Integrated SET Plan

CETP

Clean Energy Transition Partnership

Input Paper to the

Strategic Research and Innovation Agenda

Renewables Technologies

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

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1 Introduction

The Clean Energy Transition partnership will accelerate the transition towards a zero-carbon, flexible, sustainable, reliable and affordable energy system and its clean technologies through targeted transnational research, innovation and demonstration actions. The value of the technology specific research will boost the energy transition and will go beyond joint calls, representing a European knowledge community on energy transition and inspire learning and policies for implementation across technologies.

The partnership will address different challenges where new research is needed to enable the industry, consumers, and policy makers to take the decisions needed for driving the transition forward. Technology research is important for finding a low cost and feasible pathway for transition that is just and secure for the different regions and Europe as a whole.

This input-paper points especially to relevant technology-oriented research that will benefit from the coordination and joint effort that the Clean Energy Transition Partnership represents. Increasing the development rate reducing the time spend going from research-to-market is needed for solving the transition challenge fast enough and at lowest possible costs. The ambition of this paper is to focus on technology relevant research, but it also points toward what joint research that provides needed knowledge and competence for the accelerating the clean energy transition., as illustrated in Figure 1.

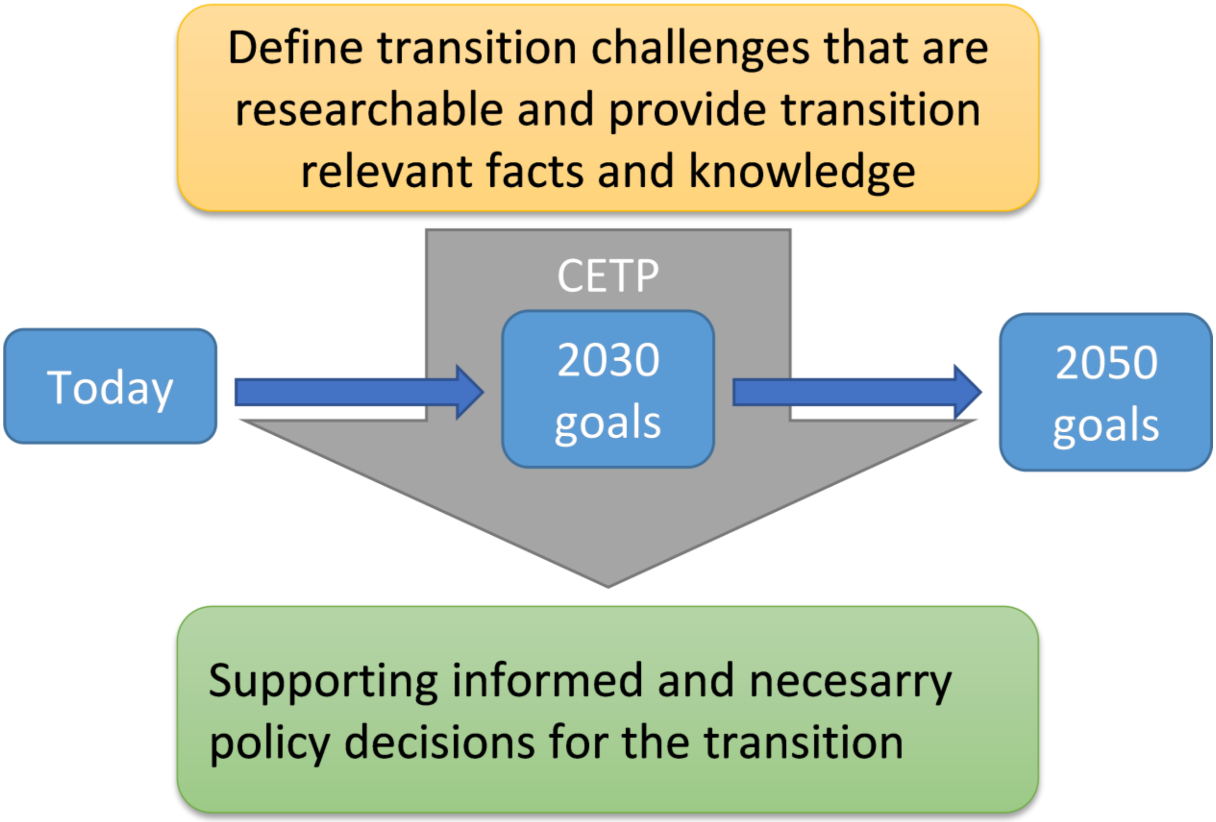

Figure 1. Role of CETP in the transition

As shown in the figure the focus in CETP is on the goals, ex mix of technologies and solutions that defines the energy system of 2050 respecting the dynamics of transition with different goals for the different steps. The main purpose of the CETP is not only to find the optimal technology mix in 2050 but to deliver relevant results that transformed into policy facilitate a just, fair and inclusive transition to this future goal. As a consequence the technology relevant challenges proposed will be put into system level perspective by the other input papers. Technology and system level research must be combined when addressing the challenge of the climate-neutral energy system.

1.1 Organisation of this Paper

In the introduction the paper points to the relation between the technology research and the objectives and challenges of the energy transition, which is exactly what will be facilitated by the CETP. The benefit of the partnership is to do research together on and across technologies when solving the holistic and cross-sectional challenges of the energy transition.

A summary of the recommended research challenges to be solved can be found in Chapter 2 of the paper, while Table 1 below list the headings of the different challenges developed by the authors and co-authors for the different technology chapters.

The technology research is important and closely related to research related to the system level transition challenges as described in the introduction but there is in particular one challenge that is elaborated further in this paper and that is the challenge of a climate-neutral energy system. This can be found in chapter 3.

The selected transition enabling technologies are described in individual chapters. In these chapters the reader can find valuable details about the proposed research, definition of the research frontier and the impact from the proposed research. This input paper is a summary that helps the reader to see the larger lines in the proposed research while keeping track of the specific research challenges for the individual technologies. The aim is that this perspective will provide the understanding how the Clean Energy Transition Partnership can help solving these challenges within the context of the objectives of the energy transition. The different enabling technologies are by nature very different, but they have the same need for a common framework that allows them to exploit their capabilities to the fullest. Despite the differences it will also be important for different technologies to exploit synergies across common vectors as circularity, digitalization as well as technology components such as energy storage solutions. Relation between Technologies and the Energy Transition

It must be remembered that the Clean Energy Transition Partnership is more than individual technologies. The technologies are the enabler of the energy transition providing the solutions to the system level challenges that must be tackled as well. The energy transition must be just and affordable and it must be swift as the urgency to contain the climate change within acceptable limits is increasing. It is imperative that Europe leads and stays in front of the green transition and uses it for creating new jobs and improving everyday living and our society. Therefore, the paper for each technology chapter describes how it impacts and contributes to solve the systemic challenges most relevant for this technology. This varies from technology to technology. In practise this means that research for solving a system level challenge should take care to consider and include links to relevant technologies and technology research and likewise the technology research must consider its relevance in a broader perspective to find its optimal role and contribution to the transition.

In addition, there also exist cross-cutting challenges for the technologies where coordination will reduce double work and costs as the research can learn from and re-use research across technologies and scientific fields of interest. The technology chapters describe how they relate to the relevant cross-cutting challenges.

One strength of the partnership is to exploit the possibility to learn from research on different technologies. In this first phase of the partnership work we have asked the different technologies what research that are especially important for that technology to expand and fully utilize its potential in the transition. In future work it will be possible to focus more on but one-to-one synergies between the technologies as well as synergies between and within groups of technologies. Many of these synergies will be easier to see, rank and implement once the partnership has started and the cross-technology competence and understanding has increased.

TABLE 1: Identified challenge by stakeholders		
CH1.1 Concentrated Solar Power **(link)**	CH1.1.1	Central Receiver and Line-Focusing power plants with lower LCOE
	CH1.1.2	Reliable and cost-effective medium and high-temperature thermal storage systems.
	CH1.1.3	Turbo-machinery developed for specific conditions of solar thermal power plants.
	CH1.1.4	Reliable and cost-effective solar fuels production.
CH1.2 Photovoltaics (link)	CH1.2.1	Powering the energy transition
	CH1.2.2	Supporting economic recovery and building the Strategic Value Chains for renewables (i.c. PV)
CH1.3 Offshore Wind (link)	CH1.3.1	Improved Wind Turbine Technology
	CH1.3.2	Offshore Wind Farms & Systems Integration
	CH1.3.3	Floating Offshore Wind & Wind Energy O&M and Industrialisation
	CH1.3.4	Ecosystem, Social Impact & Human Capital Agenda
	CH1.3.5	Basic Wind Energy Sciences for Offshore Wind
CH1.4 Onshore Wind (link)	CH1.4.1	Wind Turbine Technology
	CH1.4.2	Grid & Systems Integration
	CH1.4.3	Wind Energy Operation, Maintenance & Installation
	CH1.4.4	Ecosystem, Social Impact & Human Capital Agenda
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	CH1.5.2	Role of geothermal electricity and heating & cooling in the energy system responding to grid and network demands
	CH1.5.3	Improvement of overall geothermal energy conversion performance for electricity production, heating & cooling
	CH1.5.4	Develop full reinjection electric and heating & cooling plants integrated in the circular economy
	CH1.5.5	Methods, processes, equipment and materials to ensure the steady availability of the geothermal resources and improve the performance of the operating facilities
	CH1.5.6	Development of geothermal resources in a wide range of geological settings
	CH1.5.7	Advanced drilling/well completion techniques
	CH1.5.8	Innovative exploration techniques for resource assessment and drilling target definition
CH1.6 Bioenergy (link)	CH1.6.1	Sustainable carbon for the globe
	CH1.6.2	Integration of biomass to future sustainable energy system
CH1.7 Carbon Capture Utilisation & Storage **(link)**	CH1.7.1	Getting the commercial framework right
	CH1.7.2	Accelerating timely deployment at scale of CCS and CCU technologies
	CH1.7.3	Driving costs down – through R&I, learning by doing and economies of scale
	CH1.7.4	Enabling rapid scale-up to deliver on the climate goals
	CH1.7.5	Enabling EU citizens to make informed choices regarding the benefits that CCS and CCU bring
	CH1.7.6	Production, optimisation and integration of blue hydrogen with CCUS
CH1.8 Ocean Energy (link)	CH1.8.1	Design and Validation of Ocean Energy Devices
	CH1.8.2	Foundations, Connections and Mooring

	CH1.8.3	Logistics and Marine Operations
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CH1.9 Hydropower (link)	CH1.9.1	Increased flexibility from hydropower plants
	CH1.9.2	Utilization and expansion of European hydropower's storage capacity
	CH1.9.3	Markets and services for hydropower's
	CH1.9.4	Environmental design
	CH1.9.5	Social acceptance
	CH1.9.6	Basic Hydropower Sciences
CH1.10 Solar Thermal Heating & Cooling (link)	CH1.10.1	Solar District Heating (SDH)
	CH1.10.2	Solar Heat for Industrial Processes (SHIP)
	CH1.10.3	Solar thermal use in buildings
	CH1.10.4	Financing/business models for solar thermal

2 Overview of Challenges

This chapter is a summary of the main challenges defined in the technology chapters, but also the challenges defined for how to include and utilise the technologies in the energy transition and a climate-neutral energy system. More details about the proposed research can be found in the respective chapters in the annex.

This input paper describe research to enable a low-cost energy transition with early emission reductions and large industrial potential for a set of technologies. The technologies are: Concentrated Solar Power (CSP), Photovoltaic (PV), Offshore Wind, Onshore Wind, Geothermal energy, Bioenergy. Carbon Capture Utilization and Storage (CCUS), Ocean Energy, Hydropower and Solar Heating & Cooling. What binds them together is their connection to energy. The capabilities of these technologies as enablers in the clean energy transition is different. Some can deliver energy; some can provide energy and storage; while other can provide a carbon sink or even both be carbon sink and deliver energy.

The selected technologies are not the only enabling technologies in the energy transition, some of the obvious ones not mentioned are storage technologies such as: batteries, hydrogen, and compressed air, but also the technology that will enable a more flexible demand, technologies adding to the electrification and a cleaner industry with power-to-x. In the end it is the combination and the interplay between all these technologies that though fair competition will create green jobs, affordable energy, energy security resulting in a competitive Europe driving the energy transition forward.

2.1 Enabling Technology: Concentrated Solar Power

Expected impact:

CSP plants need to reduce their electricity cost (LCOE) to become more competitive with other renewables (i.e., wind and PV) or develop hybrid solutions in combination with other technologies. Specific targeted impacts to achieve this objective are:

- LCOE reduction of CSP technology to 0,09 EUR/kWh in Southern Europe locations (around 2050 kWh/m^2/year), without any additional constraint by 2025, targeting 0,08 EUR/kWh by 2030, providing competitive dispatchable solar power (e. g. during night).
- Feasibility of novel material approaches via validation in lab or demonstration in relevant environment (liquid, solid, PCM or TCS media).

- Cheaper thermal energy storages achieving, by 2030, at least 10% of heat consumed in industrial processes in Europe delivered through concentrated solar technologies.
- Thermal energy cost ≤ 0.03 EUR/kWh (T<400ºC, small scale applications) and ≤ 0.02 EUR/kWh (T>600ºC, large scale applications).
- Demonstration of H_2 solar thermal production viability (target cost of 3 €/kg H_2 by 2030).

Identified Challenges

CH1.1.1 Central Receiver and Line-Focusing power plants with lower LCOE

- Advanced heat transfer fluids for higher working temperatures.
- Receivers for average solar fluxes > 1MW/m^2 and T >600ºC, with efficiency > 85%.
- Self-calibrating and cheaper heliostats, below 90 EUR/m^2 (installed).
- Components with lower maintenance cost and longer life time (*see CC challenge 5, circularity*).
- High precision heliostat field and automated control for long focal distance and/or high temperature applications up to 1200°C.
- Innovative plant configurations achieving better use of solar energy resource
- Cheaper line-focusing collector designs.

CH1.1.2 Reliable and cost-effective medium and high-temperature thermal storage systems.

- Thermal storage systems and materials for T < 550°C with improved cost effectiveness.
- Suitable thermal storage systems and materials for T > 600ºC and T > 750ºC, with investment cost < 15 EUR/kWh.
- Suitable and cost-effective PCM thermal storage systems for 200–300ºC.
- Cost-effective and highly autonomous medium- and high temperature systems for industrial solar heat applications.
- Autonomous and smart solar fields, providing solutions to satisfy 24h operation.
- Collector designs with investment cost <400 EUR/m2 for small line-focus solar fields.
- More reliable and cost-effective receiver tubes (even non-evacuated).
- Cost-effective polygeneration solar systems, including hybridization by integrating power generation from the produced industrial heat or from waste heat (*see CC challenge 5, circularity*).

CH1.1.3 Turbo-machinery developed for specific conditions of solar thermal power plants.

- Specific steam turbine developed for CSP applications (< 200MW).
- Supercritical CO_2 turbomachinery.

CH1.1.4 Reliable and cost-effective solar fuels production.

- Suitable high temperature (600-1000°C) receivers adapted to fuel production.
- Innovative fuel production processes.
- Materials and functional materials for increased robustness, efficiency and durability (*see CC challenge 5, circularity*).

You can find a more detailed description of the above-mentioned challenges in Annex 1.

2.2 Enabling Technology: Photovoltaic (PV)

Expected impact:

The proposed research related to photovoltaic solar energy (PV) will enable and facilitate large-scale deployment of PV and generation of renewable electricity, which is a cornerstone of the future sustainable energy system. This supports realizing policy goals for emission reduction in the short, medium and long term. Moreover, the research will help seizing the economic opportunities related to the energy transition by providing the basis for a highly innovative and globally competitive European PV industry sector over the entire value chain.

The challenges to be addressed in relation to photovoltaic solar energy (PV) can be divided into three clusters, which relate to the PV technology and its deployment, to the PV industry sector, and to energy system and cross-cutting issues, respectively:

Identified Challenges

CH 1.2.1 Powering the energy transition

Renewable electricity is a cornerstone of the global and European sustainable energy system of the future. Solar energy and wind energy are key technologies to make electricity available in large quantities, at affordable cost and in an environmentally and societally sustainable way. To enable this, energy system integration (including storage and P2X) and thus further reduction of generation cost and enhanced flexibility and diversification are needed, as well as integration into our living environment and circularity in all parts of the value chain.

Underlying Challenges are:

- Performance enhancement at module (silicon, thin films, tandems) and Balance-of System/system levels, for efficient use of available areas and as lever for cost reduction;
- Cost reduction at component, system and LCoE levels, in particular to enable large-scale deployment of integrated PV applications, storage and solar Power2X;
- Further enhance lifetime, quality and reliability, safety and so sustainability (*see CC challenge 5, circularity*);
- Flexible solutions for PV integration (buildings, infrastructures, vehicles, landscapes, etc.) and for floating PV, based on modules/ foils and semi-fabricates.

CH 1.2.2 Supporting economic recovery and building the value chains for renewables (i.c. PV)

Achieving the aim of the Green Deal to make Europe's economy sustainable offers great opportunities to support economic recovery from the crisis and to build the strategically important value chains of renewables, including PV solar energy. For the EU industry to be successful in the global competition, excellent technology and rapid innovation are essential. These are proven strengths of the EU PV ecosystem that have to be ambitiously developed further, jointly between research and industry and between member states.

Underlying Challenges are:

- The Challenges for Cluster 1 are also key for this Cluster, but an additional Challenge is:
- Advanced industrial technologies and manufacturing concepts for the PV value chain ('PV made in Europe').

Cross-cutting and system level challenges that are also important for PV

- Implementing Industry 4.0 concepts;
- Societal acceptance and participation;
- Options for flexibility and electrification;
- Energy and electricity market design.

You can find a more detailed description of the above-mentioned challenges in Annex 2.

2.3 Enabling Technology: Offshore Wind

Offshore wind is positioned to fuel Europe's energy transition. Targeted R&I support will strengthen the leading role of the European industry in the global market and can lead to the development of a 450 GW offshore wind sector.

Expected impact

- Offshore wind turbines will grow in size to 20-30 MW leading to further cost reduction and improved system integration.
- By technology development and cooperation with storage solutions offshore wind farms will be able to deliver power on demand.
- By sector coupling the massive amount of offshore wind energy will be the backbone to produce bulk renewable hydrogen.
- In 2050 the yearly investments in European offshore wind is around €45bn.
- In 2050 there will be 454,000-608,000 green jobs related to European onshore and offshore wind.

Ambition

- Implementation of offshore wind power requires positive business cases: increasing the market value and reduction of cost of electricity and reduced uncertainties of revenue.
- Improved wind turbine technology leading to lower cost and improved system integration.
- Sector coupling for uptake of the massive amount of offshore wind power: production of renewable hydrogen and electrification of the industry is an urgent research task.
- Creating a 450 GW offshore wind sector requires opening new areas at sea: developments in bottom fixed in deeper water and development of floating wind power is essential.
- The large offshore wind sector needs to become completely circular: recycling of blades, re-manufacturing and CO^2-free shipping are areas that require developments.
- Nature-inclusive building of offshore wind farms and multi-use of the space they occupy requires intense research and development.

Identified Challenges

CH1.3.1 Improved Wind Turbine Technology

- Integrated design of next-generation large-sized wind based on accurate comprehensive simulation of the machine and its environment.
- Optimal design life based on a comprehensive understanding of the degradation and damage mechanisms (materials and components).

CH1.3.2 Offshore Wind Farms & Systems Integration

- Validated energy system science models to assess the value of wind power in markets with 100 % variable renewable energy supply in the future electricity grid, including energy system integration (power-to-X) and industrialisation.

- Dynamic operation of very large wind power clusters providing power quality and stability in (offshore wind farm) converter-based systems.

CH1.3.3 Floating Offshore Wind & Wind Energy Industrialisation

- New concepts and validation methods for integrated design models for floating wind power plants taking into account site-specific structural and electrical design conditions, soil damping, breaking waves, soil-structure-fluid interaction, air-sea interaction, and wind conditions.
- Wind Energy Operation, Maintenance & Installation (O&M)
- Condition-based maintenance based on accurate reliability models that predict the remaining lifetime or failure probability for a given load history.
- Extension of service life through optimised human or robot-assisted O&M procedures based on (big-)data analysis of automated and remote inspections (*see CC challenge 5, circularity*).

CH1.3.4 Ecosystem, Social Impact & Human Capital Agenda

- Technologies and designs to improve recycling and end-of-life solutions, embedded in the overall ecological and economic policy and legal framework (*see CC challenge 5, circularity*).
- Maintaining social acceptance by understanding the mechanisms behind it, e.g. socio-economic benefits, environmental impact assessments and by high-quality education and employment

CH1.3.5 Basic Wind Energy Sciences for Offshore Wind

- Improving the understanding of atmospheric and wind physics using high-performance computing, digitalisation and measurements to develop exact experimental and numerical models.
- Aerodynamics, structural dynamics (including new materials), and offshore wind hydrodynamics of enlarged wind turbines.

You can find a more detailed description of the above-mentioned challenges in Annex 3.

2.4 Enabling Technology: Onshore Wind

Onshore wind is the cheapest source of renewable energy and is the backbone of Europe's energy transition. Targeted R&I support will strengthen the leading role of the European industry in the global market towards 750 GW onshore wind capacity by 2050.

Expected impact

- Onshore wind turbines will grow in size to 6-7 MW and become more flexible resulting in further cost reductions and improved system integration.
- Onshore wind farms will further increase flexibility through technical developments.
- Through sector coupling the onshore wind energy will be able to decarbonise the mobility and heating sectors.
- Through spatial planning optimal use of land for onshore wind will be achieved.
- Development of hybrid renewable centrals delivering flexibility (wind + X)

Ambition

- Improved business case through reduction of costs despite electricity price uncertainty.

- System integration and reduced uncertainty in electricity prices: increase the uptake of onshore wind power by production of renewable hydrogen, coordination with electric transportation and heating sector.
- Simplification of permitting process (including repowering procedures and environment) to sustain the growth of the onshore wind sector.
- Archive a circular onshore wind energy sector. Components that require developments are: recycling of blades, remanufacturing of components and CO_2-free transportation.
- Increased sustainability with regards to nature use, environment and society.

Identified Challenges

CH 1.4.1 Wind Turbine Technology

- Novel flexible turbine designs including optimal design life based on simulation and a comprehensive understanding of the degradation and damage mechanisms of modern and new materials, as well as electrical and mechanical components (*see CC challenge 5, circularity*).

CH 1.4.2 Grid & Systems Integration

- Integrated forecasting of power production, power demand and short-term storage.
- New system services and innovative hybrid solution for increased flexibility.

CH 1.4.3 Wind Energy Operation, Maintenance & Installation

- Smart and dispatchable operation, monitoring and control of wind farms.
- Lifetime assessment, extension of service life, robot-assisted maintenance and predictive maintenance through digital tools and models (*see CC challenge 5, circularity*).

CH 1.4.4 Ecosystem, Social Impact & Human Capital Agenda

- Improved installation, transportation, recycling, and end-of-life solutions.
- New design, planning and operation of wind farms centred on increased social acceptance and minimize the environmental impact throughout the life cycle.

CH 1.4.5 Basic Wind Energy Sciences for Onshore Wind

- Improved understanding of atmospheric boundary layer and flow physics by using high-performance computing, digitalisation and measurements to develop experimental and numerical models suitable for very large turbines.
- Multi-physics (aerodynamics, aeroacoustics, structural dynamics, material science, and electrical system) and multi-scale modelling and testing of very large and flexible onshore wind turbines/subsystems.
- Disrupting wind turbine technology and systems engineering for integration of wind energy for applications outside of the electricity sector.

