Integrated SET Plan

CETP

Clean Energy Transition Partnership

Input Paper to the

Strategic Research and Innovation Agenda

System Integration

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The Clean Energy Transition Partnership is a transnational joint programming initiative to boost and accelerate the energy transition, building upon regional and national RDI funding programmes.

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1 Introduction to Energy Systems Integration

1.1 What is Energy Systems Integration?

The development of a climate-neutral energy system in the EU raises challenges due to the complexity of this large-scale heterogeneous system. In its recently published communication[1] "*Powering a climate-neutral economy: An EU Strategy for Energy System Integration*", the European Commission stimulates energy system integration because it contributes towards effective, affordable and deep decarbonisation of the European economy in line with the Paris Agreement and the UN's 2030 Agenda for Sustainable Development. Energy systems integration is needed because, on the one hand, the supply of energy will shift towards sources that produce electricity – to a large extent wind and solar power – because these are the most affordable sources of renewable energy, and on the other hand because decarbonization of many demand sectors involves a shift towards electricity or hydrogen (or other carbon-free molecular energy carriers). Moreover, the variability of solar and wind energy requires the development of flexibility by increasing infrastructure capacity and connections between energy infrastructures, demand response and energy storage capacity. The stress test of the system is a *Dunkelflaute*, a prolongued period with limited solar and wind energy.

The term energy system integration refers to the coordinated planning and operation of the energy system 'as a whole', across multiple energy carriers, infrastructures and consumption sectors. Therefore, energy system integration involves coordinated planning of energy infrastructures, efficient investment signals to market players and consumers and efficient operation of the integrated system. The latter requires a rethinking of energy markets and regulation, from wholesale to retail markets, and from the CO_2 market to the regulation of network operators, in order to achieve reliability and in an economically efficient manner. The policy objectives remain to deliver climate-neutral, reliable and resource-efficient energy services, at the lowest possible cost to society, but system integration requires a more holistic approach both to policy making and to system analysis. Integrated of the energy system is intended to minimise the costs of the transition towards climate neutrality for consumers while increasing energy security.

Energy system integration supports:

- A **shift in energy demand** from fossil fuel to decarbonized electricity, hydrogen or heat;
- A **shift in energy production** to renewable and low-carbon sources;
- The development of **flexibility options**;
- The **integration** of electricity, gas and heat networks leading to energy system optimization;
- **Coordination** between the development of variable renewable energy sources, flexibility options, energy infrastructures and the decarbonization of energy demand.
- **Bi-directional** energy flows, as consumers play an active role in energy demand and supply: by linking up the different energy carriers and through localised production, self-production and smart use of distributed energy supply, system integration can also contribute to greater consumer empowerment, improved resilience and security of supply;
- A **circular energy system**, with energy efficiency at its core, in which cogeneration and waste heat recovery are utilized.

[1] COM(2020) 299 final.

A view of how the energy system can evolve towards a fully decarbonised energy system by 2050 and the impact of system integration is described by ETIP SNET.[2] The share of renewables will need to increase swiftly, to about 55% by 2030 and 84% in 2050.[3] The remainder will need to be provided by sources that are perhaps not fully sustainable, but still low-carbon, such as nuclear power and fossil fuel with carbon capture and storage. The degree to which these latter sources will play a role is a subject of political debate but is not a key issue with respect to the issue of energy systems integration. Regardless of the details of the energy mix, the integration of high shares of variable renewables will require a significant redesign of the energy system optimization and coordination. In order to keep minimize the cost of the future energy system while keeping it reliable, energy systems integration is needed in order to provide more flexibility and energy balancing options, including:

- stronger **interconnections** between energy infrastructures and between infrastructure levels, extending pan-European networks to improve the match between supply, demand and storage, e.g. unlocking the potential of large offshore wind farms (e.g. in the North Sea), power-to-X technologies and solar energy (e.g. in the south of Europe);
- **new low-carbon European networks** such as low carbon hydrogen and CO_2 networks;
- more **storage** capacity, helping to match demand and supply dynamics more locally and over multiple time frames;
- better integration of consumer markets to unlock **demand response** and integrate small-scale generation and storage, from the residential and industrial sectors alike;
- low-carbon **flexible generation** units (e.g. geothermal, biomass and thermal power plants fitted with CCS);
- new energy conversion (PtX) options and integration of different energy vectors (electricity, molecule-based energy vectors, heating/cooling etc.);
- enhanced **system operation** to get the most from the flexibility provided by system resources (e.g. improving forecasting, shortening decision-making processes, extending automation, increasing coordination, etc.);
- modernized **energy markets** in order to achieve a fully interconnected market with a level playing field across different energy vectors and system levels (from international trade to consumers); this may be achieved in part by enabling new schemes and digital platforms that facilitate the integration of all actors, increasing spatial and temporal granularity, combining centralized and local structures, ensuring security and transparency, and minimizing transaction and operational costs.

1.2 How can Energy Systems be integrated?

System flexibility can be reached in several ways: upgrading of the entire electricity value chain (generation, transmission, distribution and customers, and energy storage), reinforcing or creating new links with other energy networks, via for example power to heat/cold, power to gas/liquid and connections with the electrical components of the transport network, increasing the capabilities of RES through the improvement of their predictability and mechanism development for the future systems network services, through demand flexibility, both of residential and commercial consumers, and energy storage. While most renewable energy is produced as electricity, energy can be stored more cheaply in

[2] https://www.etip-snet.eu/etip-snet-vision-2050/; https://www.etip-snet.eu/wp-content/uploads/2020/02/Roadmap-2020-2030_June-UPDT.pdf.

[3] European Commission, 'Powering a climate-neutral economy: An EU Strategy for Energy System Integration'. COM(2020) 299, Brussels, 8 July 2020.

the form of heat or molecules (gases like hydrogen and liquids like methanol and ammonia). Energy system integration is to ensure that all these solutions are coordinated in a cost-effective manner.

