TM and TIS–and past EEM studies have tended to focus on microeconomic issues such as technological innovations and consumer preferences (Köhler et al., 2018). In these cases, impacts at the macro level–the socio-technical regime within the MLP–have been merely the result of patterns emerging from within the micro level. However, EEMs can also be directly applied to macroeconomic processes. For example, Stirling (2010) applied EEM principles to analysing energy diversity at the regime level. Likewise, Safarzyńska and van den Bergh (2017) propose an integrated model that combines an EEM with a macro-evolutionary model directly within financial and energy markets at the macro-level.

In any case, despite the great potential of EEMs to model complex systems, their use in energy transition research remains minimal. Considering the fact that a great number of supply and demand EEMs have already been developed within the economics community that are directly relevant to transitions theory (see Köhler et al. (2018) for examples), EEM methods could theoretically be applied to a variety of micro- and macro-level energy transition processes.

4.2.5 Socio-ecological systems models

As discussed in section 3.3, a socio-ecological system (SES) is defined as a complex and adaptive system consisting of a bio-geophysical unit and the social actors and institutions associated with it (Glaser et al., 2012). In other words, it is a conceptualisation of an ecological environment and the humans that operate

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within it, including all social and other institutional elements. The modelling of an SES, therefore, is an attempt to bridge the dynamics of human systems and their interactions with ecological systems within an integrated modelling domain. As such, SES models are generally viewed as a type of IAM, while also often being conceptually very similar to ABMs (Köhler et al., 2018). Indeed, they can be seen as a further variation of the ABM approach, one that has been extended to include more-detailed ecosystem feedbacks.

Traditional ecological models simulate the complex processes within natural systems under some simplified representation of anthropogenic pressure. At the same time, bio-economic models generally attempt to determine resource use or harvest levels that optimise the benefits to human systems under certain basic resource constraint assumptions. As a hybrid of these two model types, SES models aim to include more detailed considerations of both the social and ecological aspects of these models (Schlüter et al., 2012).

Perhaps unsurprisingly, SES models thus far have mostly been driven by modelling literatures from the fields of ecology and economics and used to conceptualise more conventional natural resource problems in areas such as fisheries, land-use and water management. However, Halbe et al. (2015) suggest that many strong similarities exist between SES modelling and transition modelling. Firstly, much like changes in an SES, transition processes occur across multiple domains–say, energy producers, consumers, regulators, etc. They also occur across multiple levels, from the micro-scale activities of individuals or smaller groups to the macro-scale of social norms or larger institutions. This, again, connects with the principles of the MLP. Thirdly, path dependency is a key element of SES models and transition processes. Lastly, the drivers and self-reinforcing mechanisms that drive regime change in transition mechanisms are also present in SES models.

Accordingly, as with EEMs, SES models appear to have many attributes that make them applicable to use in transition modelling applications. However, again, the use of SES approaches in the field of transition modelling has been relatively low to date. And, as with many complex systems modelling approaches, the high levels of flexibility offered by such models are accompanied by the usual difficulties relating to manageability and uncertainty (Schlüter et al., 2012).

Perhaps the best example of applying SES modelling approaches in the transition modelling field comes from the School of Social Ecology at Alpen-Adria University in Vienna. Here, much notable work has been undertaken in an attempt to examine the interplays between socio-economic, political and institutional drivers, the decisions of individual actors, and the ecological processes and patterns that surround them. A detailed overview of much of this work can be found in Haberl et al. (2016).

4.2.6 System dynamics models

The second general approach to modelling complex systems is the use of system dynamics models (SDMs). In contrast to ABMs, which are driven by the different behaviours of individual agents, SDMs are more concerned with the causal relationships and feedbacks that occur *between* elements in the system. That is, SDM takes a more holistic and endogenous approach to system simulation, one that focuses on the structure and dynamics of an entire system rather than the components in isolation (Bolwig et al., 2019).

