European Commission

LOW CARBON ENERGY OBSERVATORY

CLEAN ENERGY TECHNOLOGY SYNERGIES AND ISSUES

Joint Research Centre

EUR 30006 EN

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Contents

Foreword

The LCEO is an Administrative Arrangement being executed by DG-JRC for DG-RTD, to provide top-class data, analysis and intelligence on developments in low carbon energy supply technologies. Its reports give a neutral assessment on the state of the art, identification of development trends and market barriers, as well as best practices regarding use private and public funds and policy measures. The LCEO started in April 2015 and runs to 2020.

Which technologies does it cover?

- Wind Energy
- Photovoltaics
- Solar Thermal Electricity
- Solar Thermal Heating and Cooling
- Ocean Energy
- Geothermal Energy
- Hydropower
- Heat and Power from Biomass
- Carbon Capture, Utilisation and Storage
- Sustainable advanced biofuels
- Battery Storage
- Advanced Alternative Fuels

In addition, the LCEO monitors future emerging concepts relevant to these technologies.

How is the analysis done?

JRC experts use a broad range of sources to ensure a robust analysis. This includes data and results from EU-funded projects, from selected international, national and regional projects and from patents filings. External experts may also be contacted on specific topics. The project also uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050.

What are the main deliverables?

The project produces the following generic reports:

- Technology Development Reports for each technology sector
- Technology Market Reports for each technology sector
- Report on Synergies for Clean Energy Technologies
- Annual Report on Future and Emerging Technologies (information is also systematically updated and disseminated on the online FET Database).

Techno-economic modelling results are also made available via dedicated review reports of global energy scenarios and of EU deployment scenarios.

How to access the deliverables

Commission staff can access all reports on the Connected LCEO page. These are restricted to internal distribution as they may contain confidential information and/or assessments intended for in-house use only. Redacted versions also be distributed publicly on the SETIS website.

Acknowledgements

The following authors contributed to this report:

Chapter	Author(s)
3. R&D initiatives	Carlsson J
4. National/international projects	Carlsson J, Uihlein A
5. Modelling	Nijs W, Ruiz Castello P
6. Grid support services using LCEO technologies	Carrara, S., Kapetaki Z, Kougias I, Magagna D, Miranda Barbosa E, O'Connell A, Padella M, Prussi M, Scarlat N, Taylor N, Uihlein A, Vazquez Hernandez C
7. R&D synergies	Chondrogiannis S, Kapetaki Z, Kougias I, Jakubcionis M, Magagna D, Miranda Barbosa E, O'Connell A, Padella M, Scarlat N, Shortall R, Taylor N, Telsnig T, Uihlein A, Vazquez Hernandez C
8. Conclusions and future R&D directions	Carlsson J, Kapetaki Z, Kougias I, Jakubcionis M, Magana D, Miranda Barbosa E, O'Connell A, Nijs W, Padella M, Ruiz Castello P, Scarlat N, Shortall R, Taylor N, Telsnig T, Uihlein A, Vazquez Hernandez C

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Abstract

The objective of this report is to provide recommendations for long-term R&D priorities for crosscutting EC funded projects in the energy domain. Nineteen JRC experts analysed synergies and issues of the future energy system in following areas:

- objectives of Horizon 2020 projects were compared with national and international projects;
- key energy technologies for a cost-effective energy transition using the energy system model JRC-EU-TIMES;
- development trends of LCEO technologies with regard to their potential to provide grid support services; and
- R&D synergies between LCEO technologies to accelerate development and use research budgets efficiently.

1 Introduction

The EU energy system is going through a major transformation with the objective to become sustainable, secure, competitive, and climate neutral by 2050.

Variable renewable energy (VRE) sources like wind and solar are expected to contribute with the largest capacity growth and move to the centre of energy supply, thus balancing electricity supply and demand will become more challenging. In addition, decentralised generation requires new grid structures that can handle multidirectional flows of energy. The cost of reaching high shares of variable renewables will depend on the composition of the energy system. Costs will be influenced by potential synergies and issues between production technologies of the energy system, the needs for grid reinforcements or flexible power, curtailment of variable renewables, demand response uptake etc.

The approach chosen to introduce and operate VREs in the energy system is important. The cost-effectiveness of the total energy system is not only about installing the cheapest technologies or building variable renewable power plants (e.g. wind) where the resources are best. Optimising the mix of VREs can bring synergies, e.g. where sunny and windy periods are complementary. By locating variable renewable plants strategically, aggregate variability and costs for transmission and distribution can be reduced, e.g. rooftop PV in a city can be more cost-effective than distant large-scale PV even if generation costs for rooftop systems are higher. Such factors are of high importance to achieving the Energy Union objectives: the delivery of security of supply, a transition to a sustainable energy system with reduced greenhouse gas emissions, industrial development leading to growth and jobs and lower energy costs for the EU economy. In particular, synergies may accelerate growth of low carbon technologies and optimise the investments needed, both in terms of the technologies themselves, the grid infrastructure improvements, additional storage, load management strategies, new market mechanisms etc.

The transformation of the energy system requires a diverse and affordable portfolio of low carbon energy supply technologies. There are several initiatives on-going and at European level the SET-Plan[1] provides coordination. Most technologies analysed within the LCEO can contribute to the mitigation of issues related to large deployment of VRE in the future energy system. For example, hydropower and bioenergy provide flexible low carbon power generation that can be help balance the grid. New wind and solar PV can be designed or operated as to reduce variability, for instance in the case of wind power plants by optimising the design for a different wind speeds. The combination of VRE technology and energy carrier can also be used for storage/load balancing. For example excess wind or PV energy can be used to produce hydrogen using an electrolyser, which later produces electricity in fuel cells when VRE production is low or can be used as feedstock in industrial processes that otherwise use hydrogen produced using fossil fuels.

The LCEO project distinguishes crosscutting energy research areas as either trans-technology (within the power system) or cross-sectorial. Trans-technology aspects were analysed in a previous report in 2017 (D2.4). This report (D2.6) analyses both trans-technology and cross-sectorial aspects, although the focus is still on the former. The analysis includes the transport and heating and cooling sectors, as well as smart city concepts.

This report has the following structure: Section 2 presents the methodology and data sources used in the analyses; Section 3 analyses the H2020 projects in terms of their objectives and main outcomes. Section 4 research priorities of major national and international projects inside and outside Europe. Section 5 presents synergies and issues based on results from energy system modelling using JRC-EU-TIMES. Section 6 presents how expected technology development of LCEO technologies could help providing grid support services. R&D synergies between LCEO technologies are identified in Section 7. Finally, recommendations for future research priorities are presented in Section 8.

2 Methodologies and data sources used

The main objective of this report is identifying future long-term R&D areas for H2020 projects. The following methods and data sources were used to achieve that objective.

R&D initiatives

H2020 projects

The Compass database was used to identify projects. The screening was performed by searching for keywords related to trans-technology and cross-sectorial topics or combinations of technologies, e.g. 'load balancing', 'solar'&'wind', or 'smart cities'. From the project summaries information about objectives of projects, expected outcomes, and the combinations of technologies treated per project was gathered. All projects might not have been identified with this approach. Nevertheless, we are confident that a sufficient number of representative projects were identified to draw conclusions for the purpose of the study.

Fusion charts were used to map interrelations between projects, technologies treated, and their objectives. This allowed concluding about which combinations of technologies that are more common, which technologies that pursue R&D synergies in projects etc.

The keywords seen in the table below were used to examine the scope of the identified projects.

Table 1. Key words used to identify the scope of identified EU projects. Synonyms or related keywords in italics were combined.

Purpose					
Flexibility	Integration	Hybrid system	Demonstration	Pathways	Regulation
Innovation	Energy policy	Circular economy	Standardisation	Governance	
Low carbon technologies					
Solar	Wind	Ocean	Bioenergy	Geothermal	Hydro
Facilitators					
Smart grids	ICT	Storage			
Sectors					
Water	Food	Heating	Transport	Industry	Agriculture
Cities					
Content					
Model	Socio-economic	Cost-Benefit Analysis	Business model		

International and national projects

We searched information about national and international projects on the internet, e.g. websites of well-known research organisations and universities, in particular related to renewable system integration. Primarily, the analysis concerned the scope and objectives of trans-technology and cross-sectorial projects when publicly available. Similarly, projects of international organisations addressing research on integration of renewables analysed were analysed, e.g. IEA, IRENA.

Modelling

The project uses the JRC-EU-TIMES energy system model to explore the impact of technology and market developments on future scenarios up to 2050. These scenarios help inform decision makers on the technology choices through which the EU can meet its climate and energy goals under different global energy scenarios, thereby supporting the accelerated development and deployment of low carbon technologies. The methodology of the modelling is described in [2]

LCEO technologies from trans-technology perspective

This section describes how LCEO technologies can perform grid support services and thereby mitigate issues in the future energy system, e.g. how new operating practises could mitigate issues. Future R&D areas contributing to mitigation of such issues are identified per LCEO technology.

R&D synergies between LCEO technologies and neighbouring sectors, e.g. transport, heat

The project members identified R&D synergies between LCEO technologies by discussing and analysing potential similarities. Four groups were created where most R&D synergies were expected:

- flexible technologies;
- variable technologies;
- heating and cooling technologies;
- power to fuels.

Discussions were held between experts in those groups. Only R&D synergies with significant positive impact to the deployment of two or more technologies and potential to save research budget were considered relevant. The potential cost savings in terms of research budget were not assessed.

Suggestions for future R&D priorities

Chapter 8 makes recommendations on long-term R&D topics of future trans-technology and cross-sectorial projects.

3 R&D initiatives

In order to explain the EC research framework, this chapter begins with an introduction of the Integrated Roadmap of the SET-Plan with particular focus on actions IV (resilience & security of energy system), which align well with the scope of this report.

Then EC-funded R&D projects, national and international projects are analysed. The objectives of the EC-projects are compared with objectives of national and international projects in Section 4.

3.1 EU co-funded projects

Integrated Roadmap of the SET-Plan

The formulation of the energy challenge under Horizon 2020 was based on the SET-Plan. The Integrated roadmap of the SET-Plan consolidates the updated technology roadmaps of the European Industrial Initiatives [1]. It proposes ten research and innovation actions to accelerate the energy system's transformation and facilitate integration, see third column of Figure 1. The key actions are pursued along four axes: (1) innovation chain, (2) value chain, (3) EU dimension, and (4) the energy system. For each axis, a set of challenges and actions were agreed by the SET-Plan stakeholders.

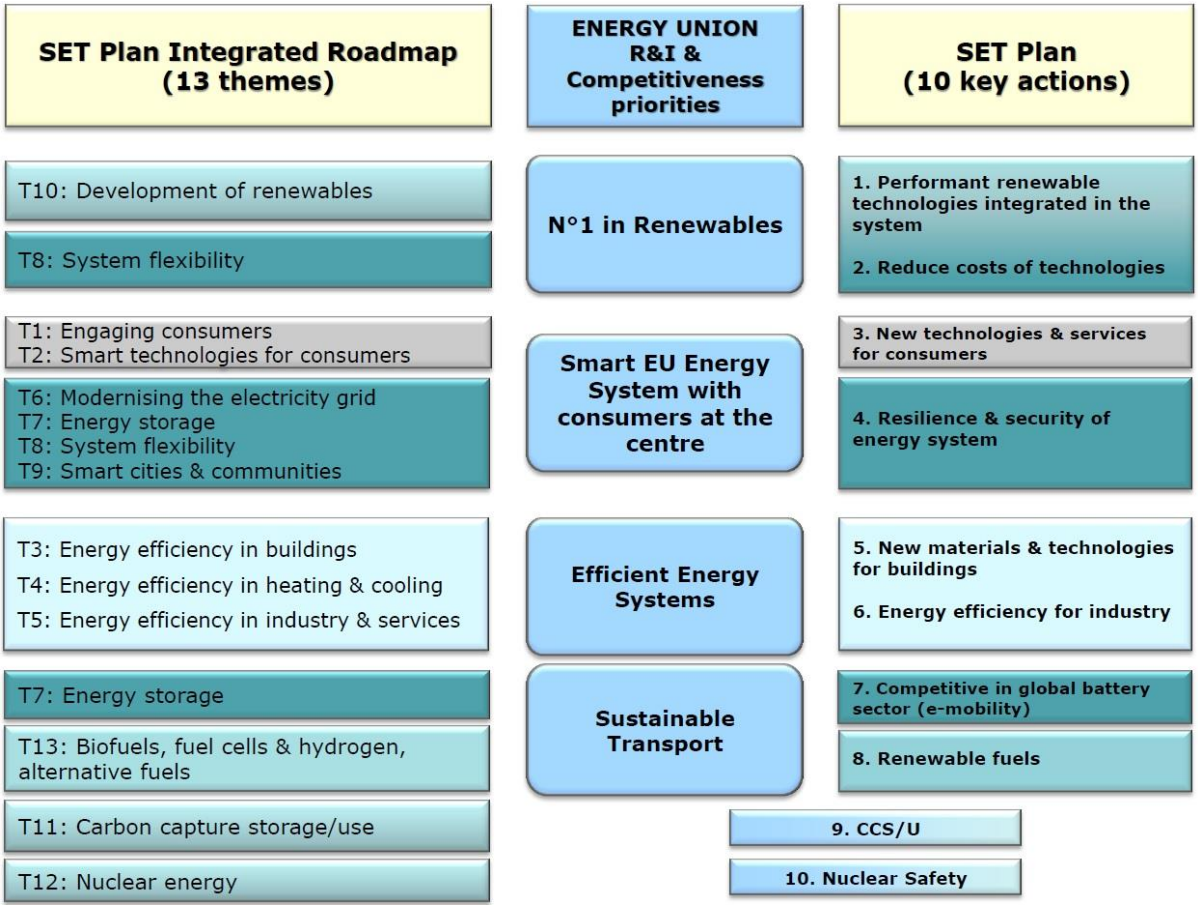


Figure 1. Ten actions of integrated SET-Plan. [1]

Action 4 of the Integrated roadmap of the SET-Plan [1] describes the research and innovation actions with regard to resilience and security of the energy system. Its overarching goals are to develop and operate energy systems with an appropriate level of resilience, reliability, leveraging the use and integration variable renewables. The targets formulated are:

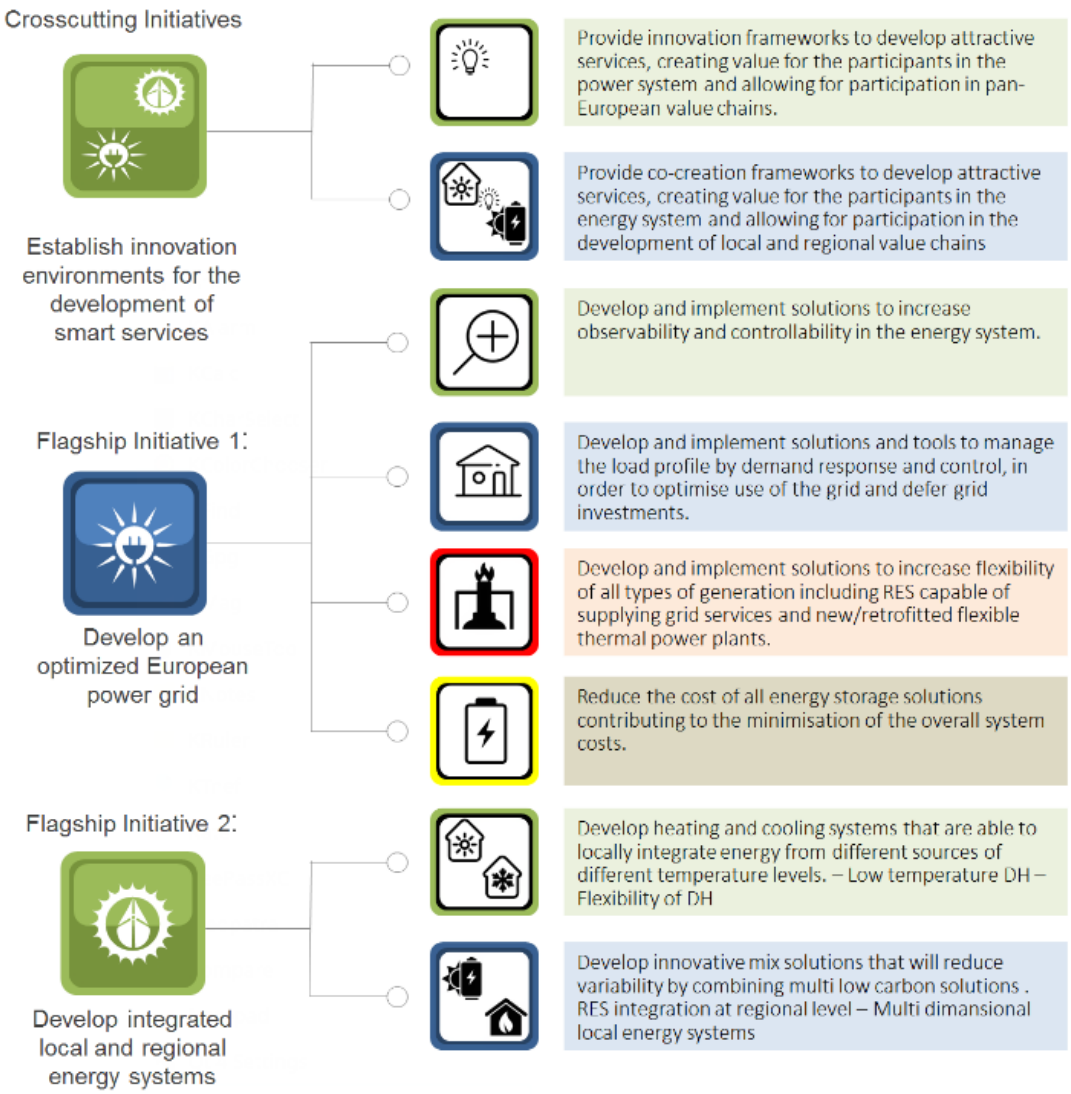


Figure 2. Targets formulated under Action IV of the Integrated roadmap. [1]

Similarly, the SET-Plan states that flexibility in the energy system can be obtained from centralised and decentralised thermal power generation technologies, including CHP, sector regulation, market design, empowerment and integration of end-users etc. Innovation environments to develop smart services for local and regional energy systems are also needed.

Based on the indications from the European Technology & Innovation Platforms (ETIP), the programmes of recent ERANETs, and the benchmarks and planning related to mission innovation, the following budgetary indications for energy research are given: [3]

- EUR 100 million/year for RD&I on crosscutting activities – usage of digitalisation, new regulatory and market approaches and the concepts of living labs;
- EUR 350 million/year for RD&I activities on Flagship initiative 1 – develop an optimised European power grid that enables appropriate level of reliability, resilience and energy efficiency, while integrating variable renewables;

- EUR 250 million/year for RD&I activities on Flagship initiative 2 – develop integrated local and regional energy systems that make it possible to efficiently provide, host and utilise high shares of renewables;

The shares of budgetary indications are compared with spending on crosscutting R&D components in H2020 projects in the following section.

H2020

Horizon 2020 is the biggest EU research and innovation programme with nearly EUR 80 billion of EC funding during 7 years (2014-2020). From this, EUR 5.9 billion is allocated to energy research. This report identified 86 projects with a total budget of EUR 623 million with significant crosscutting (trans-technology and/or cross-sectorial) components, see Table 2. Most projects (EUR 470 million) were funded in the call of the H2020 Competitive low carbon economy. [4]

Table 2. H2020 work programme funding of projects with focus on crosscutting aspects as of April 2019.

Research work programme	No. energy projects identified as trans-technology or cross-sectorial	Total budget (EUR million)
Competitive low carbon economy (H2020-LCE)	61	470
Growing a low carbon, resource efficiency economy with a sustainable supply of raw materials (H2020-SC)	11	33
Digital solutions for water: linking the physical and digital world for water solutions (H2020-WATER)	4	16
Waste: a resource and to recycle, reuse and recover raw materials (H2020-WASTE)	2	17
Smart and sustainable cities (H2020-SCC)	6	71
SME instrument (H2020-SMEINST)	1	15
Energy efficiency call (H2020-EE)	1	1.7
Total	86	623

The number of projects with specific R&D components (keywords) and their budgets can be seen in Table 3. The main R&D components per project were determined from their description in COMPASS. Equal shares of the budget were allocated to each R&D component. For example, five R&D components were assigned to the SABINA[1] project, meaning that 1/5 of the project budget was allocated to the keywords heating, smart grids, storage, power-to-heat, and ICT. The R&D components with the largest allocated budget are demonstration, followed by Model and Smart grid.