A key obstacle to energy system integration is the fragmented way in which it is governed. Electricity, natural gas, heat and new energy vectors like hydrogen are organized and regulated differently. Moreover, consumer markets are disconnected from wholesale markets, with different taxes, different time resolution of products (e.g. a flat annual price). Some consumer groups are affected by the European Emission Trade System for CO_2 while others are not. The networks for electricity and natural gas are regulated monopolies, but those for hydrogen and heat not or not always. In order for an economically efficient integrated energy system to develop, the financial incentives to producers, network operators, storage providers and large and small consumers will need to be realigned so a level playing field for competition develops. This requires a rethinking of the governance of the energy sector:

- It needs to be ensured that innovations and new investments compete in a level playing field[4], from behind-the-meter flexibility of consumers to large-scale storage and hydrolizers.
- The infrastructure planning processes need to be coordinated between the different European energy infrastructures – electricity, hydrogen, natural gas, heat, CO_2 and perhaps other energy vectors – and between European states to ensure that, despite the long planning times for major infrastructure project, the European energy system is ready to handle the high volumes of low-carbon energy that are to be developed in the next decades.

Similar challenges exist with respect to energy systems research, as traditionally, research has been conducted within the same sectoral silos. Moreover, most research has focused on technological components and on the consumer interface, while the current computer modelling capabilities for studying the energy system as a whole is inadequate for dealing with the current challenges.

To understand both the policy and research challenges at hand, it is helpful to consider the energy system as having a set of different dimensions among which integration needs to be achieved. Figure 1 depicts these five dimensions. The geographic dimension refers to the cross-border integration of European energy markets. While this has been an attention point since the liberalization of the markets in the 1990s, the energy transition has lifted the issue to higher prominence as long-distance system integration is a relatively low-cost way to integrate variable renewable energy. An important aspect is of course that the existing infrastructure should be used efficiently, which means that market integration continues to be relevant.

The second dimension is the system level, from distribution to transmission, and perhaps in the future to continental overlay networks, for electricity, natural gas and the new networks that will be required for hydrogen, and perhaps other molecular energy vectors and CO_2. As more generation and more flexibility options are developing at the local level, the integration of these resources into system balancing and network congestion management are increasingly requiring TSO-DSO cooperation.

The timescale dimension refers to the fact that one can no longer abstract from short-term system behaviour in long-term planning. The business case for a new battery or electrolyzer depends on short-term price fluctuations during its life span, so the investor needs to have a detailed understanding of the future energy system in which the asset is to function in order to make an investment decision. As a consequence, long-term (planning) decisions require insights in short-term (operational) system behaviour.

The fourth dimension is the increased coupling of different energy vectors. Many decarbonization options lead to electrification, e.g. of transport, heat and industry. At the same time, hydrogen or another molecule-based energy vector will be necessary for storing and transporting energy while CO_2 networks will be needed to support decarbonization where electrification or fuel switching, e,g, with hydrogen, is

[4] For a specification of a level playing field in this context, see page 16 of 'Powering a climate-neutral economy: An EU Strategy for Energy System Integration'. European Commission COM(2020) 299, Brussels, 8 July 2020.

not feasible and to deliver carbon dioxide removals from the atmosphere, e.g. through the application of CCS to bioenergy. While natural gas now only can be combusted, e.g. in a power plant, the development of hydrolyzers means a two-way connection between electricity and gas. The link with heat networks is also relevant, because storing heat is relatively cheap form of energy storage and therefore a potentially important source of system flexibility. Additionally, cogeneration of heat and electricity demonstrates the efficiency and cost benefits that sector integration can deliver. District heating and cooling networks offer a ready-made, proven solution for the decarbonisation of the heating and cooling sector.

The final dimension was already mentioned in the introduction: the adjustment of the regulation and market design of an integrated energy system. The energy transition requires a nearly complete rebuilding of Europe's energy sector over the coming decades. The required investments are made by competitive companies, regulated network operators, consumers and other organizations such as energy cooperatives and energy communities. The degree to which these investments are coordinated depends on the market design and regulation of the system, as they determine the investment incentives for the actors.