You can find a more detailed description of the above-mentioned challenges in Annex 4.

2.5 Enabling Technology: Geothermal Energy

The Deep Geothermal Implementation Plan has defined 8 challenges that will unlock the technical and economic potential for geothermal energy.

Expected impact

- Established procedures to ensure that public and societal benefits are identified and realized.
- Increased reservoir performance in sustainable yield for at least 30 years lifetime and reduced the power demand of operating facilities.
- Improved overall geothermal energy conversion efficiency by 20% in 2050.
- Ensured production costs below 10 €ct/kWhel for power and 5 €ct/kWhth for heat by 2025.
- Demonstrated technical and economic ability of innovative exploration approaches and tools to increase the drilling success rate by 20% in 2025 and 50% in 2030 compared to 2015.
- Reduce the unit cost of drilling by 50% in 2050 compared to 2015.
- Demonstrate the technical and economic value of flexible geothermal plants for power, heating, cooling and high-temperature energy storage.

Identified Challenges

CH1.5.1 Optimal integration of geothermal heat in urban areas

- Demonstrate new heating concepts for urban areas and/converting conventional district heating networks of urban areas into renewable heating systems;

CH1.5.2 Role of geothermal electricity and heating & cooling in the energy system responding to grid and network demands

- Improve design and operation methods to allow for fluctuations of heat and power demand.
- Find the best way to integrate geothermal capabilities in the energy system, including: heating, cooling, energy storage, power generation and flexibility provision.

CH1.5.3 Improvement of overall geothermal energy conversion performance for electricity production, heating & cooling

- Improved design of improved heat exchangers and pumps, optimized selection of materials, new working fluids, increases in expander efficiency etc (see CC challenge 5, circularity).

CH1.5.4 Develop full reinjection electric and heating & cooling plants integrated in the circular economy

- Develop and operate geothermal zero emission plants with capture of greenhouse gases, storage and reinjection schemes for the development and exploitation of geothermal reservoirs, in particular those with high content of non-condensable gases (NCGs).

CH1.5.5 Methods, processes, equipment and materials to ensure the steady availability of the geothermal resources and improve the performance of the operating facilities

CH1.5.6 Development of geothermal resources in a wide range of geological settings

- Development and demonstration of innovative methods and techniques for reservoir development and exploitation in a wide range of geological settings, including complex and untested geological conditions.

CH1.5.7 Advanced drilling/well completion techniques

- Develop novel and advanced drilling technologies based on automation, new drilling fluids minimizing reservoir damage and introduction of improved cementing and cladding; including percussive drilling for deep/hot wells, e.g. fluid hammers, and non-mechanical drilling technologies such as: laser, plasma, hydrothermal flame drilling.

CH1.5.8 Innovative exploration techniques for resource assessment and drilling target definition

- Digitalization offers unparalleled opportunities through improved software, computing power, big data management, machine learning and knowledge discovery.
- Piloting and demonstrating new tools and techniques coupled with innovative modelling techniques, increasing measurement precision and acquisition rates, and applying faster analysis, processing, inversion and integration of acquired data to achieve useful yet accurate models of potential subsurface reservoirs.

You can find a more detailed description of the above-mentioned challenges in Annex 5.

2.6 Enabling Technology: Bioenergy

Biomass provides 67% of the total primary energy production of renewable energy in the EU-28, offering sustainable electricity, heat and transport fuels. An increase is needed especially within aviation and marine fuel, but also in biobased industries for chemicals and products. Currently about 40.000 people in Europe are working on Bioenergy and Biofuels and a similar amount on biomaterials.

Expected impact

There is a big potential to strengthen the industry around biomass where bioenergy can play a significant role in the energy transition. Impacts of proposed research include:

- Achieving full potential of circular bio-economy
- Optimized and balanced use of biomass as a scarce but renewable resource
- Obtaining public acceptance and addressing the concerns
- Realizing employment opportunities from biomass use
- Supporting cost reduction by technology development for energy, fuels and industry applications (See ETIP Bioenergy SRIA)
- Ensuring the competitiveness of extension of the carbon cycle and carbon negative solutions.
- Supporting market uptake of new technologies, market organisation and trade.
- Enabling tailored, flexible integration of bioenergy concepts with local infrastructure

Challenges identified

CH1.6.1 Sustainable carbon for the globe

In the Circular Bio-Economy fossil carbon is left in the ground while aboveground biogenic carbon circulates without accumulating or even depleting carbon in the in the atmosphere. Biomass is the source of sustainable carbon, now and in the future. Development of circular and carbon negative technology solutions in bioenergy are therefore important challenges in the energy transition.

- Investigating and supporting the role of bio energy from society (public, scientific) perspective
- Improving the efficiency of biomass production in a circular economy
    - Increasing the feedstock availability and accessibility at competitive costs.
    - Using crop residues for energy and other bio-based uses while preserving soil quality
    - Developing dedicated crops, growing methods and technologies to use marginal and released land for production of advanced bio-fuels and bio-based materials.

- Linking biomass resources to markets in a cost-effective way (developing tradable intermediates and market organisation)
- Innovative ways to integrate bioenergy and material uses to circularity
- Providing sustainable carbon for CCU enabling negative emissions
    - Combine increase of biomass resources and sustainable biomass use with end of life carbon capture and permanent storage, Bio-CCS known as BECCS.

CH1.6.2 Integration of biomass to future sustainable energy system

- Ensuring benefits from bioenergy in enabling smooth transition
    - Bioenergy can be used for balancing the grid and providing storage options, acting thus as a stabilising factor in the renewable power and heat supply system.
    - Implementation of biofuels for decarbonisation of the transport sector especially long distance transport (long haul, jet fuels and marine fuels)

You can find a more detailed description of the above-mentioned challenges in Annex 6.

2.7 Enabling Technology: Carbon Capture Utilisation & Storage (CCUS)

Expected outcome

This 7-year partnership is crucial to set a commercially viable basis for the industrial-scale deployment of CCS and CCU technologies, reducing costs of the technology while raising efficiency and scaling up. R&I activities on CCS and CCU are crucial to achieve climate change mitigation and carbon dioxide removals within this decade, delivering climate benefits for European citizens while, at the same time, safeguarding existing jobs and creating new ones, protecting industrial manufacturing activity and welfare in many EU regions where energy-intensive industries are based.

Undertaking R&I activities on CCS, CCU will be critical to address current challenges on the commercial framework, legal and regulatory issues, technical development of CCS, CCU, and in parallel, to support the EU to become a global leader in low-carbon economy. Creating awareness and involving citizens to make informed decisions is another crucial task for the years ahead.

Identified challenges

Challenges to the large-scale deployment of CCS and CCU technologies still exist, but R&I activities can support the development and large-scale deployment of the technologies in a decisive way.

CH1.7.1 Getting the commercial framework right
(see also 13.3.6 and 13.3.7.)

Standardised CO_2 specifications

- Incentives for carbon negative solutions and low-carbon products
- CO_2 stream composition, including technical considerations such as pressure, temperature and physical state and MMV
- Methods for measuring biogenic/fossil CO_2 ratio
- Data on emissions from CO_2 capture technologies
- Harmonization of legal standards / regulations relevant for the development of a European CO_2 transport- and storage-network.

CH1.7.2 Accelerating timely deployment at scale of CCS and CCU technologies
(see also 13.1, 13.2, 13.3.4, 13.3.5)

- Adaptation of current capture methods to new areas as well as development and deployment of higher TRL capture

- CCU technologies at commercial scale to achieve carbon circularity
- The role of CCS in enabling clean hydrogen
- The role, feasibility and scale of Carbon Dioxide Removals
- Flexible Power Generation
- Projects of Common interest
- Value-chain analyses of CCS and CCU transport systems
- Developing European CO_2 storage by Computational tools in process engineering & intensification (e.g. AI-driven process control, machine learning for catalyst development)

CH1.7.3 Driving costs down – through R&I, learning by doing and economies of scale
(see also 13.3.1, 13.3.2)

- High-TRL CO2 capture technologies (from TRL 5-6 to TRL 7-9)
- Next generation CO2 capture technologies
- CO2 capture in industrial clusters and energy applications

CH1.7.4 Enabling rapid scale-up to deliver on the climate goals
(see also 13.3)

- This refers to the whole array of CCS and CCU research needs.

CH1.7.5 Enabling EU citizens to make informed choices regarding the benefits that CCS and CCU bring
(see also 13.3.7)

- Harmonised guidelines for life cycle sustainability assessment
- Public awareness and social acceptance of technology solutions towards achieving climate neutrality goals.
- Engaging communities in local projects through development of participatory monitoring programmes.

CH1.7.6 Production, optimisation and integration of blue hydrogen with CCUS

Europe's goal of a hydrogen economy can be met cost-effectively when considering technology research and innovation for synergistic production, optimization, and integration of green and blue hydrogen into the energy system. Blue hydrogen provides a path for upscaling Europe's hydrogen infrastructure and thus helps to overcome challenges for the large-scale uptake of a green hydrogen value chain in Europe.

- Explore the transition and synergies between green and blue hydrogen production (natural- and biogas reforming, capture technologies)
- Hydrogen as energy carrier to enable the decarbonisation of the heating/cooling of the building stock, transport sector, power sector and other industrial processes and facilities
- Integrate hydrogen and CO2 capture facilities in industrial sites and clusters
- Condition liquid hydrogen for safe transport and storage, and exploit synergies with CO2 transport and storage

You can find a more detailed description of the above-mentioned challenges in Annex 7.

2.8 Enabling Technology: Ocean Energy

The following Challenge Areas represent a set of R&I fields that the ocean energy sector has identified as most worthy of investment during the next period of 4-5 years. Design and validation of ocean energy devices have the highest priority.

Identified challenges

CH1.8.1 Design and Validation of Ocean Energy Devices

The primary focus of this challenge is the demonstration of wave and tidal energy technologies, and the challenge encompasses the research, design, development, demonstration and validation of ocean energy devices and their subsystems.

- New innovative designs for ocean energy
- Design validation with updated research infrastructure
- Demonstration cases of ocean energy
- Reduction in operation and maintenance procedures for ocean energy
- Increase Europe's global lead and accelerate commercialization of Europe's world-leading ocean energy technologies, companies and projects.

CH1.8.2 Foundations, Connections and Mooring

This challenge focuses on improving device mooring and foundation solutions and the best solutions for bringing ocean power ashore to the energy system.

- Optimised design for foundations, connections, and mooring
- Improved installation, operation, and maintenance of mooring solutions
- Increased survivability in extreme weather events

CH1.8.3 Logistics and Marine Operations

Ocean energy operates in an inaccessible, corrosive environment with tough weather conditions. This challenge the ocean technology through the whole value chain from: technology development and demonstration to installation, operation, maintenance, and decommissioning of ocean energy devices.

- Collect and share operation experiences of ocean energy devices and define best practice solutions.
- Improve installation, operation, and maintenance of ocean energy devices getting more energy, longer lifetime, lower cost and lower environmental footprint.

CH1.8.4 Integration in the Energy System

Ocean energy is not yet making a massive contribution to the European energy system. However, in view of a higher contribution in the medium-long term, some challenges should be addressed now:

- What socio-economic benefit can ocean energy provide?
- How can ocean energy best contribute to the energy transition in terms of the level of grid connection, installation size?
- What support can ocean energy provide for other renewables such as solar and wind energy?

You can find a more detailed description of the above-mentioned challenges in Annex 8.

2.9 Enabling Technology: Hydropower

Expected impact

Today, hydropower generates about 36% of the renewable electricity in the EU and the storage capacity exceeds 185 TWh.

- Hydropower can balance wind and solar power plants, and store excess energy when variable renewables generate more than needed.

- Hydropower is the largest provider of medium to long term storage and with targeted research hydropower can increase the ability to balance and support the energy system and greatly reduce the cost of the energy transition.
- The proposed research activity focuses on increasing the flexibility of hydropower plants, the expansion of energy storage capacity, social acceptance and application of sustainable environmental design of hydropower.

Challenges identified

CH1.9.1 Increased flexibility from Hydropower plants:

- This includes research on; fatigue and lifetime on technical installations, how to increase the ramping rates, and develop new innovations for the electrical layout with controls that give a strong grid support. It will also be important to find solutions that combines hydropower energy storage technologies; batteries, H2, CAES etc.

CH1.9.2 Utilization and expansion of European hydropower's storage capacity:

- Increasing storage capability through research on; dam safety, moderate expansions and flexible operation of existing reservoirs, and increased power output.

CH1.9.3 Markets and services for hydropower's capabilities:

- Ability to use and expand hydropower's capabilities in the energy transition requires research on develop models of future revenues, tools for the estimation of the remaining lifetime of hydropower plant components are important. In addition, the development of tools to support assessment of the long-term hydropower resources and its associated risk in river basins with multiple water users under present and future climate situations is needed.

CH1.9.4 Sustainable hydropower:

- This includes the development of environmental design for multiple interests of the water in the system, which includes fish passage technologies, water resources availability, planning and regulation, and optimization of storage of water resources. Development of new tools for estimating and compensating lost ecosystem services and biodiversity in rivers and reservoirs, development of guidelines to include environmental constraints in hydropower operation and scheduling models, and optimization of existing hydropower infrastructure to changing climatic conditions due to climate change.

CH1.9.5 Sediment handling:

- Today's largest challenge for hydropower installations in many parts of Europe is the sediment deposits in reservoirs and erosion of the technical installations. In order to cope with this, research within innovative designs of hydraulic structures, flushing techniques, sediment bypass systems, and the environmental impacts are needed.

Relation to cross-cutting issues:

Digitalisation: There are multiple cross-cutting issues within the future R&I priorities for hydropower. The digitalization of hydropower plants will have common research topics with other technologies.

Cross sectional: Hydropower can mitigate climate change and must be seen together with land use and food production.

Social acceptance: The social aspects can be addressed through common research on all renewables with focus on the acceptance of new renewable technology and its need for flexible operation.

Material Sciences: Improved understanding of material that can endure high fatigue loads over many years is needed together with numerical tools for fatigue analysis of key components. Develop materials/coating to reduce sediment erosion.

You can find a more detailed description of the above-mentioned challenges in Annex 9.

2.10 Enabling Technology: Solar Thermal Heating

The European Solar Thermal Technology Panel (ESTTP), part of the European Renewable Heating and Cooling Technology and Innovation Platform (ETIP RHC), identified a set of priorities which will enhance the role of solar thermal heating in the EU energy framework, providing a significant contribution to the energy demand for space heating, domestic hot water heating, industrial process heating and district heating and cooling. Main advantages of solar thermal systems include the exploitation of locally available solar irradiation, the integration with thermal energy storage and the consequent opportunity of exploiting storage capacity to provide flexibility to the power grid. Solar thermal is widely manufactured in Europe and has always had excellent acceptance among European citizens as one of the 100% renewable technologies. There are currently more than 10 million solar thermal systems in Europe, corresponding to an installed heat generation capacity over 36 GWth.and thermal energy storage capacity equivalent to 180 GWhth.

Expected impact

By effectively addressing the challenges listed in the following paragraph, a strong impact on the adoption of solar thermal technologies across different applications will be reached and a total solar energy supply equivalent to 31,000 TOE will be reached by 2040.

This will be possible thanks to:

- Improved business models reducing initial investment costs for end users, supporting efficient integration of solar thermal systems into existing heat generation and distribution systems and correctly valorising feed-in of thermal energy in thermal networks.
- Increased number and average size of large scale systems, with reduced planning and implementation periods.
- Developed concepts to support a sustainable and healthy use of land around cities and industrial areas for solar thermal energy.
- Enhanced methodologies for design, operation, monitoring and evaluation (including economic parameters), especially of large solar thermal system.
- Coupling heating-electricity, allowing to unlock additional economic benefits for solar thermal and other renewable technologies, both at product level (hybrid systems) and system level.

Identified Challenges

CH1.10.1 Solar District Heating (SDH)

District heating and cooling is a powerful vector to integrate renewable and excess heat/cold and use it to supply homes, offices and even industries. The potential of solar thermal in district heating (DH) is clearly being demonstrated in some 200 SDH systems across Europe. The demand on district heat that can be covered by solar heat combined with seasonal storage is by far the biggest untouched potential for use of solar heat.

Large storages can store thermal energy from summer to winter. With the installation of seasonal storage pit solar thermal can provide the base load heat for many of the 6000 heat networks in Europe – from

Helsinki to Leipzig and Madrid. Drake Landing in Canada is an example on how communities can have 100% of their heating from solar thermal using seasonal storage.

District cooling is currently at a low level of distribution only at rather few cities but with a great potential for expansion. Cooling is emerging massively by climate effects and increasing comfort demands. While today most district cooling systems are powered by waste heat or environmental heat combined with electric driven heat pumps, solar heat is today only used on campus level in cold water grids.

CH1.10.2 Solar Heat for Industrial Processes (SHIP)

According to IRENA, industrial process heat accounts globally for more than two-thirds of total energy consumption in industry, and half of this process heat demand is low- to medium-temperatures (<400°C). Solar thermal can therefore cover part of that energy demand by exploiting locally available solar irradiation. As such, it should be considered as a key technology in future regulations affecting energy supply in industry (e.g. minimum RES shares in industry).

Solar heat for industrial processes (SHIP) is at an early stage of development but is considered to have huge potential for solar thermal applications. Currently, concentrating solar heat systems (CSH) reach temperatures of 400°C and even above. They may directly supply steam systems by injection. 635 operating solar thermal systems for process heat are reported in operation worldwide. The total gross area of the 301 documented systems which are larger than 50 m² is 905,000 m² gross and the thermal capacity is 441 MWth.

Continuous process management, which can be achieved through innovative process technology and which makes the use of renewable energies at low temperature level possible, would lead to further significant reduction of the energy input and can be defined as a future long-term goal. In Europe, the size of SHIP (solar heat for industrial process) installations, is growing every year. Until 2018, the largest SHIP plant in Europe was 2MW, since then new plants became operative and reached 12MW.

The reasons for the low growth rates are mainly commercial and market related issues, namely the need for demonstration of the technology in diverse industrial heat processes, as a way to gain confidence from industrial clients and demonstrate the performance and reliability of such solutions.

In addition, alternatives for the future carbon neutral industrial heat supply, such as hydrogen or power-2-heat, are substantially more expansive. While the named solutions are of utmost importance for total decarbonization SHIP has lower costs for specific decarbonization for suitable solar shares.

CH1.10.3 Solar thermal use in buildings

In EU households, heating, and hot water alone account for 79% of total final energy use. 84% of heating and cooling is still generated from fossil fuels while only 16% is generated from renewable energy sources. Around 70% of the EU population lives in privately owned residential buildings.

Solar thermal are a 100% renewable energy (RE) solutions both in existing and in new individually heated & cooled buildings (residential and others) that are not possible to connect to district heating and cooling (DHC) grids due to limited existence (e.g. some southern European countries) or are difficult to connect to DHC grids, e.g. due to either its remoteness (in rural areas), or due to its low energy demand (new, low-energy buildings or passive houses).

Solar thermal systems used at building level, either residential or commercial, cover space, water heating, and solar cooling applications. These are the most common solar thermal systems, ranging from thermosyphon solar water heaters of 1.4 kWth very common in Greece, or more efficient compact and forced solar water heaters in South Europe, to combi-systems for space and water heating between 7 and 14 kWth in single family houses, popular in central Europe to larger systems (up to 500 kWth) in multifamily houses or even bigger ones for commercial uses. The integration into buildings and nZEB/Passive-house concepts, the combination with other solutions in hybrid products and the use as enablers of sector coupling are functionalities that will be important for the development of such solutions, for which improvements at component level are also relevant.

CH1.10.4 Financing/business models for solar thermal

Solar thermal applications need a substantial scale up in size, to make a clear impact in the upcoming renewable energy mix. Applications such as large scale (1-100MW) Solar District Heating (SDH) and Industrial Process Heat (SHIP) can replicate the successes of Solar PV utility scale, provided they can profit of advanced project financing tools and methods, much the same way they have been deployed in large scale PV. This technology is expected to provide a substantial contribution in the future energy mix as showed in the graph below, but additional financing tools and new business models are needed to achieve this goal.

You can find a more detailed description of the above-mentioned challenges in Annex 10.

2.11 Challenge: Integrating Climate Neutral Technologies

While it is the prerogative of MS/AC to design their own clean energy system according to specific national, political and industrial factors, a fully integrated, interconnected and resilient energy system must be created in Europe. With a European energy system, not limited by frontiers or regulatory barriers and energy carriers, the structure for a climate-neutral energy system will help to lower the cost of the transition and improve the society. By increased international competitiveness, new jobs and services can be developed, and mechanism of a just and fair transition can be implemented.

This is crucial to enable a constant and optimal balancing of energy solutions throughout the energy transition and in the end archiving a climate-neutral energy system. Here, the combination of energy source availability, energy source technology mix, and energy infrastructure that follows the different choices made at local community level and the specific conditions and situation of each country or region (“*United in diversity”*) should be coordinated. This in turn requires the integration of energy infrastructures across borders, between energy sectors and from European to local level.

Expected impact:

The proposed research for a climate-neutral energy system will help realizing the policy goals for greenhouse gas emission reductions from energy production as defined for 2030 and 2050. In the pursuit of this impact the Partnership will:

- Improve EU’s energy security of supply, by utilising the renewable energy potential in Europe and thus lessen the dependency of energy importing from the outside.
- Provide affordable and competitive energy. The partnership is to decrease the cost of energy production from the different technologies in the framework of circularity and resource availability.
- Aim for a fair and inclusive energy transition. The CETP will contribute to fact-based decisions and debates and give the technical and practical implementation of the transition the mechanisms that will make "fair and inclusive" possible.

Main challenges to be addressed:

The climate-neutral energy system will be facilitated by these three main challenges

CH1.11.1 Technologies at work:

- How to develop a mix of enabling technologies that provide clean, secure, and affordable energy?
- What flexibility and energy services must the technologies provide to ensure energy system operation and energy citizenship at different stages in the energy transition?

- How can the technology be developed into a competitive delivery with respect to both energy, flexibility, and services?

CH1.12.2 Market design

- How to design a single energy market over a large geographical area for different energy sources, energy carriers, and energy infrastructures?
- How to design for the interdependency for different energy products within each energy carrier and between energy carriers.
- What is the best approach to achieve a single energy market? Is it: top-down, bottom-up, starting with one energy carrier and expand or start with all carriers in parallel? How to ensure a speedy development of the energy market in an fair and transparent way that support further development and immediate emission reductions?

CH1.12.3 Digital marketplace

- How should the digital market infrastructure be designed and operated.
- How can a digital marketplace support empowerment for citizens, the industry, and the public sector?
- How to use digitalization and build-in resilience to ensure operation of the energy system in case of natural disasters or cyber-attacks?

Annex

Challenge 1: Concentrated Solar Power

Challenge 2: Photovoltaic (PV)

Challenge 3: Offshore Wind

Challenge 4: Onshore Wind

Challenge 5: Geothermal Energy

Challenge 6: Bioenergy

Challenge 7: Carbon Capture Utilisation & Storage (CCUS)

Challenge 8: Ocean Energy

Challenge 9: Hydropower

Challenge 10: Solar Thermal Heating

Challenge 11: Integrating Climate Neutral Technologies

Input Paper to the CETP SRIA Renewable Technologies

Challenge 1
Concentrated Solar Power

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1 Introduction

Heat production using solar energy is based on photo-thermal conversion; the photo-thermal effect is produced by a) photoexcitation due to absorption of solar photons using an optical absorber surface (black surface), b) energy release by photons to the absorber surface (heat production) and c) transfer of the produced heat using a thermodynamic fluid [1]. The photoexcitation can be observed in inorganic materials, such as noble metals and semiconductors, as well as inorganic materials such as carbon-based materials, dyes and conjugated polymers [2]. The efficiency of photon-thermal conversion can be very high (> 60 %). For this reason, this kind of conversion is the most efficient method to convert solar energy into usable energy. Solar collectors are devices that enable efficient photo-thermal conversion by reducing infrared losses.