Table 3. Major components/keywords of research topics for crosscutting research projects as of April 2019.

	Number of projects	Budget [EUR million]
Demonstration	34	63
Model	41	60
Smart grid	27	52
Integration	34	47
Storage	26	46
ICT / digitalisation	25	40
Flexibility	21	39
Transport	15	30
Heating	17	21
Innovation	16	20

Figure 3 displays a fusion map, where the blue dots represent the H2020 projects and the yellow dots the R&D components. The size of a blue dot is proportional to the budget of a project, whereas the size of a

[1] SmArt BI-directional multi eNergy gAteway

yellow dot (research topics) is proportional to the number of interconnections with other projects. The fusion map shows how R&D components are clustered, in other words if they often occur together in projects.

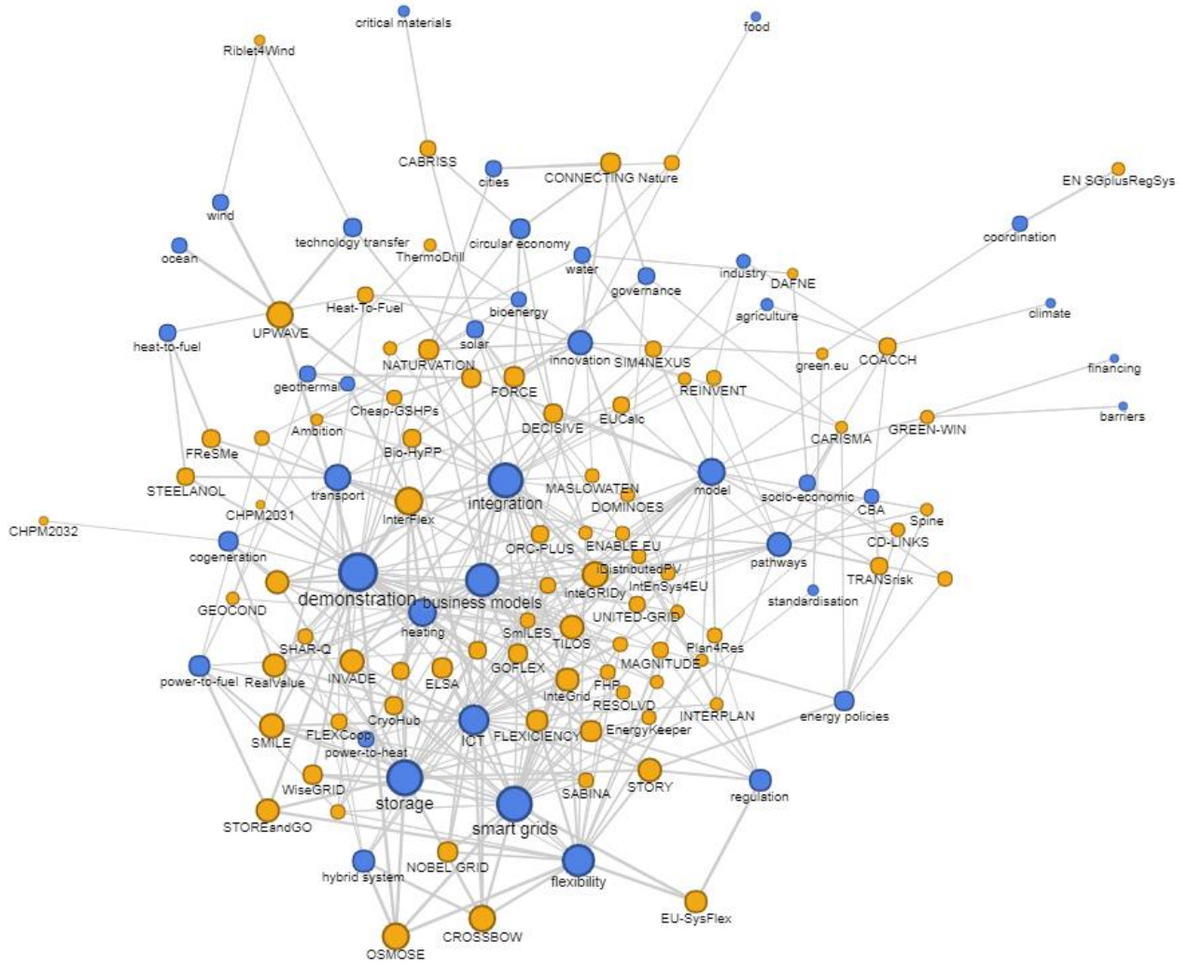


Figure 3. Interconnections between H2020 projects and their R&D components. The sizes of blue circles illustrate amount of funding to a R&D component whereas the sizes of yellow circles illustrate the number of interconnections.

From analysing Table 3 and Figure 3, it can be noted:

- the largest cluster of blue dots (H2020 projects) concerns Integration, Business models, Demonstration, and Heating and Transport. Based on the methodology explained above, it is estimated that it received about EUR 200 million in H2020 until April 2019; This cluster have similar profile as the Flagship initiative 2 of ETIP with integration of energy sectors and demonstrations at local level.
- the second largest cluster relates to R&D components on Flexibility, ICT, Smart grids and Storage, which is estimated to receive about EUR 180 million until April 2019. This cluster resembles the Flagship initiative 1 of ETIP with the aim of creating a stable and secure power grid that allows integration of variable renewables.
- the third largest cluster encompasses models, Cost-Benefit Analyses, socio-economics, pathways, and standardisation. It accounts for about EUR 60 million. The societal aspects (e.g. job creation) and economic aspects are pronounced in these projects.
- The individual projects with the largest amount of funding (>EUR 15 million) usually involves demonstration of a technology, e.g. smart grids with other technologies, or integration across sectors.

The two largest clusters identified compare well in terms of content with the two Flagship projects of ETIP. A similar match in scope is less evident for the crosscutting topic of ETIP, although the third largest cluster of H2020 projects have some similarities.

4 National projects

National projects on trans-technology or cross-sectorial (cross-cutting) topics relevant to this report were analysed. The aim was to collect novel ideas for future research areas of H2020 projects. Only projects with an innovative or different approach from the H2020 are listed in Section 4. Other projects are listed in Annex II.

4.1 Europe

4.1.1 Germany

The main funding body for energy research on federal level is the Federal Ministry for Economic Affairs and Energy (BMWi). Assistance is aimed primarily at technologies that meet the requirements of the energy transition, e.g. energy efficiency and renewable energy.[2]

During the 6th Energy Research Programme, funding of about EUR 5 billion was awarded from 2012-2017 [5]. The important projects concerned individual technologies (such as wind, solar, H_2, fuel cells) and energy efficiency (in industry, services, and buildings). Another main area was energy system analysis and cross-technological research, for example:

- "P2X" aims at chemical storage of electricity during power peaks through electrolysis. H_2 and synthesis gas will be produced and the project will assess how the synthetic gas can be converted to chemicals later.
- "Carbon2Chem", consists of major companies from chemical, steel, energy and automotive sectors and will reduce emissions from the steel industry. The gases from the steelmaking process will be used as a raw material for chemical production.
- "SynErgie" is helping to make energy demand of industry more flexible in order to align electricity use with volatile supply. Technological possibilities for flexibility are identified and demonstrated. Energy intensive processes will be managed intelligently and automatically so that electricity networks will be stabilised and larger share of renewables can be accommodated.

4.1.2 UK

Important British projects identified containing components from cross-cutting topics:

Energy systems at multiple scales of UKERC

The UKERC programme on Energy Systems at Multiple Scales addresses the challenges from introducing VRE. The solutions studied are e.g. greater use of demand side management and storage for balancing, expansion of continental networks, and sharing of reserve facilities between greater numbers of users. It especially studies the impact of wind variability on the gas system and the potential for demand side and interconnector contributions to system balancing; [6].

Multi-energy vector integration innovation opportunities of CATAPULT Energy Systems[3]

The project assesses the challenges and opportunities for SMEs to exploit their skills, capabilities and assets to enable a future multi-vector energy system. It aims to provide an understanding of where the opportunities arise from increased multi-energy vector integration. A methodological approach was adopted which included a landscape review, stakeholder engagement activity and analysis of three multi-vector case studies.[7]

Smart City – Intelligent energy integration for London's decentralised energy projects [8]

The objective of this project is to understand and demonstrate the role that smart systems in decentralised energy production, transmission and distribution in London and the management of energy demand. It concerns an urban energy system capable of heat storage, electricity demand-side management and active network management providing electricity generating capacity when required to support the electricity distribution network. It also considers how intelligent energy systems might evolve in London until 2050, the

[2] https://www.bmwi.de/Redaktion/EN/Artikel/Energy/research-for-an-ecological-reliable-and-affordable-power-supply.html

key technologies that would be deployed, and the organisational structure and key actors required supporting an intelligent and integrated energy system.

4.1.3 France

Smart Buildings as nodes of Smart Grids (SBnodesSG)

This project aims to explore the potential of smart buildings as "smart nodes" within smart grids. In the SBnodesSG, the buildings will become active participants in the energy ecosystem, beyond the simple service to the smart grid. They will both optimise individually and collectively in real-time interaction with the occupants and become the nodes of the new smart grid, especially electrical networks, heat or gas networks. The project also aims at optimising the energy consumption of information technologies. Carbon-free local production (e.g. solar PV) will be added to the buildings.[9]

Micro-réseau électrique intelligent (microgrid) intégré au bâtiment

The AC and DC microgrids are studied as a mean to integrate more renewable energy sources in the public grid. A systemic approach is adopted to study the interfaces and controls adapted to each mode of operation and specific intermittent aspects. The system proposed uses a prosumer incorporating solar PV, storage, grid connection and loads. The microgrid incorporates vehicle-to-grid, vehicle-to-home, and infrastructure-to-home strategies, and thus offers new services in the urban space. [10]

Ecotechn'hom [11]

This project aims to develop a synergistic, technological and sustainable management of industrial sites harmonised with its territorial and urban environment in collaboration with various network managers (electricity, gas, water, heat, transport, ICT).

This includes the creation of circular and aggregated management of energy, waste and transport between the entities of the site, and complementary entities to integrate for more synergies, e.g. storage, as well as changing behaviours by awareness-raising actions.

The objective of the project is to reduce the energy bill of the industrial site by 20% in 3 years and 50% in 10 years. Then the know-how developed should be transferred to 10 other industrial sites in the next five years.

4.1.4 Sweden

Renewable energy supply and storage: Guide for planners and developers in sparsely populated areas [12]

Aims at helping small communities to overcome the challenges associated with implementing renewable energy systems. The guide provides information about how to develop affordable, and reliable, renewable energy projects, using off-the-shelf technologies. The guide is designed to be highly adaptable, and it provides formulas for calculating the costs and benefits of particular energy and heating systems based on the need for the community. It answers questions like if it is better to store energy in insulated water tanks or in electricity batteries.

4.1.5 Denmark

Flex4RES [13]

Flex4RES will demonstrate how high shares of variable renewable energy can be efficiently integrated into the energy system through a stronger coupling of energy markets across Nordic and Baltic regions. It investigates how an intensified interaction between coupled energy markets, supported by coherent regulatory frameworks, can facilitate the integration of high shares of VRE, in turn ensuring stable, sustainable and cost-efficient Nordic energy systems.

[3] Not-for-profit centre of excellence that help to identify and address innovation priorities and market barriers, in order to decarbonise the energy system at the lowest cost. Among its objectives are: to create demand pull for energy system innovation by removing barriers and open markets, to support UK innovators to test and commercialise new processes, products, services.

4.2 Projects outside EU

4.2.1 USA

Energy Systems Integration Facility of NREL (National Renewable Energy Laboratory) [14]

NREL has the Energy Systems Integration Facility which has the following capabilities:

- mega-watt scale power hardware-in-the-loop simulation capability to test grid scenarios with high penetration of renewable energy;
- interconnectivity to external field sites for data feeds and model validation;
- virtual utility operations centre;
- smart grid testing lab for advanced communications control;
- multiple parallel alternating and direct current experimental busses with grid simulations and loads.

NREL also has renewable resource management and forecasting research which focuses on measuring weather resources and power systems, and converting these into operational intelligence. In the coming years they will further expand simulations on high-performance computers of the power system, which enable evaluation of large deployments of new technologies and control systems across cities and larger regions.

The Cities Leading Through Energy Analysis and Planning (Cities-LEAP) of US DOE [15]

The project delivers standardised, localised energy data and analysis that enables cities to lead clean energy innovation and integrate strategic energy analysis into decision making. The project allows cities to:

- set climate and energy goals;
- prioritise and implement energy strategies;
- see impacts of potential climate and energy action plans;
- learn from peers about city energy planning best practices;
- get access to credible data and transparent, usable analytic methodologies;
- make data-driven energy decisions.

Three teams led by local governments have been selected to develop and pilot data-driven decision frameworks. The frameworks are developed together with academic institutions, technology companies, utilities, regional planning bodies, and non-governmental organisations.

4.3 International projects

IEA

The IEA does work on system integration of renewables. Several reports were published on this topic, e.g. (1) "Re-powering markets" which analyses the market framework for low-carbon power systems and the balance that policy makers must strike between supporting innovation and competition while at the same time mobilising capital, (2) "Status report of power system transformation 2018" provides an overview of how power plants provides flexibility and improves energy security. In addition, the IEA Technology Collaboration Programmes (TCPs) promote collaboration between the participating countries and organisations on research and innovation topics. System synergies fool under horizontal groups such as the Energy Technology Systems Analysis (ETSAP TCP) programme as well as horizontal end use programmes (for buildings, industry and electricity and for individual renewable technology areas). Recently a report on Digitalisation was published too, which also covers integration aspects.

5 Insights from energy system's modelling

This chapter presents insights on the potential success of different technologies by using a two-step approach. The first step captures the influence of global developments on EU technology choices through external global energy deployment scenarios and their effect on investment costs based on learning effects. This step is described in [2] and in [16]. The second step is an analysis of the EU energy system up to 2060 with normative climate and energy related targets. This analysis identifies key technologies in terms of deployment within the EU. Technologies with a high deployment across the scenarios that require high additional investments compared to a baseline scenario are considered as key enabling technologies for R&D.

The scenarios analysis with JRC-EU-TIMES is normative with respect to the overall climate and energy policy goals but exploratory for technology choices. In other words, the cheapest technology portfolio is calculated for given boundaries of the system. With the given assumptions on technology evolution and techno-economic parameters, a future will be projected that respects these boundaries and timelines, forcing technologies to be deployed. The techno-economic parameters implicitly take into account the technologies readiness.

5.1 Scenario definition

In-house scenarios have been developed with the JRC-EU-TIMES model to explore energy prospects within the EU. A wealth of scenarios has been produced in the framework of LCEO, but only these four are considered.

- **Baseline:** it is a "business-as-usual" scenario which does not envision any dedicated efforts aimed at stabilising the atmospheric concentration of GHGs. In this scenario, the EU is assumed to reduce its energy-related CO_2 emissions by 48% by 2050 with respect to 1990, as in the EU Reference Scenario 2016 [17]
- **Diversified:** this is a mitigation scenario where all known supply, efficiency and mitigation options (including nuclear and Carbon Capture and Storage, CCS) are deployed in order to achieve a long-term temperature increase lower than 2°C. In the EU, this corresponds to an 80%-reduction of CO_2 emissions in 2050 with respect to 1990.
- **ProRes:** this scenario achieves the same long-term climate targets as the previous one, but with a stronger focus on renewables, as nuclear is phased out and CCS is not deployed (however, Carbon Utilisation technologies are allowed, the main of which is the production of diesel/kerosene by combining hydrogen and CO_2).
- **ZeroCarbon**: this scenario has the same main technological assumption as Diversified, but the decarbonisation effort is taken to 100%-reduction of CO_2 emissions in 2050 with respect to 1990. In terms of scenario design, this scenario is very comparable to the scenario EC 2050 LTS 1.5TECH. [18] The ZeroCarbon scenario results share the large amounts of RES with the ProRES scenario, as a consequence of the higher reduction of CO_2 and because the underground CO_2 storage is limited to 300 Mt/year.

Table 4. LCEO Scenario definition in JRC-EU-TIMES.

Scenario	CO_2 2050	Nuclear lifetime extension	New nuclear	CO_2 storage under the ground	CO_2 storage in materials	CO_2 reuse
Baseline	-46%	YES	YES	YES	NO	YES
Diversified (or Div1)	-80%	YES	YES	YES	NO	YES
ProRes (or Res1)	-80%	YES	NO	NO	NO	YES
Zero Carbon	-100%	YES	YES	YES < 300 Mt/yr	YES < 100 Mt/yr	YES

5.2 Insights from CO_2 flows

The CO_2 flows are a first step to better understand technology interaction. Sectors reduce CO_2 in different ways and results differ also based on the level of ambition. Increased GHG reduction ambition brings new technology choices or needs.

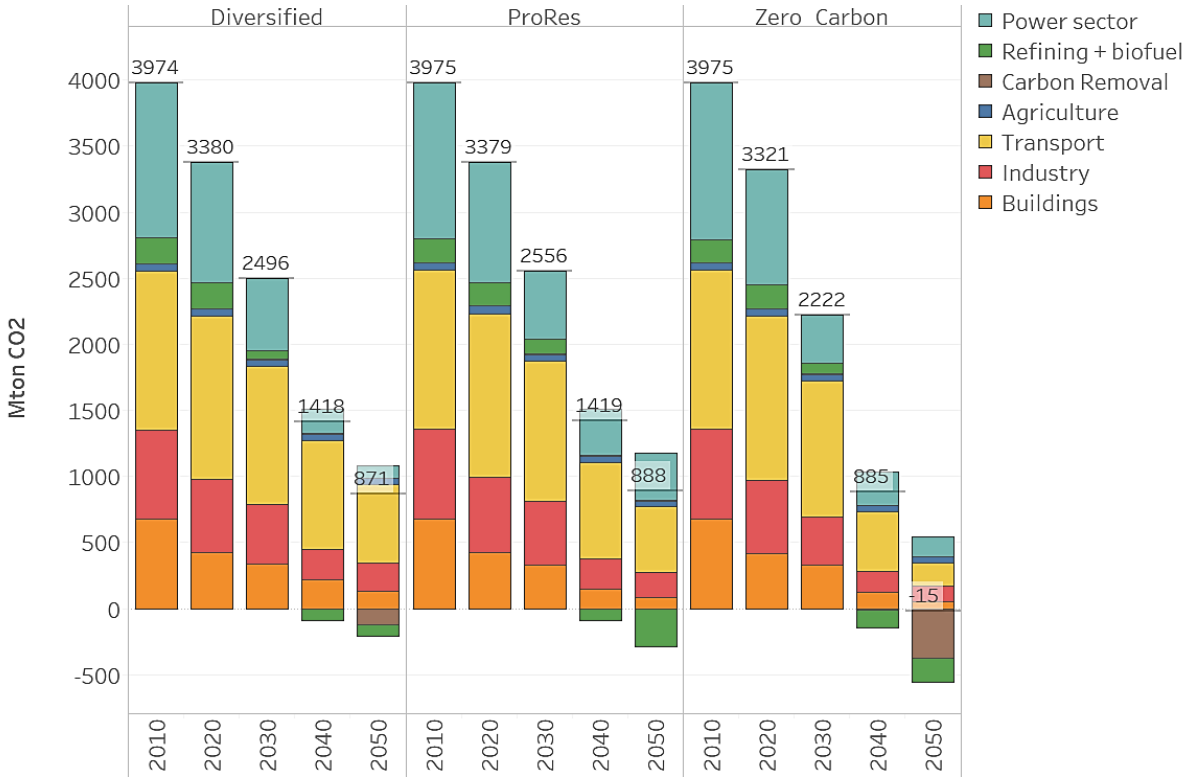


Figure 4. Evolution of total energy related CO_2 in the EU energy system, per sector.