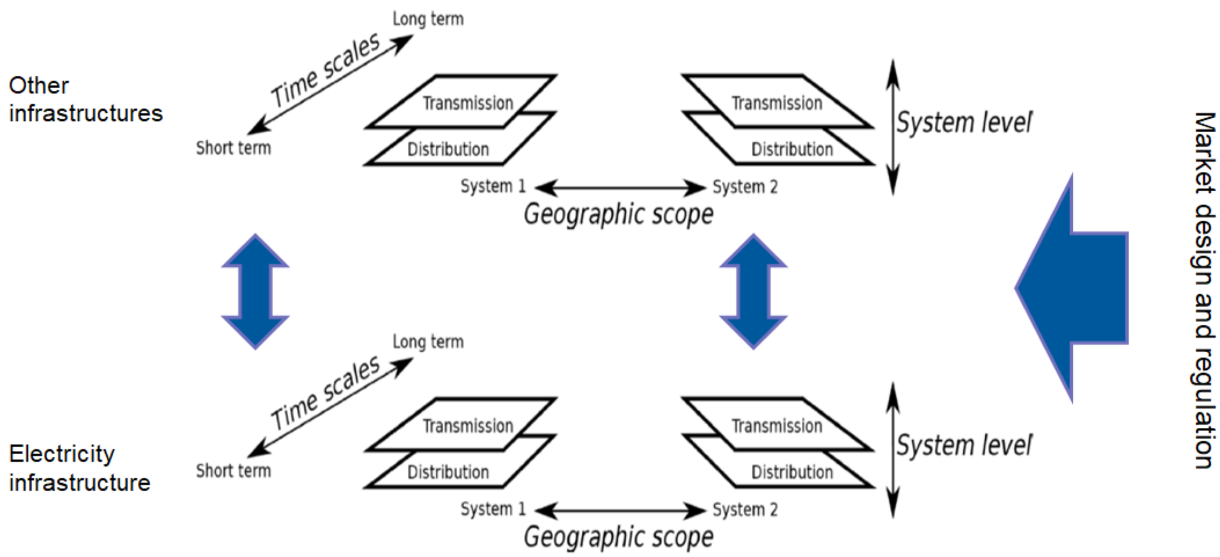

Figure 1: Energy System Integration

1.3 Two Missions: System Integration at the European and at the Local Level

The ETIP SNET Roadmap 2020-2030 and the Set Plan IWG4 Implementation plan (revision) identified **two missions** with respect to energy systems integration. The first is the identification and realization of the energy backbone infrastructure of the future, which needs to be coordinated with the development of renewable energy, flexibility, changes in energy demand and other societal trends. The obstacles to the expansion of the electricity grid and the development of infrastructures for hydrogen, for perhaps other molecular energy vectors and for CCS and CCU cause an urgent need to identify different infrastructure development pathways that can facilitate a future low-carbon energy system. Research needs concern a significant expansion of computer modelling capabilities in order to identify investment needs (in the networks as well as, for instance, the locations and capacities of energy storage facilities and hydrolyzers) as well as changes to network investment decision processes for European networks and improved operation of interconnected networks, e.g. with respect to energy balancing and congestion management in cross-border and cross-vector interconnected networks.

Failing to tackle this challenge entails a risk of uncoordinated, piecemeal infrastructure development that is lacking in capacity and costlier than necessary. On the other hand, it is not possible to design a new energy system from scratch: it will evolve over time, through investments that are made limited knowledge of the future. The challenge is therefore to provide a regulatory framework that coordinates these incremental decisions as well as possible and that minimizes the risk of large mistakes. In the end, a combination of bottom-up market dynamics and top-down infrastructure design will need to lead to the desired outcomes.

At the local level, the geographic scope is smaller but the system scope is larger, as here heat networks may also play a role, and the energy system needs to integrate electric transport, heating and cooling. Also, at this level, there is a large modelling challenge to understand the optimal local energy infrastructure choices, as they are influenced by the geography, building stock, climate and consumer behaviour. Likewise, operation local energy systems, with reverse power flows and heterogeneous volatile resources, poses a significant challenge, e.g. regarding congestion management in radial distribution networks. Again, market design and regulation play a key role in providing guiding the operational and investment decisions of grid operators, market parties and prosumers along the pathway to a low-carbon system, the contours of which are only beginning to become clear. It is important to utilize the infrastructure already in place to minimize the costs of the transition. Tailored, locally determined solutions and systems will be required.

In summary, we discern to high-level missions with respect to energy systems integration, in line with the SET Plan IW4 and ETIP SNET:

- The **European integrated energy system**, where electricity distribution and transmission grids are seen as the “backbone” of the future low-carbon energy systems with a high level of integration among all energy carrier networks, by coupling electricity networks with gas, heating and cooling networks, supported by energy storage and power conversion processes. Such energy systems will be fully-digitalised, with a high level of automation.

- The **regional and local energy system** composed of locally and regionally available energy sources, built infrastructure, specific production and consumption characteristics as well as user and consumer structures from different sectors, including the transportation system. They have an important role to play in reaching the Energy Union targets. They are part of the living environment of citizens, including, in some cases, highly ambitious clean energy goals of specific communities and regions. In this framework, complementing the approach developed in the first dimension, focus is given to decentralised energy systems. Digitalisation and new business models may provide new opportunities and regional and local innovation ecosystems play a very important role. Local markets will need to be improved and integrated with wholesale markets in order to optimally benefit from local generation, storage and demand flexibility.

2 Overview of Challenges

At the core of energy systems integration is a complete redesign of the energy system with the goals of facilitating renewable energy as well as complementary low-carbon flexibility options and shifting consumption from fossil fuels to electricity and hydrogen. These low-carbon flexibility options include capturing CO_2, to eliminate remaining emissions and also to remove CO_2 from the atmosphere. To minimize the social costs of these significant and rapid changes to both the supply and demand sides, a holistic approach is needed. Ideally, an integrated energy system facilitates an optimal combination of flexibility options for the electricity system which, in turn, allows connecting variable renewables (wind and solar) as well as new consumption profiles, for instance of electric vehicles, effectively and efficiently. However, as decision making is to a large degree decentralized, system integration in practice may be characterized by coordination as much as by optimization.

As mentioned in the introduction, the energy transmission can be characterized by two missions[5]:

1. Develop an optimised integrated European energy infrastructure;
2. Develop integrated local and regional energy systems.

Within each mission, related clusters of challenges can be identified, namely planning, operation and governance (market design and regulation). In addition, at the local level, the interface of the consumer with the system – smart grids, energy communities, peer-to-peer trade etc. provides an additional set of challenges. Based on the above documents, the EERA Strategic Research and Innovation Agenda ('White Paper') and the European Commission's 2020 vision on energy systems integration, the main challenges to energy system integration are described below. The societal and the research and innovation aspects of each challenge are described.

Please keep in mind that the below challenges pertain to energy systems integration. There are many other challenges to the energy transition, such as the NIMBY syndrome, social equity, digitalization and circularity, as well as technology development challenges, but these are not within the scope of this paper.

System Planning: Designing the Seamlessly Integrated Energy System of the Future[6]

Societal Challenge

The overall challenge to designing and planning an integrated energy system is to overcome the silos among energy vectors, between system levels and between infrastructure operators and market parties that exist in society. The planning of new infrastructures needs to include the development an efficient mix of flexibility in all parts of the energy system. Planning steps include scenario setting based on reliable, consistent and transparent hypothesis, parameters and relations as well as the development of integrated and complete planning tools that can address holistically an energy system in which all vectors interact with one another. This requires an entirely new approach to energy system modelling, as will be elaborated below.

At the European level, the challenges are to integrate the development of energy infrastructure across borders and between electricity and molecule-based vectors such as hydrogen. Completely new infrastructures need to be developed, e.g. for offshore wind, which may include innovations such as high voltage direct current networks as well as offshore power-to-gas conversion, hydrogen and CO_2 networks. Challenges are not only in the joint planning, but also the financing of these infrastructures.