The field of system dynamics is closely aligned with the broader field of systems theory and systems thinking–e.g., see Meadows (2009) for an overview. Indeed, the modelling of population and economic growth against the limitations of natural resources undertaken as part of the original Limits to Growth study (Meadows et

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al., 1972) is considered to be a prominent early example of SDM (Richardson, 2011). However, the field traces its roots back to the 1950s, when the burgeoning field of computing allowed researchers to construct models to solve simple business management and market-based problems. It was not until the late 1960s that the leading researcher in the field–Jay Forrester–began to apply system dynamics principles to other, non-corporate fields. During this period, the four standard elements of a SDM were formally defined (Forrester, 1968):

- ***System boundary***

  As with many models, the system itself must be well defined. Anything that lies beyond the system boundary is assumed to have no influence on the functioning of the activities simulated within the model.

- ***"Feedback loops"***

  The nodal building blocks of the model, it is here that the complex interactions between system elements occur. Again, assuming that the system is enclosed entirely within its boundary implies that all causal relationships are self-contained and endogenous in nature. As such, the functionality of the system can theoretically be analysed and defined solely according to the relationships that operate within these feedback loops (Richardson, 2011).

  A simple example might be that income level increases the likelihood of adopting a new technology. This is one feedback loop. Meanwhile, as more people adopt the technology, the price may rise. This is another feedback loop. The collective interaction of all such loops, thus, defines the functioning of the system as a whole.

- ***"Stocks"***

  Level–or system state–variables that define the current quantity of a system parameter at a given time. A stock could represent the level of any number of quantifiable parameters, from public opinion levels or commodity prices to more literal 'stock' values such as the global levels of available crude oil.

- ***"Flows"***

  Rate variables that define the changes in stock levels over time. Flows reflect the outcomes of activities that occur within feedback loops. An increase in a commodity price or a reduction in a social acceptance level are simple examples.

This focus on feedbacks, stocks and flows means that SDMs are more analogous to chemical, electronic or mechanical processes, where systems are driven by the intrinsic relationships between components within a fixed system. The highly quantitative nature of SDMs also means that they are very well-suited to computer simulation (Richardson, 2011). Indeed, many of the most common software applications used to simulate systems within the fields of chemical and mechanical engineering, among others, are considered to be examples of SDMs.

Furthermore, as SDMs are capable of simultaneously modelling micro-, meso- and macro-level relationships they are also thought to be conceptually and theoretically very suitable for emulating transition processes across the three levels of the MLP. A thorough overview of the applicability of SDMs to transition research

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is provided by Papachristos (2019). A more specific survey directed at the use of SDM in the modelling of energy transitions is also provided by Bolwig et al. (2019) who also postulated an example of a potential model architecture.

More specific examples are provided by Walrave and Raven (2016), who used an SDM to specifically simulate the MLP processes of de-alignment, re-alignment and technological substitution pathways defined by Geels and Schot (2007), as introduced in Section 3.1. Meanwhile, Moallemi and Malekpour (2018) used an SDM to simulate historical transition processes in the Indian electricity sector.