Based on the insights from Figure 4, Figure 5 and

we conclude:

In a Diversified EU that decarbonises by using all technology options, including CCS and nuclear power

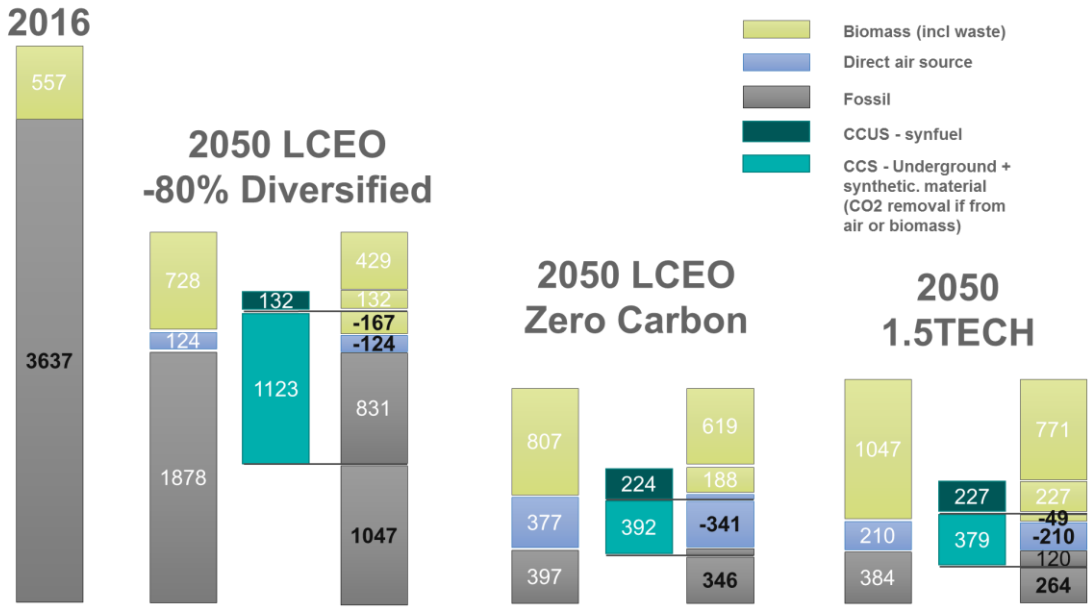
- almost 60% of the total CO_2 is stored or used, mostly captured from power production or fossil based hydrogen or collected as a by-product from the production of 2nd generation biofuels;
- additional CO_2 is also directly captured from the air, especially under the assumption of a high technology learning rate;
- permanent storage of CO_2 occurs in the countries where underground storage of CO_2 has not been restricted yet;
- such transformations would require a rapid scale-up of CCS technologies.

In a ProRES EU that decarbonises with mainly renewable resource

- Power-to-Liquid (electrofuel) complements biofuels in sectors with no easy electric alternative like aviation. The CO_2 that is required to produce for example kerosene is collected mainly as a by-product from 2nd generation biofuel facilities;
- biomass is in most cases equipped with CCS, whether it is for power, heat or biofuels;
- without option to permanently store CO_2, Direct Air Capture does not play a role.

In a ZeroCarbon EU

- CO_2 captured from fossil is mostly process related; most CO_2 is captured from Direct Air Capture;
- more CO_2 is reused than in a Diversified world, but less than in ProRES. The CO_2 that is required to produce e-fuels is again collected mainly as a by-product from 2nd generation biofuel facilities;
- the level of carbon removal equals the level of carbon being put in the atmosphere from some very hard to abate fossil uses.



- **Figure 5. Carbon neutrality visualised via the CO_2 flows; positive bold numbers contribute to CO_2 in the atmosphere, negative bold numbers are carbon removal from the atmosphere.**

- **Table 5. CO_2 flows in 2050 in all LCEO scenarios and the EC LTS 1.5TECH.**

[Mt/year]	CO_2 capturing			CO_2 storage and use			CO_2 interaction with atmosphere	
	Fossil	Biomass	DAC	CO_2 storage under the ground	CO_2 storage in materials	CO_2 reuse	CO_2 to atmosphere	CO_2 removal (biomass or DAC permanent storage)
2016	0	0	0	0	0	0	3637	0
Baseline	137	122	0	193	0	56	2281	-66
Diversified	863	299	124	1123	0	132	1047	-291
ProRes	72	316	0	0	0	399	781	0
Zero Carbon	47	188	377	296	96	224	346	-341
EC LTS 1.5TECH	120	276	210	298	80	227	264	-259

5.3 Sector coupling synergies

We look into sector coupling by looking at buildings, transport and the power sector. In Figure 6 the evolution of power use is represented by bars for the different scenarios. It is particularly interesting to focus on how the power is used. All sectors show an increased electrification, expressed in absolute terms as in graph 6 but also in relative shares because the relative changes of the final energy are much smaller. Industry faces a doubling of their power use, heating and cooling for buildings a tripling and transport even higher. Electricity use in figure 6 includes both the direct electricity and the electricity for the production of hydrogen/e-fuels.

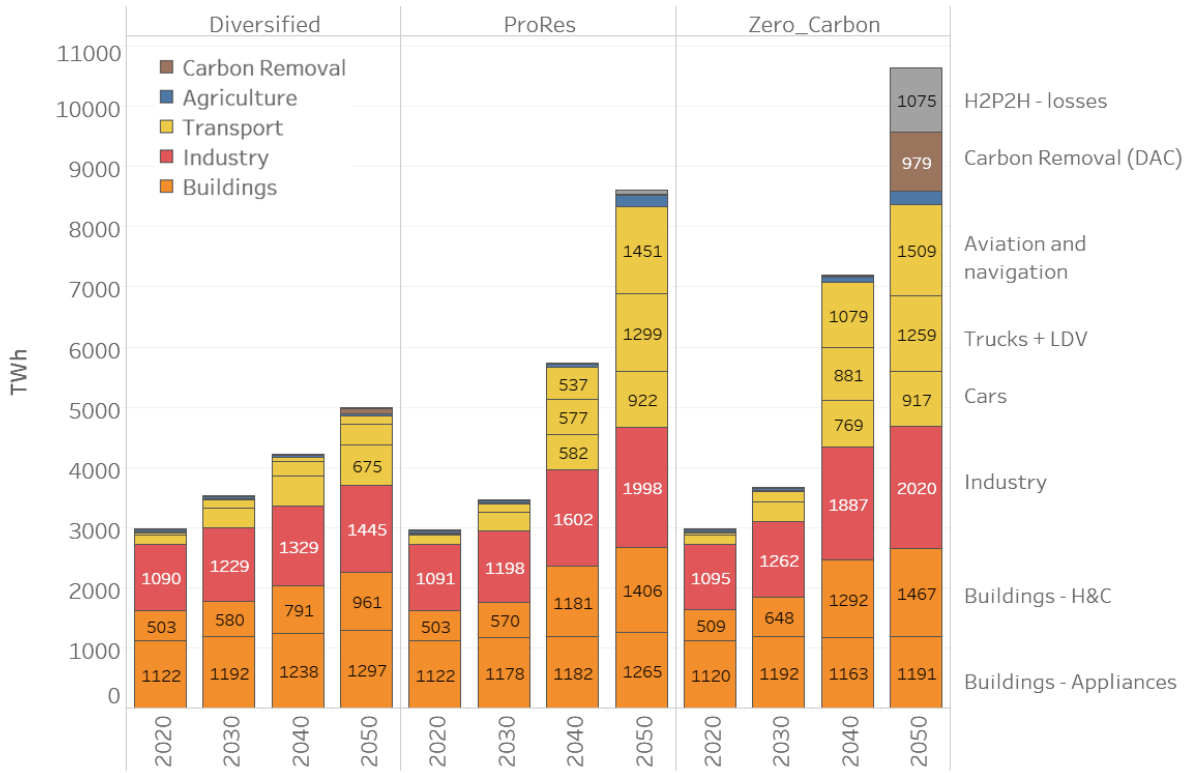


Figure 6. Evolution power use, per sector and application.

In Figure 7, the electricity for hydrogen and derived synfuels is split from the other power uses. Now it becomes even clearer that on top of the electrification that occurs from using electricity as a final energy carrier in buildings and vehicles, the largest increase comes from the production of hydrogen and derived fuels.

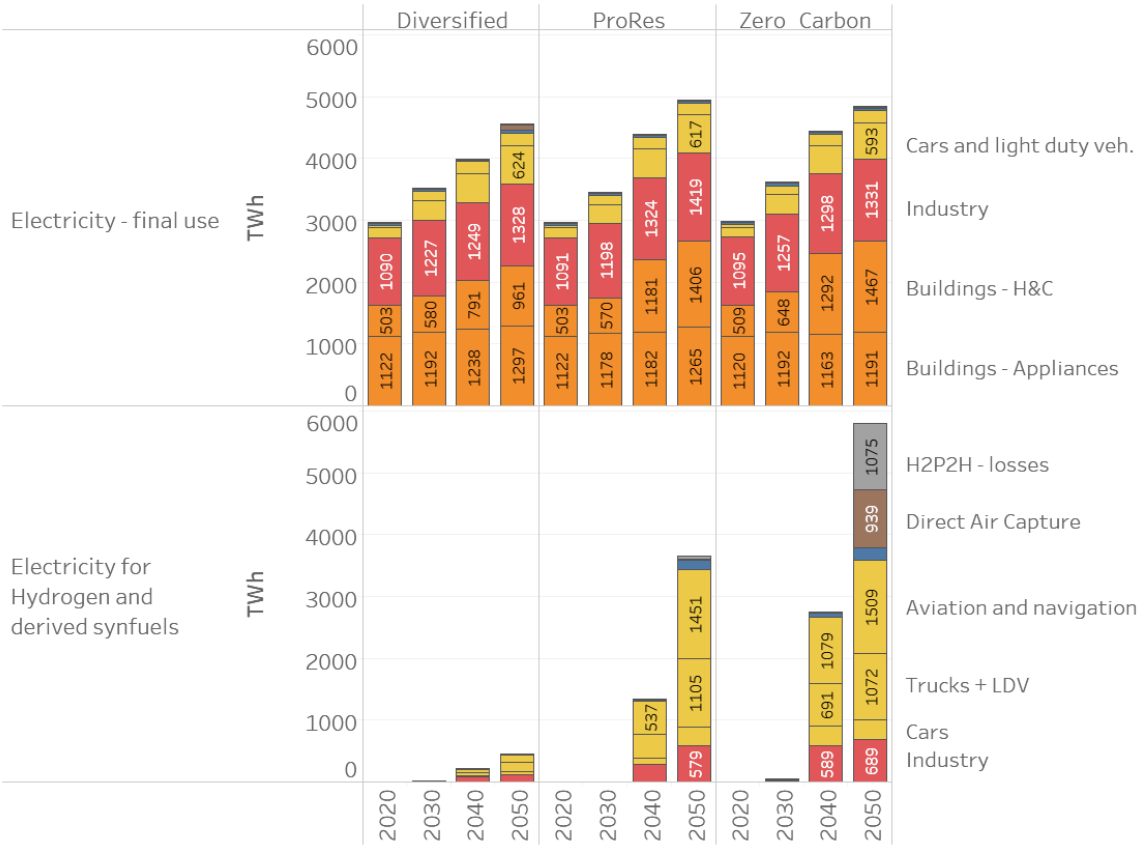


Figure 7. Evolution power use, split in final use and new uses for producing hydrogen and e-fuels

The impact of this increased electricity use comes with a huge need for more power production that also needs to be zero carbon to reduce the overall GHG emissions. Figure 8 presents for 2030 and 2050 possible evolutions of the power system, depending on the scenario. The LCEO Diversified and IEA B2DS show a modest increase. The EC LTS 1.5TECH scenario shows almost a tripling compared to today's capacity level. The ProRES and ZeroCarbon scenarios show a total capacity that is a factor 4 or nearly 6 times the current capacity. This is a consequence of the sector coupling where decarbonisation of heating&cooling, road vehicles and also airplanes and the production of negative emissions all require energy. The new capacities also have lower full load hours requiring more capacity for the same power production. As mentioned in the scenario definition, the ZeroCarbon and EC LTS 1.5TECH are very comparable in terms of scenario design; still there is a large difference in the power sector. This can be explained by the fact that in the EC LTS 1.5TECH, more biomass and waste resources are used in total (+2 400 PJ) and that more wind is installed offshore so that less capacity is needed for the same power production. Also, the total use of energy is lower in the EC 1.5TECH: 54 000 PJ (1285 Mtoe) versus 61 000 PJ in the ZeroCarbon (1451 Mtoe). This difference of 7000 PJ is comparable to the difference in use of solar energy.

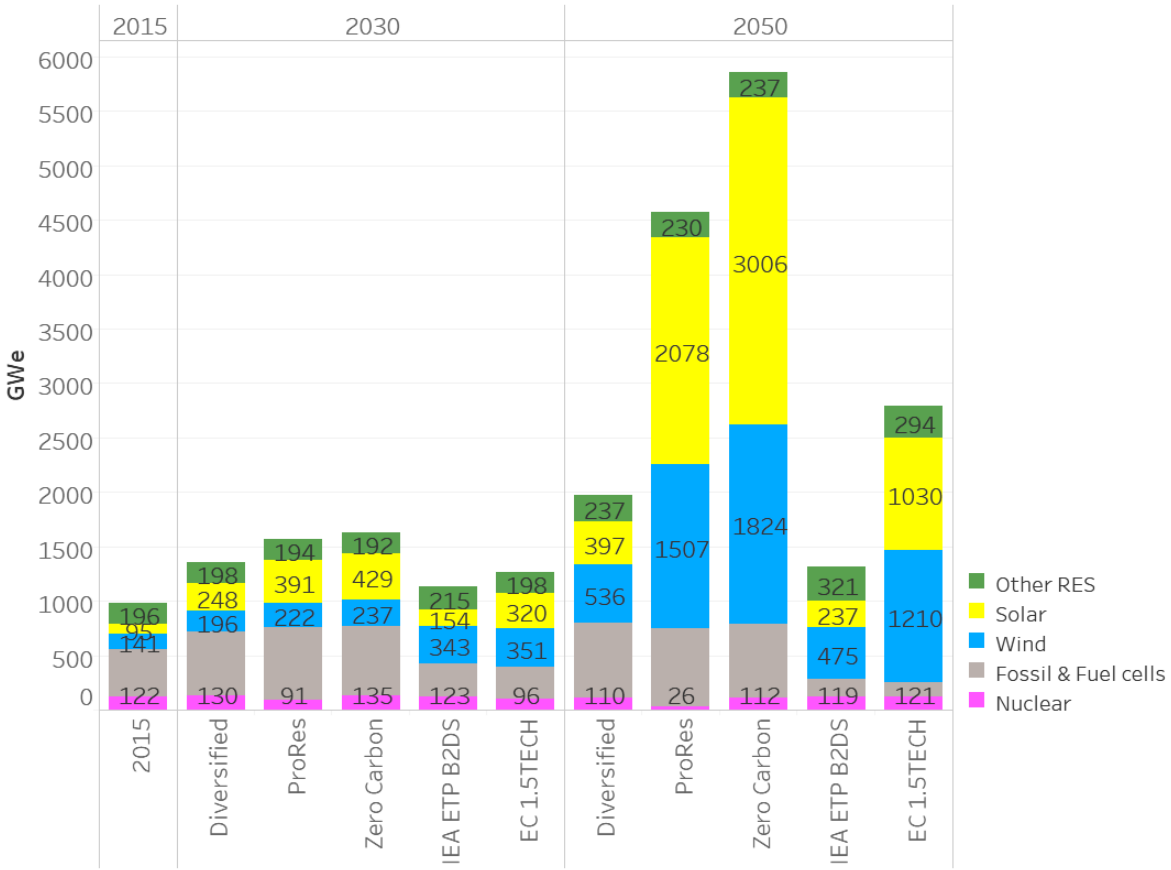


Figure 8. Evolution of power capacities, per technology.

5.4 Key enabling technologies for R&D areas to achieve cost reductions

For identifying key technologies for R&D, we look into investments because a large part of the energy system will be made up of capital intensive technologies For that reason, these results are useful only for R&D targeted to cost reductions.. Some technologies with a low CAPEX are also widely deployed in decarbonisation scenarios. This does not hold for biomass based technologies because of the large operational costs but our method even identified biomass based technologies as key, even only on the CAPEX basis. These would benefit mostly from efficiency improvements which are often limited.

Figure 9 presents the average annual investments in Low Carbon technologies for all periods up to 2050 (BEUR/year up to 2050). The bulk in the power sector comes from solar (including both PV and CSP), wind (including both onshore and offshore) and nuclear. The investments in nuclear consist of lifetime extensions and also for new power plants, except in the ProRES scenario. The numbers for solar and wind reflect markets that can reach up to 100GW of capacity additions on a yearly basis and for that reason can be as big as 60 or 80 BEUR per year, on average. The sector with the largest absolute investments is the transport sector. The green bubbles represent electric vehicles and include the total cost of the car. Electric cars are the largest future low carbon technology market in any scenario, however the battery share in the total cost reduces to below 10%. As a comparison, the cost of the battery is separately shown (as part of the total cost). The majority of the vehicles are electricity driven, but trucks mainly run on hydrogen. Trucks that run on synthetic fuels are not included in the graph because these are regular trucks that are similar to the diesel trucks. Both hydrogen production and biofuels are also large investments that require electrolysis and advanced biofuel production technologies. For heating and cooling, the largest investments are in advanced electric H&C devices such as heat pumps, outcompeting biomass boilers. Insulation is the second largest with an annual investment around 10-15 BEUR per year. Direct Air Capture investments are shown to put the CAPEX requirements into perspective of the total energy system. Direct Air Capture can contribute with an overall investment of on average 6 BEUR per year.

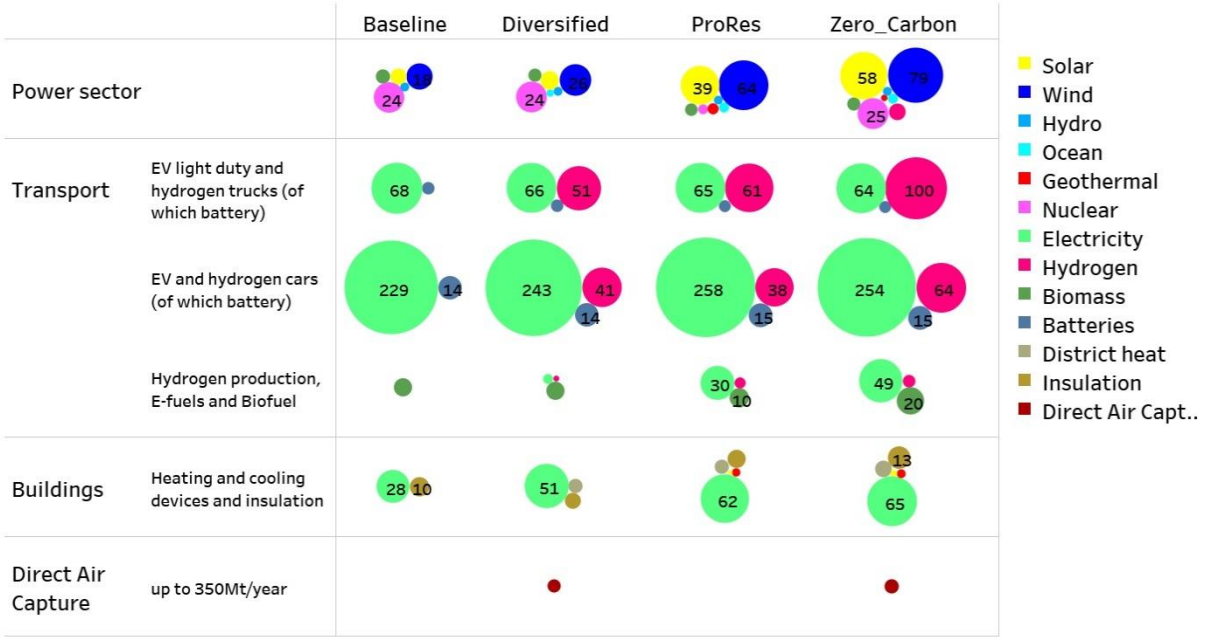


Figure 9. Average investments in Low Carbon technologies (BEUR/year up to 2050, transport covers only road transport).

Figure 10 and Table 6 conclude on key enabling technologies for R&D areas by analysing the additional investments when comparing to the Baseline scenario. The idea is that R&D should give special attention to key future transformations that are not part of a baseline scenario.