At the local level, the challenge is to integrate the development of multiple vectors (electricity, heating & cooling, natural and green gas, water) in the context of shifts in energy consumption, e.g. for transport, heating and cooling, and local renewable energy generation. Given the lower cost of storing energy in heating and cooling systems and in electric vehicles, the cost of flexibility can be minimized by integrating these sectors. Attention should be paid to the fact that these solutions work on short (hours to days) and long (weeks to months) timescales, so solutions with different characteristics should be combined.

Research and Innovation Needs

The energy sector is so complex, the factors shaping the transition so diverse, the risks and possibilities so vast, that computer models are an inevitable tool for understanding many of the decisions that are to be made. At the same time, the current modelling toolbox needs further development. There will be a major challenge at the local, national and trans-national levels to provide scenarios and cross-sectoral analyses which provide cost effective pathways for decarbonization. The impacts of energy markets on the performance and long-term development of the energy system, the impact of policy changes on

[5] Set Plan IWG4 Implementation plan (revision); ETIP SNET Roadmap 2020-2030.
[6] Research Area RA4 of the ETIP SNET Roadmap 2020-2030 – Planning – holistic architectures and assets

markets and the impacts of sector coupling are some examples of important social challenges that could benefit from significant improvements in modelling and simulation.

In previous years, different models have been developed with respect to the long term planning of the energy system. In several European and national projects, long term planning models are combined with more specialized or detailed unit commitment/economic dispatch models, grid interaction models, market models etc. to improve the understanding of the possibilities for the clean energy transition pathways. The Joint Research Centre, driving the development of the TIMES model, is currently developing the POTENCIA model, which assesses policy impacts in member states in a consistent way and will be made available in open-source format. Currently however, the modelling results at national level do not provide sufficiently detailed energy transition models pathways. For instance, it is difficult for national modelling exercises to build on the Clean Planet for All outcomes in a bottom-up exercise using more specialized grid or market models or increased detail in building stock or industrial process data. New techniques for coupling (integrating) computer models need to be investigated, as they may present a flexible alternative to existing multi-sector models.

The CETP may become a strong instrument for connecting bottom-up national modelling exercises to European-level models in order to explore the consistency and feasibility of national strategies. Modelling these national/trans-national pathways consistently with the EU vision is an important challenge which can provide a basis for a futureproof industrial investment strategy, infrastructure investment strategy for utilities, and a robust set of national policies. Models of transition pathways are particularly challenging to develop, as they need to consider the lead time and path dependence of infrastructure development, interdependencies between energy vectors, and the interrelations with investment decisions by market parties and consumers. The models must also enable decisions to be made by the stakeholders and must also support different degrees of autonomy to some extent.

From a research point of view, modelling and simulating complex integrated energy systems is a key challenge for understanding integrated energy systems. There is a large need to develop better knowledge and tools for ensuring interoperability, interaction and compatibility of the different technologies in the system (co-existing renewables and conventional synchronous generation, multi-energy generation, responsive demand, energy storage, active interconnections, etcetera). This scientific challenge is not focused on technical aspects or the physics of energy systems but is aimed at presenting understandable explanations of the technical, economic and policy challenges to energy systems integration. These models are essential for designing regulations, e.g. grid codes, to ensure a safe and reliable operation of the system.

System Operation: Operational Integration of Integrated Energy Systems[7]

Societal Challenge

Tools and systems for the development of the overall energy system control architecture (central and decentralized) and optimal operation need to be integrated between system levels (distribution, transmission and cross-border). They will need to be able to cope with progressively increasing variability and uncertainties. An example is the dynamic operation of large offshore wind power clusters, e.g. for the provision of system services in future low-inertia, converter-based power systems. Particular attention needs to be paid to extreme weather events, as they increasingly affect both the supply and demand sides, while their magnitude varies significantly from year to year. Tools and devices for system monitoring, control and protection need to be improved and their data shared, leveraging the advanced forecasting capabilities in all sectors.

For the electricity sector, the operational challenge is how to maintain system reliability while shifting away from the controllability of thermal power plants to a range of other flexibility options: energy storage (electricity, gas, heating/cooling, water), networks (e.g. applications of FACTS in the electricity

[7] Research Area RA6 of the ETIP SNET Roadmap 2020-2030 – System operation

networks), networks capacity increases, energy storage, sector coupling (electricity, gas, heating, cooling, water, hydrogen, carbon neutral fuels) and energy conversion (P-t-X). Maintaining system reliability is to a large extent a matter of efficiently and effectively integrating all these options in operational control.

Research and Innovation Needs

Flexibility is essential for operating a low-carbon energy system, which is characterized by the intermittency of wind and solar energy. Interactions between conventional generation/regulation methods and renewable generation systems may pose serious operational challenges. For maintaining operational reliability, new devices, algorithms, components, decision support and systems are required that – to a certain extent – operate seamlessly under different conditions and provide a certain autonomy in operation. Artificial intelligence and other aspects of digitalization provide opportunities as well as risks that need to be understood better. Next, these algorithms and components need to be integrated and tested in trial fields. Tools and simulation are required to design these integrated systems, to analyse and to evaluate their benefits and impacts, and to support their field integration. As consumers and energy communities become more flexible while the generation of electricity becomes more variable, a particular question is how electricity balancing mechanisms will need to be adapted.

The operational stability challenge will increase as renewable share grows and conventional electromechanical generators are stopped or replaced with CCS-enabled generators. Therefore, new modelling and simulation techniques are necessary to represent the new phenomena that appeared in power systems as a consequence of the penetration of renewables, e.g. fast power oscillations that seriously threaten the system stability. Such new models should accurately represent new interactions in integrated energy systems such as the interactions between the AC network, meshed DC grids and other energy vectors. Such models should be connected to market simulations (co-simulation) to analyse the reciprocal impact between markets operation and systems operation. This is particularly important when local energy systems (new local operation and markets) are considered.