To increase the solar collector efficiency, concentrating collectors such as compound parabolic collectors (CPC), Linear Fresnel Reflector (LFR), Parabolic Trough Collector (PTC), Solar Tower and Solar dish can be used. The optical concentration is crucial because the heat losses are proportional to the absorber area and not to the solar collector aperture. In Concentrating Solar Thermal (CST) technologies, there is a decrease in the absorber area and an increase in the aperture area, allowing an efficient collection of solar light [3]. The CST technologies can reach a concentration factor from 5 to more than 1000. Changing the concentration factor is possible to realise a solar plant that can work at a temperature from 60°C to more than 1000°C. This technological flexibility allows the adaption of CST technologies to several industrial processes, like water desalination, or the emerging green applications related, as example, to solar chemistry and material processing. The use of CST technologies for electricity production, traditionally known with the acronym CSP (Concentrating Solar Power) and more recently with STE (Solar Thermal Electricity) to distinguish between solar concentration for PV plants and solar concentration for solar thermal power plants, have been already tested solutions, relatively cheap and available at high TRL. For these reasons, CSP is among the most important sustainable technologies that can reduce the fossil fuel consumption of processes and their corresponding carbon footprint. Unfortunately, CST technologies are still gathering a slow pace of commercial deployment. In addition, to facilitate the penetration of CST technologies in the industrial and emerging green sectors it is crucial to: i) identify strategic applications for CST energy (e.g. green chemistry, drying, desalination or production of electricity); ii) identify solutions to improve the solar system efficiency; iii) identify solutions to reduce CAPEX and OPEX; iv) identify solutions to increase the durability of the solar plant; v) promote the use of CST systems.

2 Technology Status

Technology status of CST technology, for electricity production, can be summarized on Table 1, which indicates the baseline technological characteristics for the currently most common CST systems: parabolic trough and central receivers (also known as solar towers) systems. In 2019, 8150 MW of CSP commercial projects were either in operation or in advanced construction, worldwide. The majority of these projects (around 5840 MW) were related to trough designs, due to being normally considered as most bankable for project financing. Tower projects (around 1890 MW) allow to higher maximum temperature and hence increased efficiency for power generation and thermal heat storage, reason why it could achieve lower electricity costs in locations of low attenuation of the light between the mirrors and the receiver. Linear Fresnel technology, another CST line-focusing system, has much lower commercial deployment (415 MW, also in 2019).

	Parabolic Trough	Central Receiver (Tower)
Receiver	Line absorbers with high absorptivity (>95%) and low emissivity (<10%/400ºC)	Metallic point receivers
Heat Transfer Fluid	Thermal oil at max. 395 ºC	Molten salt or steam; max. working fluid temperatures of 570 ºC
Thermal energy storage	Two-tank molten salt	
Power cycle	Rankine with superheated steam (ORC for small facilities)	Rankine with superheated steam
Capacity factor (2050 DNI location)	27%, or greater with TES	26%, or higher with TES
Land area required	2.4 – 3.2 hectares/MW (direct area, including TES)	
Water consumption	$3.5\ m^3$/MWh (with wet cooling, as for fossil plants) $0.05\ m^3$/MWh (dry cooling option)	
CO2 footprint	22 gCO_2/kWh	

Table 1: Main current characteristics of State-of-the-Art commercial CST technologies [4]

Although Tower Projects are less common than Parabolic Toriugh CSPs, the first have higher efficiency as the temperature of the Heat Transfer Fluid (HTF) is typically also higher (570 ºC against 395 ºC, considering the reference fluids used as HTF in both technologies). Reference Parabolic Trough specifications, considering the existing HTF and TES (Thermal Energy Storage) possibilities are [5, 6, 7]:

- If thermal oil is used as HTF (most common situation), normal temperature is 390 ºC, and the flux on the receiver is about 42 (peak)/25 (mean) kW/m^2. TES hot temperature is 390 ºC, being 290 ºC the cold one (two-tanks nitrate molten salt systems). The standard condenser temperature for heat rejection is 40 ºC.
- If molten salts are used as HTF, the receiver temperature is 500 ºC, with a flux of about 42 (peak)/25 (mean) kW/m2. In this case, the hot and cold storage of TES is 500 ºC and 300 ºC, respectively (two-tanks system).
- If water/steam is used as HTF, a typical receiver temperature is 500 ºC, with the same previous values of solar flux. In this case, there is no commercial TES available.

In the case of Central Receiver projects, typical reference specifications also depend on considered HTF and TES availability, as follows [7, 8]:

- For molten salts as HTF, the receiver temperature is 565 ºC; the peak flux on the receiver is 1,000 kW/m^2 and the typical mean flux around 750 kW/m^2. TES temperatures are 565/290 ºC (hot/cold), and the condenser temperature is 40 ºC.

- In power plants using water/steam as HTF, the typical top temperature is 550 ºC with flux values on the receiver around 600 kW/m2 (peak) and 350 kW/m2 (mean). No TES available in this case.

The weighted average LCOE of these commercial CST plants fell by 47% between 2010 and 2019 [9], with a wide range of options for still widely improving the performance and cost-effectiveness of the technology [10, 11, 12].

3 Ongoing Research

Cost reduction of the energy produced is the main objective of ongoing research in the field of CST technologies. This overall objective is based on three specific challenges:

- Investment cost reduction
- Operation & maintenance cost reduction, and
- Efficiency increase

Although a significant progress has been achieved during the last two years in the priority R&I activities defined in the Implementation Plan for the CSP SET-Plan (hereinafter referred to as "the IP"), there are still nowadays many innovative ideas for technology improvements and cost reduction. However, stakeholders have pointed out that the significant lack of public funding at European level is slowing down the development of more technology improvements that have been identified, and sometimes even unsuccessfully proposed to the reduced number of public calls for CST technologies.

Some innovative ideas to reduce optical losses in linear Fresnel concentrators are now under development to increase the overall plant efficiency. It is also worth mentioning that commercial plants with linear Fresnel concentrators using molten salts in the receivers have been implemented in Europe (Sicily) and China (Dacheng Dunhuang), thus proving the industrial engagement in this technology. The main challenge at present in the field of linear Fresnel concentrators is the efficiency increase to become more competitive with parabolic trough plants.

Concerning parabolic trough collectors current research is aimed at using molten salt as heat transfer fluid, thus increasing the solar field nominal temperature and therefore the overall plant efficiency. Novel evacuated collector tubes (ECTs) covered with infrared (IR)-reflectors on the partial area of glass envelope are being investigated to effectively reduce the heat loss and enhance the performance of the receiver tubes. The expected impact is a relative heat loss reduction of up to 43.8%. An intensive testing of the critical components is required to evaluate degradation and failure mechanisms and to develop mitigation measures. This testing will be performed as soon as the required funding is available.

There is also a significant R+D effort in Europe for the use of silicone based heat transfer fluid (HTF) in parabolic trough collectors. A new grade of silicone based HTF was introduced in 2019, with a vapour pressure similar to that of the thermal oil currently used as HTF in commercial parabolic trough plants. Current R+D effort is devoted to evaluate the technical aspects of this new silicone-based oil (i.e. aging tests, fire tests at small and full scale and hydrogen accumulation, mainly). Non-technical aspects (qualification guideline, market barriers, cost analysis, etc.) are being investigated also.

The main target in the field of open volumetric receivers is a gain in thermal efficiency of more than 3%-points with large commercial receivers (80 – 125 MWth). Together with other improvements, a total receiver efficiency increase from 70% to 85% seems feasible at commercial scale, as well as a significant improvement in load change capability (from 10% to 90% in less than 300 s). Current R&D activities in this field are also devoted to the evaluation of new porous structures that have shown promising results in preliminary tests at lab scale. The detailed design of the receiver and the air duct of a pre-commercial plant of about 10 MWe is well advanced and an alternative design for this plant as a CSP/PV hybrid concept is being developed.

A strong research activity is ongoing concerning solar thermal power plants with molten-salt central receiver. Improvements to increase the efficiency and safety of the receiver are being investigated, and some of them have been already implemented in commercial plants. The main challenge related to the molten salt receivers is the increase of the solar flux density without jeopardizing their lifetime and reliability. Additionally, innovative receiver designs with a target of a 50% CAPEX reduction for similar performance have been proposed and they are under study. Technical improvements of the molten salt hot tank are also being investigated to avoid the problems found in the first commercial plants. There are also R+D activities related to the steam generator to increase its lifetime and reduce the maintenance costs.

The high impact of the atmospheric attenuation on the efficiency of central receiver plants, independently of the working fluid used in the receiver, is motivating ongoing research to develop accurate and reliable measurement systems for atmospheric attenuation. Although outstanding results have been already achieved (a prototype is working on-line efficiently since two years ago in Spain) there are nowadays several R+D groups working on this topic. There is also a significant research effort devoted to improve the operation and maintenance of the heliostat field. Cheaper heliostats provided with a self-calibrating system are being developed in current R+D projects and they could be commercially available in a short term. The target in this topic is a specific cost of less than to 90 €/m^2. Additionally, to water-less heliostat prototypes currently under evaluation, there are many proposals (i.e., design of sCO_2 cycles, innovative heliostat field lay-out and multi-tower approaches) to accomplish the target of LCOE reductions in the range of 7-12 % for central receiver plants.

Concerning "Pressurized air cycles for high efficiency solar thermal power plants", only the R&D activities of the current European project POLYPHEM are related to that topic. An advanced pressurized air solar receiver is being developed to drive a Brayton cycle. The project will validate a prototype with a 40 kWe topping Brayton cycle with a stated ending TRL of 5. No other project aligned with this R&I topic has been identified. The use of particles as new heat transfer fluid for high temperature cycles (>700°C) is studied in the framework of the European Project Next-CSP. Fluidized particles flowing inside a tubular solar receiver are also used as heat storage medium. A 3 MWth solar receiver and associated components (storage tanks, heat exchanger and gas turbine) will be tested in 2020-2021. Open particle receiver demonstration to provide heat and power to pasta manufacturer in Italy in the MW scale is under preparation in the European Project HIFLEX (2021-2022)

Ongoing research activities related to "Beam Down" technology is mainly focussed on the use of dense suspensions of solid particles as direct absorption solar receivers, thus identifying some requirements to select good candidates. It is expected that the implementation of the Yumen Xinneng 50 MW commercial Chinese CSP/STE plant, which is the first large-scale commercial CSP/STE plant in the world using innovative beam-down molten salt tower technology, will boost the R&D effort on Beam Down technology. There are at present several European R&D projects developing several innovations related to thermal storage (SOCRATCES, ProMS, VESUW). Nevertheless, the technical progress so far achieved in this field during the last two years is very limited. A significant R&D effort is being devoted to develop cost-effective thermal storage systems for temperatures greater than 565ºC. Another priority topic in the field of thermal energy storage is the development of phase change materials (PCM) with a melting point in the range 200ºC-300ºC. The efforts devoted to this topic so far have been unsuccessful.

In spite of the great interest that development of specific turbomachinery for the requirements of solar thermal electricity plants has for this sector, a very little R&D effort has been devoted in the last two years. Various turbine manufacturers have shown their interest on developing advanced concepts for improved flexibility of turbines in CSP/STE plants and development of air Brayton turbine combined with sCO_2 systems. However, the lack of public funding to support this effort (no related H2020 call has been issued since the publication of the IP) has been a significant barrier to enable such R&D activities.

4 Technical Potential

According to IEA, the historical production of commercial CST technology in 2019 was 15,6 TWh and the organization forecasts a worldwide contribution, in the Sustainable Development Scenario, of 53,8 TWh in 2025 and 183,8 TWh (around 60 GW of installed power) in 2030, from this technology [13]. However, the technical potential of CST, just for electricity production, is much higher; if we also add the capability of provide thermal energy for industrial heat applications, such potential multiply due to the distributed potential contribution and a large number of industrial applications suitable of fitting CST technologies. The yearly world thermal energy consumption of the industrial sector is higher than 23600 TWh, and a significant portion of this energy consumption can be delivered with CST technologies [14], thus increasing their potential.

Thanks to the thermal storage capability, the power generated by CST power plants is fully dispatchable and, therefore, these plants can perform the role of base load and also making possible the penetration of very high rates of renewable electricity in sunny countries (complementing the non-dispatchable technologies like PV and Wind). In Southern Europe the DNI (Direct Normal Irradiation) is around 2000-2100 kWh/m^2/yr, and with these solar values, the technology is fully viable as already has been demonstrated in Spain. In other world locations, with higher DNI values (2400-2600 in North Africa and Middle East countries, 2800-3000 in South African countries, or even 3300 kWh/m^2/yr in Chile), the potential is also significantly higher as the performance and power cost of these plants could be up to a 50 % lower than in the case of European plants.

Another important technical factor that could strongly promote the deployment of CST technology for electricity production in scenarios close to 100% of renewable energy generation, is the necessity of a specific amount of synchronous electricity generation to guarantee system inertia levels above the current critical ones and, as a consequence, sufficient grid stability. Advances in electronics and converters will certainly reduce the current inertia levels limit but the eventual feasibility of full disappearance of synchronous electricity generation from power grids is still unknown [15].

5 Economic Potential

Recent estimations provide LCOE values starting from 142 USD/MWh in ongoing CST project development in China (country with the highest current activity in this technology) at locations with DNI above 1,800kWh/m^2/yr [16]. As the local policies and conditions, added to the climatic ones, could be very different from one country to another. Lowest bidding price for dispatchable CSP power reaches 73 USD/MWh (DEWA project case in Dubai). Up to 2019, around 80% of all worldwide commercial deployment of CST technologies has been made by European companies. Assuming a conservative 50% share in the future developments up to 2030 and the previous estimation of 60 GW worldwide installed to that year, a business market of around 100 billion Euros (considering an average investment of 3-3.5 million Euros per nominal installed MW) to the European CST industry, is estimated.

Besides, it should be noticed that electricity generation by CST technology with thermal energy storage can be more competitive when the comprehensive net costs of these plants are compared to other renewable energy sources, like wind or PV (Net Cost = Levelized Cost of Energy + Transmission Cost + Integration Cost – Energy Benefits – Ancillary Service Benefits – Capacity Benefits) [17]. Typically, in today's competitive power markets, the value of energy is determined in advance taking into account that real-time energy imbalances, mainly as a consequence of load forecast errors, constitute only a few percent of total energy market financial settlements. The addition of variable wind and solar production to these markets may increase the quantity of balancing energy transacted in real-time, and possibly the volatility of prices, providing more value to operational flexibility. This is why the energy storage development will be the key element which will probably determine the final contribution of different generation technologies to the grid systems. And this is a unique advantage of CST enabling dispatchable power supply on demand thanks to the integration of low-cost thermal energy storage.

The size of the CST system with storage can be designed to fulfil specific demand profiles, even full load operation for 24h is possible (e. g. Cerro Dominador plant in Chile). With this load-shifting capability, CST is perfectly suited for the delivery of power during the evening, night and morning when PV cannot deliver (much) power. To obtain high shares of renewables even in these time periods, battery storage is the main alternative solution. However, CST can provide this at significantly lower cost, even when predicted cost reductions for both technologies are taken into account. Current cost for thermal storage systems in CST plants are in the range of 20-26 USD/kWh, being in the case of batteries around 350-450 USD/kWh; the expected achievement by 2025 of both technologies is around 16-18 USD/kWh and around 200-325 USD/kWh, respectively (one order of magnitude gap, at least) [18, 19].

To illustrate this difference more clearly, one should keep in mind that just the depreciation of a battery system that costs 300 USD/kWh and is used for one cycle every day equals 82 USD/MWh[1]. This number does not include neither the cost of O&M of the battery system, nor the cost of the renewable electricity and inherent losses of battery system, that adds another 30–50 USD/MWh to the overall electricity cost.

The situation of CSP is particularly favourable for medium and long-term storage capacity. This fact guarantees the economic viability of CST technology for the coming future and its necessity to the achievement of a full decarbonized energy sector by 2050.

Finally, it should be also considered the additional important contribution of CST projects to local inclusive growth, job-creation, manufacturing, construction and rural development, as already demonstrated in countries like South Africa and Morocco.

6 Challenges

6.1 Challenge 1: Central Receiver Plants with Lower LCOE

Central receiver solar plants need to reduce their electricity cost (LCOE) to become more competitive with other renewable technologies (i.e., wind and PV) or develop hybrid solutions in combination with other renewables. At present, the most mature technology for commercial plants is based on molten-salt receivers. However, other technologies that are still less developed should not be disregarded and further R+D effort should be devoted to assess their commercial potential. The challenge proposed is not technology-specific, so that any innovative idea related to central receiver technology aimed at reducing the current LCOE would be eligible (e.g. new working fluids, new heliostats, new receiver materials and designs, etc.) without limiting the R+D effort to molten-salt tower technology. Innovative plant field designs (e.g. multi-tower approaches or beam down), volumetric receivers, particle receivers or pressurized receivers would be eligible if the ideas proposed clearly show that they would lead to a LCOE reduction, which is the key overall challenge nowadays.

<u>Targeted/expected impact from proposed R&I</u>

- LCOE[2] reduction of tower technology to 0,09 EUR/kWh in Southern Europe locations (without any additional constraint), by 2025, targeting 0,08 EUR/kWh by 2030, providing competitive dispatchable solar power (e. g. during night). These cost targets imply that the industry does not face additional constraint in Europe regarding the size/type of the plant, the financial conditions, a radiation of 2050 kWh/m2/year (conditions in Southern Europe) and within Power Purchase Agreements (PPA) with a duration of 25 years.
- Solar Rankine cycles with the same efficiency than conventional fossil fuels ones.
- Feasible commercial solar Brayton cycles validated experimentally.

[1] At an annuity rate of 10% that equals 15 years of lifetime at an interest rate of 5,5%

[2] LCOE calculation methodology, assumptions and parameters according to IRENA definitions in the Annex 1 of [26]

Specific challenges to achieve targeted impact

- Receivers for mean solar fluxes >1MW/m2
- Receiver thermal efficiencies higher than 85 percent for temperatures above 600 ºC
- Working fluids with T > 600ºC for Rankine cycles
- Working fluids with T > 750ºC for unfired Brayton cycles
- Self-calibrating and cheaper heliostats, below 90 EUR/m2 (installed)
- Mirrors with anti-soiling coatings
- High precision heliostat field and automated control for long focal distance and/or high temperature applications up to 1200°C
- Innovative plant configurations achieving better use of solar energy resource and technologies
- High degree of automation of condition monitoring of all relevant plant parameters to optimize O&M, including virtualization of plants, augmented reality and remote supervision.

6.2 Challenge 2: Line-Focus Solar Power Plants with Lower LCOE

Although central receiver solar plants usually have higher efficiencies than line-focus plants in areas with clear-sky conditions, because of their higher temperature and thermodynamic cycle efficiencies, there are many sunny places with a significant atmospheric attenuation where large tower plants are not the best option. The shorter focal length of line-focus concentrators makes these technologies more attractive for sunny places with atmospheric attenuation. Therefore, improvement of line-focus solar power technologies to reduce their costs should be included within the R+D priorities for this sector. The use of working fluids thermally stable at temperatures higher than 425ºC would increase the power block efficiency. Also, the improvement of the environmental footprint of the thermal oils currently used in parabolic trough plants, as well as the LCOE reduction through hybridization concepts, should be eligible within this challenge. There is still margin to reduce the solar field cost and the maintenance effort demanded by some key components at present, like the receiver tubes and the elements used to connect the receiver tubes of adjacent parabolic-trough and linear Fresnel collectors. Any innovative idea clearly showing a good potential for LCOE reduction in line-focus solar power plants would be eligible within this challenge

Targeted/expected impact from proposed R&I

- LCOE[3] reduction of line-focusing technology to 0,09 EUR/kWh in Southern Europe locations (without any additional constrain), by 2025, targeting 0,08 EUR/kWh by 2030, providing competitive dispatchable solar power (e. g. during night). These cost targets imply that the industry does not face additional constraint in Europe regarding the size/type of the plant, the financial conditions, a radiation of 2050 kWh/m2/year (conditions in Southern Europe) and within Power Purchase Agreements (PPA) with a duration of 25 years.
- Solar Rankine cycles with the same efficiency than conventional fossil fuels ones.

Specific challenges to achieve targeted impact

- Advanced heat transfer fluids with lower environmental footprint for working temperatures higher than 450ºC
- Cheaper collector designs

[3] LCOE calculation methodology, assumptions and parameters according to IRENA definitions in the Annex 1 of [26]

- Mirrors with anti-soiling coatings
- More efficient, cost-effective and reliable receiver tubes
- More cost-effective and reliable flexible connections
- Higher degree of automation of plant control by condition monitoring and AI
- Innovative plant configurations achieving better use of solar energy resource and technologies

6.3 Challenge 3: Turbo-Machinery Developed for Specific Conditions of Solar Thermal Power Plants

Turbine manufactures have pointed out that the use of turbo-machinery specially designed taking into consideration the technical and operational constraints of solar thermal power plants could increase the overall plant efficiency, which in turn would increase the competitiveness of solar thermal power plants. Turbomachinery specially designed for the specifics of highly competitive solar thermal power plants would enable higher overall plant efficiencies, improved operational flexibility and reduced first-time and maintenance costs. The European turbine manufactures must be the key players in the accomplishment of this challenge, because they would also be the main beneficiaries from a commercial stand-point.

Targeted/expected impact from proposed R&I

- Increase of 3 points in the overall plant efficiency
- Improved performance (cycle and turbine efficiency)
- Improved operational flexibility
- Reduced first-time, maintenance and service costs

Specific challenges to achieve targeted impact

- Optimized steam turbine developed for the specifics of a modern and very competitive CSP with improved efficiency, operational flexibility, as well as reduced first-time and service costs [Note: Although the required steam turbine designs and technologies do exist in principal from large power output generation applications, the development need arises for adopting these to considerably smaller power output ranges in CSP applications (<200MW)].
    - Steam turbine with elevated steam pressures (e.g. supercritical) and high steam temperatures (≥600°C)
    - Compact steam turbine design with thin walled components, lower weight and optimized speed
    - Upgraded steam turbine technologies adopted for the specifics of CSP applications – e.g. advanced 3D airfoils, quasi-hermetic seals, advanced bearings (e.g. magnetic bearings)
    - Robust large last stage blades to maximize efficiency and operational flexibility - e.g. number of starts, steam purity requirements, etc.
    - Cost-effective and oxidation resistant alloys by extending the application of steel to higher temperatures (e.g. up to 650°C)
    - Advanced concepts for improved flexibility in CSP applications using state-of-the-art technologies (e.g. artificial intelligence, machine learning, digitalization)

- Supercritical CO_2 turbine (design, operational concepts, rotordynamics, etc.) for high cycle efficiencies and more compact turbomachinery.