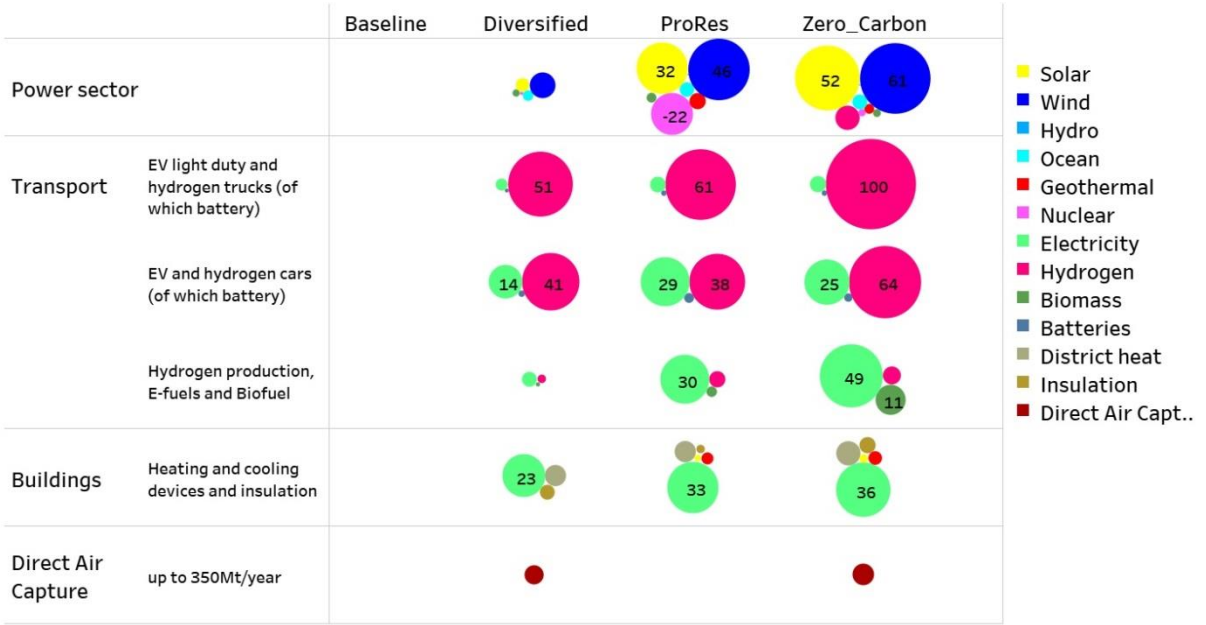


Figure 10. Additional average investments in Low Carbon technologies, compared to the Baseline (BEUR/year up to 2050)

Table 6. Ranking of low carbon technologies based on additional average investments (BEUR/year up to 2050).

	Diversified	ProRes	Zero Carbon
1	H_2-trucks (+51)	H_2-trucks (+61)	H_2-trucks (+100)
2	H_2-cars (+41)	Wind (+46)	H_2-cars (+64)
3	Heat pumps (+23)	H_2-cars (+38)	Wind (+61)
4	Electr. cars (+14)	Heat pumps (+33)	Solar (+52)
5	Wind (+8)	Solar (+32)	H_2-production (+49)
6	District heat (+5)	H_2-production (+30)	Heat pumps (+36)
7	DAC (+5)	Electr. cars (+29)	Electr. cars (+25)
8	Insulation (+3)	District heat (+6)	Biofuels production (+11)
9	H_2-production (+3)	E-fuels (+3)	District heat (+7)
10	Solar (+2)	Geothermal power (+3)	Fuel cells power (+7)
11	Light Duty EVs (+2)	Light Duty EVs (+3)	DAC (+6)
12	Ocean (+1)	Ocean (+3)	E-Fuels hydrogenation (+4)
13	E-fuels (+1)	Geothermal heating (+2)	Light Duty EVs (+4)
14	Biomass for power (+1)	Biofuels production (+1)	Insulation (+4)
15	Biofuels production (+0.2)	Biomass for power (+1)	Ocean (+3)

From today up to 2050, additional investments to transition from a baseline to a low carbon or carbon neutral system are following seven technologies that are in the top-10 of each scenario:

1. Hydrogen vehicles
2. Wind
3. Solar
4. Hydrogen production
5. Heat pumps
6. Electric vehicles
7. District heating

For a zero carbon scenario, following three technologies are to be added:

8. Biofuel production (with reuse of all carbon)
9. Fuel cells
10. Direct Air Capture

We conclude that the sharp rise of both final and indirect uses of electricity drive the power system to new levels that are at least tripling its total capacity. Electric vehicles, heat pumps (possibly with district heating) push the final use of electricity to new levels. Regarding indirect uses of electricity, much more is required than only the integration of renewables in our current system. Renewables, mainly wind and solar, are used in new ways and provide for example low-carbon hydrogen for vehicles, industries and e-fuels for planes. The production, transportation and distribution of hydrogen requires investments that are comparable to the investments in solar power. For a zero carbon scenario, following technologies also require high additional investments: biofuel production (with reuse of all carbon), fuel cells and Direct Air Capture.

6 Grid support services using LCEO technologies from load balancing aspect

The electricity grid is a dynamic entity comprising physical assets (generators, storage, distribution and transmission systems), digitalised control, monitoring and trading systems and a regulatory component setting out the framework for the safety, security and market functionalities. It currently faces radical change on several fronts: from digitalisation and new market designs, from deep penetration of variable renewable generation and from increasing coupling with the heat and transportation sectors [19], Generators (including VREs) need to play several roles in this context, notably for load balancing and supporting grid stability: e.g. provision of flexible power and ancillary services [20], but also through participation to an overall data management and market systems. In the former VRE generators can also complemented by specific flexible alternating-current transmissions system technologies, including reactors, capacitors, synchronous condensers, static VAR compensators and static synchronous compensators [20]

The LCEO technologies can provide some level of grid support services, but in different ways and degrees. Flexible power plants can simply ramp up or down power. Future versions of such plants can be designed to ramp up and down power quicker, or to operate in wider power ranges. Similarly, variable power, e.g. future wind power can be designed to produce more power at sub-optimal levels[4], or to curtail power when demand is low. Excess power from flexible and variable power plants could be stored or used to produce synthetic fuels, and then reused when power demand is higher than production. Demand response making use of electric vehicles and plug-in hybrid electric vehicles will also play an important role when integrating VRE.

The potential grid support services that LCEO technologies can provide were analysed individually.

6.1 Variable renewable electricity

6.1.1 Wind

From a technological point of view, wind energy could support the grid through decreasing the specific power[5] of the wind turbine (e.g. deployment of larger rotors at same generator rating at existing turbines). During the operational lifetime of a turbine, grid support services can be provided through cutting its production peaks by operating the turbine below its design point (at derated power). Furthermore, curtailment of wind energy is currently performed to provide frequency support to the grid.

Regarding other ancillary services, currently wind power plants must provide active/reactive power control, frequency/voltage control and fault ride-through control as required by grid codes. Firstly, they must regulate their active and reactive power during normal operation according to a reference value. Secondly, they must support the voltage and frequency of the power by providing or absorbing reactive power and active power respectively. Their capability to regulate voltage highly depends on the wind turbine technology, however variable-speed wind turbines (representing the majority of the wind turbines currently installed) are able to provide additional reactive power through advanced control of their power electronics. Finally, wind power plants also provide fault ride-through capability by being capable of staying connected during low voltage conditions (mostly happening during short circuit faults in the grid) and resume their pre-fault normal operation shortly afterwards.

In a near future with a large displacement of conventional power plants, wind energy will be required to provide some enhanced control features such as inertial response[6] and power oscillation damping[7] at plant level similarly to conventional power plants. Currently, wind power plants already have technical capability of injecting short-term additional active power into the grid due to the fast response of wind turbine controllers and the energy stored in the aerodynamic rotors although this capability is strongly dependent on wind speed conditions. They can also damp the power system oscillations but the location of the wind turbines may be a physical limitation. Nevertheless, a proper coordination among wind farms is still needed to provide these

[4] From generator point of view. It is not sub-optimal from a system point of view.

[5] The ratio between rated power and area swept by the rotor blades

[6] It refers to the short-term additional active power contribution that can temporarily be released by using the stored kinetic energy in the rotating mass of variable speed wind speed turbines.

[7] It refers to the damping of electromechanical oscillations which are typically undesirable in the power system as they limit power transfers on transmission lines, in some cases may even induce stress in the mechanical shaft of synchronous generators, and ultimately may lead to system collapse in extreme situations.

enhanced ancillary services and avoid a future unstable power system operation [21]. Furthermore, future grid codes could require wind farms to provide other advanced ancillary services like virtual inertia[8] and improve predictions of their power output during critical weather situations. For the latter, in the new market design legislation forecast accuracy is incentivised by e.g. wind farms assuming full balance responsibility.

In order to provide frequency support the accuracy of wind speed measurements and predictions are of relevance. One technique for further improving wind speed measurements is LIDAR (Light Detection and Ranging). Moreover frequency measurement is under debate, for example, the location of frequency sensing equipment to trigger frequency support methods [22].

Co-location of wind energy and storage devices holds the potential to prevent curtailed electricity at times of when wind farms offer balancing capacity to the system and to allow wind farms to offer ancillary services. About 300 MW of co-located projects are operational using battery systems, pump hydro, power to gas or flywheel storage. Among others examples for wind energy projects with battery storage providing fast frequency response can be found in DK (Vestas - Lem Kaer ESS Demo), UK (Vattenfall – Pen y Cymoedd Wind Farm) and Spain (Acciona Barasoain experimental project). Similarly selected wind energy projects install battery storage to improve their black start capabilities after shut down [23].

Even though it is still in a early stage of development future hybrid solutions in offshore wind could lead to a more stable energy generation profile compared to current offshore wind farms. Concepts include wave energy systems sharing the same offshore platform with conventional offshore wind energy. hybrid concepts are still at a very low technology readiness level and still have to overcome major technical barriers towards commercialisation (e.g. de-stabilisation issues,).

Identified trans-technology R&D areas:

- improvement of wind speed measurements and forecasting predictions;
- operation of wind power plants at sub-optimal configuration;
- provision of financial incentives for wind farms to offer balancing capacity.

6.1.2 Solar PV

Photovoltaic systems already contribute 4% of electricity in the EU and are set to be a major future provider. Higher levels of deployment will require additional flexibility in the grid, but at the same time PV systems can also contribute to load balancing and ancillary services. The scope for this depends on the configuration of the overall system or plant and the grid interface managed by a power controller, including a supervisory control and data acquisition (SCADA) system and communications network. Looking forward these functionalities form part of the digitalisation of power generation and grid management [20], [24], [25].

For a utility scale plant (typically > 5l MW), the power controller unit will combine the output of multiple inverters and associated PV arrays, as well as power storage capabilities, see Figure 11. The configuration will reflect the business model for the plant e.g. fixed power PPA, ancillary services or a mixture of both. There is some scope for using the physical configuration of the PV arrays themselves to determine the basic power output profile. Use of single axis trackers has become common in utility scale plants to optimise output over a day. Fixed systems can be oriented more to the west (in the northern-hemisphere) to favour power output in the afternoon/evening. Increasing the ratio of module power capacity to inverter capacity (DC oversizing) can also provide more scope for voltage support services. As well as storage capabilities, hybridisation is possible with other generators e.g. wind, behind the power controller to compensate PV's daily and seasonal power variations.

For smaller systems, particularly on the distribution network, the power controller and inverter can be the same unit with a broad range of capabilities, also needed to address specific issues such as over-voltage on feeders, unwanted harmonics from inverters and reverse power flows to transformers [26]. System level resilience may be reduced since inverters do not have physical inertia (no rotating parts) and limited virtual inertia capability. Challenges include the data privacy and cyber-security issues related to coordinating

[8] Unlike conventional generation, the RES do not provide any mechanical inertial response that can compromise the frequency stability of the power network. Virtual inertia refers to a power converter control emulating properties of a rotating electrical machine.

multiple systems on residential and commercial buildings, as well as the cost effectiveness and sustainability of realising battery or other storage capabilities behind the meter or as a grid service from a central unit.

As for wind power, the capability to better manage the inherent intermittency is being addressed with advanced weather forecasting. These may use numerical weather prediction models, statistical models or combined hybrid models. Satellite earth-observation services can be a key contributor here and the current capabilities offered by Copernicus are highlighted in the ESA 2019 market report [22] and the Copernicus Climate Change Service (C3S) project CLIM4ENERGY reports [27].

Identified technology R&D areas:

- continued improvement of numerical weather prediction and forecasting at individual plant and grid levels
- improved power electronics for providing extended and more powerful ancillary services;
- optimisation of aggregated virtual power plant management techniques for decentralised electricity generation, including issues of data privacy and cyber security,

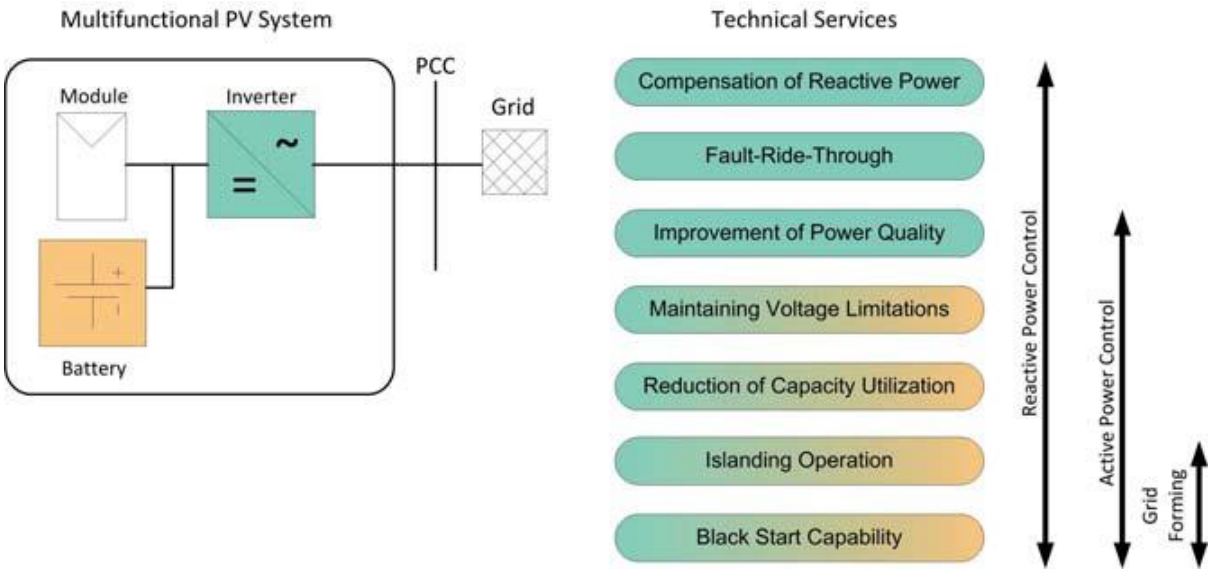


Figure 11. Technical services offered by PV and battery systems [28].

6.1.3 Solar thermal electricity

The STE (also referred to as concentrated solar power, CSP) can be categorised as a quasi-VRE, since the use of thermal storage systems can ensure continuous generation during intermittent variations in solar irradiance and for many hours after sunset. Modern storage system designs typically target at least 8 hours generation at rated power. Indeed power dispatchability is a key selling point for the sector as it works to bring costs down and become more competitive with other low carbon technologies. As for PV and wind, accurate production forecasting is seen as critical for both the plant and overall system operators.

Concerning load balancing and other grid support services, as synchronous generators CSP plants can offer in principle the same range of possibilities as conventional plants. Up to now, the operational emphasis has been on maximising the power output, however there is growing interest in providing potentially lucrative ancillary services. The Spanish Gemasolar plant (20 MW_e) has released data on a successful demonstration of flexible operation (two different load levels during a day). For the Aurora CSP plant in Australia (150 MW, 8 hour storage, currently in development) a key element in its financing is the intention to use part of its capacity to serve peak evening demand. In the US there are plans for CSP "peaker" designs, aiming to compete with gas turbines during the high daily power ramp as PV comes off-line and the evening load increases rapidly. This need could be addressed by modular, smaller (10-50 MW) CSP units with construction time < 1 year.

Hybrid combinations with convention thermal plants offer an alternative route to exploiting solar thermal process heat. A recent review highlights advantages such as the possibility use small plants (even several MW) and that the solar DNI resource requirements are somewhat reduced: sites with >1700 kWh/m^2/y may be

viable, compared to >2000 kWh/m^2/y for stand-alone STE. This would significantly enhance the range of potential EU locations.

Identified R&D areas:

- dry cooling technology (gas or biomass-fired plants for locations with scarce water);
- anti-soiling coatings for heliostat mirrors and cleaning techniques that minimise water consumption (PV);
- numerical weather prediction (PV, wind, ocean);
- efficient and economic sun tracking equipment (concentrated PV);
- elevated temperature receivers and heat transfer fluids: temperatures of up to 1000°C are potentially reachable for central receiver design (conventional thermal plants with supercritical steam cycles, geothermal plants);
- use of pressurised CO_2 as heat transfer fluid (CCUS, geothermal plants with CO_2 working fluid). Pressurised gas has poor heat transfer properties, but ease of handling and possibility to run a high efficiency Brayton Cycle would be advantageous.

6.1.4 Ocean energy

Ocean energy technologies have the potential to mitigate the effect of large-scale deployment of VRE. On the one hand, tidal energy is of highly predictable nature, with diurnal and semidiurnal cycles, which can assure a smooth output to the grid and offers the possibility of storage of excess electricity. Wave energy, on the other hand, does not offer the same level of predictability as tidal energy, however it still offers higher predictability compared to wind energy (23% in terms of resources and 35% in terms of power output) [29].

Tidal energy is a very good technology to be coupled with energy storage solutions. The highly predictable nature of the resources allows directing any electricity produced to the grid, or alternatively to be stored. Two projects in Europe are exploring the possibility to employ the excess electricity from tidal energy for the production of hydrogen. The Surf N' Turf project developed at the European Marine Energy Centre, explore the feasibility of employing an electrolyser powered by two tidal energy generator (SR1-2000 from Scotrenewables and the Tocardo TFS) and to an 800 kW wind turbine. Similarly, the upcoming deployment[9] of the Sabella D10 turbine in Ushant will be coupled with electrolyser for the generation of hydrogen from excess electricity. These projects have two main advantages: 1) they evaluate options for storing electricity generated by tidal stream generators, which can operate reliably for 20 hours a day; 2) they open the possibility for exploring new markets for islands by developing integrated RES systems. Nova Innovation is coupling their 300 kW tidal array with a Tesla battery to store excess electricity to be able to provide base load electricity to the Shetland islands. [30]

Wave energy presents strong compatibility with wind energy in terms of resources. Theoretical level studies on the integration of wind and wave energy farms have already been undertaken to assess the possibility of smoothing energy output to reduce the variability of the resource and of the output. Studies in the US have shown that a wind/wave energy farm could reduce hours of zero output from 1334 hours in case of 100% wind farm to 115 hours if a 50% wind and 50% wave farm was built. [31] Similarly, a Danish study, based on the production data of wind turbines and a prototype wave energy converter operational on the west coast of Denmark has shown that the combination of wind and wave energy reduces the variability of power output by 31%, providing thus a smoother input to the grid; while at the same time reducing the time of zero production to 6%. [32]

Identified R&D areas:

- implement forecasting system for accurate wave prediction to improve remote device control;
- identify way to reduce the variable outputs of wave and tidal current energy technologies through storage systems;
- investigate and develop mooring solution that can be applicable to wave, tidal and wind technologies;

[9] Expected for October 2018.

- explore the possible combined use of ocean energy technologies for heating and cooling;

6.2 LCEO flexible power generation and energy carriers

6.2.1 Hydropower

Reservoir hydropower provides flexibility and storage to the energy system, and it allows generating electricity at the moment it is needed. Conventional hydro stations store large amounts of water in reservoirs which is an indirect form of energy storage. Water is released according to the demand according to strategies that range from intra-day to intra-annual planning. Assuming perfect market conditions hydropower production can be planned according to price expectations and it can be used when it provides the largest value to the system. This has a positive impact both on the companies and the consumers and contributes to reducing power price volatility.

The great flexibility and storage capabilities of hydropower plants facilitate the integration of other VRE, e.g. solar PV, wind. Hydropower is a predictable, controllable and reliable technology that can provide this feature. The role of hydropower for enabling the successful integration of VRE has been highlighted in several European countries. Furthermore, in some cases renewables integration has been based on hydropower capacities of neighbouring countries (e.g. Switzerland, Norway, Austria).

Hydropower is one of the few renewable technologies that can provide ancillary services with profit under the current technological state and market conditions (primary regulation, secondary regulation, etc.). This is an additional contribution to the reliability of the grid apart from the one in terms of energy and capacity reserves. The ancillary services that it can provide are:

- regulation of frequency - hydropower helps to maintain the power frequency by continuous modulation of active power;
- voltage support - hydropower can control reactive power and thus it regulates voltage through injecting or absorbing reactive power. This is a continuous service to control local transmission voltages (response time: seconds);
- spinning reserve - when hydropower plants operate below their maximum power, they can provide spinning reserves or additional power supply very quickly. Thus, the system can respond to unexpected load changes in the grid (primary control);
- non-spinning reserve - hydropower can act as fast-start generators and provide on short notice generating capacity that was previously not connected to the system (response time: ~10 minutes);
- black start capability - hydropower stations are restored to operation without relying on the external electric power transmission network. Therefore, hydropower is the typical black start source to restore an entire electricity network in case of complete outage.