Governance, Market Design and Regulation of an Integrated Energy System[8]

Societal Challenge

The ultimate goal of market design and regulation for an integrated energy system is to achieve the necessary coordination between all actors and energy vectors to achieve the most cost-efficient and reliable integrated energy system. Therefore, efficient market design needs to reflect all energy vectors and their markets and not be limited to one-sided provision of flexibility (via conversion technologies) towards the electricity vector. A prerequisite for efficient market-based coordination is efficient integration of the different energy markets. A fundamental challenge in this respect is how to internalise expected long-term costs, e.g. of climate change, into the current market design and regulation.

The investment and the operational decisions of market parties, consumers and network operators are to a large extent guided by financial incentives and legal constraints. Therefore, an integrated energy system requires careful reconsideration of these incentives and constraints. Infrastructure development and operation are guided by national, sectoral regulation. (The heat and cooling sector is not regulated at the European level, leading to a very heterogeneous approach to how and whether it is regulated.) This mono-sectoral, national or regional focus needs to be integrated in order to develop the European energy infrastructure of the future. Electricity network development is constrained by permitting, while the transport costs per unit are higher than for gas, but the conversion of power to gas is accompanied by significant energy losses. The challenge of creating an optimal combination of both infrastructures is complicated by the role of national gas: this may be (partially) substituted by hydrogen or similar molecule-based energy vectors, or else continue to be used in combination with CCS and CCU. This

[8] Research Area RA2 of the ETIP SNET Roadmap 2020-2030 – System economics

double challenge can only be addressed through an integrated planning process, supported by integrated energy system models.

The decisions of market parties and consumers, on the other hand, are influenced by the market design, the regulation of CO_2 and other external effects, subsidies (e.g. for renewable as well as fossil energy and for energy storage), network tariffs and congestion management methods, and energy taxes and levees. Market design for an integrated energy system needs to take a holistic approach (as opposed to defining optimal market design for separate energy vectors) and take into account the specifics of different energy vectors in order to achieve cost-effective decarbonisation of the EU economy. To understand the potential effects of policy changes in this area, holistic system modelling is needed. This poses a significant challenge for energy modelling, scenario development, data collection and the involvement of stakeholders and the general public in these analyses.

Research and Innovation Needs

New market designs, and new modes of coordinating the planning of energy networks with the markets, need to be developed to integrate the energy system, from global system level (e.g. integrated gas-electricity network planning by ENTSO-E and ENTSO-G), to local or microgrid level (e.g. local energy communities). An example would be fully integrated markets at a local (district) level – possibly in a form of energy communities – which interact with global electricity and gas markets. Many other variants are thinkable, depending on the criteria (objectives) and system properties, and will have different accompanying business models. The impacts of tariff design, subsidies and taxes on the actors in the energy system should also be considered. The performance of the energy system should not only be evaluated in terms of reliability, economic efficiency and emissions, but, especially in the context of local markets for sector integration, the social aspects for just energy transition also need to be considered.

Market-based sector integration will require innovative regulation to find its way in practice. New and changing roles in the system can be envisioned. Defining a step-wise regulatory and policy roadmap towards the implementation of a well-functioning market design for integrated energy systems will be required. Regulation-free zones and demonstration pilots involving energy communities will be essential for benchmarking innovative tariff schemes and local – regional market concepts.

A different challenge is to develop new market designs and services to innovations such as those of aggregators and digital platforms. Peer to peer services are a development that may provide benefits for the energy system, e.g. with respect to energy balancing and network congestion management. As the technology and governance of the energy sector change, the business models for the different actors, products and services along the entire value chain, i.e. generation, transport, data analytics/mining conversion, storage, metering, delivery, prosumers, energy conservation and use etc., need to be innovated.

New market instruments need to be tested, first in models and then in pilots. The many European member states serve as a natural laboratory for changes to market design and policy instruments. However, because such experiments can be costly, they should be preceded by detailed computer modelling. Energy market models need to be scaled to include the relevant energy vectors and markets, which means that they may need to cover multiple energy vectors, consumer and national markets, cross-border connections, and reflect both the technical and the regulatory complexity. As regulation is the outcome of a political process, it rarely is optimal; therefore, models should also consider robust pathways that 'satisfice' the requirements in a feasible manner, rather than only focusing on a theoretical optimum. Current models can do this only in a limited manner, so much development is required. To test expected policy impacts, agent-based models that simulate the behaviour of the market players, network companies and consumer in relation to the physical systems are needed. While this modelling challenge is substantial, the cost of these models is a fraction of the cost of misguided investment decisions in the energy sector. Participatory modelling, in which the stakeholders are involved from the beginning of the modelling process, can help support the policy making process and improve the social acceptance of the results.

As a second research method, The High-Level Panel of the European Decarbonisation Pathways Initiative advocates the development of 'Transition Super-Labs', which are 'very-large-territory initiatives of real-life management of the transition from typical fossil-fuel-based local economies to zero-carbon ones'[9]. It is apparent that the difficult choices that society needs to make regarding the way in which the energy transition should proceed will be governed by different local parameters into account. Transition super-Labs can serve as a real-life laboratory in which systemic innovation for the transition to a fully decarbonised economy is tested at scale in locations where particularly difficult transition efforts are required.

Consumer Markets, Prosumers and Energy Communities[10]

Societal Challenge

The complex relation of the consumer and prosumer (be it an individual, a community, a commercial user, an industry) with the energy system; is spans from the societal changes characterised by a progressively increase of environmental consciousness that triggers behavioural and process changes, addresses the relationship of the consumer towards energy system technologies and covers the solutions in the hand of the consumer that enable to be an actor in the energy system. In the future energy system, the prosumer plays a central role, influencing the system not only by investment decisions, but also by adapting its behaviour with respect to flexibility and mobility. Industrial flexibility is a key factor in integrating more renewable energy sources in the system. In the residential environment, user comfort is a key factor for driving and adopting innovative technological solutions such as e.g. smart management of building heating systems.

Research and Innovation Needs

Giving the consumer a central role in the energy system requires the set-up of bottom-up demonstration projects which are supported by industrial, commercial and/or residential consumers. A key challenge is to leverage on scalability and replicability of demonstration projects, while still acknowledging the different geographical and social situations in urban environments. In the cross-cutting paper, the research and innovation needs with respect to consumers and energy communities are further elaborated on.