6.4 Challenge 4: Reliable and Cost-Effective Medium and High-Temperature Thermal Storage Systems

Dispatchability is the main benefit of solar thermal electricity when competing with wind or PV. This dispatchability is provided by the thermal energy storage systems. The working temperature of the storage systems commercially implemented at present in solar thermal power plants is either 390ºC or 565ºC, depending on storage media (diathermic oils/molten salts). This already commercial solution can be improved in terms of energy density storage and cost-effectiveness through innovative storage configurations and the use of combined sensible/latent heat systems. Anyway, the current storage temperatures are not high enough for supercritical steam Rankine cycles or Brayton cycles with supercritical CO_2 (sCO_2), which would have higher efficiencies. Development of thermal storage systems for T > 600ºC is needed to allow the implementation of supercritical steam Rankine cycles, while thermal storage for T > 750ºC are required for tower plants with a sCO_2 or Brayton cycles. The nature and storage medium for these two temperature levels are likely to be different and the technical constraints will be different too, e. g. solid materials promise cost-effective solutions for high temperatures.

Thermal storage systems are also highly relevant to industrial process heat applications as specific developments are needed for different temperature ranges. Specifically, the development of suitable thermal storage systems based on latent heat (phase change materials, PCM) or the enthalpy of reversible chemical reactions (thermochemical energy storage, TCS) have the potential to substantially boost the commercial deployment of these solar systems in the industrial sector, thus contributing to its decarbonisation [20]. Availability of cost-effective and reliable PCM thermal storage systems for the medium temperature range (200-300ºC) would make the use of direct steam generation (DSG) feasible for solar heat industrial process applications, thus contributing to a wider commercial implementation of these solar systems, while improving the environmental footprint due to the replacement of thermal oil by water in the solar field.

<u>Targeted/expected impact from proposed R&I</u>

- Feasibility of novel material approaches via validation in lab or demonstration in relevant environment (liquid, solid, PCM or TCS media).
- More sustainable and environmental friendly novel materials for thermal energy storage
- Cost-effective sensible-heat thermal energy storage for T>600ºC

<u>Specific challenges to achieve targeted impact</u>

- Thermal storage systems and materials for T < 550°C with improved cost effectiveness
- Suitable thermal storage systems and materials for T > 600ºC
- Suitable thermal storage systems and materials for T > 750ºC
- Suitable and cost-effective PCM thermal storage systems and materials for the 200–300ºC range, with investment cost lower than 40 EUR/kWh (thermal) of storage capacity
- Target for cost of sensible-heat thermal storage system lower than15 EUR/kWh (thermal) of stored energy for temperatures higher than 600ºC, including heat exchangers.
- Low cost thermal storage materials, in particular, obtained through a circular economy approach

6.5 Challenge 5: Cost-Effective and Highly Autonomous Medium- and High Temperature Systems for Industrial Solar Heat Applications

Decarbonisation of the industrial sector is one of the priorities of the EU to achieve a carbon-neutral energy system. Since the industrial sector is responsible for 32% of the total World energy consumption and 74% of the energy consumption in this sector is heat, development and implementation of renewable energy systems to supply thermal energy for industrial heat processes is essential to achieve the objectives of the EU. About 40% of the thermal energy consumption in the industrial sector is within the range 60–300ºC. These systems are often relatively small, which result in the demand for a robust and highly automated system to reduce O&M cost and to increase the efficiency of the solar system for industrial processes. However, the sector still needs the development of highly autonomous solar fields to further reduce maintenance requirements and to increase the amount of thermal energy delivered to the industrial process. Also, significant cost reductions may be additionally achieved by the use of direct steam generation, which has many advantages over the use of thermal oil or pressurized liquid water as working fluid in line-focus solar fields. For high-temperature industrial heat applications with temperatures up to 1000°C the development of suited receiver materials, technologies and autonomous solar fields promise to provide low-cost thermal energy reducing the release of CO_2 significantly to the atmosphere.

Targeted/expected impact from proposed R&I

- Application of concentrated solar to industrial processes/synergies of the solar thermal industry. with existing industrial processes achieving a 10% of heat consumed in industrial processes in Europe delivered through concentrated solar technologies, by 2030.
- Thermal energy cost ≤ 0.03 EUR/kWh (thermal) for temperatures lower than 400ºC, in small scale applications.
- Thermal energy cost ≤ 0.02 EUR/kWh (thermal) for temperatures higher than 600ºC, in large scale applications.

Specific challenges to achieve targeted impact

- Autonomous and smart solar fields, e.g. fail detection software, active & predictive management of the solar plant.
- Suitable high temperature (600-1000°C) receivers adapted to industrial processes
- To achieve specific investment cost lower than 400 EUR/m2 of solar collector surface for small line-focus solar fields
- Materials for increased robustness and durability
- More reliable and cost-effective receiver tubes (even non-evacuated)
- Low melting point heat transfer fluids to reduce operating costs
- Solutions to satisfy 24h operation
- Development of software tools for predictive design and test a solar plant in an industrial environment
- Materials and functional materials for increased robustness, efficiency and durability
- Hybridization by integrating power generation from the produced industrial heat or from waste heat

6.6 Challenge 6: Reliable and Cost-Effective Solar Fuels Production

Concentrated solar energy systems can be employed in the production of "solar fuels" (any chemical compound that can react with oxygen releasing energy), using two possible approaches: in the so-called solar thermochemical processes they can supply high-temperature process heat as the necessary energy source for the performance of endothermic chemical reactions for the production of chemical substances that can be used downstream in the chemical industry for the synthesis of liquid hydrocarbon fuels or ammonia, or stored/transported and used for off-sun electricity production when and where needed. Alternatively, in electrochemical processes, CST systems with their function as electricity providers can supply (in addition to other renewable sources like photovoltaics or wind power) the renewable electricity for electrolysis of steam; obviously CST systems can provide both the electrical and thermal energy required for a number of hybrid processes which use electricity as well as thermal energy. Up until now, such CST-driven processes for solar fuels production involve reforming and gasification of carbon-containing feedstocks, or thermochemical water/carbon dioxide splitting cycles employing either sulphuric acid (for water splitting only) or redox oxides. With respect to the latter, currently, technical solutions based on reactors without high-temperature moving parts, incorporating the maximum possible redox material quantity per volume and integrating at the time being the most efficient schemes of (only) gas-phase heat recovery, seem to offer the easiest way to scale-up beyond the lab-scale level and significant progress in such solar reactor design has been made. Indeed, the full process value chain from CST-driven syngas production via water and carbon dioxide splitting to liquid hydrocarbon fuels has been shown to be technically feasible at a pilot solar field/reactor level, but nevertheless, no such process has been so far demonstrated at the several hundred kW level and relatively long-term operation.

Targeted/expected impact from proposed R&I

- Demonstration of hydrogen production cost potential comparable to that from fossil fuels or alternative RE-based process routes like, e.g. PV/Wind-driven electrolysis (target cost of 3 €/kg H2 by 2030).
- Demonstration of potential benefits of future CST plants if co-producing electricity and solar fuels as a new business opportunity in the field.

Specific challenges to achieve targeted impact

- Solar-to-fuel conversion efficiencies ≥ 15 %, with the integration of heat recovery.
- Proof-of-concept operation of solar fuels production reactors, comparable to "traditional" chemical industrial plant operation.
- Materials that can perform reliably at process temperature levels that will not require shift to expensive overall plant infrastructure.
- Use of materials that do not exhibit toxicity and/or corrosion issues especially under the extreme conditions that many thermochemical cycles require.
- 1 MW scale demonstrator with at least 500 hours of operation time.
- Development and construction of custom-made solar fields capable of achieving the high temperatures required on high-efficiency receivers/reactors.

7 Relation to Cross-Cutting Issues

Hybridization with other renewable energies for power production. Efficient and competitive hybridization of solar thermal electricity, especially with PV, bring significant benefits as it can increase the penetration of intermittent renewable energy technologies. This hybridization not necessarily should be at plant level neither at grid connection point; it can also be done at system level. CSP with capabilities of Thermal Energy Storage, decoupling energy capture and power dispatch and displacing production precisely when the resource is not available, can be then used as a complementary solution to overcome intermittency issues of other renewables such as solar Photovoltaic panels (PV) and Wind turbines. Both of these technologies are greatly influenced by the unpredictability and instability of environmental conditions, placing their reliability, as power generation solutions, rather limited. Therefore, PV can generate during the day while CSP is capturing energy to be dispatched at night. However, there are still issues to be solved to optimize this integration to overcome problems such as PV ramp rate control and temperature-decreasing efficiency of PV modules, being therefore needed specific research activities.

Cross cutting topic related to the challenges #1 (Central Receiver plants with lower LCOE) and #2 (Line-focus solar power plants with lower LCOE).

Integration into the grid at large scale. Grid Integration of variable renewable energies is an issue concerning the grid management, and mainly affecting wind, PV and solar thermal electricity. Here is where CSP can provide the most valuable insight. In order to achieve large penetration rates of intermittent renewables, you need both (i) fast-response storage (i.e. batteries to guarantee supply during small gaps) and (ii) massive storage for planned dispatch (i.e. CST). Here targeted support can be provided CSP, for example via auctions for sliding feed-in premium, in accordance with technology- or even site-specific requirements. This can be a useful and cost-effective alternative to high carbon prices. One of the most important features of auctions to facilitate CSP market uptake is that they value dispatchability of electricity generation [21]. This can be achieved by requiring firm power with a specified generation profile which is complementary to fluctuating RES generation which will be mainly characterised by PV in places with rich solar resources. Other possibilities for CSP to receive the right market signals are higher remuneration levels at times of higher demand or a required minimum storage time for RES projects. Research is needed to design these CSP targeted support mechanisms.

Cross cutting topic related to the challenges #1 (Central Receiver plants with lower LCOE), #2 (Line-focus solar power plants with lower LCOE) and #4 (Reliable and cost-effective medium and high-temperature thermal storage systems).

Flexibility provision. At the policy level, a recent analysis of policy pathways [22] for the energy transition in Europe has shown that, regarding flexibility provision, there are no clear preferences or plans for flexibility provision, in any country or in any corner of the policy space. The main options – increasing dispatchable and carbon-free generation, deploying storage, or reinforcing grids and interconnections – are rarely specified by countries and, when they are, the deployment levels are almost always low. Recently published model-based assessment of the future market uptake of CSP is Europe have shown that CSP could be the fifth largest contributor to RES generation in Europe in 2030, serving as "gap filler" for the system flexibility to the EU power system that would rely on large shares of variable renewables. However, there is a need for dedicated support of CSP in the near to mid future. Therefore, CSP can be part of the solution, but political interest in CSP is weak. A part of the answer may lie on the European level where legal frameworks both for developing flexible technologies and ideas for further integration and cooperation on flexibility exist. Research is needed to evaluate the role that CSP can play in flexibility provision for the European energy union.

Cross cutting topic related to the challenge #4 (Reliable and cost-effective medium and high-temperature thermal storage systems).

Advanced materials: Innovative, advanced materials to be developed for CST are also of high interest in other technologies. High-temperature applications (CST, Fusion/Fission, high-temperature fuel cells, etc.) require metallic or ceramic materials that withstand the thermal load - often intermittent - over a long period. Some of these applications also operate in harsh climates or environments, i.e. elevated ambient temperatures or dusty or aggressive industrial or desert environments. Others use materials that may harm the surrounding structural materials, e.g. abrasive particles in particle receivers or fluidized bed heat exchangers. Also, innovative and cost effective structural materials need to be developed that are not only of benefit for concentrating solar thermal systems. In recent years there were first research projects developing fibre reinforced concrete of plastics as structural materials. Another area of common interest is on functional materials such as anti-reflective films, anti-soiling coatings for glass covers, solar selective coatings for absorbers (CST, low temperature collectors, PV) or nanostructured materials to enhance thermal conductivity. Metallic, ceramic foams used as high-temperature solar absorbers may also be additionally coated with catalytic substances which are then expanding their usage towards solar chemical reactor technologies for fuel production or towards fuel cell technology. Research is needed to develop innovative structural or functional materials that help to lower cost, increase lifetime and be environmentally sustainable.

Challenges in the cross-cutting issue input paper relate to all indicated challenges

RES cooperation between European countries. Renewable energy cooperation is expected to play an important role as a way to ensure an effective and affordable low-carbon energy transition in the EU. One of the renewable energy technologies which may benefit from the use of the cooperation mechanisms is concentrated solar power. Recent research has shown that in the absence of RES cooperation support – i.e. when a "High Country Risk" is prevailing in many of the southern European host countries of expected future CSP developments – significantly higher specific support is required. At the aggregated EU level, a clearly positive impact of RES cooperation exists, specifically of the levelling of country risk in the financing, on RES-related support expenditures. This indicates that strong differences in financing conditions across EU countries as we still see them today are less preferential for the decarbonisation of the EU's electricity sector. In this sense, EU's RES and CSP cooperation mechanisms are fully consistent with EU's energy transition and energy integration. Also, recent research [23] has identified the drivers and barriers to the use of cooperation mechanisms for CSP deployment. The most relevant drivers to the use of the cooperation mechanisms for CSP in the future – in descending order of importance- include: the dispatchability nature of CSP, new domestic jobs and industrial opportunities, complementarity with PV and policy ambition (renewable energy targets). Most relevant barriers, also in descending order of importance, are the higher costs of CSP compared to other renewables (on an LCOE basis), heterogeneous regulated energy prices and support schemes, resistance to lose sovereignty over energy market and existing interconnections capacities. Research is needed to address barriers and potentiate drivers in order to materialise these CSP cooperation projects in Europe.

Challenges in the cross-cutting issue input paper relate to all indicated challenges

Sustainability aspects, green growth and job creation. Recent research [24] has also demonstrated that CSP deployment will create value-added and employment that will be mostly retained in Europe as opposed to investments in PV that will to a large extent be produce outside Europe particularly in China. CSP electricity has also a low environmental footprint. However, it seems that it could originate some social risks in their value chain mostly outside the European Union that should be minimized guaranteeing the social responsibility along the value chain of all the components. Research is needed to improve the sustainability performance of CSP power.

8 System Level Challenges that Must be Solved to Realize the Potential

Implementation of a European Electricity Market. This should be based on the interconnection of European grid systems with common management rules and principles. This system-level challenge is somehow associated with the cross-cutting issue of "Integration into the grid at large scale", because such a unified European market would be of significant help for a far greater penetration of renewable energies due to the possibility of electricity transport between distant places, thus achieving better grid stability and more efficient use of power lines. To achieve this goal, current structural electricity market distortions should be removed, and the market transparency should be increased to make possible a fairer introduction of all renewables in the global European context. On top of permitting a high penetration of renewables, the implementation of a unique European electricity market could provide additional gains as high as €3.9 billion/yr, as some authors recently estimate [25].

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Input Paper to the CETP SRIA Renewable Technologies

Challenge 2

Photovoltaics

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1 Introduction

Renewable electricity is expected to become a cornerstone of the future sustainable, climate-neutral energy system. It may become the 'primary fuel of the future', not only serving the well-known electricity needs, but, by electrification, also powering heating and cooling in urban environments and industry, transport and mobility, and in some parts of the world, desalination. Thus, renewable energy and other low-carbon technologies, with PV solar energy as a prominent element, are drivers of the energy transition and will play a key role in achieving the European Green Deal targets [1, 2]. Moreover, the related industry sectors have been identified as value chains of economic and strategic importance. They offer great opportunities for job creation and can thus make important contributions to the economy and to the EU Recovery Plan. Availability of world-class technologies, solutions, policies and instruments is a prerequisite for success and joining forces on research and innovation between Member States is a proven approach to benefit in an optimum way from Europe's distributed strengths. Moreover, they guarantee an independence in the strategic important energy sector and generally in the security of energy supply. The Clean Energy Transition Partnership aims to facilitate cross-border collaboration and this Strategic Research and Innovation Agenda identifies the fields that are crucial for the energy transition on the one hand and will benefit from collaboration on the other hand.

2 Technology Status

Over a period of decades, PV solar energy has developed from an option serving high-value niches to a renewable energy technology prepared for competitive terawatt-scale deployment. The achievements obtained in the last 20 years by research, innovation, industry development and deployment with important contributions from European companies, organisations and countries are impressive:

- Increase of the annual and cumulative global installations by well over two orders of magnitude, reaching 115 gigawatt-peak (GWp) and 630 GWp in 2019, respectively, achieved by successful market incentives and development of commercial markets (with almost 20% of cumulative capacity installed in Europe);
- Reduction of typical component and system cost (and prices) as well as generation cost (Levelized Cost of Energy; LCoE) by up to an order of magnitude, resulting from a powerful combination of innovation and economies of scale in manufacturing and installation, with LCoE values now indicatively ranging from 0.02 to 0.10 €/kWh for different geographical locations, system sizes and types and financing conditions;
- Performance enhancement of commercial solar panels by more than half, with 21% efficient solar modules now available at low cost (typically <0.25 $/Wp) and a range of silicon and thin-film module technology options on the market to serve different applications;
- Track record of lifetime and reliability, with PV systems in operation for 25 years or even more;
- A well-filled pipeline of new technologies and advanced version of existing technologies (silicon, thin film, tandem, and more) in laboratories and pilot production, enabling robust continued performance increase over time, even well beyond the limits of current technologies, opening up new applications and facilitating further cost reduction;
- A range of new PV system types and designs demonstrated for small-scale decentralized as well as large-scale central use, including advanced power management, aimed at physical (e.g. in buildings) and energy system integration;
- Strongly reduced embedded energy and carbon footprint, with Energy Return on Energy Invested now typically 10 to 40 for different geographical regions and technologies [3].

3 Ongoing Research

In 2017, the SET Plan Temporary Working Group on Photovoltaics (TWG PV) set up an Implementation Plan (IP) [3] that describes the technological and non-technological R&I activities that need to be implemented in order to achieve the strategic targets adopted in the SET-Plan Declaration of Intent (DoI) on PV [5]. The IP is based on ongoing R&I activities (conducted at national and/or at European level and/or by industry), which already support the strategic targets. The core of the Implementation Plan is a selection of R&I activities to be carried out by the various actors (SET Plan countries, stakeholders and, within its mandate, the EC).

1. PV for Building Integrated PV and similar applications

The R&I activity on Building Integrated PV (BIPV) aims at developing a market pull approach for innovative and integrated PV solutions that will allow a faster market uptake of new PV technologies and a more intensive and multi-functional use of the available surface area in Europe, including quality and reliability. This requires a multidisciplinary approach and close collaboration between the PV/BIPV and building sectors. Sub-activities cover for example bifacial applications. In addition, other integrated approaches like PV installations on or along roads, waterways and agricultural land, which will become very important in the near future, are covered.

Generic PV funding budgets on national level already cover topics like higher cell and module efficiencies and quality issues. Specific R&I on the integration topics and production technologies, related to specific market segments, as well as joint demonstration and feasibility projects would require additional efforts and EU cooperation.

2. Technologies for silicon solar cells and modules with higher quality

Wafer-based silicon (cSi) technologies have the largest market share (>90%) in the worldwide solar PV sector. The main objective of this activity is to develop and implement advanced cSi PV technologies for high-quality, high-performance cells (≥24%) and modules in high-throughput industrial manufacturing processes, including (for the PV sector) new materials and production equipment. These products will serve as differentiator for the European PV industry by means of significant efficiency benefits and better performance related to sustainability aspects and recyclability of modules (PV Ecolabel, Ecodesign and Energy labels).

Across Europe, a broad set of R&I activities is addressing this activity. Based on experience of the last years, approximately up to 70% of the total PV budget on national, regional and European level is used for funding in this part of the PV sector.

3. New technologies & materials

Crystalline silicon based solar cells as well as some thin film technologies are gradually reaching their theoretical efficiency limit. The most promising approach (at least on the short and medium term) to go beyond this limit are tandem technologies. Concrete options are perovskite or III/V-semiconductor top cells on silicon bottom cells. Another option is a stack of two thin-film cells, for instance using perovskites and CIGS (a compound semiconductor containing Cu, In, Ga, and Se). A third route is the development of cost-effective concentrating PV (CPV). The aim of this activity is to bring these technologies to an economically feasible level. Therefore, scale-up of cell processing on an industrial level, reduction of costs, new materials and the combination of two cell technologies via new interlayers or module integration, stability of devices and in the end, the environmental impact are addressed.

Research on tandems employing perovskites, Si and/or CIGS and the development of CPV devices is carried at a high level. European collaboration on competing concepts and on production equipment/ processes will in most cases be an efficient solution bringing synergies.

4. Development of PV power plants and diagnostics

The aim of this activity is to develop and demonstrate business models and streamline the processes for effective operation and maintenance of residential and commercial plants in order to keep the plant performance and availability high over the expected lifetime. Development of detailed monitoring and analysis methodology of PV power plants is essential for optimized performance, but also for the learning and necessary input to improve the technology. Due to incompatibility and the accompanying extra costs, however, this is often not yet done according to good industry practices. European collaboration along the whole value chain ensures critical feedback on R&I activities related to long term performance and quality.

Aspects of energy system integration are included, but as an integral part of the PV system. In addition, new concepts for integrating PV power plants into the environment are investigated, e.g. Floating PV or Agrophotovoltaics (APV). These allow to reduce conflicts in land usage, which might become a limiting factor for PV installations in the near future.

A substantial number of national initiatives addresses this topic.

5. Manufacturing technologies (for cSi and thin film)

Further reduction of system and generation costs (LCoE) for wafer based silicon PV and thin film technologies are strongly supported by the implementation of high-throughput, high-yield industrial manufacturing technology. This includes production equipment (Capital Expenditure; CAPEX) and materials (Bill of Materials; BOM) costs as well as product quality (efficiency and performance). Advances in this field strengthen the European manufacturing industry. The introduction of new materials and cell/module designs enforces advances in the field of manufacturing technologies, including the introduction of Industry 4.0 ("smart factory") in PV, and strengthens the European manufacturing equipment industry.

European equipment producers are well established and market leader worldwide in a significant range of technologies. Current R&I addresses the proof of concepts in a (quasi-continuous) mode near large-scale manufacturing with (equal or better) product quality.

6. Cross-sectoral research at lower TRL

With respect to high level R&D, European research labs are still the leading institutions worldwide. A closer cooperation of these labs could help maintaining this position in order to support European industry with cutting edge research results. On a topical level, this activity covers all the other activities described above, with a focus on the low-TRL parts of the total R&I programs. Activities in this field should be further strengthened.

4 Technical Potential

The technical potential of PV solar energy is very large, both globally and in Europe, and PV is therefore expected to become one of the corner stones of the future sustainable energy system or even the biggest energy source in absolute terms [6, 7, 8, 9, 10], serving the growing electricity needs but, by conversion, also supplying heat as well as fuels and feedstocks (power-to-heat, power-to-fuel and power-to-feedstock: P2X), see also 'Economic potential'. This development, usually referred to as 'electrification', is important for a rapid energy transition and increases the potential role and impact of electricity from PV and wind energy far beyond what has been anticipated in the past. In several European countries, PV already covers more than 5% of the annual electricity demand, which was initially foreseen only after 2020. Photovoltaics currently covers 3% of total EU electricity demand, with a potential estimated at around 15% in 2030. Many countries have just started to install PV on a larger scale. Due to this fact the PV market will grow rapidly; up to 12 TW are expected to be installed in 2030 worldwide [11]. Moreover, manufacturing capacity and installed capacity can be expanded rapidly, with short lead times between planning and realisation, especially since some of the most experienced companies for manufacturing technology and installation are based in Europe. Actual deployment levels will therefore be determined rather by, among others, considerations concerning energy system and technology portfolio optimisation, societal and political preferences and further cost reductions; see also next Chapter.