Pumped hydropower storage (PHS) is the dominating utility-scale power storage technology, currently accounting for approximately 96% of the global energy storage capacity[33]. PHS stations further support the optimal use of VRE. In periods of low prices (usually coinciding with periods of abundant VRE output), PHS stations operate in pumping mode and store the excess energy in the form of stored water in an upper reservoir. This water is then released to the downstream reservoir to produce electricity in periods of high prices, with are usually periods of high net demand (demand minus the output of variable energy sources). Its role in grid stability and frequency regulation is crucial and even more effective than conventional hydropower schemes. PHS with variable speed turbines has the ability to regulate power in both pumping and power generation modes, providing additional flexibility to the power system. On the other hand, the do not offer "natural" inertia, since they do not employ directly-coupled to the grid synchronous generators.

Run-of-river hydropower stations, without water storage capabilities, do not provide back-up but are nevertheless able to partially provide primary frequency control. Although such run-of-river source is generally variable and non-manageable, it is reasonably predictable. Thus, run-of-river is usually considered part of the base load.

Identified R&D areas:

- co-locating hydropower with different generation technologies for efficient land use, e.g. wind, floating solar PV;

- advanced control technologies and off-the-shelf components to enable cost-efficient hybrid systems for mini/micro-grids, e.g. solar PV-hydro;
- virtual power plants: develop advanced control systems that jointly regulate solar PV and hydroelectric output;
- co-locating hydro stations, e.g. run-of-river hydropower stations, with battery storage to allow balancing services to the grid and avoid the wear of relevant machine parts (bearings, seals).
- The hybridisation of fast energy storage systems and hydropower stations (conventional or PHS) to enable advanced flexibility and frequency control in the power systems.

6.2.2 Geothermal

Geothermal power plants can provide both base load to the system as well as load balancing. For example, a geothermal power plant in Hawaii can operate between 22 MW to 38 MW. In geothermal binary cycle power plants, e.g. Organic Rankine Cycle (ORC) plants, the ramp rate may be as high as 30% of nominal power per minute. Still, however, nearly all geothermal power plants are operated as base load plants due to economic considerations (e.g. no incentives for load balancing).

Identified R&D areas:

- More research and development is needed to couple geothermal power production with energy storage technology specific for geothermal energy. (in other words store heat in the underground for later usage). Examples are Aquifer Thermal Energy Storage (ATES) Systems and Borehole Thermal Energy Storage (BTES) Systems.
- Geothermal Underground Storage could also be used and combined with solar thermal applications. Heat absorbed by solar thermal plants can be stored underground, typically on a seasonal basis, for heating/cooling applications. In addition, geothermal underground storage could increase power generation and dispatchability of CSP plants.
- evaluate possibility of share technology transfer with submarine geothermal resources.

The synergies between geothermal energy and CCUS are described in Section 6.2.6.

6.2.3 Heat and Power from Biomass

Biomass could be used directly for heat and power generation and for the production of energy carriers that include solid (wood chips, wood pellets, torrefied biomass), liquid (bio-oil, bioethanol, biodiesel) and gaseous fuels (biogas, biomethane, syngas, bio-hydrogen). The conversion of biomass to heat, power and energy carriers is performed through a variety of thermo-chemical and bio-chemical/biological pathways. There are also multiple routes involve biomass conversion to chemicals and materials, that creates important synergies between various biomass conversion technologies.

Biomass power plants can be used as a base-load to deliver continuous electricity or for grid balancing, having certain flexibility capability in operation, allowing generating electricity at the moment it is needed.

Biomass power plants, coupled with heat storage, could offset heat shortfalls and vary their electricity output in response to grid conditions and provide grid flexibility. Biomass cogeneration plants with condensing turbine with steam extraction have a certain level of flexibility to generate electricity according to the needs. However, the flexibility is limited and also depends on the heat demand which has to be satisfied through the steam extraction.

Biogas from Anaerobic Digestion (AD) is used for electricity and heat production in electricity only plants, heat only plants or CHP plants using gas engines, Stirling engines, gas turbines, micro turbines and fuel cells. Electrical capacity ranges from tens of kWe up to a few MWe. Power production from biogas can be used for electricity grid balancing and biogas can provide electricity at the moment when electricity demand is higher (at peak load). Biogas upgraded to natural gas quality can increase the share of renewable energy in the natural gas grid and then be used in connection with gas storage to provide electricity at the moment when electricity demand is higher (at peak load) or to compensate for the variable renewable energy production from solar and wind power. Biogas injection into the gas grid can exploit the huge storage capacity of the gas systems connected to the gas storage facilities, enhancing energy security. Biomethane can be used in a

number of end-use applications (heat, power and transport fuel) at the location where energy is needed and at the moment where electricity generation from other renewables is lower.

Identified R&D areas:

- improving performance of large scale biomass cogeneration and reduce costs
- biomass combustion integration with CCS and CCU to provide negative net emissions;
- Hydrogen production from biomass gasification plants with CO_2 capture represents another synergy.
- micro and small scale biomass combustion with improved reliability and techno-economic performance, flexible fuels, low emissions (mainly particle) and reduced maintenance costs;
- process conditions reactor design to improve bio-oil quality and consistency, process reliability and for broadening feedstock base for bio-oil;
- new techniques including catalytic pyrolysis, for pyrolysis oil cleaning, purification and upgrading of bio-oil for the production of heat and power, biofuels and biochemicals from bio-oil or its fractions;
- gasification process improvement to ensure reliable long-term operation, cost reduction, improvement of the syngas cleaning and upgrading;
- improving performance, process control and process optimisation for biogas production from Anaerobic Digestion and to enlarge the feedstock base to new & difficult substrates & increase biogas yield;
- R&D is needed on hydrogen gas separation and purification, catalysts, advanced materials adsorption materials and gas separation membranes;
- R&D to design new biorefinery value-chain concepts and achieve process integration that maximize product and energy yield and lead to the efficient use of biomass, energy, water and nutrients.

6.2.4 CCUS

Carbon capture and storage (CCS) has been demonstrated as a feasible technology to reduce CO_2 emissions. CO_2 utilisation, under specific circumstances, can also lead to emissions reduction. The combination of carbon capture, utilisation and storage (CCUS) and renewables can contribute to achieve faster reductions.

Identified R&D areas:

R&D in CO_2 capture, utilisation, and storage, overlaps with the R&D needs of a variety of technologies. Capture is linked to sustainable advanced biofuels (see also 0) as well as hydrogen production. Hydrogen production from coal and/or biomass gasification plants with CO_2 capture represents another synergy. Its application is not limited to coal or biomass.

In certain utilisation processes CO_2 is combined with H_2 to synthesise fuels and certain chemicals that can also serve the purposes of energy storage. The necessary H_2 is obtained through electrolysis that consumes a considerable amount of electricity which needs to come from renewable sources for a sustainable process.

6.2.5 Sustainable advanced biofuels

Biomass of different sorts including non-food and non-feed biomass, e.g. agricultural and forestry residues and municipal solid waste (MSW) and aquatic biomass, can be converted into a variety of energy carriers. These include solid, liquid and gaseous fuels such as wood chips and pellets, biogas, bioethanol, biodiesel, bio-oil and bio-hydrogen that can be used to generate heat and power, or advanced biofuels for transport.

The conversion of biomass to bioenergy and biofuels carriers is performed using a variety of pathways based on thermo-chemical and bio-chemical/biological technologies. The choice of conversion route generally depends on the type of biomass treated and the energy product required. For example, biomass pyrolysis produces bio-oils that can be used to replace fuel oils in heat and power production, be upgraded to feedstock for advanced biofuels, converted to fuel additives and final fuels, to chemical intermediates and final products. Pyrolysis can also be used as a pre-treatment step for gasification and biofuels production.

Biofuels, and importantly advanced biofuels technologies for the production of transport biofuels (such as cellulosic ethanol, BTL, BioSNG, Bio-oil and HVO), enable synergies and interactions within and outside of the biofuels industry leading to the integration of different energy carriers.

Identified R&D areas:

A list of possible areas for research studies to foster synergies and interactions between advanced biofuels technologies with different energy carriers, within and outside of the biofuels industry are as follows:

- In general, many processes, both existing and new, need hydrogen to transform biomass into reduced hydrocarbon-like fuels; for example hydrogenated vegetable oil or algae oil processing to biofuel, upgrading of pyrolysis oils, drop-in biofuels (i.e. there are no blend limits with fossil fuels) from sugar. The hydrogen conventionally comes from steam-reforming natural gas, but could be substituted with renewable sources, such as the 'AER-gas' absorption-enhanced biomass steam reformer, or electrolysis from excess renewable electricity.
- capture and utilization of CO_2 from bio-ethanol (from fermentation);
- Algae can be used as a CO_2 capture method when in low volumes to transform CO_2 into a biofuel (which in turn is a way of CO_2 utilisation);
- innovative processes for renewable hydrocarbon biofuels production
- innovative synthesis process to make synthetic fuels, methane, ethanol by combining CO_2 with H_2 obtained via electrolysis using excess renewable electricity (catalytic methanation, biological processes, etc);
- similarly to ethanol fermentation, CO_2 can be separated in an almost pure stream from biogas upgrading to biomethane. Synthetic fuels (from Fischer-Tropsch process) can be produced;
- production of synthetic fuel by combination of CO_2 (either from fermentation of CCU) with H_2 from excess renewable electricity;
- use of CO_2 for biomass production, for energy and materials purposes, via accelerated plant growth, e.g. algae;
- use of by-products or residues from current biofuel production;. For example, glycerol (from biodiesel production via transesterification) combusted or digested at external industries for energy production; or indeed the biogas could be upgraded and fed into the natural gas grid;
- use of by-products from advanced biofuel production (these are not likely to be made in large volumes yet). For example, lignin used to make a liquid fuel, or liquid feedstock for further upgrading to fuels;

6.2.6 Advanced alternative fuels

As mentioned in the CCUS and sustainable advanced biofuels sections, some advanced alternative fuels can have a synergistic effect across sectors. Converting electricity (via water electrolysis), and subsequent synthesis (with CO or CO_2) into a gaseous or liquid fuel, enables a coupling of sectors, which in turn can offer advantages for the whole energy system. Fuels produced are generally known as Power-to-Gas (PtG) (based on the methanation reaction) and Power-to-Liquids (PtL) (which typically involve Fischer-Tropsch (FT) synthesis or methanol production). In using electricity and CO_2 in this way, the resulting fuels bring both the possibility to act as storage for fluctuating RES, and a way to recycle carbon.

Identified R&D areas:

Links to projects focused on hydrogen production via electrolysis could be beneficial, as advanced fuel manufacture via fuel synthesis is one possible option to make use of the hydrogen. In a similar way, CO_2 capture projects could find synergies with advanced fuel synthesis projects as an option for using the captured CO_2. Other possible synergies include electricity grid research; both in the effects extra demand electrofuel projects would have on the grid (if they are not powered by – or if only partially powered by - their own additional renewable electricity source), and in the likelihood or extent such systems could in reality work on excess or curtailed grid electricity. Research focused on reducing the scale of Fischer Tropsch plants (and thus the capital costs) could be beneficial to the fuel synthesis step for electrofuels. Novel ways of fuel

synthesis, for e.g. bacteria that consume CO_2 (from various sources) and H_2 to synthesize fuels could be also synergistic.

6.2.7 Hybrid plants

Hybrid combinations with convention thermal plants offer an alternative route to exploiting for example solar thermal process heat. The host plants can be fired by all relevant fuels, although biomass and waste materials are of most interest in the present context. The steam integration points include feed water heating and cold reheat line for the boiler, and steam boost and superheated steam for the turbine. For combined cycle gas turbine plants, syngas and high temperature air are also options. The later concept has been demonstrated in the EU SOLUGAS project near Seville, Spain, with direct solar heating of a gas turbine's pressurized air.

Integrated bioenergy hybrids can ensure flexible operation for both energy supply and energy storage. Several combinations include bioenergy and solar thermal systems; bioenergy and Solar thermal electricity (STE); bioenergy and heat pumps; bioenergy and geothermal; and bioenergy and waste heat recovery. In these systems bioenergy can serve as a complementary heat source for power production in combination with different sources. The role of bioenergy in a hybrid system depends on the application: bioenergy is used to support the other renewable energy source; or other renewable energy sources are used to support bioenergy production. For emerging and new hybrid technologies further investment in R&D is needed to better integrate the various sources into a complex system, to achieve process optimisation in a tailored application and minimise costs. More research is needed to achieve the integration and understand the operation of bioenergy hybrids in a variable renewable energy system.

Identified R&D areas:

- hybrid combinations with gas or biomass-fired conventional thermal plants;
- use of pressurised CO_2 as heat transfer fluid (CCUS, geothermal plants with CO_2 working fluid). Pressurised gas has poor teat transfer properties, but ease of handling and possibility to run a high efficiency Brayton Cycle would be advantageous.

7 R&D synergies between LCEO technologies

The assessment criterion for the identification of R&D synergies is a potential common interest to invest in R&D from at least two technologies. The synergy could improve overall performance for the two technologies, reduce costs, or increase sustainability. Although the potential cost impacts are not assessed, it is assumed that they are not marginal. Besides R&D synergies, we identify areas that can be considered to fall predominantly within one technology area but have a dependent relation towards other technology areas (but as such are not willing to invest in R&D in that domain). Additionally, R&D spillovers towards low-carbon energy technologies from conventional technologies are highlighted.

The R&D synergies between LCEO technologies were analysed in four groups. The groups were primarily organised based on type of energy produced, or operational modes.

1. *geothermal, hydropower, biomass for heat and power, and CCS* – contains mainly flexible power plants able to follow load demand. CCS is included too, since it was expected that it has synergies with geothermal;
2. *wind, ocean, and solar* – contains plants providing variable renewable power. It is dependent on for instance weather conditions like wind and solar;
3. *geothermal, solar thermal, biomass for heat and power* – plants aimed at delivering energy to meet heating demand, e.g. district heating;
4. *CCUS, sustainable advanced biofuels, heat and power from biomass* – plants aimed at producing new fuels, e.g. biofuels, hydrogen.

7.1 Geothermal, hydropower, biomass for heat and power, and CCS

7.1.1 Geothermal and CCS

The SET-Plan Integrated Roadmap [34] has identified drilling, reservoir stimulation and management as key research priorities in the geothermal sector due to their high contribution to capital costs. CCS would also benefit from cheaper drilling. The key performance indicator (KPI) for drilling research activities is to lower the cost by 25% from the current estimated price of EUR 10 million for a 5 km well either by optimizing current drilling technologies or by development of novel drilling technologies. For reservoir stimulation, the KPI is to lower costs by 25% from the current EUR 4-8 million for each EGS.

Resource characterisation, site monitoring and increasing of public awareness are key research priorities shared by the geothermal and CCS industries which can benefit from common research incentives:

1. More thorough mapping and characterisation of the subsurface may contribute to the more accurate identification of CO_2 storage volumes and at the same time reduce the risk of future geothermal projects being initiated in areas where probability of success is low. In some circumstances, identified geological formations may suit for the two technologies, i.e. CO_2 may be used as the heat transfer fluid from the formation to the surface installations.
2. Better geophysical tools for site characterisations may enable better leakage risk assessment for CCS and could decrease the number of abandoned geothermal projects by up to 25%.
3. Better monitoring methods may enable more accurate detection of moving CO_2 plumes, cheaper (through automated and more robust instruments) monitoring campaigns (mass movements and seismic as well as geochemical monitoring) both in the CCS and geothermal sectors.

In a combined CCS-EGS plant, the use of water as extraction fluid can be replaced with CO_2. To use CO_2 as extraction fluid can be more efficient than, for instance, the use of brine.

7.1.2 Hydropower and geothermal

Hydropower development will also benefit by R&D in drilling technologies, which is often the target of geothermal R&D. Advanced tunnelling techniques allow avoiding above ground water convey solutions. The latter require the construction of temporary access roads that involve additional environmental and economic impact. Further strengthening the existing designs to withstand larger forces and drill over larger distances and heights will increase the range of applications.

7.1.3 Biomass power and heat, and CCS

Sustainable biomass combustion coupled with carbon capture utilisation and storage (CCUS) is an option contributing to decarbonisation on the short to medium term, as one of the few options leading to negative emissions from power production. Carbon captured from anaerobic digestion and from power production can be used as a feedstock for biomethanation and for algae production. Biomass is a key option for a fast and significant decrease of carbon emissions into the atmosphere on the short term. Bioenergy plants can operate providing energy solutions at small (ORC systems, Stirling engines) to medium to large scale. A large number of bioenergy solutions are already available in the market place, and they are applied at various size ranges.

7.1.4 Geothermal , biomass, and concentrated solar power

The efficiency of a geothermal power plant increases with the use of elevated temperatures for the heat transfer fluids. A pressure drop is usually observed during extended operation of hydrothermal reservoirs and hence the flow of available fluids to the plant, leading to reduced power production. Bioenergy hybrids coupling bioenergy production with geothermal or solar thermal / power can provide the offers a fast way to increase the share of RES and flexibility in heat and power production in district heating networks and power grids. The power production may be maintained either by drilling additional wells to maintain mass flows (provided the reservoir is large enough) or by coupling a biomass boiler to the steam collection system to increase the temperature, as done in ENEL's Cornia 2 plant in Italy. This hybrid technology may be very relevant where ample amounts of biomass are available near geothermal plants. Hybridisation with concentrated solar thermal systems has also been proposed for suitably sunny locations.

7.1.5 Thermal cycle

The supercritical CO_2 cycle could improve efficiencies for a wide range of thermal power plants.[10] R&D on materials improvement, operation and maintenance, cost reduction and increased efficiencies can be some for mutual benefits resulting from these synergies.

7.2 Variable power (wind, ocean, solar)

The development of variable power technologies and their integration with the grid offers the potential for concerted areas of research.

As seen in section 6 new technologies are being developed in order to improve the final power output. However, synergies are not limited to power output but also other R&D areas which may result in more efficient and more reliable power conversion technologies.

7.2.1 Co-location of VRE plants

Wind and solar PV

The combination of wind and solar PV at a single geographical location can offer positive synergies in infrastructure, project development and plant performance. This includes cost savings from joint usage of land, grid connections and other infrastructures such as roads and substations etc., cost, as well as risk savings from joint permitting and development processes and smoother feed-in profile at grid connection point.

Analysis of wind and solar resources for Europe indicate a weak disassociation, suggesting a degree of local complementarity of the two sources in many regions. A strong effect from the diurnal cycle is observed in some regions. Also, a significant dependence on the month (higher absolute values in summer) and on the time scale (increase in absolute value with the extension of the time window that is considered for the correlation) is apparent. (Miglietta et al, 2017). Nevertheless, there are some key aspects that need to be carefully considered when wind and solar PV are combined: ratio of wind and solar PV capacity depending on site conditions and grid restrictions, controller settings to optimize the business case, deep understanding of interdependencies, active/reactive power and electrical setup.

[10] Irwin, L.; Le Moullec, Y. (2017) *Science* 356 (6340), pp. 805-806

Wind and wave

As mentioned in Section 6.1.4 wave and wind have strong compatibility in terms of resources. The advantages offered by wind-wave combined systems have also prompted researchers to develop different types of wind-wave energy devices [35]. In particular, areas of integration are found in terms of sharing structures, sharing operational costs and reduction of structure loads. The economic aspect is one of the strongest point for the investigation of combined wind-wave technologies [36]; however, their development is hindered by the status of development of wave energy technology, due to the fact that wave energy technologies are yet to become commercially viable. Given the difference in technology readiness level between offshore wind energy and wave energy, it can be expected that until issues related with wave energy are solved the development of combined wind-wave technology will be discarded in favour of conventional offshore wind or for turbines [37].Even in the case of more advanced wind-wave technologies, such as the Danish Floating Power Plant, it can be seen that the balance of plant in terms of energy generation is swayed in favour of large wind turbines. As mentioned in Section 6.1.4 wave and wind have strong compatibility in terms of resources. The advantages offered by wind-wave combined systems have also prompted researchers to develop different types of wind-wave energy devices [35]. In particular, areas of integration are found in terms of sharing structures, sharing operational costs and reduction of structure loads. The economic aspect is one of the strongest point for the investigation of combined wind-wave technologies [36]; however, their development is hindered by the status of development of wave energy technology, due to the fact that wave energy technologies are yet to become commercially viable. Given the difference in technology readiness level between offshore wind energy and wave energy, it can be expected that until issues related with wave energy are solved the development of combined wind-wave technology will be discarded in favour of conventional offshore (floating) wind turbines [37].