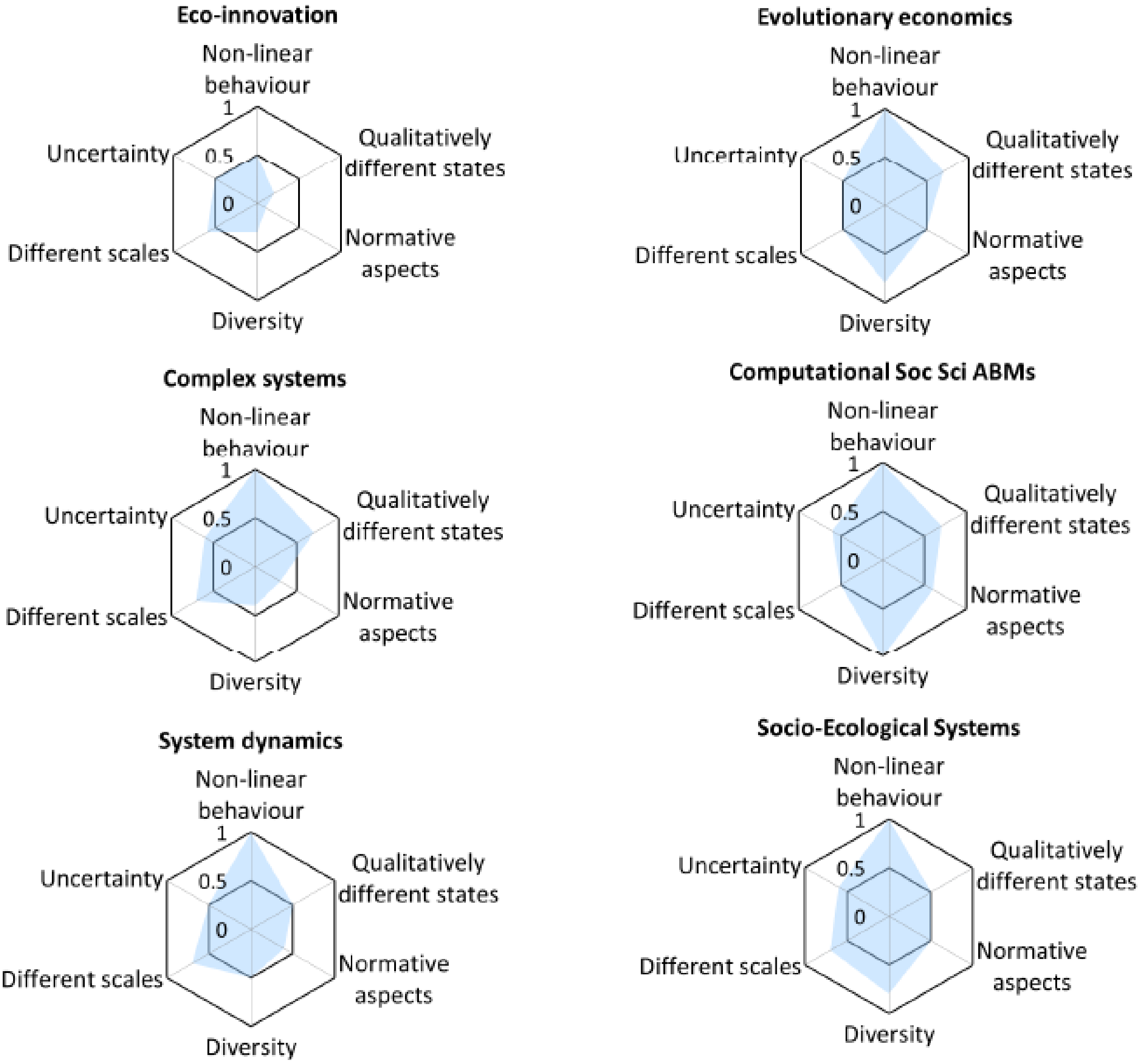
The collection of modelling processes developed within the field of SDM are thought to provide another powerful and adaptable approach to the modelling of transition processes and further research into its potential use is expected. Nevertheless, it is accepted that the highly quantitative nature of SDM may limit its application to the more qualitative aspects of these processes such as changes in social norms or behavioural heterogeneity (Köhler et al., 2018). However, as with other modelling processes, the applicability of an SDM is likely to increase significantly when utilised as part of a multidisciplinary approach. For example, Moallemi and Malekpour (2018) found that the effectiveness of SDMs can be greatly improved when used in conjunction with participatory processes.

4.3 Comparison of available frameworks

- Determining the strengths and weaknesses of each methodology in relation to transition processes guides the choice of framework or approach, if any, to be utilised in the development of the ENVIRO and QTDIAN modules
- Each of the six accepted frameworks and approaches are compared with a list of six elements previously identified as being key features of a transition modelling tool

A summary of all six frameworks and approaches in relation to the six key features of transition model discussed in section 4.1 is shown in Figure 40. The results suggest that IAMs, although widely used to simulate energy systems and the transition processes that occur within them, generally lack the level of detail required to simulate complex aspects of socio-technical systems undergoing transition processes. Meanwhile, the results confirm the potential of ABMs to model all these aspects to acceptable levels. It is hoped that the models of the future will prove capable of combining the strengths of all of these tools to enable more robust and dependable models to be created.