[9] European Commission. 'Final Report of the high-Level Panel of the European Decarbonization Pathways Initiative'. Brussels, 2018.
[10] Research Area RA1 of the ETIP SNET Roadmap 2020-2030 – Consume, prosumer and citizen energy communities

3 Detailed Description of Challenges

The research pathways considered in the missions to address the challenges have been structured along the same line as in the ETIP SNET Roadmap 2020-2030.

3.1 Challenge 1: Develop an Optimal Integrated European Energy System

3.1.1 Mission 1.1: Integrated Energy System Planning – Developing the Seamlessly Integrated Energy System of the Future[11]

This research area addresses the design and planning of the Integrated Energy System overcoming the silos among energy vectors. It considers the necessary approaches and tools to plan and analyse the integrated energy system under all perspectives: from scenario setting based on reliable and transparent hypothesis, parameters and relations down to integrated and complete planning tools, addressing holistically an energy system where all vectors interact and foster one another. Holistic energy system design and analysis facilitates all processes that are necessary for a reliable, economic and environmentally friendly operation of smart electricity systems. It includes:

- Integrated energy system modelling and simulation across all dimensions of Figure 1: From long-term system planning to short-term system stability analysis, across energy vectors, across member state borders, across system levels, and including energy markets and regulation;
- The embrace of uncertainty as a key issue, both in model the system and in policy and investment decisions;
- System planning, considering jointly the development of different types of networks and vectors (electricity, heating&cooling, gas, hydrogen, CO_2, water, transport), considering synergies and mutual efficiency enhancements; planning methods considering cost-effective flexibility means along the value chain (demand response, energy storage, generation, transmission, cross-carrier) as well as resilience under high uncertainties (variable generation) and against natural and human-related threats (single and multiple contingencies);
- The evaluation of the needs for flexibility of all types (generation, storage, demand and the networks) along the entire energy value chain, in consideration of the uncertainties, variabilities and risks;
- Environmental aspects (externalities, Life Cycle Analysis (LCA)), societal and economical evolutions (cost-benefits analysis, Life Cycle Cost (LCC) thinking etc.);
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This holistic approach involves particular challenges to energy system modelling and simulation; Section 3.3 describes these.

3.1.2 Mission 1.2: Operating Integrated Energy Systems[12]

This research area addresses the tools, assets and systems for the development of the overall control architecture (e.g. from hierarchical system control to coordinated collaborative concept, development of the roles of the actors in the system (TSO, DSO, etc.) from direct control to delegation with the subsequent optimal operation of an integrated energy system under progressively increasing variabilities, constraints and uncertainties, also linked with extreme events and climate changes. It spans

[11] The contents of this Sub-mission is derived from the ETIP SNET Roadmap 2020-2030 – Research Area RA4 - PLANNING - HOLISTIC
ARCHITECTURES and ASSETS

[12] The contents of this Sub-mission is derived from the ETIP SNET Roadmap 2020-2030 – Research Area RA6 – SYSTEM OPERATION

across the tools and devices for system observability, through advanced monitoring, control and protection, leveraging the advanced forecasting capabilities in all sectors. It comprises:

- The tools and devices for the system observability (from control architectures to sensors, data management and backup, enabling their filtering, aggregation, condensing and concentration);
- The solutions for safe system operation, protection and control. A particular case is the operational integration of DC grids, which are at more cost-efficient than AC for long distances and at sea as well as for microgrids. The challenge is on the interoperability of hybrid ac-dc networks at all the system levels (HV, MV and LV);
- The solutions for transforming renewable generation units/plants into actual grid forming systems, able to energize and regulate power system integrated by heterogeneous energy sources under arbitrary operating conditions, without relying on operational services provided by fossil-based electromechanical generation plants.
- The operational planning of the energy systems, through scheduling and optimisation of active/reactive power;
- The solutions for system operation that, based on market requests for ancillary services, can automatically provide complex control actions (grid couplings, activation of flexibility services and new market request for replacement of activated services) and advanced control room solutions supporting expanded levels of automation;
- The sciences of forecasting and risk analysis, including generation and load forecasting at different time scales and the consequences and mitigation for errors, the effects of climate changes and extreme events, thus triggering the resilience and remedy actions, comprising threats, vulnerabilities, contingencies, mitigation and restoration;
- Operational dispatch models taking into account different energy vectors.

3.1.3 Mission 1.3: Market Design and Regulation of an Integrated Energy System[13]

To reap on the promises of system integration it is crucial to properly align the market designs of different energy vectors, as opposed to solving exclusively the planning and operational challenges listed above. Market design for an integrated energy system should on the one hand take a holistic approach (as opposed to defining optimal market design for separate energy vectors) and take into account the specifics of different energy vectors so that cost-effective decarbonisation of the EU economy can be achieved.

This research area addresses business models, market design, governance and operation linked with the energy system, its opportunities and constraints. It comprises:

- The design of energy markets at all geographical scales, addressing from the pan-European cross-border wholesale electricity and gas markets, products, services and businesses, down to local, neighbourhood, aggregated, retail, peer-to-peer market of energy products and services (flexibility, ancillary services, electricity, gas and heating/cooling, water etc.), in combination with the European Emission Trade system and other environmental regulations, subsidies and taxes, to ensure optimal financial operational and investment incentives for market parties and consumers;
- The regulation of energy networks should ensure optimal development and operation across borders and energy vectors;

[13] The contents of this Sub-mission is derived from the ETIP SNET Roadmap 2020-2030 – Research Area RA2 – SYSTEM ECONOMICS

- The business models for the different actors, products and services applicable to the energy system (electricity, gas, heating/cooling, hydrogen, CO_2, carbon neutral fuels, water, etc.) along its value chain: generation (e.g. CHP), transport (flexibility), data analytics/mining conversion (efficiency, flexibility), storage, metering, delivery (forecasting, demand response, aggregation), prosumers (aggregation, peer-to-peer, energy communities), conservation (efficiency), use (demand response, flexible energy uses, mobility) etc;

Market and regulatory reform should facilitate optimal operation of the whole, integrated energy system, and not only deal with separate cost-efficiency and reliability gains of individual energy vectors. In theory, this might mean that some energy vectors will achieve a lower level of cost efficiency, if the total system benefits are higher than in the case of separate market design and operational optimization of individual energy vectors.