Solar PV and CSP

In suitable locations, CSP and PV can be combined on one site. In such a configuration, PV can generate power during sunlight hours, also providing auxiliary power to the CSP plant for control systems, pumps, heaters etc. The CSP side stores part or all of the heat produced during the day for electricity generation after sunset.

Hydro and wave-tidal

Research in wave and tidal technologies has resulted in findings and technological progress that originally target applications on offshore systems. Advances include novel designs of turbines for tidal range projects (e.g. the triple regulated bulb turbine), as well as ultra-low head hydro turbines originally developed for wave energy converters (e.g. the wave dragon) [A]. Such designs are expected to reach higher levels of technological maturity, since they have already been tested and applied in full-scale projects like the Swansea Bay tidal lagoon project. As soon as sufficient technological maturity has been secured, such technological advancements can be transferred to onshore applications, and specifically to a subset of hydropower systems that convert the kinetic energy of rivers and tides into electricity known as hydrokinetic. The potential synergies can be two-directional: New technologies specifically developed for marine applications can be transferred for new onshore hydropower development. This will allow the installation of small-scale hydropower stations with very low (or zero) environmental and ecological footprints, because hydrokinetic systems do not require the construction of dams/weirs [B]. At the same time, current and future low-head hydropower technologies can potentially be "marinised" in order to be compatible for offshore applications.

7.2.2 Offshore components

The development of offshore renewable technologies such as offshore wind (with floating or fixed support structures), ocean energy technologies, and potentially floating solar PV; presents a number of synergies across the technologies, despite different applications.

A JRC analysis on shared R&D activities for wind and ocean energy showed that 40% of the cost components could be addressed by common research, with the potential to produce economic benefits for both sectors [38]. Particularly multipurpose floating platforms might offer synergies between offshore wind and wave energy as recently identified by the SET-Plan working group on offshore wind [39]. Moreover R&D synergies in offshore wind could arise from future emerging technologies such as combining floating offshore wind with airborne wind energy systems (AWES) [40] [41].

Synergies between different renewable offshore technologies concern both specific technological aspects, such as the development of magnet generators or the sharing of common structures, as well as ancillary topics such the development of electrical infrastructure.

The key technological areas that could benefit from concerted R&D actions are:

- Moorings, foundations and anchoring. There is significant crosscutting overlap in mooring and foundation requirements between offshore floating wind, tidal and wave power and the oil and gas sector, while diversity is largely due to the distinct environmental design and operating conditions associated to mooring loads. For example floating wave power systems tend to be dominated by first order wave loads, whereas a tidal installation would have higher relative mean loads. Despite the differences in the design, as highlighted in [37], concerted R&D actions could ensure increased power output and survivability of the device. Lessons learnt could be applied in the long term for the development of floating PV technologies, like the one of developed by Oceans of Energy.
- Power take-off (PTO), especially with regard to the development of direct-drive turbines (tidal and wind).
- Combined wind-wave converters offer potential in terms of grid balancing, however its development is hindered by the lack of reliable wave energy conversion.
- Development of cost effective multi-MV multipurpose modular floating platforms
- Materials and coatings. There is significant crossover in the use of materials (blades, structure) between the different offshore RES technologies. One particular aspect is the resistance of corrosion and biofouling which requires to be addressed in the development of coatings.

To a certain extent, a number of EU co-fund projects have already addressed common R&D issues, such as POSEIDON[11] (aimed at developing a hybrid wind and wave plants), MARINET[12] (which comprises a network of research centres and organisations to research on marine renewable energy systems) or MARINA PLATFORM (aimed at developing deep off-shore multi-purpose renewable energy conversion platforms for wind/ocean energy conversion).

Additional areas for joint R&D of non-technological nature that could benefit of wind and ocean energy technologies:

- Operation and maintenance procedures, based on shared experience and vessels and harbour infrastructures;
- Social and environmental impact studies, aimed at reducing unknowns with regards to potential impact and increasing social acceptance of wind and ocean energy farms;
- Electrical infrastructure: cables, connectors, power converters and substations, and grid integration issues, which find a broader scope in the integration of variable renewables in the energy system as discussed in section 7.2.4.

7.2.3 Weather/climate forecasting

Forecast RES production with a high level of accuracy is key for the system optimisation in terms of its integration. Present forecasting techniques are usually divided into day-ahead forecasting and hour-ahead (intra-day) forecasting, which differ from the perspective of accuracy and applicability. In general, with the current penetration of RES, day-ahead schedules are applicable, while intra-day forecasts are currently of smaller economic value. There is still a high potential lying in the inclusion of exogenous data, as well as data from other meteorological databases, which could significantly increase forecasting accuracy, thus contributing to increase RES availability and their contribution to a flexible energy network system. Improvements can be achieved applying generation forecasting models based on machine-learning algorithms and utilising hybrid approaches that combine weather forecasts, local ad-hoc models, historical data, and real time measurements. In the recent years, due to the improvement of climate models, there was an increase in the use of climate predictions, basically forecasts of atmospheric conditions for time horizons ranging from 3-4 weeks to six months. This information may be valuable for planning maintenance and operation of RES to deal more effectively with the inherent uncertainty of renewable resources.

[11] Funded under the EU H2020 programme. Public funding: EUR 1.14 million. Active: 2015-2017
[12] Funded under the EU FP7 programme. Public funding: EUR 9.0 million. Active: 2011-2015

The key technological areas of heat production that could benefit from concerted R&D actions are:

- Improve RES forecast accuracy by means of new ensemble models considering individual forecasting models for power generation and meteorological conditions, including linear, nonlinear and probabilistic methods; test of hybrid approaches that combine weather forecasting, local ad-hoc models, historical data, and on-line measurement. Estimate secondary/tertiary power reserves against RES forecast accuracy/error.
- The implementation of prediction strategies based on weather forecasts for variable power technologies, such has solar PV, wind energy and wave energy; can translate in improved performance of the systems and better power output. Better forecasts have a direct impact on the value of electricity generated, and affect the dispatchability of RES in the energy system. A reliable forecast of the energy supply allows for better regulation of energy demand, favouring increased supply from RES.
- The broader availability of weather/climate information systems and data, such as Copernicus and EMHIRES, provide the foundation for the development of forecasts systems; facilitating the demand-response and integration of renewable electricity in the energy system.
- Augmented resource mapping and forecasting systems, aimed at increasing production and efficiency of RES systems, could results in higher predictability and higher power output.
- Forecasting is already a critical theme for solar and wind integration in the energy system, and can be in the future as well for ocean generated electricity. Different players in the system have different perspectives, both in relation to the timescale and to the geographic coverage: centralised forecasting provides system-wide data, whereas individual operators may require site specific (or decentralised) forecasts.
- There is a common basis in the field of numerical weather prediction, but the technologies have specific and somewhat divergent requirements. Wind forecasts face issues such as down-sizing to specific local terrains. Solar PV requires information on cloud coverage and movement and needs to also consider more widely dispersed power sources with many local variables in relation to the individual system set-ups.

	Type of Forecast	Time Horizon	Key Applications	Methods
Generation	Intra-hour	5-60 min	Regulation, real-time dispatch, market clearing	Statistical, persistence
	Short term	1-6 hours ahead	Scheduling, load-following, congestion management	Blend of statistical and NWP models
	Medium term	Day(s) ahead	Scheduling, reserve requirement, market trading, congestion management	NWP with corrections for systematic biases
	Long term	Week(s), Seasonal, 1 year or more ahead	Resource planning, contingency analysis, maintenance planning, operation management	Climatological forecasts, NWP
Decision Support	Ramp forecasting	Continuous	Situational awareness, curtailment	NWP and statistical
	Load forecasting	Day ahead, hour-ahead, intra-hour	Scheduling, economic dispatch, congestion management, demand side management	Statistical

Figure 12 Range of forecast time horizon, applications and methods for VREs.

7.2.4 Power electronics, grid systems and storage

The electricity sector is at the centre of the energy transition, due to both its share on the overall energy consumption and its capability to play a central role in the integration of different energy sectors (electricity, heating & cooling and transport). However, this necessitates a considerable effort for the modernisation of the power system. This section identifies RD&I needs on smart power systems with a particular focus on issues relating to the integration of LCEO technologies. It is noted that the drivers behind the effort to "smarten" the power system go beyond LCEO integration, and include among others accommodation of active customers, electrification of transport, emergence of smart cities, and sectoral integration.

Power electronic converters

Development of smart inverters is a crosscutting RD&I activity, given that they are an integral component of VRE technologies (mainly wind and PV), as well as of battery storage. Of great interest is the provision of enhanced ancillary services, such as synthetic inertia, fast frequency response, enhanced fault-ride through capability and voltage control. Further, with the development of microgrids the capability of LCEO and storage technologies interfaced with the grid through power electronic inverters to operate in islanded mode, i.e. disconnected from the main grid, will become increasingly important.

Enhanced O&M through data analytics

The digitalisation of networks and generation technologies in the sense of enhanced communication, data acquisition and data analytics offers the opportunity for sophisticated preventive maintenance procedures, reducing costs and downtimes and increasing the lifetime of assets. It can also increase the overall efficiency of the power system by reducing losses in the grid and increasing the combustion efficiency of thermal generation technologies including LCEO ones (e.g CHPs).

Virtual Power Plants

The proliferation of distributed generation, mainly based on LCEO technologies, necessitates the full integration of these resources into power system operations and power markets. Aggregation of such resources, along with storage technologies and Demand Response, into a Virtual Power Plant can lead to an "equivalent" power supply unit trading both energy and ancillary services with full controllability.

Microgrids

With the proliferation of distributed resources, storage, demand response and Electric Vehicles (EVs) along with the opportunities that digitalisation and sectoral integration can offer, the currently centralised, to a great extent, power system could transform in the long-term into a multitude of semi-autonomous microgrids. Microgrids can be understood as cells which mostly self-balance their energy needs, exchanging energy and services with other cells only when necessary. RD&I activities on microgrids, specific to electricity, include control techniques and automation for frequency and voltage regulation, capability for islanded operation and automatic re-synchronisation with the power system, fault diagnosis and protection schemes in the absence of large centralised power plants based on synchronous generators, and contribution to power system restoration.

Microgrids can be considered to a significant extent as the technical layer of local energy communities. The latter necessitate innovative market schemes and technologies for trading energy and services in their interior, between them in peer-to-peer schemes and between energy communities and the centralised power markets. Transactive energy schemes and distributed ledgers have been identified as one of the most promising technologies in this area.

Enhanced Grid observability and controllability

Enhanced Grid observability and controllability will contribute to a series of interlinked targets:

- Reduction of variable RES curtailment, increase of grid hosting capacity for VRE, especially in the distribution system, and deferment or postponement of grid expansion.
- Operational security and reliability in a power system with increased penetration of VRE technologies with low or no mechanical inertia
- Enablement of new market players, including among others of active customers, aggregators, and energy communities.

Digitalisation of the power system is the underlying process that can lead to a "smarter" grid. Communication of an ever increasing volume of data will require the development of decision-making support tools coupled with advanced automatic control. Specific RD&I activities in the above fields include Wide Area Monitoring Systems integrating actual measurements and forecasts on VRE production and on demand, Phasor Measurement Units for enhanced state-estimation of the transmission system, fault diagnosis and new protection schemes for bi-directional power flows, smart substations, automatic grid reconfiguration, self-healing distribution systems, and microgrids.

New transmission technologies

New transmission technologies include RD&I activities in new materials (e.g. superconductors), employment of ICT for enhanced utilisation of transmission assets (e.g. Dynamic Line Rating), HVDC links, and Flexible AC Transmission Systems.

HVDC connections are particularly important for the connection of offshore wind farms and transmission of power in long distances. RD&I priorities include further technological advancements, interoperability between different vendors and standardisation, operational procedures for mixed AC/DC transmission grids, and protection and control schemes for multi-terminal HVDC grids, such as the one envisaged in the North Seas.

Flexible AC Transmission Systems are power electronic based devices that can increase the controllability and flexibility of the transmission system, offering among others fast reactive power support and control of power flows in AC systems.

Electricity storage

Electricity storage can offer a multitude of services in power systems with increasing penetration of LCOE technologies of which a predominant portion is variable RES, including time arbitrage, addressing short-term net demand variability, congestion management and enhanced ancillary services such as very fast Frequency Containment Response. Moreover, coupled with VRE plants they can form almost fully dispatchable virtual power plants facilitating their integration into power markets in which they are subject to full balancing responsibility. Employment of storage devices can greatly enhance the capabilities of microgrids for self-balancing and provision of ancillary services, such as frequency and voltage control.

It is noted that most current forms of electricity storage can address net demand variability in the time-horizons from minutes-hours (e.g. battery storage) to few days at best (e.g. pumped-hydro). Seasonal variations can be addressed only by transformation to other energy carriers (Power-to-Gas, Power-to-Liquid and Power-to-Heat).

The key technological areas of heat production that could benefit from concerted R&D actions are:

- RD&I activities in the field of Virtual Power Plants include identification of ICT needs and development of aggregation algorithms and automatic control, along with the necessary market and regulatory interventions for providing a level-playing field to such market players.
- Enhanced grid observability and controllability - identification of the necessary ICT requirements, integration of IoT, and big data analytics are among the RD&I requirements specific to the digital layer of the emerging smart power systems, along with interoperability and standardisation of communication protocols and cybersecurity.
- A particular field of RD&I work in new transmission technologies is communication of data and information between Transmission System Operators (TSOs), and between TSOs and Distribution System Operators along with the development of respective methodologies for the secure operation of a power system with increased penetration of distributed resources. In parallel, market platforms have to be developed for the trading of ancillary services (e.g. for balancing capacity and energy) in pan-European level on the one hand and for the activation of flexibility by resources that can be connected down to the Low Voltage level on the other.
- RD&I priorities on FACTs include further technological advancements aimed at cost reductions, and operational procedures for coordinated control of FACTs, HVDC links and storage devices in the interconnected European grid.
- Cost reductions on electricity storage, specifically for battery storage. RD&I activities include lifecycle impact depending on ancillary services provided, development of duty-cycle standards, integrated design of battery storage devices and providing a "second life" to automotive batteries for power

system applications. In parallel, significant improvement has to be made, regarding all storage technologies, in developing valid business case models and the necessary regulatory framework accommodating the specific characteristics of storage.

7.3 Heat production (geothermal, solar thermal, biomass for heat and power)

Identifying synergies for R&D for heat production technologies is a challenging task, mainly due the broadness of area covered and peculiarities of the technologies involved. Some heating technologies use different fuels as an energy source. Thus they face challenges stemming from fuel supply and combustion tasks, which need to be solved to increase feasibility of such technologies. Other technologies, such as geothermal or solar heating and cooling, are tapping into other type energy sources, thus the challenges faced are also of the different kind. Nonetheless, some synergies between heat production technologies can be identified in order for coordinated R&D activities to be beneficial to all heating technologies.

The SET-Plan Integrated Roadmap[34] has identified challenges faced by different renewable heating technologies and actions to address them. Some challenges and actions are limited to one particular technology, while others are applicable to a number of cases.

The key technological areas of heat production that could benefit from concerted R&D actions are:

- Technological improvements of materials, components and processes shared by two or more technologies;
- Integration of different technologies in so-called hybrid units;
- Integration of heat generation technologies into small- and large-scale energy systems, such as smart houses and smart grids.

Identified RD&I activities:

- Development of high temperature- and high corrosion resistant heat exchangers. The results of such R&D activity would be beneficial for all heating technologies, such as biomass cogeneration, SHIP (solar heat for industrial processes), geothermal heating and others;
- Development of efficient and reliable systems for cleaning of surfaces of heat exchangers. Research on technological solutions to lower deposit formation could also be beneficial;
- Improvement of geological exploration technologies. Exploration of subsurface imaging is crucial prior to locating drilling targets in the case of geothermal heat extraction [34]. However, development of innovative and cost-effective subsurface imaging tools of investigating down to reservoir depth could benefit other heating technologies as well. The crucial aspect of intermittent heating technologies, such as solar heating, is availability of suitable heat storage. Better identification and qualification of geological sites for long term heat storage could improve market prospects of such technologies;
- The development of a next generation of medium and high temperature collectors. Such collectors would be beneficial for use of solar heat in industry and for solar thermal electricity installations.

Integration of different technologies into hybrid units is identified as a priority action for a number of heat production technologies in the SET-Plan Integrated Roadmap [34]. This could be related to the following concerted R&D actions:

- Development of Solar Compact Hybrid Systems (SCOHYS). Such systems would combine solar and a back-up heating source (based on bioenergy, heat pumps, etc.) focusing on compact, simplified and robust system design. This action should consist of developing simplified water storage, improved hydraulic and safety, and smart controller and monitoring technologies.
- Development of high-efficiency trigeneration/polygeneration systems. Polygeneration technologies might balance daily and seasonal changes in solar energy production and loads of boilers, increasing plant availability, peak load duration and economic performance. R&D activities should address the optimisation of plant design, and the identification of business models for two-way tri-generation and poly-generation energy networks.

- The possibility of combing geothermal, solar and biomass energy to stabilise the combined energy output. In such a case excess heat from latter sources might be injected into the ground thereby keeping a more stable geothermal source temperature in the long term;
- Improvement of operation and maintenance procedures of different heating technologies based on shared experience and vessels and harbour infrastructures.

Integration of heat generation technologies into small- and large-scale energy systems could be addressed through the following joint R&D actions:

- Development of concepts for the operation of a hybrid electric/heating/cooling grid;
- Improvement of heat production system designs and development of operation procedures taking into account challenges of integration into smart houses and smart grids;
- Addressing the challenges of system integration (smart interfaces, new capabilities of equipment, new or improved services to system, forecast). The concerted R&D actions could focus on the development of compact heating systems integrating solar and backup-heater, development of improved control and monitoring concepts by using new ICT technologies (self-learning and self-adapting, using weather forecasts), development of standardized hydraulic and electrical inter-connections between all solar thermal and HVAC-systems of the building and so on.

Bioenergy can have a significant role as a flexible component for heat production. Bioenergy hybrid systems are available in the heating sector, particularly for small scale in residential sector and in the district heating network at larger scale. Integrated bioenergy hybrids can ensure flexible operation for both energy supply and energy storage. Integrated bioenergy hybrids include bioenergy and solar thermal systems; bioenergy and heat pumps; and bioenergy and waste heat recovery. Bioenergy can be used either as a base load producer or to complement other heat sources during peak demand. Further investment in R&D is needed to integrate various bioenergy and other renewables in hybrid heat systems and to achieve process optimisation.

7.4 Power to fuel, CCUS, sustainable advanced biofuels (incl. intermediate bioenergy carriers) and heat and power from biomass

Power to fuel allows using excess power production to store energy in a fuel, which can be used later when demand is higher than supply. The fuel produced can be for instance methane or hydrogen or other liquid fuels, as described in the LCEO Technology Development Report Advanced Alternative Fuels 2018.

7.4.1 Wind and ocean and green hydrogen

Both wind and ocean energy technologies present synergies with other technology sectors. Wave energy farms could be considered for aquaculture, while synergies exist between the wind energy sector and pumped-hydro-storage as well as with hydrogen. Some examples are the WESpe[13] project which researches on wind-hydrogen energy storage or the NIP-H2BER[14] project aimed at developing and operating a wind-hydrogen production facility including a public hydrogen filling station. Some examples of R&D activities in this area are the FhG-ISE sub-project (part of the WESpe project[15]) or PtG250-II[16] (consisting on scheduling a 250 kW power to gas plant with intermittent renewable energy).