5 Economic Potential

The cost of PV solar energy has come down drastically in the past decades (see also 'Technology status'), but further technology developments on component (including solar modules) and system levels will drive further cost reduction, reaching typical, sustainable LCoE values below 0.01 €/kWh for large installations in sunny regions and 0.02 to 0.03 €/kWh in moderate insolation regions in the medium to longer term. Such very low LCoE levels are particularly important when electricity from PV (and wind) is needed for large-scale electrification, using conversion technologies (P2X, see previous Chapter) or when electricity is stored. Conversion and storage are essential for electricity from PV and wind energy to be integrated in the total energy system and thereby to become 'the sustainable primary fuel' of the future, but they also introduce significant cost in addition to the mere cost of generation. The full economic potential of PV is therefore determined to a large extent by the cost of the combination of generation and storage or conversion. However, since PV generation costs are expected to come down to such extremely low values, also the combination of PV generation with storage or conversion has a huge economic potential.

6 Challenges

Powering the Energy Transition

Renewable electricity is a cornerstone of the global and European sustainable energy system of the future [6-12]. Solar energy and wind energy are key technologies to make this electricity available in sufficient (i.e. very large) quantities, at affordable cost, and in an environmentally and societally sustainable way. To enable this, integration into the energy system (incl. storage and P2X) and therefore, further reduction of generation cost and enhanced flexibility and diversification are needed, as well as integration into our living environment, and circularity in all parts of the value chain [13].

Supporting Economic Recovery and Building the Value Chains for Renewables

Achieving the aim of the Green Deal to make Europe's economy sustainable offers great opportunities to support economic recovery from the crisis and to build the value chains of renewable energies, incl. PV solar energy. For the EU industry to be successful in the global competition, excellent technology and rapid innovation are essential [14]. These are proven strengths of the EU PV ecosystem that have to be ambitiously developed further, jointly between research and industry and between member states.

6.1 Challenge 1: Performance Enhancement for Efficient Use of Available Areas and as Lever for Cost (LCoE) Reduction

Description of the transition challenge

The energy transition challenge also represents a spatial challenge. Very large-scale deployment of renewables also requires large areas for installation of systems (and, to a lesser extent, of the energy infrastructure needed for transport, storage and conversion). Ideally, these areas serve dual or even multiple purposes and PV solar energy is applied in an integrated way, combining electricity generation with building skin functions, physical infrastructure, ecosystem services, electric vehicles, agriculture, and more (see Challenge 4 hereafter). However, efficient use of the best available areas is needed and therefore further enhancement of the energy performance in terms of power conversion efficiency and energy yield or related units is needed, from today's typical level of 20% for commercial technologies to 25-30% in the medium term and 30-40% in the longer term. Such performance enhancement is also crucial as a lever for further reduction of generation cost (Levelised Cost of Energy; LCoE - see Challenge 2 hereafter), since area-related CAPEX and OPEX scale inversely with conversion efficiency of the installation.

This challenge needs to be addressed primarily by stakeholders specialised in the heart of PV technology: cells, modules, foils, power converters etc. In other words, a joint effort of research and manufacturing industry is essential. Beneficiaries are all users of PV, ranging from system designers and manufacturers of integrated PV elements, through project developers and investors to system owners and operators.

To address this challenge successfully, it is essential to have a complete and well-operating European PV innovation and manufacturing ecosystem. Specifically: research needs industry as a partner and vice versa, industry should be present over the entire (strategic!) value chain, and industry needs a domestic market (only export to other parts of the world is not sufficient) to be able to develop and innovate. If any of these conditions is not fulfilled or if a part is weak or absent, the challenge cannot be addressed properly in the highly competitive global context.

Overarching impacts

- Efficient use of available areas for renewable energy generation/ reducing competition between different kinds of land use, thus further increase of conversion efficiencies;
- Reduced cost of renewable energy (i.e. solar electricity);
- Reduced embedded CO_2 when green manufacturing and circular economy principles are applied.

Specific impacts

- Keeping Europe in the premier league of global PV science and technology;
- Supporting EU PV manufacturing industry to create a viable complete European value chain.

Issues to be addressed

- Advanced silicon technologies (advanced passivation, heterojunction, back-contact, etc.);
- Hybrid tandem technology (in particular perovskites/silicon);
- Thin-film tandem technologies (including perovskites/CIGS and perovskites/ perovskites and III-V compounds);
- Optimized module technologies (including interconnection, glass coatings) to lower losses and thereby increasing performance.

6.2 Challenge 2: Cost Reduction to Enable Large-Scale Deployment of Integrated PV Applications, Storage and Solar P2X

Description of the transition challenge

The cost of PV solar energy installations and hence of PV electricity generation has come down dramatically over the past decades: by well over an order of magnitude since 2000 and by almost two orders of magnitude since 1980. PV is now competitive in a large number of markets in Europe and worldwide and even is the lowest cost renewable electricity option in selected parts of the world already. This has accelerated PV deployment and global installations will exceed 1 terawatt (TW) soon, as a first step to the tens of TW needed in the longer term. Nevertheless, ambitious further cost reduction (by typically a factor 2 to 4) as well as lifetime and quality enhancement (see following challenge) are essential to account for the need for (and costs associated with) energy system integration, i.e. storage at different levels in the system and power conversion to low- and high-temperature heat, fuels and feedstocks, and the need for physical integration and function combination (see Challenge 4 hereafter).

Overarching impacts

- Making renewable electricity available for large scale use at competitive cost and in the appropriate form, including for storage and P2X;
- Enabling new technical options for an energy system based on renewables, e.g. storage integration.

Specific impacts

- Supporting EU PV industry to be successful in global competition;
- Enabling new business models within the renewable energy system;

Issues to be addressed

- Low or zero-loss crystallisation and wafering of silicon;
- High-throughput processes for cell manufacturing, interconnection and module assembly, for silicon and thin films (including roll-to-roll and printing);
- New absorber materials (e.g. perovskites, compound semiconductors and others) for reduced energy and material costs;
- Energy yield improvement by tuning the PV technology for specific climates and applications;
- New and recyclable encapsulation materials;
- Decreased material usage for Balance Of System (BOS) and system designs.;
- Making PV ready for digitalization and integration into the energy system of the future, e.g. PV panels with added sensors or other added functionalities;
- Optimized PV system components, in particular power electronics, converters etc.;
- Advanced and automated functions for data analysis, fault detection, diagnosis, maintenance planning and/or reporting;
- Technical solutions and business models to support high plant performance, availability and income over the expected lifetime of the PV plant.
- Cost reduction of new PV integrated applications through technological and production related progress as well as upscaling national niche markets (see also challenge 4);

6.3 Challenge 3: Further Enhance Lifetime, Reliability and Sustainability (Quality and Circularity)

Description of the transition challenge

Over decades of use, PV solar energy has built an excellent track record of (long) lifetime and (high) reliability in practical installations. This is a prerequisite for investments and has enabled large-scale deployment. Moreover, the embedded energy in PV installations has been reduced drastically, and with it, the energy pay-back time (EPBT), the energy return on energy invested (ERoEI) as well as the equivalent carbon footprint of PV solar energy electricity generation. The challenge is now to ambitiously further increase performance and reduce cost, also by the introduction of new technologies, while (and by) maintaining and even enhancing lifetime, reliability and sustainability. In particular, PV solar energy has to be developed from the inherently renewable energy technology it is already to a circular technology, compatible with sustainable deployment at the multiple TW-scale needed for big impact (i.e. tens or even hundreds or thousands of km^2); see also the Cross-cutting issues hereafter.

Overarching impacts

- Securing an affordable, high quality, resilient energy supply for Europe;
- Helping to realise a fully sustainable (i.e., not only climate neutral) economy.

Specific impacts

- Achieving 'circular solar', with low embedded energy and with reduced dependence on critical materials;
- Supporting cost reduction by enabling long(er)-period business models;
- Ensuring the competitiveness of sustainable EU PV solar manufacturing.

Issues to be addressed

- Recyclability and design-for recycling/ design for sustainability;
- Low environmental impact materials and more efficient manufacturing technologies, especially by reducing net demand of scarce resources and energy (thereby reducing energy payback time and carbon footprint (Global Warming Potential) of PV);
- Increased lifetimes and lifetime warranties, and accelerated tests to predict and quantify lifetime and degradation rates;
- Establishing a lifetime-relevant quality assurance scheme at system level;
- Eco-labelling and energy-labelling, including setting standards based on accurate data bases for material demand, flow and impact throughout the life cycle.

6.4 Challenge 4: Flexible Solutions for PV Integration (Buildings, Infrastructures, Vehicles, Landscapes, etc.) and for Floating PV

Description of the transition challenge

The PV solar energy sector has been able to achieve spectacular cost reduction by successful innovation in combination with huge economies of scale and standardisation. Although cost reduction has been decisive for market growth, the high degree of standardisation of products and solutions now limits the desired flexibility of use. In particular, integration of PV into buildings, physical infrastructures, vehicles and landscapes as well as the use of PV in floating structures for inland and offshore use requires large application flexibility and diversity on the one hand and sufficiently low cost on the other hand. Traditionally, these two requirements are very difficult to combine and the challenge is thus to make new manufacturing concepts and product designs available that combine the better of two worlds: maximum flexibility of use with the low cost achieved for standard applications, also referred to as 'mass customisation'. This can be done by introducing Industry 4.0 concepts into the PV manufacturing chain.

Overarching impacts

- Enhancing public support/ societal enthusiasm by offering attractive deployment options;
- Making optimal use of available areas, reducing competition between different kinds of land use;
- Bringing renewable generation closer to the consumers in an aesthetic way; Enabling local power supply.

Specific impacts

- Making flexible manufacturing and product/ application concepts for integrated PV available, allowing it to grow from niches to mainstream markets;
- Enabling a local and competitive production of tailored and flexible PV products in Europe;
- Realizing technological options for Integrated PV for all suitable installation sites;
- Reduction of material consumption by integrating PV into existing substructures.

Issues to be addressed

- Integrating the PV supply chain with others, such as the building supply chain;
- Adjusting PV products to the specific needs and processes in other sectors, such as building, automotive and agriculture; ensuring compliance of integrated PV products and systems with norms and standards in those sectors;
- Demonstrating long-term reliability of Integrated PV products taking into account the specific challenges and requirements;
- Developing manufacturing technologies for tailored and flexible products with a particular focus on digital Industry 4.0 solutions, based on high-performance and low-cost PV technologies.

6.5 Challenge 5: Advanced Technologies and Manufacturing for the PV Value Chain ('PV made in Europe')

Description of the transition challenge

Europe has a world-class position in PV research, technology and applications. It has also played a pioneering and ground-breaking role in market development followed by upscaling of manufacturing. In the past decade, however, market growth and industry development has primarily taken place in Asia, although still strongly building on advanced European manufacturing technology and equipment. To seize the great economic opportunities associated with further growth of PV manufacturing and deployment to the terawatt-level, to supply the solutions for the wide variety of integrated and other PV applications needed for a rapid and optimal energy transition and to reduce dependence of imported hardware (renewables are a strategic value chain), (re)building a strong European PV industry is vital. This has only become more urgent and explicit with the introduction of the European Green Deal ('building a climate-neutral European economy') and the Recovery Package ('repair and prepare for the next generation'). For a successful PV industry sector, advanced and novel PV technologies, with high performance, excellent sustainability and flexibility/ diversity of use need to be developed and taken into production in a joint effort between research, industry and end users. Bankability and competitiveness are boundary conditions, taking into account key aspects of quality and sustainability, to create a level playing field. This, in short, is the challenge to be addressed.

Overarching impacts

- Establishing the PV value chain;
- Enabling technological sovereignty and reducing import dependence;
- Supporting economic recovery.

Specific impacts

- Supporting the EU PV industry to compete in the global market, with high-quality, sustainable processes, technologies and products;
- Ensuring market availability of products and solutions needed for integrated PV and other new applications;
- Realizing Industry 4.0 within PV manufacturing, leading to smart factories.

Issues to be addressed

- Transfer 'from lab to fab to roof or field' of the results obtained in research (see 4 previous Challenges), both for advanced versions of existing technologies and for novel technologies;
- Rapid qualification and field testing (procedures) of new technologies and applications (i.e. options without a track record), to support bankability;
- Digitization of PV manufacturing;
- Enabling high-quality PV modules as differentiator for the European PV industry by means of significant efficiency benefits and better performance related to sustainability aspects and recyclability of modules.

7 Relation to Cross-Cutting Issues

The specific challenges for PV described in the foregoing have strong relations with (and are part of) broader developments and related cross-cutting issues in the energy transition. Specifically, these are:

7.1 Sustainability and Circularity

Climate neutrality is a necessary feature of a sustainable economy, but it is not sufficient. Closing material cycles (circularity), reducing embedded energy and using earth-abundant elements as much as possible, for instance, are important other aspects (see for example [13]. Although many challenges in this field are technology-specific and can only be addressed at individual sector level, there are also challenges that have to be addressed at a higher levels (i.e. for industry sectors jointly and at European or even global level). This is particularly the case for the development of meaningful standards, such as those concerning eco-design, eco-labelling, eco-impact, and energy labelling as well as implementing market drivers in which these standards are required.

7.2 Digital Transformation and Industry 4.0

Manufacturing, design, installation, operation and maintenance of renewable energy technologies and other aspects of the energy transition have made impressive progress over the past decades. Yet, we are only at the beginning and the biggest part of the transition is still to come. The challenge is to optimize or even re-invent the way the sectors work, by making optimum use of data all over the value chain (from mining, through manufacturing and installation, to end use and recycling) to achieve the goals of the transition in the best possible way: societally fair, environmentally sustainable, economically affordable, and strategically wise, to mention a few important aspects. Examples in this context are the implementation of 'Industry 4.0' concepts, for instance to combine 'high volume' (low cost) with 'high mix' (flexibility of use) and for deep renovation of buildings, and the use of digitalisation/ blockchain technology to achieve robust transparency of value chains, which is needed for ultimate labelling of products and solutions. An important aspect is the creation of digital twins to ensure high performance and sustainability of products throughout their production and lifetime.

New options also arise in the field of PV systems and power plants by using the chances from increased digitisation consequently. New business models for developers and operators of PV power plants as well as electricity marketers will evolve through smart monitoring using sensors, drones, artificial intelligence and big data analysis. Also cost savings in O&M will be achieved, e.g. through predictive and event-based maintenance. Downtimes will be reduced and energy yield will be increased. In addition, a comprehensive analysis of systems and a systematic feedback loop from system to component quality will allow deep learnings. A long term vision would be to analyse and connect data from component manufacturing via construction to operation of PV power plants.

7.3 Societal Acceptance and Participation

The energy transition is very challenging technologically, but also societally. Societal acceptance, or preferably even enthusiasm, is an important factor to accelerate the transition and achieve the goals in time. Understanding the factors that determine acceptance/ enthusiasm, gaining experience with different forms of public participation and involvement, and designing optimum deployment policies, to mention just a few, are therefore important elements of the CETP Strategic Research and Innovation Agenda. Sharing best practices between stakeholder groups, regions and countries, open innovation, field labs and other approaches are needed to make rapid progress in these fields.

8 System Level Challenges that Must be Solved to Realize the Potential

Renewable electricity is expected to become a cornerstone of the future sustainable, climate-neutral energy system. It may become the 'primary fuel of the future', not only serving the well-known electricity needs, but, by electrification, also powering heating and cooling in urban environments and industry, transport and mobility, and in some parts of the world, desalination. Moreover, and very important, renewable electricity will be used to produce fuels (hydrogen, hydrocarbons, and more) and feedstocks. To realise this ambition, PV shares important challenges with wind energy and other renewable energy technologies, as summarised in the following.

8.1 Options for Flexibility and Electrification

Building a reliable energy system with wind energy and PV solar energy as key components requires cost-effective, smart and reliable options for flexibility, storage and conversion of electricity into other energy carriers. The related challenges can be divided into two categories, distinguished by their level, scale and purpose.

8.1.1 Power Management, Integrated and Local Storage

The challenge is to use the power electronics and intelligence in renewable energy generators not only for their basic function (e.g. dc/ac conversion), but also to supply auxiliary services, such as real-time grid (quality) support, remotely controlled (short-term) power management, production aggregation enabling 'virtual' power plants, etc. These functions can be combined with local or regional (e.g. battery) storage, which may be integrated into the generator or the user (e.g. vehicles) when needed or advantageous. Selected related challenges are cyber security, privacy, suitable business models and regulatory frameworks, system operational robustness and (especially for storage technologies) sustainability and circularity.

8.1.2 Large-Scale Storage and Conversion

When large capacities of wind and PV solar energy are installed, generation (on purpose/ by design) often exceeds the actual demand for direct electrical functions. The electricity then generated will either be stored or converted into heat, fuels or feedstocks (power2heat, power2fuel, power2feedstock; P2X). The challenge is to achieve economic competitiveness of combination of generation and conversion or storage, but also to make conversion technologies available that are sustainable. This challenge is partly addressed in the Green Deal.

8.2 Energy and Electricity Market Design

Current energy and electricity markets have not been designed or optimized for large-scale deployment/ presence of renewable electricity generators such as PV solar energy and wind energy. The challenge is to design and implement market models that facilitate acceleration of the energy transition and allows the transition to follow an economically, environmentally and societally optimal path.

8.2.1 Taking All Relevant Costs and Benefits into Account

The first specific challenge is to design the electricity and, broader, energy markets in such a way that economic, environmental and societal costs and benefits are taken into account, at least to the degree that is needed for a rapid and optimized energy transition. This requires 'giving value' to aspects that are so far not or only partially included, but that are important for the energy transition process itself or address related challenges such as enhancing biodiversity and circularity.

8.2.2 Developing Appropriate Regulatory and Legal Framework

Well-functioning of energy and electricity markets and a rapid energy transition rely on the design and implementation of an appropriate regulatory and legal framework: 'the rules of the game'. Since the roles and responsibilities of stakeholder groups in the energy system (related to generation, distribution, flexibility, use, etc.) have changed and will change further, and new groups become actively involved (e.g. consumers), there is an urgent need for a framework that reflects, facilitates and/or steers these developments. The challenge is to combine effectiveness with speed and Europe-wide adoption.

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Input Paper to the CETP SRIA Renewable Technologies

Challenge 3
Offshore Wind

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1 Introduction

The European energy transition requires mass electrification in energy use in households, transport and industry. In addition, hydrogen, synthetic transport fuels and heat are more and more produced using electric power. Offshore wind energy is marked as one of the key renewable energy resources that will deliver the bulk of the renewable energy (450 GW) in 2050. That energy will mostly be used to meet direct electricity demand and partly for the production of renewable fuels. The development of these volumes of offshore wind create enormous economic opportunities for Europe, and there are also challenges to be resolved to make it happen.

We name three key issues to be tackled:

1. Cost of offshore wind must be further reduced (both bottom fixed and floating) to make the energy transition affordable and to maintain the competitiveness of the European industry,

2. Integration of very large volumes of offshore wind energy in the energy system

3. Spatial planning and ecology: to mitigate environmental impact as well as develop co-use of the space occupied by offshore wind farms.

Innovation is required to address these issues to make the energy transition successful.

Offshore wind is positioned to fuel Europe's energy transition. This creates enormous economic opportunities. There are also issues to be addressed through R&I: cost reduction, system integration and spatial integration.

2 Technology Status

Today onshore wind is the cheapest source of new installed power capacity in many parts of Europe. And offshore wind is not far behind as it has achieved significant cost reductions in the past years. From the second half of 2009, the offshore wind levelized cost of electricity (LCOE) globally has fallen by 44%[1]. Thanks to major public and private investments in R&I and economies of scale, costs decreased from EUR 150/MWh (2014), to EUR 65/MWh (2017)[2] reaching EUR 40-50/MWh (2019)[3].

Still, governments and consumers expect wind energy to continue decreasing cost to accelerate the shift away from fossil fuels. The sector is under continuous pressure to deliver high quality end products at low cost.

The European wind industry is competitive mostly due to its excellence. To retain a competitive advantage the sector continuously needs to develop and market the best technology available. This requires significant investments in Research & Innovation (R&I), and given the cost reduction pressures, companies need stable and secure revenues to sustain investments in technology development. EU support for R&I in wind energy plays a pivotal role to help the energy sector nurture radical solutions that challenge the status quo. The development of new breakthrough applications and technologies will help establish wind energy at the heart of the energy transition and boost the competitiveness of the European wind industry in the global market.

The technology developments are fast; about every three years a new generation of wind turbines appears in the market, leading to further improvements and cost reductions. There are continuous developments in supporting technology such as installation vessels, support structures, grid

[1] UNEP & BloombergNEF, Global trends in renewable energy investment (2019)
[2] ETIP Wind, Strategic Research and Innovation Agenda (2018, p. 5)
[3] WindEurope, offshore wind in Europe – Key trends and statistics (2019, p. 8, 31)

developments, O&M, etc. This enables an extensive European offshore wind supply chain to have the technology leadership position in the world creating over 77,000 full time jobs in 2020 to 201,000 jobs in 2030.

Delivering on the ambitious 2050 targets of 450 GW installed offshore wind power, requires significant technology developments to reduce cost, enable the integration in the energy system and to mitigate environmental impact while being fully circular by design.

Targeted R&I support will strengthen the leading role of the European industry in the global market.

The development of a 450GW offshore wind sector requires continuous and focussed R&I.

3 Ongoing Research

The fast technology development and the implementation of innovation combined with economies of scale are the reason that at this moment offshore wind projects are cheaper than new nuclear power and gas-fired power plants. Modern offshore wind farms have lower power variability and higher capacity factors than in the past, helping the integration of offshore wind power in the energy system. In 2019 there was 22 GW of offshore wind installed in Europe. But over the last ten years it has attracted average annual investments of EUR 8,4 billion, fuelling the development of a thriving sector. This has created jobs and worldwide exports in equipment, skills and services.

Scaling up from 22 GW (2019) to 450 GW (North Sea, Atlantic Ocea, Baltic Sea, Southern European Waters) by 2050 will require a visionary approach. The current 2030 policy framework can deliver 111 GW by 2030. Governments must start setting the course for enabling higher levels of deployment. A key role in this path is represented by collaborative research activities fostering European excellence within science and technology driven research projects.

- **Implementation of offshore wind power requires positive business cases: increasing the market value and reduction of cost of electricity and uncertainties of revenue**
- **Wind turbine technology is required to be improved until 2050 leading to lower cost and improved system integration**
- **Sector coupling is crucial for the uptake of the massive amount of offshore wind power: direct electrification of the industry, transport and heating as well as the (off-grid) production of renewable hydrogen include urgent research tasks**
- **Creating a 450 GW offshore wind sector requires opening new areas at sea: developments in bottom fixed in deeper water and development of floating wind power is essential**
- **The offshore wind sector is moving towards full circularity. Recycling solutions for blades, new manufacturing processes of components and CO2-free transportation methods need to be developed.**
- **Nature-inclusive building of offshore wind farms and multi-use of the space they occupy requires intense research and development.**

4 Technical Potential

The anticipated volume of offshore wind energy in the energy mix is dependent on many factors. An accepted scenario is that of the European Commission (2018) and WindEurope, where 450 GW of installed capacity in the year 2050 delivers around 1,800 to 2,000 TWh of electrical energy. This also requires around 100,000 km^2 including areas with high shipping densities, fisheries and many other activities. The growth path towards these volumes is considered feasible and still requires enhanced coordination among Member States in maritime spatial planning and investments in Research & Innovation, in particular to further reduce cost and allow effective integration into the energy system and the environment.