- The governance of the markets made of European and national acts, policy and regulation, grid rules (for ancillary services, capacity, etc.).

- Digital platforms such as blockchain, IoT and cloud computing may facilitate entirely new types of energy markets. Existing markets mechanisms/technologies may be (partially) replaced by new ones that enable existing and new types of actors to participate. In addition to the challenge of designing these new markets, a question is how mixed, hybrid systems of new services within a traditional market environment should work.

The mission is to create an efficient market-based coordination of integrated energy systems across all relevant timeframes and accompanying regulatory framework.

3.2 Challenge 2: Develop an Integrated Local and Regional Energy Systems

The main challenge at local level will be setting up communities of residential, commercial and industrial consumers, and promote their seamless integration into the energy system. This is not a straightforward mission. One of the main challenges is the unlocking the full potential flexibility, for instance taking into account local boundary conditions of the grid when pursuing national market objectives. Connecting to citizens and prosumers is already a challenge in itself, where improving user comfort and the relationship between consumers and technology is a key factor. Innovative business models can provide the services needed to the consumer and improve the overall system efficiency.

In summary, local demonstration projects are needed where energy communities can unlock the full potential of a consumer-centric energy system. The sub-missions below describe the key factors for successful, scalable and replicable demonstration projects.

3.2.1 Mission 2.1: Consumer, Prosumer and Citizen Energy Community[14]

This research area addresses the complex relation of the consumer and prosumer (be it an individual, a community, a commercial user, or an industry) with the energy system. It addresses:

- The societal changes characterised by a progressively increase of environmental consciousness that triggers behavioural and process changes (sustainable mobility choices, corporate responsibility and transparency, distributed renewables integration, demand response by the user, energy and water conservation measures, neighbourhood comparison and related rewards, etc.);

- The relationship of consumers towards energy system technologies (leveraging early adopters and digital fanatics, looking at the user-friendliness of technologies, smart appliances, prosumer device control, solutions, APPs, market tools etc.);

[14] The contents of this Sub-mission is derived from the ETIP SNET Roadmap 2020-2030 – Research Area RA1 - CONSUMER, PROSUMER AND CITIZEN ENERGY COMMUNITY

- The solutions that allow consumers to be active in the energy system (roles for, and integration of, consumer-owned DER, smart metering, storage, micro CHP, heat pumps, EVs, smart appliances, incentives, dynamic tariffs, etc.), including the questions of privacy and digital security;
- Identification of social strategies that allow end-users and communities to adopt and tackle the ethical and epistemic challenges that arise into local and regional energy systems. Such strategies should allow people and communities to face those threats and risks associated to the local energy systems that affect their quality of life, social well-being and distributive fairness.
- The role of consumer flexibility in energy balancing and security of supply.
- The contribution of energy communities to societal challenges such as energy poverty.
- Development of 'consumer interfaces' – all the ways in which consumers and energy communities interface with the energy system that reflect the interests of consumers, such as environmental values, comfort and community. Gamification, for example, may complement financial incentives.
- Testing new concepts in living labs.

3.2.2 Mission 2.2: Economics, Market Design and Regulation[15]

This research area addresses business models, market design, governance and operation linked with the energy system, its opportunities and constraints, as seen from a regional and local perspective. It comprises:

- The design of local energy markets, considering neighborhood, aggregated, retail, peer-to-peer market of energy products and services (flexibility, ancillary services, electricity, gas and heating/cooling, water etc.), that serve society's broader interests such as security and affordability of energy supply.
- The business models for the different actors, products and services applicable to the local energy system (electricity, gas, heating/cooling, hydrogen, CO_2, neutral fuels, water, etc.) along its value chain: i.e generation (e.g. CHP), transport (flexibility), data analytics/mining conversion (efficiency, flexibility), storage, metering, delivery (forecasting, demand response, aggregation), prosumers (aggregation, peer-to-peer, energy communities) conservation (efficiency), use (demand response, flexible energy uses, mobility) etc;
- The development of services, creating value for the participants in the energy system (i.e. customers - households, commercial - and allowing for participation in the development of local and regional value chains (from investments to customer services): scalable, customisable and replicable solutions from a very local to an interregional level, leveraging synergies by building on digital platforms accounting for security, privacy requirements and trade-offs.
- Regulation of the energy networks: user tariffs and congestion management;
- Regulation of CO_2 and stimulation of renewable energy;
- Development of operational mechanisms and local energy markets based on digital platforms, e.g. by embedding local regulatory aspects in smart contracts, tokenization, settlement and ledgering, considering digital safety and security.

[15] The contents of this Sub-mission is derived from the ETIP SNET Roadmap 2020-2030 – Research Area RA2 – SYSTEM ECONOMICS, with special reference to local aspects, integrated, where appropriate, with specific points from the SetPlan IWG4 implemetation plan (2018)

The relation between these topics is that the market design and regulation strongly affect the business models and the development of services. The research challenges are:

- To develop the entire set of market design, network regulation, regulation of CO_2, support for renewable energy, taxes and other incentives that affect the choices of consumers, network operators and market parties, in such a way that they make efficient low-carbon investment and operational decisions;
- To develop business models and services that optimally fit within these financial incentives;
- To model the effects of proposed changes to the economic incentives in order to support policy development.