Similarly, the SET-plan Implementation Plan for offshore wind energy identifies hydrogen production as one R&D synergy for wind in its priority action for system integration. Moreover, synergies with the oil & gas sector might lead to opportunities to re-use the existing infrastructure (e.g. presence and availability of empty oil and gas fields might give opportunities for energy storage (CAES, H_2), CO_2-storage and other)

7.4.2 Gas purification: R&D synergy between Heat and Power from biomass, hydrogen fuel cells

Traditionally, purification of H_2 and CO_2 streams after the water-gas-shift reactor is performed by solvents, e.g. amines, ammonia, advanced amines (for instance, combined with polymers, with specific coatings),

[13] Funded under the German BMWi programme. Public funding: EUR 3.26 million. Active: 2013-2017
[14] Funded under the German BMWi programme. Public funding: EUR 4.45 million. Active: 2012-2016
[15] Funded under the German BMWi programme. Public funding: 3.91 M€. Active: 2013-2017
[16] Funded under the German BMWi programme. Public funding: 0.6 M€. Active: 2014-2016

potassium carbonate, amino acid with salts, ionic liquids (improved chemical and physical solvents) or by sorbents e.g. calcium oxide, activated carbon, charcoal, sodium carbonate, crystalline materials (such as metal organic frameworks – MOF, and zeolites). Absorption by amines and physical solvents like Rectisol and Selexol, and adsorption by sorbents, are ready for implementation. However, R&D is still on-going on improved separation solvents and sorbents. Membrane technology can also be considered to purify gas streams. Membranes can already be applied in biogas upgrading facilities, so R&D investments to develop low cost and reliable membranes could introduce further benefits for the implementation of this technology.

7.4.3 High temperature electrolysis: R&D synergy between hydrogen fuel cells and nearby heat sources

High temperature, solid oxide electrolysers can co-electrolyse H_2O and CO_2 into H_2, CO and O_2. The syngas may then be used for the production of synthetic fuels. This innovative technology has a low TRL. High temperature electrolysers offer high efficiency compared to low temperature electrolysers so they would ideally be operated in areas with a nearby (waste) heat stream, e.g. from industry or CCUS.

7.4.4 Algae: R&D synergy between sustainable advanced biofuels, heat and power from biomass and CCUS

Utilization of flue gas containing CO_2 for production of algae (both microalgae and macroalgae) can combine CCUS, heat and power from biomass and sustainable advanced biofuels. The produced algae can be converted into gaseous and/or liquid biofuels.

Algae grow optimally at CO_2 concentrations of 15-20% at a temperature 20-35°C. The temperature of flue gases from conventional power plants is around 65-95°C, therefore a cooling step is required. Carbon capture efficiencies of algae might vary between 45-70% in closed cultivation systems and between 25-50% in open systems.

R&D synergies can be identified between CCUS and algae-technologies. These aim of developing innovative system designs that enhance the CO_2 mitigation and growth of algae, while minimizing the operational costs. Major R&D is still needed for technical breakthroughs on microalgae cultivation, harvesting, separation and dewatering processes. Major R&D breakthroughs are still needed to develop viable downstream processing of algae for advanced biofuels production, including pre-treatment/hydrolysis processes, oil extraction and biochemical (anaerobic digestion, fermentation) and thermochemical (pyrolysis, hydrothermal liquefaction) conversion technologies. R&D synergies between algae-technologies and heat and power from biomass exist and anaerobic digestion of algae is a good option, considering the high moisture content of algae. The produced gas has multiple uses for heat and power and biofuels.

7.4.5 Fermentation: R&D synergy between sustainable biofuels, CCUS and hydrogen fuel cells

Fermentation is a wet biomass treatment method taking place at anaerobic conditions, which produces a gas of mainly H_2 and CO_2 of relatively high purity. The separation of these two components can be straightforward, and thus, less expensive than obtaining H_2 and CO_2 from other means. This would lower the operational costs of H_2FC. Particularly for CCU, different CO_2 purity levels are needed for different utilisation processes which may affect their availability and cost. For instance, methanol synthesis should use a quite pure stream, while mineralisation can use a capture method utilising mixed streams. Due to the capture costs in power plants or industrial processes, investors may be attracted by other purer sources, like CO_2 from fermentation instead of incurring the costs of CO_2 capture. The nearly pure CO_2 stream from fermentation processes is an excellent source for the beverage industry. Still, a purification step with a scrubber is essential to remove any odour ingredients that can influence flavour perception. As such, an R&D synergy between CO_2 purification and food science can be identified.

7.4.6 Anaerobic digestion: R&D synergy between heat & power from biomass and sustainable biofuels

Anaerobic digestion is decomposition of (wet) organic material to biogas by bacteria, in anaerobic conditions, and produces a gas that is mainly CH_4, CO_2, and small amounts of other gases. There are pathways for dark fermentation to produce H_2. There are several options for the cleaning and upgrading the biogas to remove the contaminants and CO_2 and to increase the concentration of CH_4. This produces a high CO_2 concentration

gas stream. Several technologies for CH_4 and CO_2 separation, including Pressure Swing Adsorption (PSA), Pressurised Water Scrubbing (PWS), physical scrubbing (e.g. selexol, genosorb), chemical scrubbing using amines (e.g. MEA, DEA), Pressure Swing Adsorption (PSA), cryogenic technologies, and separation through membranes. The produced biomethane could be injected into the natural gas grid for subsequent use in fuel cells, gas engines, turbines or boilers for heat and power or as a fuel in natural gas vehicles.

7.4.7 Gasification: R&D synergies between heat & power from biomass, sustainable biofuels, CCUS and hydrogen fuel cells

Gasification is the thermo-chemical conversion of biomass at high temperature, by partial oxidation, into a fuel gas (syngas), rich in CH_4, CO and H_2 and a range of other non-combustible gases. Gas clean-up is required to reduce contaminant (tars, alkali metals, sulphur, chlorine compounds, heavy metals and particulates) concentrations. The resulting gas can be used for heat and/or electricity production or for synthesis of biofuels, e.g. hydrogen, Fischer-Tropsch diesel, Synthetic Natural Gas (SNG) and chemicals after gas cleaning and upgrading to higher quality gas. R&D on gasification can benefit CCUS, H_2FC, SBF and the application of heat and power systems.

7.4.8 Pyrolysis: R&D synergy between heat & power from biomass and sustainable biofuels

Fast pyrolysis is a thermochemical process that produces mostly bio-oil, along with small amounts of biochar and gases, like hydrogen, carbon monoxide, and carbon dioxide. Bio-oil can be a substitute for fuel oil or diesel for heat and power production, in many applications including boilers, engines and turbines (although some modification of these systems would likely be needed prior to bio-oil use). Besides the heat and power applications, bio-oil can also be upgraded to feedstock for advanced biofuels, converted to fuel additives, to chemical intermediates and final products. Pyrolysis can also be used as a pre-treatment step for gasification and biofuels production. Biorefineries offer considerable scope for integration of fast pyrolysis processes in complex systems such as biorefineries that offer prospects for product utilisation.

7.4.9 Hot gas cleaning: R&D in sustainable biofuels to benefit CCUS, heat & power from biomass and hydrogen fuel cells

Syngas produced from biomass gasification contains several pollutants that may damage downstream equipment and thus require removal or conversion. Some pollutants are common also in flue gases from combustion of other fuels, such as NH_3, sulphur and alkali. Therefore commercial cleaning options are available for these species. Particulate matter removal is also commonly applied in flue gas cleaning trains. However, while flue gases are usually cleaned at low temperatures, in order to obtain high energy and exergetic efficiency, the syngas needs to be cleaned at high temperatures (ideally at ca. 700 – 800 °C). This poses challenges and novel technologies have been implemented for particulate matter removal, such as ceramic candles. Finally, biomass syngas contains large hydrocarbon compounds (called tars) which can create several issues downstream such as erosion, corrosion, catalyst poisoning etc. In order to remove these substances from the hot syngas, R&D is investigating several technologies based on catalytic or thermal cracking. Cleaning requirements for power and heat applications are usually lower than for catalytic processes. The research on syngas cleaning techniques can benefit gas cleaning and purification techniques needed for CCUS, H_2FC and the application of heat and power systems.

7.4.10 Hydrothermal Liquefaction: R&D synergy between Heat & Power from Biomass and sustainable biofuels

HydroThermal Liquefaction (HTL) of a range of wet biomass feedstock in the presence of water at high temperature and pressure produces a liquid bio crude or HTL oil that can be used for heat and power, as a bio-fuel and as a substitute for crude oil for chemical products manufacture. The integration of pyrolysis HTL processes in existing conventional refineries or in biorefineries provides good opportunities for development. R&D is needed to acquire critical process data, to analyse the effects of feedstock type and the operating parameters on crude oil yield and quality, and enable data analysis during biomass conversion into biocrude, for establishing reactor configuration and process validation. The greatest challenge yet to be addressed is to understand the impacts of feedstock composition and process conditions on bio-crude quality. The research on HTL processes can benefit the application of heat and power systems and the development of sustainable advanced biofuels.

7.4.11 Methanol and other alternative fuel production: R&D synergy between electricity grid balance, renewable systems, transport and automotives, chemicals and CCUS

Renewable energy-based electrolytic hydrogen can serve as a chemical storage for renewable electricity. However, "the cost to produce, store, compress, and transport hydrogen is still high".[17] Alternatively, electrical energy can also be stored via the synthesis of methanol from CO_2 and electrolytic hydrogen.

Methanol production from CO_2 usually refers to its potential as fuel. It can be used as a fuel or as a hydrogen carrier, converted into its derivatives or used as a feedstock to synthesise other chemicals such as olefins. As such, R&D synergies will benefit from improvement of catalysts for chemicals production, incentivise improvements in electrolysis and materials science. In this context, synergies can also be identified with automotive and transport industries as engines able to cope with these alternative fuels will need to be developed. When the production of methanol is from hydrogen using renewable energy that cannot be directed to the grid, specific benefits will arise for the overall energy system including addressing the variability of renewable energy systems. In addition to the option of making methanol, CO_2 and electrolytic hydrogen can be combined via methanation to produce methane and a water by-product, or indeed via Fischer-Tropsch synthesis, combined into liquid fuels. Fischer-Tropsch synthesis theoretically can produce a variety of hydrocarbons, including gasoline and diesel fuel.

7.4.12 Other synergies

Recently, the possibility to store both CO_2 and H_2 has been investigated in Austria. The process consists of injection of hydrogen together with the CO_2, creating a sustainable carbon cycle. Over 1 km depth, some microorganisms convert this substance into natural gas, which can be stored in the same geological reservoir. This gas can be withdrawn when is necessary and finally transported to the consumers via pipeline network. The project examining this process is called Underground Sun Conversion is a national project led by Rohöl-Aufsuchungs Aktiengesellschaft (RAG), Austrian universities and research institutes.

Another deployment synergy is the combination of CO_2 Direct Air Capture (DAC) and its storage in basalts. A consortium between the Swiss company Climeworks and EU funded CarbFix2 project is currently running a pilot test where the direct CO_2 capture from the air can be stored in porous basalts in Iceland. The CO_2 can be trapped faster in these rocks, making the storage process more efficient. However, the CO_2 storage assessment using basalts is still unknown in Europe. Only Iceland has made an assessment but the methodology to measure the storage capacity is still not accurate[18] and there is still no consensus in the scientific community to harmonize it. Synergies between DAC can also be identified with CO_2 utilisation for the production of fuels, chemicals and plastics as well as building materials.

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8 Conclusions and Future R&D Directions

This report analyses crosscutting (trans-technology and cross-sectorial) synergies and issues among energy technologies and within the energy system. The two overall objectives are to: 1. identify synergies among R&D topics for LCEO technologies in future H2020/Horizon Europe projects that could either reduce R&D costs or development times, 2. identify technologies that could become bottlenecks in the energy transition.

Nineteen technology experts with different specialities analysed the following topics in order to identify future R&D directions:

1. crosscutting R&D topics of H2020 projects identified the most common areas of studies and their budget;

2. crosscutting R&D topics of H2020 projects were compared with national and international projects in terms of scopes and to detect overlooked areas;

3. key energy technologies for a cost-effective energy transition with the system model JRC-EU-TIMES;

4. expected developments of LCEO technologies to provide grid support services;

5. R&D synergies between LCEO technologies to accelerate development and save research budget.

The main outcomes are summarised below.

1. H2020, national and international R&D projects

- We identified 86 H2020 projects with significant crosscutting components. The analysis of the topics of those H2020 projects compare well with the budgetary indications of the European Technology & Innovation Platforms in Action IV (resilience and security) of the SET-Plan. Especially, the topics of the flagship projects of the ETIP matches well, i.e. the development of an optimised, resilient and energy efficient European power grid, as well as on integrated local and regional energy systems that enables higher share of renewables. The crosscutting activities as defined in ETIP (usage of digitalisation, new regulatory and market approaches, and living labs) appears to have lower representation in the H2020 crosscutting projects.

- Crosscutting international and national projects were also studied. No, distinct differences in scope of H2020 projects compared to international and national projects were identified. For example, they often concern balancing of the grid, smart features, and sector coupling. Nevertheless, some topics of national projects were identified as potential areas for future H2020 projects, e.g.: (A) assessment of challenges and opportunities for SMEs to exploit skills, capabilities and assets to enable the energy transition, (B) use buildings as smart nodes within smart grids that would optimise individually and collectively, (C) develop synergies with industrial sites in collaboration with electricity, gas, water, heat and transport sectors, (D) microgrids as a mean to integrate more VRE, (E) preparation of guides for (small) communities on how to implement renewable energy systems.

- The 86 identified H2020 projects have a total budget of EUR 617 million, which is about 11% of the H2020 budget for energy. This may need to increase due to growing trans-technology/cross-sectorial issues from the large introduction of variable renewables in the future energy system

2. Insights from energy system modelling

- For the decarbonisation scenarios studied we conclude that the sharp rise of both final and indirect uses of electricity can require at least a tripling current total capacity. Electric vehicles, heat pumps (possibly with district heating) push the final use of electricity to new levels. Regarding indirect uses of electricity, much more is required than only the integration of renewables in our current system. Renewables, mainly wind and solar, are used in new ways and provide for example low-carbon hydrogen for vehicles, industries and e-fuels for planes. The production of hydrogen requires investments that are comparable to the investments in solar power. For a zero carbon scenario, the following technologies also require high additional investments: biofuel production (with reuse of all carbon), fuel cells and CO_2 Direct Air Capture.

3. Grid support services from LCEO technologies

- All present LCEO technologies can potentially provide some level grid support services. This report analysed how future LCEO could extend this capability further. Some of the R&D areas identified are: (A) improved sub-optimal production of e.g. wind, solar, from generator point of view to the benefit of the energy system, (B) co-location of generation technologies for more balanced production locally, as well as more efficient land use and less transmission lines, (C) coupling of generation technologies with new types of storages, e.g. aquifer thermal energy storage, (D) hydrogen production through high-temperature electrolysis, as well as hydrogen separation and purification, catalysts, advanced adsorption materials and gas separation membranes, (E) biomass combustion integration with CCUS to provide negative net emissions

4. R&D synergies between LCEO technologies

The analysis of R&D synergies benefitting two or more technologies, either in terms of accelerating development or saving budgets, identified the following areas:

Flexible power (geothermal, hydropower, biomass for heat and power, and CCS)

- better geophysical tools for site characterisation and mapping allowing more accurate identification of geothermal projects and CO_2 storage volumes. Better and cheaper drilling technologies would also benefit geothermal, CCS, and hydropower[19];
- sustainable biomass combustion coupled with carbon capture utilisation and storage is an option potentially leader to negative emissions;
- co-location of technologies, e.g. geothermal and concentrated solar power to allow heat storage in geothermal reservoirs;
- social and environmental impact studies, e.g. carbon capture storages;
- retrofitting procedures for existing plants to increase their flexibility and operating range.

Variable power (wind, solar, ocean)

- improved weather and wave forecasting to enhance predictability of wind, solar, and ocean production;
- co-locating wind and solar PV, as well as wind and wave technologies thereby creating synergies for infrastructure investments, project development, plant performance management, and operation and maintenance procedures;
- development of common platforms for wind and wave as well as solutions for moorings, foundations and anchoring. R&D on materials and coatings able to resist corrosion and biofouling;
- social and environmental impact studies, e.g. social acceptance of new wind and PV;

Power electronics, grid systems and storage

- smart inverters are an integral component of variable renewable technologies, as well as for batteries; to provide enhanced ancillary services such as enhanced synthetic inertia, fast frequency response continued research is needed;
- R&D activities in the field of Virtual Power Plants including identification of ICT needs and development of aggregation algorithms and automatic control, along with the necessary market and regulatory interventions for providing a level-playing field to such market players;
- cost-reduction of electricity storage can power systems with large shares of variable renewables, of many services e.g. time arbitrage, congestion management, addressing time-horizons from minutes and hours to several days.

[19] For advanced tunnelling techniques.

Heat production

- high temperature and high corrosion resistance heat exchangers, as well as improved surface cleaning methods or technical solutions to lower deposit formation;
- development of high-efficiency trigeneration/polygeneration systems with R&D primarily on optimisation of plant design, identification of business models for two-way tri-generation and poly-generation networks.

Power to fuel

- excess power to hydrogen could be important for system integration, for example to help address seasonal variations;
- synergies with gas and oil sectors exist e.g. use of depleted gas fields for storing hydrogen;
- lower cost membrane technology would benefit e.g. biogas upgrading facilities;
- high-temperature, solid oxide electrolysers would be more efficient means of producing hydrogen than today's low temperature electrolysers.

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[35] C. Pérez-Collazo, D. Greaves, and G. Iglesias, "A review of combined wave and offshore wind energy," *Renewable and Sustainable Energy Reviews*, vol. 42. pp. 141–153, 2015.

[36] L. Castro-Santos, E. Martins, and C. Guedes Soares, "Cost assessment methodology for combined wind and wave floating offshore renewable energy systems," *Renew. Energy*, 2016.

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the ocean energy sector," 2018, no. KJ-NA-29315-EN-N (online),KJ-NA-29315-EN-C (print).

[38] U. Magagna, D., Uihlein, "2015 JRC Ocean Energy Status Report," 2015.

[39] EC, "SET-Plan Offshore Wind Implementation Plan," 2018.

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[41] EC, *Study on Challenges in the commercialisation of airborne wind energy systems Draft Final Report*. 2018.

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List of abbreviations and definitions

AWES Airborne Wind Energy Systems

CAES Compressed Air Energy Storage

CCS Carbon Capture and Storage

CCU Carbon Capture Utilisation

CHP Combined Heat and Power

CPI Current Policy Scenario

CSP Concentrated solar power

DSI Demand Side Integration

DES District Energy Systems

EGS Enhanced Geothermal System

EOR Enhance Oil Recovery

ESA European Space Agency

FET Future Emerging Technologies

GHG Greenhouse gas

H2020 Horizon 2020

H_2FC Hydrogen and fuel cells

HSA Hot Sedimentary Aquifer

ICT Information Communications Technology

JTI Joint Technology Initiative

KPI Key Performance Indicator

LCEO Low Carbon Energy Observatory

ORC Organic Rankine Cycle

MSW Municipal Solid Waste

PHS Pumped Hydro Storage

PV Photovoltaic

R&D Research and Development

SET-Plan Strategic Energy Technology Plan

VRE Variable Renewable Energy

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ANNEX I – H2020 trans-technology projects identified

Table 7. H2020 projects identified as either trans-technology and/or cross-sectorial.