- **Development of more powerful turbines (up to 25MW) will lead to further cost reduction and improved system integration**
- **By technology development, and cooperation with storage solutions offshore wind farms will be able to deliver power on demand.**
- **By sector coupling the massive amount of offshore wind energy will be the backbone to produce bulk renewable hydrogen in many regions of Europe.**

5 Economic Potential

The development of high volumes of offshore wind (450 GW in 2050) creates enormous opportunities for Europe. The economic benefits will be large through creation of jobs in manufacturing of components and equipment, engineering and installation works and maintenance activities. There is also the benefit from (re)using existing infrastructure from oil & gas activities. This economic contribution extends deep into supply chains for the wind energy sector as well as maritime industry, logistics and digitalisation. Europe has a unique opportunity to capitalise on its existing technology leadership, where the benefits extend beyond the European energy transition: offshore wind is a global market.

- **In 2030 the yearly investments in European offshore wind is €29.38 billion**
- **In 2030 there are 201,000 people working in European offshore wind**

6 Challenges

6.1 Challenge 1: Wind Turbine Technology

Wind energy holds a unique place in the European industrial fabric. It is at the same time a high-tech green and heavy manufacturing industry. Innovation and technology development play a big part in the success of wind energy in Europe and EU funding for R&I acted as a catalyst for the impressive cost reductions in the sector. To sustain this trend the industry needs continued support to innovate, design and manufacture new component structures and materials and to develop new high precision manufacturing lines suited to the mass production of larger and more efficient turbines. Research and development of new materials and/or multi-material solutions should reduce component weight, increase durability and improve mechanical performance. Basically, all turbine components need to be improved: blades, drive train, power electronics, nacelle, tower etc. Transportation and installation technology also need to be improved and scaled up to match the development of bigger wind turbines in the coming years. To this aim, cooperation between the industry and academic communities should be encouraged and supported with dedicated research programmes.

Modern wind turbines are very complex machines that have to operate under difficult external conditions with relatively little maintenance compared to other industries. To ensure safe and reliable operation, wind turbines, their individual components and their dynamic interaction must be thoroughly tested. Due to the size of current wind turbines and those yet to be developed, test procedures and facilities are a challenge in themselves. The combination of large-scale R&D and test infrastructures with numerical simulations and digital twin concepts will pave the way for new technologies based on a deep understanding of the underlying science and experience projected in accessible databases.

The wind sector will grow exponentially, international alignment of technical standards and the introduction of new turbine concepts and architectures could help to reach the goals. Exploring potential of for instance superconducting generators, multi-rotor designs, airborne wind energy, smart rotors, hydraulic drive trains, batteries integration etc. could help deliver on wind energy's full potential.

Areas of research

- **Integrated design of next-generation wind turbines based on accurate comprehensive simulation of the machine and its environment which includes: Optimal design life based on a comprehensive understanding of the degradation and damage mechanisms of modern and new materials as wells as electrical and mechanical components.**
- **Internationally standardised scaled and real test methods for the (virtual) testing of components and complete wind energy systems, which are based on a solid common database.**

6.2 Challenge 2: Offshore Wind Power Plants & Systems Integration

Offshore wind has the potential of becoming the backbone renewable energy source of electricity in Europe. Its development is tightly connected with the development of offshore transmission infrastructure and, in a longer run, with the development of meshed offshore grids. High Voltage Direct Current (HVDC) technology will play a crucial role in this development, as it allows both transmitting offshore wind power and interconnecting different market and synchronous areas.

Currently renewable power operators are asked to emulate conventional power plants. This is an ineffective use of the resources and often leads to additional costs. There will be a shift from demanding renewables to adapt to the existing system to demanding the existing system to adapt to renewables. This shifting notion of how the power system works will raise some significant challenges.

Owing to their large installed capacities and their high controllability (especially when connected via HVDC), offshore wind power plants can effectively address some of those challenges, for example providing crucial reliability services, such as grid-forming or and black-start, to the onshore power system.

To meet the increasing needs for flexibility in the grid, ranging from real-time stability to short-term balancing and sustaining system adequacy in the long-term, offshore wind power plants will need to develop new solutions to decouple energy production from energy harvesting, so that power can be provided to the system when needed, and not when produced. To achieve this, integration of offshore wind power plants with hydrogen production (Power-to-X) is a promising solution. Other solutions e.g. coupling of different types of energy conversion technologies should also be investigated.

Areas of research

- **Development of integrated offshore transmission networks, including energy hubs/islands, for large scale development of offshore wind power and integration into energy systems (Power-to-X)**
- **Dynamic operation of very large offshore wind power clusters in providing power and system services in future low-inertia, converter-based power systems**

6.3 Challenge 3: Floating Offshore Wind & Wind Energy Industrialisation

For the development of floating offshore wind energy, better understanding of the wind and wave interactions at farm level is essential to optimise the layout of floating wind farms and the design of floating wind turbines. The larger motion of floating turbines creates a design challenge in terms of load fatigue to several components. The most obvious are the rotating components in the nacelle, the tower, blades, power cable and mooring lines. R&I in in some cases site-specific design models and control methods will alleviate load problems. As the size of the turbines increases, assembly and heavy maintenance operations become a challenge. Regular jack-up vessels cannot be used for installation and heavy maintenance in a floating wind farm. Innovative solutions and concepts need to be developed to ensure low cost installation and maintenance operations. The installation and hook-up of the mooring system and the dynamic electrical cable is another crucial part of the installation process of floating wind farms. Monitoring the aging of these components under cycling loads and marine growth can significantly contribute to cost reduction through lifecycle management. In waters deeper than 100m it is difficult to fix the array cables to the sea-bed. R&I will need to find solutions to overcome these challenges.

The priority is to develop floating designs that offer best value for money. A design that performs well and can be easily mass-produced at low cost. Kick-starting a new supply chain will require detailed planning and harmonisation across many economic sectors. R&I support to increase the manufacturing capacities of the suppliers, upgrade port infrastructure, develop new maritime vessels and design new grid connections support will drive floating wind forward and create significant economic impact too.

In offshore wind energy, size matters. Offshore wind turbines installed today are already the largest rotating machines in the world and the sector continues to develop bigger turbines, with 12-15 MW turbines due to reach the market in this decade. Especially for bottom-fixed offshore wind, these larger and heavier wind turbines require more space, deeper draughts and stronger installation vessels and cranes. The current stock of installation vessels is unable to install the designed 15 MW turbines. Innovative concepts and designs are needed to develop next generation vessels able to lift over 1,000 tonnes. Without solid electrical infrastructure, offshore wind farms are rendered idle. Better methods to test the integrity of cables post-production, post-transportation and post-installation are needed to limit faults and avoid high repair cost.

To reach large-scale commercialisation, the industry has identified several potential bottlenecks in the supply chain that could hinder offshore wind development in the coming years. The major issues relate to ports infrastructure requirements for serial production, dynamic export cables, and auxiliary equipment to withstand electric loads, as well as operations and maintenance technology. The wind industry and its supply chain should develop logistics models for offshore wind and identify common installation technologies and manufacturing requirements. Bigger vessels, with cranes able to lift heavier components, will alter the existing logistic flow for assembly and installation of wind turbines –

especially for bottom-fixed offshore wind. In addition, standardisation in foundation systems will facilitate offshore wind development. Common junction boxes to ease and standardise termination of inter-array cables will significantly ease installation. This would avoid costly faults and allow the same foundation systems to be used by different manufacturers, enlarging the market for the European supply chain. R&I should help find new solutions and set better standards for corrosion protection for jacket foundations.

Areas of research

- **New concepts and validation methods for integrated design models for floating wind power plants, i.e. wind turbines, cables and balance of plant technologies.**
- **Site-specific structural and electrical design condition with complete understanding of the external physical conditions (soil damping, breaking waves, soil-structure-fluid interaction, air-sea interaction, wind conditions).**

6.4 Challenge 4: Wind Energy Operation, Maintenance & Installation

Wind turbines are exposed to a wide variety of weather phenomena including extreme winds, lightning, frost and heat. These external conditions are highly variable, and turbines are built to endure them throughout their lifetime. However, due to these ever-changing external conditions, wind turbines experience a wide range of changing loads. These loads build up stress levels in key components such as blades, gear boxes and generators. More accurate understanding of the stress levels in critical components is vital to ensure wind turbines operate at their optimum capacity. Better performance management will allow the asset to be operational for a longer period of time and will lower the cost of electricity. Operators will need to connect and aggregate real time data from turbine components and possibly unmanned vehicles. The amount of data gathered for analysis will require new big data analysis techniques and solutions using the development of artificial intelligence.

Operating wind power plants is very different from operating conventional energy plants. Wind power plants often comprise multiple connected, yet independent assets that are geographically distributed. So, wind park operations come with a unique set of challenges, of which we underline two. Firstly, unlike conventional power plants, offshore wind turbines are installed in remote areas. This makes it difficult to get the people, materials and components to the asset on time, especially when an unexpected situation demands fast intervention. The sector's priority is to prevent unexpected failure modes, but R&I in digital solutions and remote sensing will help increase the active range of O&M personnel in case an error occurs. Secondly, wind farm operators and portfolio managers also operate and maintain a large number of assets compared to conventional power plant operators. More research into digital portfolio management systems will help ensure operators can optimise power production at fleet level rather than at individual turbine level. In addition, as more and more wind turbines are installed, operators will also need to develop comprehensive decommissioning strategies to deal with the number and variety of assets that will reach the end of their designed life in the coming years. Decommissioning strategies and technology need further development.

Areas of research

- **Condition-based maintenance or replacement of (sub)components based on accurate reliability models that predict the remaining lifetime or failure probability for a given load history.**
- **Extension of service life trough optimised human or robot-assisted operation and maintenance procedures based on proper (big-)data analysis of automated and remote inspections.**

6.5 Challenge 5: Ecosystem, Social Impact & Human Capital Agenda

To ensure Europe will lead the way in a sustainable energy transition, the EU must prioritise R&I funding to diversify and scale up recycling technologies. Most wind turbine components such as the foundation, tower and gearbox are recyclable, making wind turbines 85% to 90% recyclable. However, rotor blades represent a specific challenge due to the composite materials used. Demonstration of and further innovation in recycling technologies is needed to recover critical materials such as glass or carbon fibres and magnetic materials. In addition to recycling solutions, new materials will need to be developed. These materials will have to be lighter, more durable and more recyclable to increase sustainability and reduce the EU’s dependence on imports of rare earth minerals and other critical raw materials.

In the short term, industry and educational institutions should come together and map out the required skills on the one hand and the available Vocational Education and Training (VET) qualifications programmes on the other. This skill map should include cross-sectoral dialogues to discover possible synergies and develop joint skill roadmaps. For offshore wind this includes the ocean energy and offshore Oil & Gas sectors. Whilst certain skills are transversal for the entire energy sector, specific multi-disciplinary profiles such as project managers, mechanical, electrical and civil engineers, plant operators, logistic experts, offshore technicians, etc, for operations and maintenance are in high demand by the wind energy industry. In addition, the sector will need to fill in new profiles related to commerce, stakeholder management and digitalisation (e.g. big data analysts and robotics experts).

In the long term, more investments are needed to support the wind energy academic community. Professors and researchers are essential to form and educate the next generation of wind energy workers. Today many teaching positions are heavily dependent on erratic funding streams. Multi-annual EU grants can significantly strengthen and stabilise academic research and teaching in wind energy. Universities and higher education institutes should also develop more sector-specific degrees or an integrated umbrella degree (mechanical, electrical engineering, etc.). Where relevant, this should be in joint efforts with industry players who can pass on manufacturing trends and increase focus on product design and digitalisation. As the wind sector demands a highly mobile workforce, universities should offer more mobility schemes to early-stage researchers and students so that future workers can get accustomed to working in different European regions early on.

Areas of research

- **Technologies and designs to improve recycling and end-of-life solutions, embedded in the overall ecological and economic policy and legal framework.**
- **Maintaining social acceptance by understanding the mechanisms behind it, e.g. socio-economic benefits, environmental impact assessments and provision of high-quality education and employment.**

6.6 Challenge 6: Basic Wind Energy Sciences

Wind turbines are not only the largest rotating machines on earth, they also have to operate under extremely different external conditions. As a unique feature, wind turbines interact with and influence their resource (turbulent wind) via aerodynamic principles. Consequently, the blockage effect and dynamic wake of wind farms and wind farm clusters, when installed in large capacities, must be properly understood and controlled. Innovative control methods offer the possibility to optimise the performance and minimise holistic load scenarios. To fully research and understand these complex interactions of aeroelasticity and flow phenomena on all scales, sophisticated measurement techniques and high-performance computing power are necessary. Together this leads to reliable and precise experimental and numerical models for the use and further development of wind energy systems technology.

Hydrodynamics effects due to waves and currents even increase the complexity for floating and bottom-fixed offshore wind. Substructures as well as other balance of plant elements can be further improved by developing new materials, joints and installation methods. The connection to electrical, chemical (hydrogen, ammonia) or even thermal energy systems offers both opportunities and technical challenges. A system science approach will be the only way to properly address derived research and development steps.

Areas of research

- **Improved understanding of atmospheric and wind power plant flow physics by using high-performance computing, digitalisation and measurements to develop exact experimental and numerical models.**
- **Aerodynamics, structural dynamics (including new materials), and offshore wind hydrodynamics of enlarged wind turbines.**
- **Systems science for integration of wind power plants into the future electricity grid or overarching energy system (power-to-X), taking into account the requirements of industrialisation.**

7 Relation to Cross-Cutting Issues

7.1 Environment

Floating offshore wind turbines are assembled onshore and towed to site. This reduces the impact on the marine environment during installation. Floating and bottom-fixed offshore wind farms could also become safe havens for recovering marine fauna.

7.2 Circularity

Wind turbines already have a recyclability rate of 85% to 90%. Most components of a wind turbine – the foundation, tower, components of the gear box and generator – are recyclable and are treated as such. Wind turbine blades represent a specific challenge due to the complex nature of materials used to manufacture them. 15,000 wind turbine blades will be decommissioned by 2023. Dealing with this significant volume requires logistical and technological solutions for the collection, transportation and waste management of the relevant material. Today composite materials are commercially recycled through cement co-processing. Further development and industrialisation of alternative technologies like solvolysis and pyrolysis will provide the wind industry with additional solutions for end-of-life.

7.3 Digitalisation

Enhanced sensor data collection and high-quality data exchanges between wind operators and the surrounding energy ecosystem are growing significantly. Making use of this data will unlock new horizons of productivity and allow the industry to fully realise its enormous potential. Digitalisation will create new economic opportunities for wind operators, increasing the value of every single MWh produced. Innovative digital technologies will also improve turbine yields and productivity while driving down cost in design, operations and maintenance, thereby reducing the cost of energy. Digitalisation is primed to make a valuable contribution to wind energy at a crucial time for renewables. As the ongoing energy transition triggers an increase in distributed power generation, new data-related challenges are emerging. Constructed around renewables, and with a higher penetration rate of variable power generators, this new distribution-based energy system will rely heavily on innovative digital solutions for increased connectivity and interactivity between the various actors. Integrating variable renewable energy is critical to ensuring a stable system abundant with clean and affordable energy, and digitalisation is essential to this process. Cybersecurity will grow in importance as the wind sector becomes increasingly reliant on digital technologies to communicate and integrate with other actors in the energy system.

8 System Level Challenges that Must be Solved to Realize the Potential

In order to reach the ambitious targets for 2050 of 450 GW installed offshore wind power, around 1,800 to 2,000 TWh of variable electrical offshore energy must be integrated in the energy system. To facilitate this integration, solutions for onshore and offshore energy conversion and storage and interconnection must be developed. This includes the associated offshore energy infrastructure consisting of cables, pipelines, switching and interconnection hubs and logistics hubs, where synergies with the declining oil & gas sector and co-operation with blue economy sectors can be exploited.

Areas of research

- **Sector coupling is crucial for the uptake of the massive amount of offshore wind power: production of renewable hydrogen and electrification of the industry is an urgent research task;**
- **Offshore wind turbines will grow in size to 20+MW with higher capacity factors leading to further cost reductions and improved system integration.**
- **By technology development and interaction with a hydrogen system, offshore wind farms will be able to deliver power on demand.**
- **By sector coupling the massive amount of offshore wind energy will be the backbone to produce bulk green hydrogen.**
- **Validated energy systems models to assess the value of wind power in markets with 100 % variable renewable energy supply.**
- **Development of integrated offshore transmission networks, including energy hubs/islands, for large scale development of offshore wind power and integration into energy systems (Power-to-X)Dynamic operation of very large offshore wind power clusters in providing system services in future low-inertia, converter-based power systems**

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Input Paper to the CETP SRIA Renewable Technologies

Challenge 4
Onshore Wind

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1 Introduction

The European energy transition requires mass electrification in energy use in households, transport and industry. More and more the production of hydrogen, synthetic transport fuels and heat applications find their origins in electric power. Onshore wind energy is the backbone of all the renewable energy resources that will deliver the bulk of the renewable energy (760 GW) in 2050. That energy will be used for electrification and the production of renewable fuels. Onshore wind will create enormous economic opportunities for Europe and at the same time challenges.

We name three key challenges to be tackled:

1. Reduce the cost and increase the performance and the value of onshore wind to ensure the energy transition remains affordable and to strengthen the competitiveness of the European wind industry,

2. Integration of large volumes of distributed onshore wind in the energy system through the increase of flexibility and the optimisation and build-out of a more decentralised grid,

3. Spatial planning and ecology: streamlining of permitting process, mitigation of environmental impact of onshore wind farms, socio-economic aspects and community engagement.

Research & Innovation (R&I) is required to address these issues to deliver a successful energy transition built on onshore wind.

Onshore wind is one of the main pillars to support Europe's energy transition. This creates enormous economic opportunities. The associated challenges must be addressed through R&I actions: cost reduction, performance enhancement, system integration and faster, more transparent permitting process.

2 Technology Status

Today wind energy is the cheapest source of new installed power capacity in many regions of Europe. Still, governments and consumers expect wind energy to continue decreasing cost to accelerate the shift away from fossil fuels. The sector is under continuous pressure to deliver reliable and sustainable energy at low cost.

The European wind industry is competitive due to its technological excellence. To retain a competitive advantage the sector continuously needs to develop and market the best technology available. This requires significant investments in R&I, and given the cost reduction pressure, companies need stable and secure revenues to sustain investments in technology development. EU support for R&I in wind energy plays a pivotal role to help the energy sector cultivate disruptive technologies that will accelerate the energy transition. The development of new breakthrough applications and technologies will help establish wind energy at the heart of the energy transition and boost the competitiveness of the European wind industry in the global market.

The pace of technology developments in wind energy is very fast, every three years a new generation of wind turbines appears in the market, leading to continuous improvements and cost reductions. Continuous developments in manufacturing process, turbine design and improved capacity factors, enable an extensive European onshore wind supply chain to achieve the technology leadership position in the world and to create over 224,000 full time jobs in 2020 and 250,000 jobs in 2030.

In order to reach the ambitious 2050 target of 760 GW installed onshore wind power, significant technology developments are required to reduce cost, enable the integration in the energy system and to mitigate environmental impact whilst becoming fully circular by design. In the same way, special attention should also be given to repowering regulation, when end-of-life extension or grid connection points availability are not possible, which is, in some cases, preventing stakeholders to adhere to this procedure.

Targeted R&I support will strengthen the leading role of the European industry in the global market.

The development of a 760 GW onshore wind sector requires continuous and focussed R&I.

3 Ongoing Research

The fast technology development and the implementation of innovations combined with economies of scale are the drivers of expansion of onshore wind energy. Onshore wind energy is the cheapest source of new power capacity in many parts of Europe. Modern onshore wind farms have lower power variability and high capacity factors, facilitating the integration of the onshore wind power in the energy system. In 2019 there was 156 GW of onshore wind operating in Europe. However, over the last few years the pace of growth has slowed down due to regulatory and permitting issues.

Onshore wind needs to grow from 156 GW in 2019 to 760 GW by 2050. The current 2030 policy framework projects an addition of 111 GW by 2030. Governments must start setting the course to enable onshore wind to achieve its potential.

- **Onshore wind development requires positive business cases: reduction of cost and reduced uncertainties of the revenues**
- **Reduction of cost: Wind turbine technology needs continuous improvement until 2050**
- **System integration and reduced uncertainty of electricity prices: Sector coupling is crucial for the uptake of the onshore wind power: electrification of the mobility and heating sector and the production of renewable hydrogen.**
- **To sustain the growth of the onshore wind sector, it requires a simplification of the permitting process (including repowering procedures and environmental impact assessment)**
- **The onshore wind energy sector is moving towards full circularity. Recycling solutions for blades, new manufacturing processes of components and CO_2-free transportation methods need to be developed.**
- **Onshore wind farms need to be inclusive to both nature and society (e.g. social acceptance/engagement). This requires further research and technical developments.**

4 Technical Potential

The anticipated volume of onshore wind in the energy mix is dependent on many factors. An accepted scenario is that of the European Commission (2018) and WindEurope, where 760 GW of installed capacity in the year 2050 delivers around 2330 to 2995 TWh of electricity. The growth path towards these volumes is considered feasible, but requires significant investments in Research & Innovation, in particular to further reduce cost and allow effective integration into the energy system and the environment.

- **Development of more powerful and larger turbines leading to further cost reductions and improved system integration.**
- **Onshore wind farms will be able to further increase flexibility through technical developments.**
- **Through sector coupling the onshore wind energy will be able to decarbonise the mobility and heating sectors and maximise flexibility.**
- **Through spatial planning an optimal use of land in regard of onshore wind will be achieved.**
- **Development of hybrid renewable projects (wind + X (storage, PV…) will play an important role in the future**

5 Economic Potential

The total installed capacity of onshore wind in Europe will be around 760 GW by 2050. This will create enormous opportunities for Europe. The economic benefits will be large through creation of jobs in manufacturing of components and equipment, engineering and installation works and maintenance activities. This economic contribution extends deep into supply chains for the wind energy sector as well as logistics and digitisation. Europe has a unique opportunity to capitalise on its existing technology leadership, where the benefits extend beyond the European energy transition: onshore wind is a truly global market.

- **By 2030 the yearly investments in European onshore wind will be around 13.64 billion €**
- **By 2030 the number of green jobs related to European onshore wind will be around 250,000**

6 Challenges

6.1 Challenge 1: Wind Turbine Technology

Wind energy holds a unique place in the European industrial fabric. It is at the same time a high-tech green and heavy manufacturing industry. Innovation and technology development play a big part in the success of wind energy in Europe and EU funding for R&I acted as a catalyst for the impressive cost reductions in the sector. To sustain this trend the industry needs continued support to innovate, design and manufacture new component structures and materials and to develop new high precision manufacturing lines suited to the mass production of larger and more efficient turbines. Research and development of new materials and/or multi-material solutions should reduce component weight, increase technical lifetime and improve mechanical performance. Wind turbine components need continuous improvement: Blades, drive train, power electronics, nacelle, tower etc. Transportation and installation technology also need to be improved and scaled up to match the development of bigger wind turbines in the coming years. To this end, cooperation between the industry and academia should be encouraged and supported with dedicated research programmes.

Modern wind turbines are very complex machines that have to operate under very different external conditions with relatively little maintenance. To ensure safe and reliable operation, wind turbines, their individual components and their dynamic interaction must be thoroughly tested. Due to the size of current wind turbines and those yet to be developed, test procedures and facilities are a challenge in themselves. The combination of large-scale R&D and test infrastructures with numerical simulations and digital twin concepts will pave the way for new technologies based on a deep understanding of the underlying science and experience projected in accessible databases.