3.2.3 Mission 2.3: System Planning and Operation[16]

This research area addresses the design and planning of local integrated energy system overcoming the silos among energy vectors. It considers the necessary approaches and tools to plan and analyse the Integrated Energy System under all perspectives: from scenario setting based on reliable and transparent hypothesis, parameters and relations down to integrated and complete planning tools, addressing holistically an energy system where all vectors interact and foster one another. It includes:

- System planning and operation, considering jointly the development and operation of different types of networks and vectors (electricity, heating & cooling, hydrogen, CO_2, gas, water, transport), considering synergies and mutual efficiency enhancements; planning methods considering cost-effective flexibility means along the value chain (demand response, energy storage, generation, transmission, cross-carrier). This requires the scope of energy models to be expanded to multi-vector socio-economic models. As large computer models have drawbacks such as intransparency and difficulty to validate, a multi-model approach should be investigated in which models are coupled as needed.
- RES integration at regional and local levels, including different energy vectors: develop and demonstrate technologies, systems and solutions that make it possible to efficiently provide, host and utilise high shares of renewables, up to and beyond 100% in the local or regional supply, by following a holistic view on the energy system, linking different energy domains (electricity, heat/cold, gas, mobility) at different scales while considering system, market and organisational aspects, allowing for making optimal use of renewable energy sources and recovered energy.

3.2.4 Mission 2.4: Flexibility[17]

This research area addresses the needs, solutions, and tools to ensure the adequate level of flexibility to cope with all the uncertainties and variabilities of the progressively Integrated Energy System. The flexibility issues addressed in this research area embrace the entire energy system, progressively across the different vectors considered. The area comprises:

- The contribution to flexibility of through generation (improving dynamic response and reserve), transmission/distribution (improving interconnection – meshed/active), demand (responsive and parametric demand), storage (different technologies with different time scale), system operation (higher observability, faster response, predictive, …), advanced management of all

[16] The contents of this Sub-mission is based on the ETIP SNET Roadmap 2020-2030 – Research Area RA4 - PLANNING - HOLISTIC
ARCHITECTURES and ASSETS, with special reference to local aspects, integrated, where appropriate, with specific points from the SetPlan IWG4 implemetation plan (2018)

[17] The contents of this Sub-mission is derived from the ETIP SNET Roadmap 2020-2030 – Research Area RA5 – FLEXIBILITY ENABLERS and SYSTEM FLEXIBILITY, with special reference to local aspects, integrated, where appropriate, with specific points from the SetPlan IWG4 implementation plan (2018)

vectors (electricity, gas, hydrogen, heating/cooling, water) in order to manage variability and contributing to system efficiency and reliability;

- The methodologies, tools and technologies that facilitate prosumers, whether or not organized in local energy communities, to operate multi-dimensional energy systems that optimally integrate regional infrastructures and facilities, thus enabling them to contribute actively to the energy markets and to the resilience, stability and flexibility of the overall system.
- The intrinsic networks flexibility: leveraging the capabilities of electric/gas networks, including the contribution of energy storage in all forms (e.g. electrochemical, thermal, etc.) and their conversion (P-t-X, X-t-P etc.) to enhance network flexibility;
- The combined flexibility options enabling grid operators, as well as aggregators/balancing parties to make optimal use of the flexibility resources, for example, cells with all kinds, sizes and variability/controllability of networks elements, combined with energy generation, demand and conversion to and from non-electricity energy carriers (energy vector coupling);
- With special reference to DHC networks: flexibility can be obtained through technologies, systems and solutions able to minimise the mismatch between the load and supply profiles of alternative heat sources (incl. power-to-heat), reducing the use of fossil fuels in peak load and winter times and avoiding supply competition in summer times. These solutions may increase the short (hours to days) and long (weeks to months) term flexibility of district heating networks, improve the costs–benefit ratio of storage options and/ or improve the customer side integration in case of building side flexibility options.

3.3 Challenge 3: Modelling Integrated Energy Systems and Clean Energy Transition Pathways

The mission is to provide consistent, realistic, secure and cost-effective pathways for the energy transition at the local, national and trans-national levels. From a research point of view, modelling and simulating complex integrated energy systems is a key challenge for understanding integrated energy systems, since the knowledge and tools that we have today are not enough to ensure proper interoperability, interaction and compatibility of the different technologies in the system. This scientific challenge is aimed at presenting understandable explanations of the technical, economic and policy challenges to energy systems integration. This challenge also requires better embedding of modelling into society's decision-making processes by including stakeholders from the beginning, e.g. through participatory modelling. Joint scenario development (e.g. with Delphi techniques) also should be part of this, as models can help stakeholders develop future scenarios, while scenarios are in turn inputs to computer models.

Regional, national or transnational modelling exercises including detailed bottom-up information need to be performed to be connected to the European modelling results such as the 'Clean Planet for All' study. The modelling tools used in these long term clean energy transition pathways can include a variety of models with different functionalities such as long term techno-economic planning models, policy impact models, market models, generation adequacy, dispatch or security of supply models including several energy vectors, or a combination of these models to include the most possible detail in bottom-up data sources and scenarios. New techniques for coupling (integrating) computer models need to be investigated, as they may present a flexible alternative to existing multi-sector models.

The CETP can be used to combine the full detail in local national data sources with respect to building stock, mobility, industry etc. and combine this with the most state-of-the art models. The results of these modelling exercises can be compared to more top-down studies at European level or even feed into those studies. To reach these objectives, existing modelling tools need to be further developed, as the current generation of available models is not yet up to this challenge. Access to detailed local energy data will be key.

As a concrete example, the CETP could be an instrument for member states to connect their national policy projection exercises, for instance by sharing and connecting energy models, data, goals, scenarios and assumptions. Such shared national-European model-based analyses could greatly improve the consistency and quantitative detail of the analytical basis of the national energy and climate plans. A solid model-supported basis of clean energy transition pathways that is supported by national stakeholders can in turn improve the investment climate in industrial sectors. The abovementioned objectives are challenging and require the implementation and development of modelling tools which are able to provide cross-border, cross-energy vector and long term analysis of the required investments of the energy system, in combination with advanced security of supply models with a high temporal and geographical resolution.

With respect to interaction with other partnerships and instruments, the work programme of the Horizon Europe cluster 5 does not yet seem to address the challenges set out in this mission, and the CETP would be the ideal bridge between national and European modelling exercises.