Project acronym	Project acronym	Project acronym	Project acronym
MASLOWATEN	Bio-HyPP	ThermoDrill	CABRISS
green.eu	GREEN-WIN	CD-LINKS	CARISMA
TRANSrisk	SENSIBLE	RealValue	ELSA
NOBEL GRID	IndustRE	STORY	Flex4Grid
NETFFICIENT	P2P-SmarTest	FLEXICIENCY	TILOS
CHPM2030	SUN-to-LIQUID	STEELANOL	Riblet4Wind
ORC-PLUS	Cheap-GSHPs	SIM4NEXUS	FORCE
DECISIVE	DAFNE	REFLEX	DESTRESS
REEEM	CryoHub	STOREandGO	UPWAVE
GRIDSOL	FReSMe	ENABLE.EU	GEOCOND
REINVENT	CONNECTING Nature	NATURVATION	EN-SUGI
INNOPATHS	EUCalc	SmILES	PENTAGON
INVADE	Storage4Grid	WiseGRID	SABINA
InteGrid	IntEnSys4EU	FHP	GOFLEX
EnergyKeeper	SMILE	Ambition	inteGRIDy
SHAR-Q	InterFlex	iDistributedPV	Heat-To-Fuel
PUMP-HEAT	DOMINOES	OSMOSE	CROSSBOW
EU-SysFlex	INTERPLAN	RESOLVD	UNITED-GRID
PLANET	Plan4Res	FLEXCoop	MAGNITUDE
Spine	EN SGplusRegSys	SECLI-FIRM	COACCH
AXIS	MUBIC	BlueSCities	GrowSmarter
REMOURBAN	CITYKEYS	ENERWATER	

Annex II – National and international projects

Europe

Germany

The main funding body for energy research on federal level is the Federal Ministry for Economic Affairs and Energy (BMWi). The BMWI is also coordinating the 6th Energy Research Programme defining the current principles and priorities for Federal Government funding for innovative energy technology. In this context, assistance is aimed primarily at technologies that meet the requirements of the energy transition. Key areas are energy efficiency and renewable energy.[20] A broad consultation process was held to develop the 7th energy research programme which will launched in 2018.[21]

The 2018 report on energy research[5] states that during the 6th Energy Research Programme, funding of about EUR 5 billion have been awarded from 2012-2017. The important projects were related to individual technologies (such as wind, solar, H2, fuel cells) and energy efficiency (in industry, services, and buildings). Another main area was energy system analysis and cross-technological research, for example:

- „ENSURE“ is developing and testing new network structures that ensure energy supply also *when* energy production from wind and PV is fluctuating. The project will analyse how central and decentral supply can be combined in a system in an optimal way taking into account technical, economic, environmental and social aspects.
- „P2X“ aims at chemical storage of electricity during power peaks through electrolysis. H2 and synthesis gas will be produced and the project will assess how the synthesis gas can be converted to chemicals later.
- „Carbon2Chem“, consists of major companies from chemical, steel, energy and automotive sectors and will reduce emissions from the steel industry. The gases from the steelmaking process will be used as a raw material for chemical production.
- „SynErgie“ will help to make energy demand of industry more flexible in order to align electricity use with volatile supply. Technological possibilities for flexibility will be identified and demonstrated. Energy intensive processes will be managed intelligently and automatically so that electricity networks will be stabilised and larger share of renewables can be accommodated.

enArgus is a central portal providing information about all energy research projects in Germany funded by the BMWi, the BMBF (Federal Ministry of Education and Research) and BMVI (Federal Ministry for Transport and Digital Infrastructure).

www.enargus.de

[20] https://www.bmwi.de/Redaktion/EN/Artikel/Energy/research-for-an-ecological-reliable-and-affordable-power-supply.html

[21] http://www.energieforschung.de/

A search for "Synergie" on enArgus delivered more than 2000 projects of which 403 were starting in 2017 and later. The vast majority of those projects received funding of about EUR 100 000 to 500 000 (223 projects). 6 projects received more than EUR 2 million.

Table 8: Energy research projects that have started in 2017 and later and have received funding of above EUR 2 million. Source: enArgus Project name	Funding	Date	Topic
Verbundvorhaben: Begleitforschung Energiewende im Verkehr ' Teilvorhaben: Koordination, Systemanalyse, Technikbewertung, Schadstoffe und Klima	4 939 737	2018-06 to 2022-05	The main aim of this project (which is part of a larger project "Verbundvorhaben)" is to create a network of the project teams within the Verbundvorhaben as well as to ensure communication with ministries, experts, and stakeholders. The project will organise workshops and conferences. It will also ensure comparability and coherence of research results. Furthermore, an important aspect of the project is systems analysis and technology assessment
Verbundprojekt: Wärmedrehscheibe II - Erneuerbare Fernwärme 2020 - das multifunktionale Fernwärmenetz als Wärmedrehscheibe; TV: Phase 2- Umsetzung	3 052 768	2017-10 to 2022-09	The project will increase the share of renewable heating in the district heating network of Hennigsdorf to 80 %. This will be achieved by using industrial and commercial waste heat, the use of solar thermal energy and the optimisation of existing CHP plants using renewables.
Verbundvorhaben EnStadt: Pfaff EnergieIKT Implementierung des Reallabors Pfaff-Areal Kaiserslautern - Integrierte Konzepte, innovative Technologien und sozialwissen-schaftliche Forschung im Leuchtturm für klimaneutrale Quartiere	8 981 265	2017-10 to 2022-09	The city of Kaiserslautern is currently planning to build a climate-neutral new city quarter on the area of an old industrial terrain. A joint project (Verbundvorhaben) will research and develop the concepts for the planning and construction of the quarter. This lighthouse project (part of the Verbundvorhaben) will inform experts and the public about innovative smart city concepts by using simulation tools, interactive expositions, and virtual reality devices. Participatory approaches for including all actors are being developed as well..
Verbundvorhaben EnStadt:Pfaff; Implementierung des Reallabors Pfaff-Areal Kaiserslautern ' Integrierte Konzepte, innovative Technologien und sozialwissenschaftliche Forschung im Leuchtturm für klimaneutrale Quartiere; Teilvorhaben EnStadt:Pfaff ' SWK Smart Grid	3 643 409	2017-10 to 2022-09	This part of the joint project will research, develop and demonstrate innovative planning tools and technologies in the sectors energy, building, electric mobility and ICT. The project will us the quarter as a "real lab" to develop, test and optimise the tools, components, systems and services as well as business models. Co-design and co-creation will be deployed as much as possible.
Verbundvorhaben: C/sells - Das Energiesystem der Zukunft im Sonnenbogen Süddeutschlands; Teilvorhaben: Techno-ökonomische-Forschung zu Märkten, Netzen und Prosumern in einem zukünftigen Energieversorgungssystem	7 331 864	2017-01 to 2020-12	The joint project C/sells will develop and test a large scale cellular energy system with high shares of renewables for a climate friendly, efficiency and secure energy supply.
Deutsch-Französisches Fellowship-Programm in der Klima-, Energie- und Erdsystemforschung im Rahmen der französischen Initiative 'Make our Planet Great Again' - Teilprojekt Energieforschung	4 990 277	2017-09 to 2022-12	Exchange program with France in the framework of “Make our planet great again“. This program is focusing on excellent researchers in the area of climate and energy.

UK

The energy policy of the UK is set out in the Energy White Paper of 2007 and Low Carbon Transition plan of 2009. The current focus is on reforming the electricity market, rolling out smart meters and improving energy efficiency of UK building stock. Important British projects on trans-technology and cross-sectorial topics are:

Energy systems at multiple scales of UKERC

The UK Energy Research Centre (UKERC) is funded under the Research Councils' energy programme to perform whole system interdisciplinary energy research, and act as a central hub for university based research in the UK.

The UKERC programme on Energy Systems at Multiple Scales addresses the challenges from introduction of VRE. The solutions studied are e.g. greater use of demand side management and storage for balancing, expansion of continental networks, and sharing of reserve facilities between greater numbers of users. The programme operates two projects relevant for this report: 1. Modelling spatial & temporal diversity, with the objective to analyse the value and impact of energy storage facilities, demand side management and energy network capacity; 2. Impact of variability of renewable energy, has the objective to model energy balancing in Britain arising from demand for both electricity and heat and the generation of electricity. It especially studies the impact of wind variability on the gas system and the potential for demand side and interconnector contributions to system balancing; [6].

Smart City – Intelligent energy integration for London's decentralised energy projects[22]

The objective of the project is to understand and demonstrate the role that smart systems could play in decentralised energy production, transmission and distribution in London and the management of energy demand. It is about an efficient urban energy system capable of heat storage, electricity demand-side management and active network management providing electricity generating capacity when required to support the electricity distribution network.

It also considers how intelligent energy systems might evolve in London until 2050, the key technologies that would be deployed, and the organisational structure and key actors required to support an intelligent and integrated energy system.

Multi-energy vector integration innovation opportunities of CATAPULT Energy Systems[23]

The project assesses the challenges and opportunities for SMEs to exploit their skills, capabilities and assets to enable a future multi-vector energy system. It aims to provide an understanding of where the opportunities arising from increased multi-energy vector integration exists, a methodological approach was adopted which included a landscape review, stakeholder engagement activity and analysis of three multi-vector case studies.

A number of cross-cutting innovation themes emerged across the multi-vector energy studies considered: 1. novel system control approaches, 2. software development, and 3. aggregation services and associated business models.

Integrated Development of Low-.Carbon Energy Systems: A Whole-System Paradigm for Creating a National Strategy[24]

This project of Imperial College London is aimed at providing evidence and data needed to ensure that the country can build a low-carbon future. The energy systems integration looks across electricity, heating, cooling and transport. It thinks about the service needs that determine energy use, a more effective and efficient system. It studies power to hydrogen to decarbonise the gas grid or power to charge electric batteries, which later can provide balancing powers to the electricity grid. Eventually a suite of software tools is prepared to examine possible futures for the UK's energy system, as well as provides policy advice on how to make each option a reality and insights into the technologies that will be needed to support it.

Best paths - Beyond State-of-the-Art Technologies for Power AC Corridors Multi-Terminal HVDC Systems[25]

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22 https://www.london.gov.uk/sites/default/files/gla_migrate_files_destination/Smart%20City%20Intelligent%20Energy%20Opportunities_0.pdf

23 https://es.catapult.org.uk/publications/multi-energy-vector-integration-innovation-opportunities/

24 https://www.imperial.ac.uk/news/187751/designing-uks-low-carbon-integrated-energy-system/

25 https://www.cardiff.ac.uk/research/explore/research-units/centre-for-integrated-renewable-energy-generation-and-supply

The Best Paths project should develop high-level control algorithms for HVDC converters as a path of an open-access simulation toolbox for wind farms. It will analyse and report the performance of HVDC-connected wind farms during steady-state, transient and fault conditions. Finally it contributes to the development of a 50 kW laboratory-scale demonstrator for HVDC-connected offshore wind farms under construction in SINTEF Norway.

France

Convertisseur d'énergie intégré intelligent (CE2I)[26]

The project aims at applying intelligent machines and to integrate conversion by electro-mechanical, electro-electrical and control while respecting constraints of size, emissions, functional and structural reliability and eco-efficiency. Existing infrastructure of power electronics and rotating parts have problems with reliability. The use of fast electronic components is expected to mitigate the problem. The applications include cars, ships, and power production.

Chaire « Smart Buildings as nodes of Smart Grids (SBnodesSG)[27]

This project aims to explore the potential of smart buildings as "smart nodes" within smart grids. In the SBnodesSG, the buildings will become active participants in the energy ecosystem, beyond the simple service to the smart grid. They will both optimise individually and collectively in real-time interaction with the occupants and become the nodes of the new smart grid, especially electrical networks, heat or gas networks. The project also aims at optimising the energy consumption of information technologies. Carbon-free local production (e.g. solar PV) will be added to the buildings.

Micro-réseau électrique intelligent (microgrid) intégré au bâtiment[28]

The AC and DC microgrids are studied as a mean to integrate more renewable energy sources in the public grid. A systemic approach is adopted to study the interfaces and controls adapted to each mode of operation and specific intermittent aspects. The system proposed uses a consumer-producer incorporating solar PV, storage, grid connection and loads. The micro-grid incorporate vehicle-to-grid, vehicle-to-home, and infrastructure-to-home strategies, and thus offers new services in the urban space.

Ecotechn'hom[29]

This project aims to develop a synergistic, technological and sustainable management of industrial sites harmonised with its territorial and urban environment in collaboration with various network managers (electricity, gas, water, heat, transport, ICT).

This includes the creation of circular and aggregated management of energy, waste and transport between the entities of the site, and complementary entities to integrate for more synergies, e.g. storage, as well as changing behaviours by awareness-raising actions.

The objective of the project is to reduce the energy bill of the industrial site by 20% in 3 years and 50% in 10 years. Then the know-how developed should be transferred to 10 other industrial sites in the next five years.

Scandinavian countries

Renewable energy supply and storage: Guide for planners and developers in sparsely populated areas[30]

Aims at helping small communities to overcome the challenges associated with implementing renewable energy systems. The guide provides information about how to develop affordable, and reliable, renewable energy projects, using off-the-shelf technologies. The guide is designed to be highly adaptable, and it provides formulas for calculating the costs and benefits of particular energy and heating systems based on the need for the community. It answers questions like if it is better to store energy in insulated water tanks or in electricity batteries.

Flex4RES[31]

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[26] http://rev3-energie.fr/project/convertisseur-denergie-integre-intelligent-ce2i/
[27] http://rev3-energie.fr/project/chaire-smart-buildings-as-nodes-of-smart-grids-sbnodessg/
[28] http://rev3-energie.fr/project/micro-reseau-electrique-intelligent-microgrid-integre-batiment-infrastructure-urbaine-dediee-a-recharge-vehicules-electriques-ves
[29] http://vallee-energie.com/les-projets-structurants.html
[30] http://www.nordicenergy.org/project/renewable-energy/

Flex4RES will demonstrate how high shares of variable renewable energy can be efficiently integrated into the energy system through a stronger coupling of energy markets across Nordic and Baltic regions. It investigates how an intensified interaction between coupled energy markets, supported by coherent regulatory frameworks, can facilitate the integration of high shares of VRE, in turn ensuring stable, sustainable and cost-efficient Nordic energy systems. Pathways towards coherent and flexible energy systems encompassing electricity, heat, gas, and transport sectors are identified by combining technical analysis of flexibility potentials, economic analysis of markets and regulatory frameworks, and energy system modelling quantifying impacts.

Facilitating resilient power system with ancillary services from Renewable Power Plants[32]

The overall objective of this project is to contribute to the integration of large share of renewable energy in the Danish power by developing technical solutions for the provision of ancillary services by renewable power plants. Investigation of ancillary services, coordinated control, fast communication and forecast of available power are crucial steps toward a resilient power system.

The novelty of RePlan consists in the investigation and verification of: 1) the ancillary services provision from wind power and solar PV plants and 2) the suitability to coordinate their services provision to power system operator. In this respect, RePlan strives to anticipate new challenges and exploring some of the more complex issues and uncertainties related to the coordination of ancillary services.

SEMI – Sustainable Energy Market Integration[33]

This project aims to design the new market mechanism for the future Danish energy systems. It focuses on three areas: 1) interaction and unification of gas and electricity wholesale market, 2) the dynamic management of flexible sources for the integrated distribution systems to participate in the short-term market, 3) to develop business models for the optimal investment in the emerging technologies to enhance the synergies between multiple energy systems. The major deliverable will be the market models for the Danish energy system transition towards fossil-fuel free.

Global projects

USA

Energy Systems Integration Facility of NREL (National Renewable Energy Laboratory)[34]

NREL has the Energy Systems Integration Facility which has the following capabilities:

- mega-watt scale power hardware-in-the-loop simulation capability to test grid scenarios with high penetration of renewable energy;
- interconnectivity to external field sites for data feeds and model validation;
- virtual utility operations centre;
- smart grid testing lab for advanced communications control;
- multiple parallel alternating and direct current experimental busses with grid simulations and loads.

[31] http://www.nordicenergy.org/flagship/flex4res/
[32] http://vbn.aau.dk/en/projects/replan--facilitating-resilient-power-system-with-ancillary-services-from-renewable-power-plants(c63ce8ca-4244-4dca-973c-814c10a9f44c).html
[33] http://vbn.aau.dk/en/projects/semi--sustainable-energy-market-integration(9a2eaceb-39de-43ae-8b47-83e749c30306).html
[34] https://www.nrel.gov/esif/research.html

In addition, NREL's renewable resource management and forecasting research focuses on measuring weather resources and power systems, and converting these into operational intelligence. In the coming five years they will see further integration of power with simulations run on high-performance computers, which enable evaluation of large deployments of new technologies and control systems across cities and larger regions.

The Cities Leading Through Energy Analysis and Planning (Cities-LEAP) of US DOE[35]

The project delivers standardised, localised energy data and analysis that enables cities to lead clean energy innovation and integrate strategic energy analysis into decision making. The project allows cities to:

- set climate and energy goals;
- prioritise and implement energy strategies;
- see impacts of potential climate and energy action plans;
- learn from peers about city energy planning best practices;
- get access to credible data and transparent, usable analytic methodologies;
- make data-driven energy decisions.

Three teams led by local governments have been selected to develop and pilot data-driven decision frameworks. The frameworks are developed together with academic institutions, technology companies, utilities, regional planning bodies, and non-governmental organisations.

Energy modelling, analysis & control (University of Berkeley)

Questions studied by the project are: (1) how future power systems can be made sufficiently flexible to accommodate very large penetrations of wind and solar generation; (2) how distributed renewable electricity generation impact of low voltage power systems; (3) value of energy storage in large-scale power system; (4) identify energy efficiency opportunities with electricity consumption data alone.

The work focuses on building new control and optimisation frameworks to facilitate the operation of low carbon grids, especially electricity consumption and solar production data.

UCLA (University of California, Los Angeles)

At UCLA renewable forecast engines are being developed that span the whole spectrum of temporal horizons and spatial resolutions, from intra-minute to multiple day-ahead forecasts. [42]

The goal of renewable systems integration is to remove barriers to wind energy integration. To find innovative ways to couple renewable energy technologies and accelerate deployment. This is achieved through integration studies, modelling, demonstrations, and assessments at both transmission and distribution levels, coupled with working directly with utilities to help ensure adoption of best practices.

New distributed devices and systems will help deliver the flexibility by the future grid for managing VRE, engaging customers, and enhancing reliability and resiliency while keep electricity affordable.

Brazil

Brazil has ambition to reduce 43% of GHG by 2030 (2005 level) and has natural resources for it, also it has a dynamic market for renewable energy and large possibilities for synergies between different renewable technologies. In 2002, the Brazilian government created the PROINFA, a programme to stimulate the use of alternative renewable energy sources such as small hydro, wind and biomass[36]

Since the main source of energy in Brazil (72%, MME. 2018) is hydro, synergies with wind and solar (both in accelerated development, see figure below) are possible to reduce costs and keep the production. Studies have shown that photovoltaic solar panels can be installed at the same place as wind turbines, creating a more stable energy mix. This complementarity is currently being used in the northeast Brazil.

Another complementarity with hydro is being carried via biomass and follows the seasonal energy generation. This is mainly used the southeast Brazil (the biggest industrial region in Brazil.

[35] https://www.energy.gov/eere/analysis/cities-leading-through-energy-analysis-and-planning-cities-leap-demonstration-projects
[36] ANEEL (Agência Nacional de Energia Elétrica). 2018 website. http://www.aneel.gov.br/a-aneel

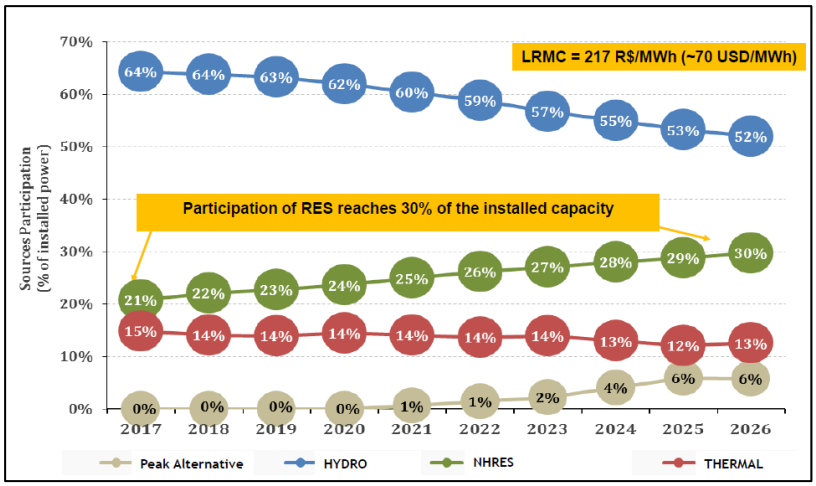

Figure- An outlook of the Brazilian energy matrix in 10 years horizon.[37]

BECCS or bio CCS is also another clean technology synergy in development, especially from sugar-cane based ethanol production, the most important bioenergy source in Brazil and currently contributing with 17.2% of the renewable energy in the Brazilian energy matrix. However this combined bio CCS is still in R&D phase, currently some sugar mills in the northeast region have installed a system to capture CO_2 from the fermentation and then to use as gas for the industrial applications.

The integration between hydro, wind, solar and biomass creates a balance in the Brazilian transmission grid and serves to modulate the seasonal production of biomass and the fluctuations of wind power and solar. A system of energy "warehouses" is then created in the hydropower plants to store the different sources of energy.

The projected energy mix in a 100% scenario of renewable in 2050 for Brazil[38] (Statista, 2018) is that solar energy will contribute with 42%, offshore wind energy 17% and hydro 11.5%.

International projects

IEA

The IEA does work on system integration of renewables. Several reports were published on this topic, e.g. (1) Re-powering markets which analyses the market framework for low-carbon power systems and the balance that policy makers must strike between supporting innovation and competition while at the same time mobilising capital, (2) Status report of power system transformation 2018 provides an overview of how power plants provides flexibility and improves energy security.

IRENA (International Renewable Energy Agency)

The energy transition pathways in Remap. The Power Sector Transformation team studies topics like how to plan for capacity expansion, ensuring reliable system operation and

[37] EPE (Empresa de Pesquisa Energética). 2018. http://www.epe.gov.br/pt
[38] STATISTA. 2018. https://www.statista.com

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