Revenue streams of renewable energy plants are likely evolving to accommodate the needs of future electricity grids and energy markets, e.g. by providing ancillary services, by developing solutions to better match up production with demand or by playing a role in the production of renewable hydrogen. This should be reflected in the design and optimisation of wind turbines, for improved performance and social acceptance, and in the corresponding technology developments.

Areas of research

- **Optimal design life based on simulation and a comprehensive understanding of the degradation and damage mechanisms of modern and new materials as wells as electrical and mechanical components.**
- **Novel wind turbine system and optimisation to account for evolving needs of the grid, market and society.**

6.2 Challenge 2: Grid & Systems Integration

A renewables-based power system will be distinctly different from the current system. Research is needed to identify and quantify the stability needs of the future power system and innovative technologies will help establish a new grid architecture that values flexibility, efficiency and reliability.

As more and more Member States will increasingly rely on variable renewables to decarbonise their economies, the power system will undergo a transformation. Currently renewable power operators are asked to emulate conventional power plants. This is an ineffective use of the resources and often leads to additional cost. There will be a shift from demanding renewables to adapt to the existing system to demanding the existing system to adapt to renewables. This shifting notion of how the power system works will raise some significant challenges. As more distributed generation will enter the grid, it is essential to enhance and accelerate communication and coordination between all actors including plant operators, system operators (TSOs/DSOs) and consumers. With increased digital communication, data management and cybersecurity become paramount. In a converter-based grid, optimising the use of existing grid infrastructure and developing High Voltage Direct Current (HVDC) technology and grid-forming capabilities will be essential. Expansion of the interconnection between European countries will largely reduce the wind power fluctuation. In addition, hybrid projects and virtual power plants need to be demonstrated at larger scale and across Europe.

To decarbonise the EU economy more variable renewable energy power plants will be installed and wind is set to become the largest source of electricity in Europe. In the short term, this will require grid operators to add more flexibility to the grid. A lack of flexibility in hardware and software at system level would lead to unnecessary and unsustainable cost. The need for flexibility is present at various time intervals. Real-time flexibility is needed to stabilise the system, short-term solutions to balance the system and sustaining system adequacy will require solutions operable on the long term.

Wind farm operators can also be expected to take on more and different responsibilities towards grid management by providing ancillary services, and to develop new solutions to decouple energy production from energy harvesting, so that power can be provided to the system when resources are low. This requires innovation in short-term and seasonal storage, multi-cultured wind farms (wind farms with more than 1 type of turbine installed) hybrid systems and further innovative solutions. At the same time, more accurate and precise forecasting of both power production and demand well help to better link demand and production and ensure optimal use of available resources.

Areas of research

- **Integrated forecasting of power production, power demand and short-term energy storage**
- **Expansion of new ancillary services and innovative hybrid solution for a flexible decentralised and converter-based grid**

6.3 Challenge 3: Wind Energy Operation, Maintenance & Installation

Wind turbines are exposed to a wide variety of weather and site conditions, including extreme winds, lightning, cold climate, heat and complex terrains. These external conditions are highly variable, and turbines are built to endure them throughout their lifetime. However, due to these ever-changing external conditions, wind turbines experience a wide range of changing loads. These loads build up stress levels in key components such as blades and generators. More accurate understanding of the stress levels in critical components is vital to ensure wind turbines operate at their optimum capacity. Better performance management will allow the asset to be operational for a longer period and will increase the market value of the MWh produced. Operators will need to connect and aggregate real time data from turbine components. The amount of data gathered for analysis will require new big data analytics and solutions using the development of artificial intelligence.

Operating wind power plants is very different from operating conventional energy plants. Wind power plants often comprise multiple connected, yet independent assets that are geographically distributed. So, wind operations come with a unique set of challenges, of which we underline two. Firstly, unlike conventional power plants, wind turbines are often installed in remote and less densely populated areas. This makes it difficult to get the people, materials and components to the asset on time, especially when an unexpected event occurs that requires a rapid intervention. The sector's priority is to prevent unexpected failure modes, but R&I in digital solutions and remote sensing will help increase the active range of O&M personnel in case an error occurs.

Secondly, wind farm operators and portfolio managers also operate and maintain a large amount of assets compared to conventional power plant operators. More research into digital portfolio management systems will help ensure operators can optimise power production at fleet level rather than at individual turbine level. In addition, as more and more wind turbines assets are installed, operators will also need to develop comprehensive decommissioning strategies to deal with the number and variety of assets that will reach the end of their designed life in the coming years. Decommissioning strategies and technology need further development.

Areas of research

- **Smart and dispatchable operation, monitoring and control of wind farms.**
- **Lifetime assessment, extension of service life, robot-assisted maintenance and predictive maintenance through digital tools and models.**

6.4 Challenge 4: Ecosystem, Social Impact & Human Capital Agenda

To ensure Europe will lead the way in a sustainable energy transition, the EU must prioritise R&I funding to diversify and scale up recycling technologies. Most wind turbine components such as the foundation, tower and gearbox are recyclable, making wind turbines 85% to 90% recyclable. However, rotor blades represent a specific challenge due the composite materials used. Demonstrations and further innovation in recycling technologies is needed to recover critical materials such as glass or carbon fibres and magnetic materials. In addition to recycling solutions, new materials will need to be developed. These materials will have to be lighter, more durable and more recyclable to increase sustainability and reduce the EU's dependence on imports of rare earth minerals and other critical raw materials.

Massive implementation of wind power must be done in a sustainable manner, creating maximum value for stakeholders, including investors, users and citizens with respect to the Sustainable Development Goals. This is achieved by taking away barriers to massive deployment, implementing more integrative development, increasing social acceptance and ensuring sufficient qualified human resource.

The challenges facing social acceptance can be related to a wide range of actual, potential or perceived impacts of a wind energy project. There is a number of concerns that have been identified by communities and previous research. This includes impacts on landscape, biodiversity, health, noise and property values. There are still some important research areas that need to be addressed to minimise these impacts and the research on social acceptance of wind energy must be more focused on translating and applying the results into policy and design.

In the long term, more investments are needed to support the wind energy academic community. Professors and researchers are essential to form and educate the next generation of wind energy workers. Today many teaching positions are heavily dependent on erratic funding streams. Multi-annual EU grants can significantly strengthen and stabilise academic research and teaching in wind energy. Universities and higher education institutes should also develop more sector-specific degrees or an integrated umbrella degree (mechanical, electrical engineering, etc.). Where relevant, this should be in joint efforts with industry players who can pass on manufacturing trends and increase focus on product design and digitalisation. As the wind sector demands a highly mobile workforce, universities should offer more mobility schemes to early-stage researchers and students so that future workers can get accustomed to working in different European regions early on.

Areas of research

- **New technologies and modular designs to improve installation, transportation, recycling, and end-of-life solutions.**
- **New design, planning and operation of wind farms centred on increasing social acceptance and minimising the environmental impact throughout the whole lifecycle**

6.5 Challenge 5: Basic Wind Energy Sciences

Wind turbines are not only the largest rotating machines on earth; they also have to operate under extremely different external conditions. Wind turbines interact with the atmosphere resulting in complex wake dynamics, at the wind turbine and wind farms level. Furthermore, terrains, including the vegetation, where the wind turbines are located, heavily influence the wind flow before it reaches the wind farm. Special flow patterns such as low-level jets leads to different load pattern and power production that need to be taken into account when designing the wind turbine. As wind turbines grow larger and larger, the understanding of the atmospheric boundary layer above 200 meters becomes more important. Until now, this part of the atmospheric boundary layer is not fully validated by the current measurements and models, as measurements above heights of 200 meter are scarce.

Innovative control methods offer the possibility to optimise the performance and minimise the loads. The wind farm control can be also used to increase the flexibility of operation, to adjust the output more closely to the demand and to provide additional ancillary services. To exploit the potential of wind farm control, one needs to understand fully the complex interactions that involve multi-physics and multi-scale flow modelling. Moreover, sophisticated measurement techniques and high-performance computing power are necessary to run these models. This will lead to reliable and accurate experimental and numerical models for large-scale deployment and technical improvement of wind energy systems.

Disrupting technologies in wind energy should be explored as well. Even if the upscaling of conventional wind turbine concepts offers a rational way of continuous cost reduction. Disrupting wind turbine concepts could bring major benefits in increasing the value of wind energy (higher capacity factor), resource efficiency (lower use of materials), and being a better neighbour (lower environmental and societal impacts). The research on disrupting technologies can be seen as basic research due to the low TRL-level and the time needed to gain technological maturity.

Areas of research

- **Improved understanding of the atmospheric boundary layer and wind power plant flow physics by using high-performance computing, digitalisation and measurements to develop experimental and numerical models suitable for very large onshore wind turbines.**
- **Multi-physics (aerodynamics, aeroacoustics, structural dynamics, material science, and electrical system) and multi-scale modelling and testing of very large and flexible onshore wind turbines/subsystems.**
- **Disrupting wind turbine technology and systems engineering for integration of wind energy for applications outside of the electricity sector**

7 Relation to Cross-Cutting Issues

7.1 Environment

Onshore wind turbines are embedded in the environment that is shared between humans and nature. It is inevitable that even low carbon energy source, as wind energy will have certain impacts on the environment and the society. The development of onshore wind energy should focus on the following three areas, minimising environmental impact, optimising social acceptance, and optimising spatial planning. Following aspects should be further developed to secure acceptance and ensure low environmental impacts,

- Develop clear and transparent spatial planning process.
- Fostering early and transparent communication between project developers, local communities and economic actors, fostering social acceptance, especially when projects are to be installed near communities
- Integrating the wind farm in landscape, making it compatible with human activities and minimising acoustic impacts
- Effective mitigation and monitoring of the potential impacts

By addressing these relevant issues, this should stimulate a more transparent and faster onshore wind deployment within the EU to reach Europe's 2050 targets of 760 GW installed capacity of onshore wind energy.

7.2 Circularity

Wind turbines already have a recyclability rate of 85% to 90%. Most components of a wind turbine – the foundation, tower, components of the gearbox and generator – are recyclable and are treated as such. Wind turbine blades represent a specific challenge due to the complex nature of materials used to manufacture them. Approximately 15,000 wind turbine blades will be decommissioned by 2023. Dealing with this significant volume requires logistical and technological solutions for the collection, transportation and waste management of the relevant material. Today composite materials are commercially recycled through cement co-processing. Further development and industrialisation of alternative technologies like solvolysis and pyrolysis will provide the wind industry with additional solutions for end-of-life.

Another important aspect to be considered, is the use of the wind production surplus as storage, which could also contribute to circularity, not only in the flow of materials from the turbines when they achieve their end of life, but using energy for the production of hydrogen even in the most remote places, which could lead to its use as a product but also contribute to the production of other fuels such as methane and / or synthetic fuels.

7.3 Digitalisation

Enhanced sensor data collection and high-quality data exchanges between wind operators and the surrounding energy ecosystem are growing significantly. Making use of this data will unlock new horizons of productivity and allow the industry to fully realise its enormous potential. Digitalisation will create new economic opportunities for wind operators, increasing the value of every single MWh produced. Innovative digital technologies will also improve turbine yields and productivity while driving down cost in design, operations and maintenance, thereby reducing the cost of energy. Digitalisation is primed to make a valuable contribution to wind energy at a crucial time for renewables. As the ongoing energy transition triggers an increase in distributed power generation, new data-related challenges are emerging. Constructed around renewables, and with a higher penetration rate of variable power generators, this new distribution-based energy system will rely heavily on innovative digital solutions for increased connectivity and interactivity between the various actors. Integrating variable renewable energy is critical to ensuring a stable system abundant with clean and affordable energy, and digitalisation is essential to this process. In order to maximise the benefits of digitalisation for all the stakeholder, openness of the data and a collaborative approach are indispensable. At the same time cybersecurity will grow in importance as critical data needs to be protected. As the wind sector becomes the dominant source of the electricity, the increasing reliance on digital technologies to communicate and integrate with other actors in the energy system should not impact security and resilience of the energy infrastructure.

8 System Level Challenges that Must be Solved to Realise the Potential

In order for onshore wind energy to achieve the full potential, the following system level challenges mustbe addressed.

The energy market design should reflect the variable nature of the wind energy production and provides financial incentives for market-oriented energy production and grid services

At the deployment policy level, there should be well-defined and stable onshore wind power targets backed by long-term stability of policy instruments to attract investments. The permitting process needs to be streamlined to avoid longer construction periods and long lead times, minimising market risks and operating risks.

At the system integration policy level, we should adopt a systemic approach, drawing together innovations in enabling technologies, market design, business models and system operation. This will create synergies and achieve the lowest system cost for the end users. This includes deployment of distributed energy resources, combining PV, Wind, energy storage, demand response and other distributed energy systems. The integration of the distributed systems in the energy market will greatly enhance the flexibility and economic efficiency of the energy system.

With respect to the social integration policy, supportive measures to local communities are needed to accelerate deployment of wind projects with shared revenues. Policies aimed to engage local communities from the early stages of wind farm development and to promote community ownership models needs to be implemented and equitable distribution of the social-economic benefits and costs should be encouraged.

To meet the human resource requirements associated with onshore wind deployment targets, education and training policies need to consider the occupational and skills requirements of the wind energy sector. The provision of education and training/re-training should reflect the evolving skills needs.

Areas of research

- **Design of energy market that takes into account the variable natures of wind power and encourage financially flexible and grid friendly operation**
- **Streamlining and speeding up of the permitting process for repowering, life extension and new onshore wind power plants**
- **Better grid interconnections between countries to reduce the variability of wind power**
- **Optimize system Integration with offshore wind, solar PV, storage, demand response etc. to achieve further system cost reduction**
- **Effective education and training to produce a competitively skilled workforce for rapid energy transition.**

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Input Paper to the CETP SRIA Renewable Technologies

Challenge 5

Deep Geothermal Energy

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1 Introduction

Geothermal energy is a valuable and local source of energy that can cost-effectively provide baseload/dispatchable electricity, heat or a combination of both. The scope of this challenge (3a) is the direct use and power generation from geothermal resources in an optimized way, which includes integrated and combined systems (e.g. heat pumps, other forms of renewable energy, and using the underground as a heating and cooling energy storage site). The utilization of shallow geothermal energy that relies on ground source heat pumps is outside the scope of this challenge.

With these features, it has the potential to provide real alternatives to replace power plants and heating systems emitting greenhouse gases, not only in Europe but also globally, in particular in some developing countries. In addition, geothermal reservoirs may also act as sites for storage of energy as well as CO_2.

Geothermal energy is increasingly seen as an energy supply option that needs to be harnessed to reach the goals of the Paris Agreement, in particular limiting the atmospheric temperature increase to well below 2 °C. Europe's industrialization and wealth generation has strongly profited from the availability of vast energy supplies and has particularly reliant on unbridled access and relentless exploitation of energy resources worldwide. The utilization of geothermal energy is key for transitioning – in a climate-neutral manner – the following end use sectors: space and water heating, agriculture, industry, as well as power generation and space cooling in choice locations (Dalla Longa et al., 2020) while exploiting reservoirs as heat storage sites to facilitate sector coupling and seasonal demand shifts.

For geothermal energy to become an energy supply option of choice, there are three key technical issues to be addressed:

1. Improving the success rate of finding productive geothermal reservoirs in a commercially viable manner (€/MW technical potential for heat in place).
2. Lowering the unit cost of developing geothermal reservoirs (€ per $MWh_{th/el}$) by both, lowering the cost of drilling and developing reservoir *and* by increasing the sustainable reservoir performance, energy conversion efficiencies and heat storage costs
3. Integrating geothermal energy into local and regional energy systems, in particular in urbanized environments.

Innovation is required to address these issues to make the energy transition successful.

2 Technology Status

The use of geothermal energy, particularly for heating applications, is steadily increasing across Europe. Growth of geothermal electricity is driven by the rapid expansion in Turkey, which is set to continue. Italy, France, Germany and The Netherlands are focusing their geothermal strategies; with other countries (the Nordics, a number of countries in Central and Eastern Europe, and South-Eastern Europe) set to follow.

Among renewables, electricity from geothermal resources is today fully competitive with fossil fuels in choice locations, with costs of about 0.07 EUR/kWh. The European industry performs excellently in the geothermal sector.

District heating and cooling has been a real success story for geothermal, since it is still expanding into new markets. Deep geothermal for heating and cooling encompasses supply to industrial and service sectors. There are 280 such plants in Europe with a total installed capacity of about 5 GWth. With about 200 new plants in planning, the installed capacity is set to grow up to 6.5 GWth by 2020.

Geothermal energy can thus represent a significant contribution to the transition towards a more sustainable energy system. Combined heat and electric power, hybridization with other renewables (solar, biomass), and support to local and sustainable economic development, security of supply and load flexibility are already recognized qualities of geothermal energy.

3 Ongoing Research

Europe's geothermal community, comprising stakeholders from the industry, the research and innovation community as well as public funding organisations have developed an Implementation Plan in the framework of the SET-Plan's Actions on technological leadership in renewable energies and associated cost reductions.

Thus, research and innovation activities of pan-European interest focus on:

- Geothermal heat in urban areas (TRL 7-9)
- Materials, methods and equipment (TRL 2-9)
- Enhancement of the available resource base (conventional and unconventional) (TRL 4-8)
- Improvement of reservoir performance (TRL 5-8)
- Exploration techniques (TRL 5-8)
- Drilling and completion technologies (TRL 3-7)
- Flexibility from geothermal CHP plants (TRL 4-9) and
- Zero emission power plants (TRL 5-7)

In addition, it is well worth noting, that virtually all countries and regions engaged in geothermal research and innovation seek local solutions reflecting the diversity of geothermal energy supply, storage and demand choices.

4 Technical Potential

Scenarios of integrated (techno-economic) assessment models for Europe that account for geothermal energy in a technically consistent manner, suggest an overwhelming need to develop geothermal heat resources for heating and cooling. Installed capacities in the low GW range today (2020) must be built out to 30-45 GW by 2030, 75-110 GW by 2040 and 100-140 GW by 2050. Most of the heat supply will meet demand from the residential and commercial sectors, followed by industrial and agricultural demand.

A similar, but less demanding picture emerges for installed capacities for power generation from geothermal energy resources: 5-10 GW by 2030 are necessary for a climate policy-compliant Europe, growing to 10-22 GW by 2040 and 15-27 GW by 2050. The range mostly owes to varying degrees of technical and commercial maturation of Engineered Geothermal Systems (EGS).

5 Economic Potential

The development of Europe's geothermal energy resources creates enormous opportunities for the European economy. Most attractive is the prospect of residential and commercial heating opportunities that are spread out throughout Europe thus enabling widespread benefits that result from job creation (EGEC, 2016). In the engineering and construction sectors, infrastructure development (e.g. the construction and operation of district heating networks), the development and commercialization of high-end technologies for finding and developing exist substantial scope for strengthening existing SMEs and for launching new businesses.

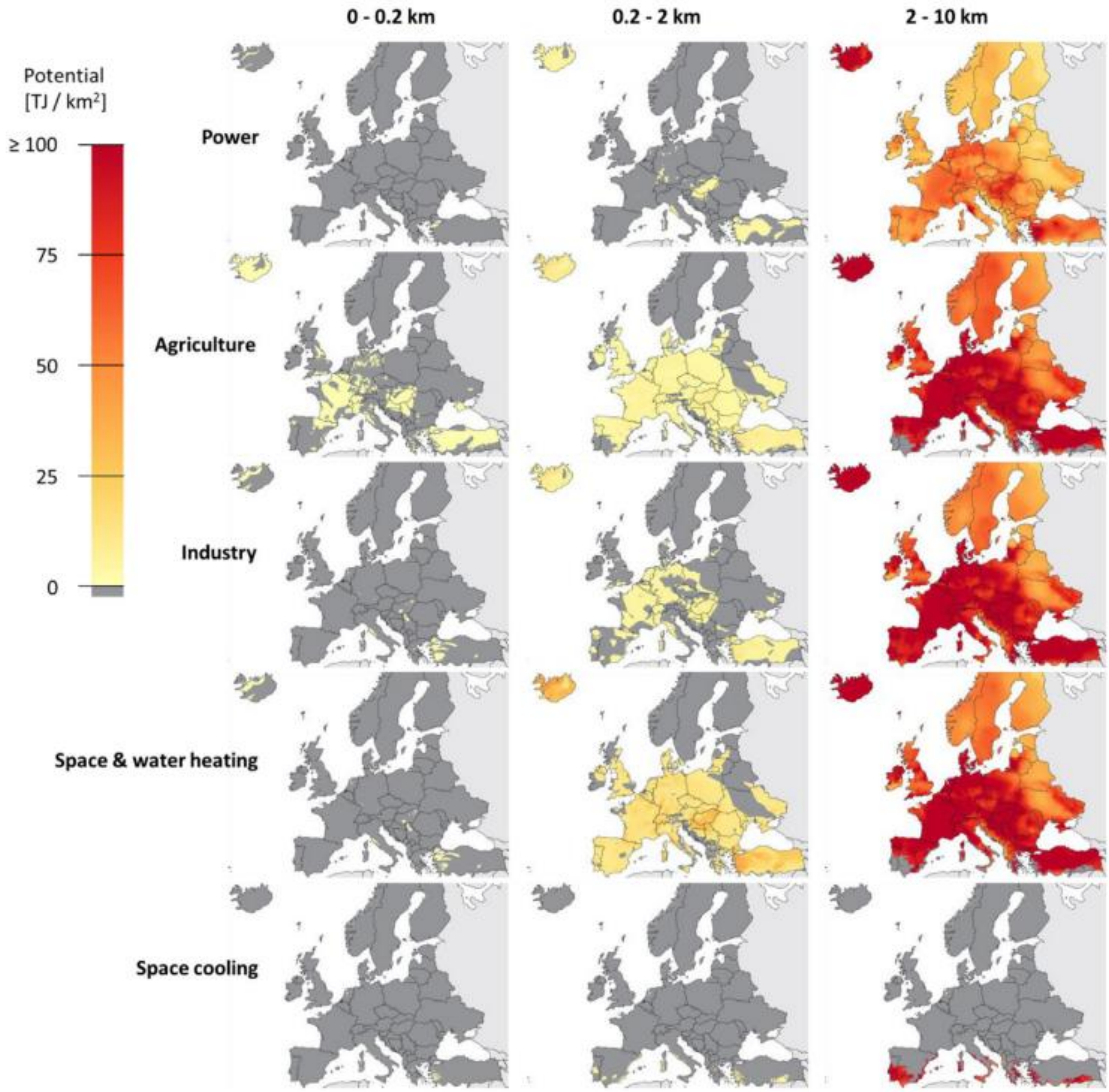

Fig. 1. Long-term economic potentials for various geothermal applications in Europe at three different depth ranges.

Figure 1: Long-term economic potentials for various geothermal applications in Europe at three different depth ranges (Dalla Longa et al., 2020). [1]

This economic contribution extends deep into supply chains for the geothermal energy sector as well as the construction sector for energy infrastructures. In recent years, digitalization has become a centerpiece in drilling of wells, sustainable reservoir management and HSE applications. Europe has a unique opportunity to capitalize on its existing technology leadership, where the benefits extend beyond the European energy transition. The worldwide importance of geothermal energy has recently become acknowledged at the political level with the launch of the Geothermal Global Alliance (GGA) at COP21. In the GGA, a coalition of 46 member countries and 40 development and industry partners, political forces have joined to increase the share of geothermal energy in the global energy mix. The GGA aspires to achieve a 500% increase in global installed capacity for geothermal power generation and a 200% increase in geothermal heating by 2030; these goals are an outstanding opportunity for Europe and its industries to capitalize on its knowledge and technology leadership.