Figure 40 Abilities of each framework and approach to address six key features of a transition model. Note that IAMs are denoted here as "eco-innovation models". Source: Köhler et al. (2018a), licence: CC-BY



4.4 Introducing ENVIRO and QTIDIAN

- A generalised summary of the purpose and required features of each model provides a simple way to understand the basic requirements of the ENVIRO and QTDIAN modules
- Simple overviews of the attributes of ENVIRO and QTDIAN modules have been provided to provide preliminary introductions to the modules and stepping-off points for the next stage of the project

Two models–or, rather, modules–are to be developed within the SENTINEL project in order to integrate transition processes into the wider group of energy and other models contained within the project. The first of these–Quantification of Technological Diffusion and Social Constraints, or QTDIAN–will attempt to investigate possible diffusion scenarios, or 'storylines', for renewable energy technologies. The second–known as ENVIRO–will aim to investigate environmental and bio-economic impacts and constraints associated with such future scenarios.

QTDIAN is a 'toolbox' of novel socio-political-technical modelling tools (small models in themselves) that capture different drivers and constraints to better understand their influence on renewable energy development. Through a better understanding of the different influence factors, decision making about the design of the energy transition will be improved. While developing the tools within the module, the overarching aim will be to investigate the possibility of applying insights from the social sciences into energy models. This will be achieved using the two approaches offered by Trutnevyte et al. (2019). Firstly, social science insights can be used to define broad exogenous narratives which inform scenario development and are "then translated into quantitative input assumptions used by the models". Outputs from the models could then be iteratively reapplied back into the QTDIAN narratives. Secondly, social science insights can be used for "structurally modifying existing models that could altogether account for technology, economy, environment, policy, and society" (Trutnevyte et al., 2019:424-425). QTDIAN will provide social future storylines and input assumptions which can be used with a variety of SENTINEL models.

An additional focus of the development of QTDIAN will be to further investigate ways to integrate the 'transition perspective' into energy models. The sustainability transition modelling community has outlined several key aspects that models should be able to reflect–e.g., see Köhler et al. (2018)–and we aim to assess which of these can be achieved within the QTDIAN framework.

ENVIRO is likely to be far more quantitative in nature and will be used primarily to assess the environmental and bio-economic aspects of transition scenarios within the project. It is to be comprised of two key components. Firstly, life-cycle assessment (LCA) methods will be used to generate a list of the environmental impacts–or, more, specifically, changes in environmental impacts–associated with energy systems containing increased levels of particular energy supply and demand technologies. According to standard LCA practices, impacts are calculated throughout the full lifetime of each element within each activity such that the processes of manufacture, installation, operation and disposal are all considered. Each assessment will generate data for the consumption of energy, raw materials and water as required inputs and the production of water pollutants, wastewater, material waste and land degradation as outputs.

The bio-economic constraints related to these inputs and outputs will then be assessed using the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) approach. MuSIASEM is a method used for analysing interactions that occur within and between levels in socio-ecosystems (Giampietro et al., 2009). By assuming that coherence is maintained across scales and dimensions, the locations of constraints within such systems can be determined. Coupling outputs of the LCA process to MuSIASEM calculations will allow the environmental and bio-economic impacts and constraints for each required scenario to be determined.

It is unclear if either of these modules will directly utilise any of the frameworks and approaches discussed in section 4.2. However, it is possible that QTDIAN may utilise some of the concepts derived from complex systems modelling and may even involve simple working examples of such models within its toolbox. ENVIRO could operate as a standalone model assessing individual scenarios but could also be integrated into one or more of the existing energy system models within the project. In this capacity it could be modified to act as an element within a broader integrated assessment modelling (IAM) approach.

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