[1] This challenge focuses on geothermal resources that are present at depths from approximately 0.2 km to 10 km. Note that resources in the depth range from 0 – 0.2 km are typically harnessed using ground source heat pump technologies. They are outside the scope of this challenge and treated in the context of a people-centric sustainable built environment in rural and urban settings

6 Challenges

The Deep Geothermal Implementation Plan has defined 8 challenges that must be overcome for geothermal to realize its technical and economic potential.

1. Establish procedures to ensure that public and societal benefits are identified and realized, concerns of civic society are understood, respected and handled with care, and progress in the licensing and permitting procedures are achieved. This includes also the acceptance by all stakeholders through fit-for-purpose engagement processes.
2. Increase reservoir performance in sustainable yield predicted for at least 30 years and reduce the power demand of operating facilities to below 10% of gross energy generation by 2030;
3. Improve the overall geothermal energy conversion efficiency, including that of bottoming cycles, of geothermal installations at different thermodynamic conditions by 10% in 2030 and 20% in 2050;
4. Ensure production costs (CAPEX and OPEX) of geothermal energy (including from currently not exploited unconventional resources, such as superhot, EGS, and/or from hybrid solutions which couple geothermal with other renewable energy sources) are below 10 €ct/kWh_{el} for electricity and 5 €ct/kWh_{th} for heat by 2025;
5. Demonstrate the technical and economic ability of innovative exploration approaches and tools to increase the drilling success rate by 20% in 2025 and 50% in 2030 compared to 2015;
6. Reduce the unit cost of drilling (€/MWh) by 15% in 2025, 30% in 2030 and by 50% in 2050 compared to 2015;
7. Demonstrate the technical and economic feasibility of responding to commands from network and grids operator, at any time, to increase or decrease output ramp up and down from 60% - 110% of nominal power or heat production;
8. Demonstrate the technical and economic feasibility of geothermal heating, cooling and high-temperature storage in a flexible district or regional heating system; cover 5% of demand in Europe by 2030 and 25% by 2050.

The following range of research and innovation activities serve to address the challenges.

6.1 Challenge 1: Geothermal Heat in Urban Areas

The scope covers technologies and methods to accelerate the European heat transition to renewable energy by providing safe and reliable geothermal based solutions for urban areas. Such solution will need to contribute to decarbonizing energy use for heating and cooling in cities and to improve air quality.

The challenge builds on direct use of geothermal energy at its core. Specifically, the activity will have the following impacts:

- Demonstrate new heating concepts for urban areas and/converting conventional district heating networks of urban areas into renewable heating systems;
- Enable the smart use of thermal grids with emphasis on flexible supply of resources (sector coupling), adapted to different source temperatures (cascading uses) and varying demand;
- In addition, position geothermal utilization (including underground storage) as a crucial pillar for the (heat) transition of the energy system.

Attention needs to be paid to assessing potential risks of such developments, such as pollution of groundwater, and consideration of social concerns to ensure the acceptance of the technology. Activities include geothermal heat for industry and agriculture, underground thermal energy storage (UTES) including high-temperature storage, innovative and multiple uses for geothermal energy (sector coupling and cascading use) and side-products, balneological systems, and design and operation of geothermal doublets.

Several demonstration projects will showcase the broad potential of geothermal energy in urban areas. Such projects provide an overall justification to qualify as a flagship activity. The projects will also demonstrate sustainable stewardship of energy resources and the added value of geothermal energy storage in terms of a large-scale transition towards renewable heat in Europe. Integrated innovative concepts will be demonstrated including smart integration into the energy system (e.g. sector coupling, cascading, matching supply with demand, heat and cold exchange). One such indicator of "smartness" will be successful minimization of exergy losses by matching the energy quality of heat (or cold) demand and supply) and possible integration of other renewables in the geothermal heat supply. This includes the development of modelling or simulation tools to account for cascading use and balanced resource management.

The impact will result in a portfolio (expected at least one per country involved) of SET-Plan country demonstration projects with good practices established, in regions such as Minewater Heerlen, Greater Munich, Ruhr Area, Frankfurt, Paris, Milan, Geneva and Bern.

6.2 Challenge 2: Integration of Geothermal Electricity and Heating & Cooling in the Energy System Responding to Grid and Network Demands

The scope of the activity covers the integration and optimization of flexible energy supply from geothermal energy resources in such a way sector coupling strategies and their implementation are enabled.

In order to cope with fluctuations of heat demand, flexible supply units should not be designed for one specific optimal condition, but in a way that optimizes the use of the heat source. Such systems should also consider hybridization with various sources of renewable heat, such as biomass or solar thermal supply options. Activities will include impact on the development of transmission and distribution infrastructure and the interplay with other flexibility options (e.g. demand-side management and storage), and test on dispatchability. Furthermore, the flexible generation (sector coupling) should be able to provide additional services to the grid such as peak power, role in electricity balancing/reserve market. At any time economic feasibility and the environmental impact needs to be monitored and assessed in comparison to other renewable alternatives.

Specifically, the activity will have the following impacts:

- Demonstrating the technical, economic and financial feasibility of responding to commands from a grid or network operator, at any time, to increase or decrease output ramp up and down.
- Demonstrating automatic generation control (load following / ride-through capabilities to grid specifications) and ancillary services of geothermal power plants.
- Demonstrate flexible heating and cooling and electricity supply from binary cycles and EGS plants, including (sector-) coupling with renewable energy sources.
- Providing solutions to specific problems of geothermal power production in isolated energy networks (islands).
- Showcasing geothermal energy storage integrated with district heating networks and dedicated equipment (heat pumps, ORC turbo-expanders, and heat exchanger networks) with hot and cold reservoirs able to cover variable demand of heating, cooling and electricity.

The expected impact will comprise a number of tests that demonstrate automatic generation control (load following / ride-through capabilities to grid specifications) including heating and cooling options by sector coupling.

6.3 Challenge 3: Improvement of Overall Geothermal Energy Conversion Performance for Electricity Production, Heating & Cooling

The scope covers activities that improve the overall conversion efficiency and reduce the cost of geothermal energy utilization, developing a 'best-practice' EU technology solution with a perspective to become a worldwide standard.

The expected impacts are to demonstrate that overall geothermal energy conversion efficiency will be improved by the development of higher performance power plants, including binary cycle power plants, able to supply both heat and electric power.

Specifically, the increase of system efficiency will be demonstrated by:

- Improved design of improved heat exchangers and pumps,
- Optimized selection of materials, new working fluids with very small GWP (Global Warming Potential)
- Increases in expander efficiency
- Improved efficiency of the cooling system by enhancement of the air-cooler condenser and matching to the cycle, or avoiding the loss of useful heat into the environment by promoting the low-enthalpy industrial use of the circulating fluid
- Utilizing geothermal fluids at high temperature (> 175 ° C) and with high content of non-condensable gases (>2%) with suitably designed binary power plants
- Introduction of bottoming/hybridization units on existing or new power plants and development of new concepts for thermodynamic cycles (working media).
- Deployment of methods that lower the potential of scale formation in pipes, especially radioactive scales.

Technical solutions need to be tested and their applicability demonstrated, promoting the flexible use of the geothermal heat source depending on demand (electricity and heat). This implies an optimization of partial load behavior and flexible control strategies for the operation of the whole system. Activities are also directed to facilitating the direct use of heat for industry and/or municipality by new and innovative business models that account for multiple uses of geothermal resources.

Ultimately, the overall impact will be an improved general performance of systems that enable the generation of electricity and heating and cooling from geothermal energy resources with medium and low enthalpy, including double flash and complex/hybrid cycle systems, organic Rankine Cycles (ORC), Kalina and supercritical CO_2cycles. There will be a number of associated impacts that result in a significantly improved efficiency of surface systems equipment/components encompassing heat recovery equipment, turbines for power only and for combined heat & power generation, and cooling generation (via heat absorption).

6.4 Challenge 4: Full Reinjection Electric and Heating & Cooling Plants Integrated in the Circular Economy

There is a need to demonstrate the feasibility of power and heating & cooling plants that are integrated in the framework of a circular economy. Specifically, cradle to cradle concepts need to be piloted and demonstrated for the application of the total reinjection of the geothermal fluids including the capture of non-condensable gases (zero emission plants), to eliminate 'waste' by finding alternative usage options and ensure long term stability of the geothermal resources or even extend their lifetime by heat storage.

The expected impact is to operate geothermal zero emission plants with capture of greenhouse gases, storage and reinjection schemes for the development and exploitation of geothermal reservoirs, in particular those with high content of non-condensable gases (NCGs).

An associated impact is the validation of the feasibility and reliability of closed-loop reinjection of geothermal fluids at high temperature (> 175 ° C) and with high (>5%) NCG content, which will require systems for capture and re-injection, and the use of chemical compounds manage the chemistry of produced fluids.

A further impact of such solutions will be an improved matching of the subsurface reservoir to the power cycle and development of new equipment (compressors, pumps, intercoolers, mixing nozzles, and possibly refrigeration equipment).

Additionally, following the cradle-to-cradle concept of a circular economy, 'waste' produced during the construction and installation of the geothermal systems will be converted to 'value', e.g. drill cuttings that can be used as construction material (buildings, roads etc.).

Furthermore, the re-use of abandoned oil and gas wells for geothermal heat production or heat storage as well as co-production of e.g. Lithium or other materials present in the geothermal fluid is also among the scope of this activity.

Essential is the demonstration of such expected impacts by way of laboratory and field tests related to full reinjection in test circuits and/or geothermal reservoirs at different resource conditions.

6.5 Challenge 5: Methods, Processes, Equipment and Materials to Ensure the Steady Availability of the Geothermal Resources and Improve the Performance of the Operating Facilities

The scope covers the development of new methods, processes, equipment and materials suitable to solve problems commonly encountered in geothermal resources development and exploitation (e.g. corrosion and scaling) at low and high temperatures. Such developments need to lead to a lower power demand of operating facilities and include the application of advanced well architectures and innovative technologies and materials, which will lower the unit technical cost of heat, power and storage.

Expected impacts include the demonstration of major innovations that increase operational availability (e.g. artificial lift techniques, heat exchangers, materials). Specifically, sustainable and reliable production from deep geothermal resources situated in a high temperature, high pressure environment, and characterized by variable geothermal fluid composition as well as dynamic reservoir response to stimulation and/or fluid production/reinjection. Major innovations include new materials and equipment needed to cope not only with hostile and aggressive reservoir environments, but also with the thermochemical and physical properties of fluids with the ultimate goal of improving equipment reliability and increasing the utilization factor of the 'plant'. Materials and/or methods and/or equipment such as production pumps for artificial lift, and heat exchangers need to demonstrate their suitability for the application in all parts of a geothermal plant to minimize operational issues related to high temperatures, scaling, corrosion, and gas content. It is to be demonstrated that the development and utilization of machine learning technology in analysis of geothermal data has significant potential in improving exploitation and operation of geothermal systems. Similarly, stable and uninterrupted operating conditions, improved performance and mitigation of risk need to be demonstrated by the integration of improved monitoring techniques, advanced dynamic reservoir simulation and an improved understanding of coupled thermal, hydraulic, chemical and mechanical processes operative in the reservoir during fluid production and reinjection.

6.6 Challenge 6: Development of Geothermal Resources in a Wide Range of Geological Settings

The scope of this activity covers the demonstration of innovative methods and techniques for reservoir development and exploitation in a wide range of geological settings, including complex and untested geological conditions.

The expected impact is the demonstration of energy efficient, environmentally sound and economically viable generation of electricity, and/or heating and cooling from geothermal resources in a wide range of geological settings, enabling geothermal energy development in new regions and supporting application concepts for local energy supply.

In addition, new geological environments, which require additional techniques to improve reservoir performance, need to demonstrate their suitability for geothermal use, enabling an unprecedented development of geothermal energy at European level (including countries with little known or presently absent resources suitable for direct use geothermal energy). This includes developing low-temperature resources, EGS, “super-hot” reservoirs in excess of 350-400°C and hybrid solutions which couple geothermal with other renewable energy sources, e.g. in combination with subsurface seasonal storage.

Specifically, impact will be expected from the adaptation and advancement of techniques to develop and operate geothermal resources, including reservoir stimulation, to suit specific geological and operational settings. Life cycle assessments (LCA) and appropriate risk management is expected to demonstrate the impact in terms of social benefits and environmental stewardship during the lifetime of a geothermal reservoir. The expected outcome will be geothermal energy in a form that can be widely deployed and competitively priced, underpinned with reduced capital, operational and maintenance costs.

6.7 Challenge 7: Advanced Drilling/Well Completion Techniques

The scope covers the reduction in drilling/well completion costs leading to reduced cost of energy (€/MWh) as innovation, learnings and experience lead to an accelerated cost reduction. Well construction represents a major share of the capital investment in geothermal projects. Hence, reductions of the lifetime cost of the wells, including environmental costs will substantially influence the overall economics of a deep geothermal plant. In particular, concepts are sought that will lead to significantly reduced drilling/well completion costs (reduce drilling time and non-productive time, reduce costs, mitigate risks) or enhanced productivity (including directional and horizontal multilateral drilling).

The overall expected impact is the reduction of cost for drilling and subsurface installations by at least 25% compared to the situation today.

Novel and advanced drilling technologies, currently not used in geothermal well construction, have to be adapted, optimized and field-tested in a variety of project settings. Technologies to be demonstrated include the introduction of drilling process automatization, of novel drilling fluids to compensate unwanted loss of circulation zones whilst minimizing reservoir damage as well as the introduction of improved cementing procedures and well cladding. The demonstration has to go hand in hand with adapted risk assessments, life cycle and social impact analysis resulting from the introduction of new technologies and methodologies. Innovative system need to be demonstrated to avoid/reduce the discharge of geothermal fluid into the environment while drilling and flow testing. This demonstration includes horizontal - multilateral wells clusters.

Advanced drilling technologies using compact, lightweight and low-noise equipment and the use of horizontal and multilateral well cluster, as well as completion techniques have to be demonstrated that minimize the impact of well construction in urban environments.

The expected impact is the validation and benchmarking of new drilling and well completion techniques by field-testing in a range of geological formations. Such technologies include percussive drilling for deep/hot wells (e.g. fluid hammers) and non-mechanical drilling technologies (such as laser, plasma, hydrothermal flame drilling).

6.8 Challenge 8: Innovative Exploration Techniques for Resource Assessment and Drilling Target Definition

The scope covers innovative, high-resolution exploration methods and tools to increase the precision for resource assessment, target definition of exploratory drilling and prediction of long-term reservoir performance.

In particular, digitalization offers unparalleled opportunities owing to improved software, computing power, and big data management, machine learning and knowledge discovery. Interdisciplinary approaches are considered paramount to integrate a broad range of exploration methods to identify promising geothermal provinces and to optimize resource assessment.

The expected impact is an increase in the likelihood of successful exploration wells in order to prove the existence of geothermal reservoirs by 20% in 2025 and 50% in 2030 thereby reducing the exploration costs. Cost reduction should also be achieved through markedly faster times required for exploration data acquisition, processing, analysis and interpretation. Specifically:

- Piloting and demonstrating the added value of identification, access, and sharing of existing data and knowledge that aim to capitalize and build on previous projects and studies. Machine-learning algorithms will be needed to demonstrate knowledge discovery approaches and the optimized use of big data sets.
- Demonstrating the suitability and cost reduction potential of exploration techniques to a wide range of geothermal play types tailored to the specificity of the site.
- Piloting and demonstrating new tools and techniques coupled with innovative modelling techniques, increasing measurement precision and acquisition rates, and applying faster analysis, processing, inversion and integration of acquired data to achieve useful yet accurate models of potential subsurface reservoirs.

7 Relation to Cross-Cutting Issues

The Deep Geothermal Implementation Working Group stresses the relevance of a number of cross-cutting issues that are crucial for gaining more widespread support for all research and innovation actions while promoting non-technical barriers/enablers:

7.1 Knowledge Transfer + Training (including Peer-to-Peer Learning and Research Infrastructures)

It is important that deep geothermal energy stakeholders demonstrate their ability for capacity building, industrial technology transfer and science & academic partnerships via knowledge exchange, with the shared goal to develop high quality, competitive and sustainable geothermal energy projects.

This includes the continued development of European Research Infrastructure Consortia (ERIC). Of particular relevance is the European Plate Observing System (EPOS) – ERIC, which supports the existing pan-European infrastructure of experimental test and monitoring facilities and infrastructures (Geo Energy Test Beds, GETB - see also https://www.epos-ip.org/data-services/community-services-tcs/geo-energytest-beds-low-carbon-energy) and making efficient and coordinated use of them.

Important for this crosscutting action is training and educating new geothermal professionals. Among the necessary actions, is a much-needed cooperation between education and training institutes and companies, creating networks for education and training involving industrial platforms, universities and research centers. Further ideas are to develop courses on geothermal energy within existing university courses and to launch new courses; to absorb the workforce of declining industries; and to promote the mobility of workers in Europe.

Support to these actions should be sought nationally, in Horizon Europe (and subsequent framework programs) Coordination and Support Actions, and in existing EC programs or support of knowledge transfer and human mobility, such as (Marie Curie, Erasmus +, ERC grants).

Continued general support to the Horizon Europe Clean Energy Transition Partnership (CETP) and specific support to the Deep Geothermal Implementation Working Group and the GEOTHERMICA ERA-NET though Coordination and Support Actions or other initiatives is recommended.

7.2 Recommendation of an Open-Access Policy to Geothermal Information (including Standard Exchange Formats)

The scope of this cross-cutting action is to facilitate access to geothermal information at the European level via the linkage of and development of an information platform, and the creation of standard and common data models at EU level. Progressive coordination of national data to facilitate data discovery and mining is an important step to provide scientists, stakeholders, investors and geothermal developers with information, which will also serve as a basis for resource assessment and feasibility studies.

Resources for this action are likely to be provided by national geological services of European countries and regions. A general commitment to open access to relevant data is recommended through a user-friendly interface with different levels for professionals and the general public seeking information. An example of a successful and existing infrastructure is the EPOS-ERIC's Thematic Core Service on Anthropogenic Hazards (TCS-AH). The TCS-AH coordinates providing services for open-access data harvesting, data mining and data management.

7.3 Environment

- Development of sustainable components, materials and chemicals for subsurface use
- Development of environmentally friendly district heating systems and power plants
- Advancing methodologies and implementation of state of the art Health, Safety and Environmental management systems

7.4 Circularity

- Implementation of cradle-to-cradle concept of a circular economy, 'waste' produced during the construction and installation of the geothermal systems will be converted to 'value', e.g. drill cuttings that can be used as construction material (buildings, roads etc.).
- Facilitating the use of existing district heating systems in utilization of new sources of heat
- Flexible design of new district heating systems, enabling use of various energy sources
- Power-plants designed for various demands and heat sources

7.5 Digitalization

The scope of this cross-cutting topic is to develop tools for numerical simulations, data management and data processing for geothermal energy projects. Main crosscutting objectives are accordingly:

- Build and share expertise about sustainable research data management plans and strategies with a particular focus on "big data" typically acquired during exploration campaigns and during production and optimization of geothermal reservoirs
- Develop and apply novel concepts of data science and machine learning aspects (signal processing theory, inverse theory)
- Develop and disseminate computing and numerical simulation codes using novel hardware architectures and software
- Foster collaboration for large-scale and high-performance computing

8 System Level Challenges that Must be Solved to Realize the Potential

Geothermal energy provides ample supplies of renewable heating, cooling and electricity for buildings and industry and is particularly suitable for urban regions characterised by mixed land-use ranging from agriculture (greenhouses), industrial facilities and residential zones. Spatial planning therefore is challenged to connect spatial development on the earth's surface with that of "3rd" dimension, i.e. expanding land and space use to the subsurface as is progressively being undertaken in European cities. An equally important challenge is the provision, modification or access to infrastructures (e.g. pipeline networks) requisite for a successful integration of geothermal heat & power in a flexible energy system.

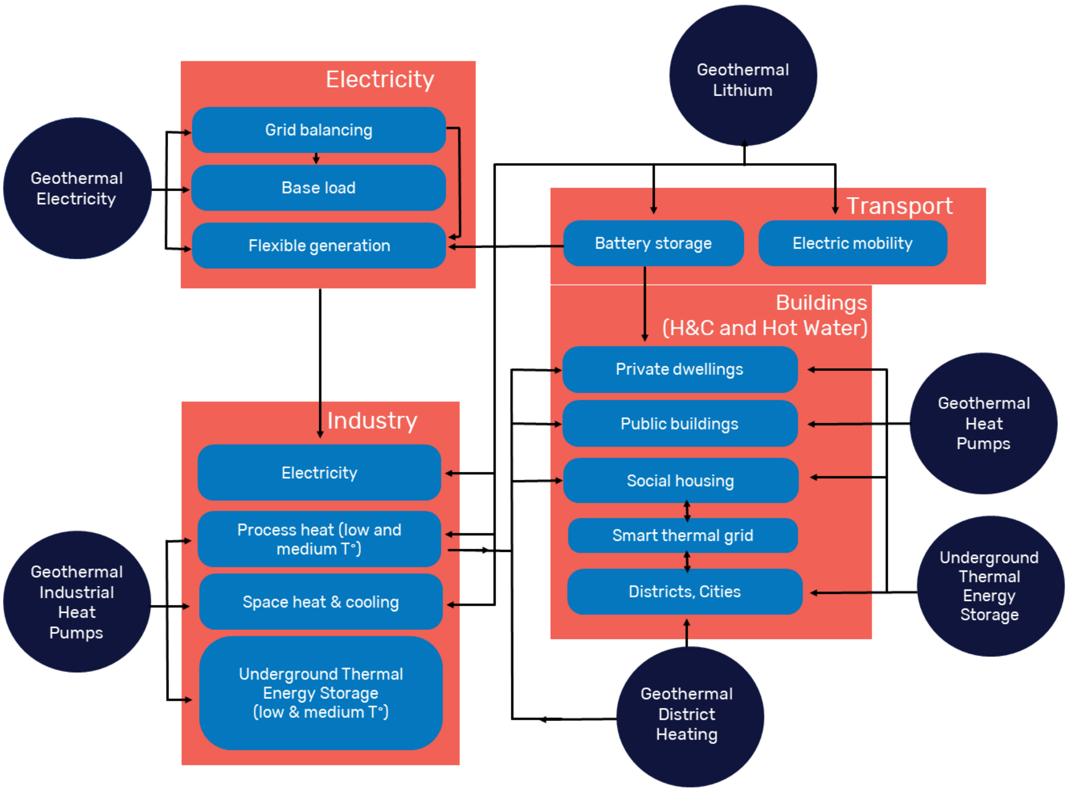

Figure 8-1Geothermal energy has the potential to contribute to most sectors of the economy, thus enabling a path towards a climate-neutral Europe. However, sources of geothermal energy need to be connected to demand sites via low-cost networks for which appropriate spatial planning processes combining surface and subsurface aspects are highly beneficial, but challenging to implement.

9 References

Francesco Dalla Longa, Larissa P. Nogueira, Jon Limberger, Jan-Diederik van Wees, Bob van der Zwaan, *Scenarios for geothermal energy deployment in Europe*, Energy, Volume 206, 2020, https://doi.org/10.1016/j.energy.2020.118060.

EGEC 2016, The Geothermal Sector Report, https://www.egec.org/wp-content/uploads/2020/07/Knowres-D1.4.6-Geothermal-sectoral-report.pdf

Input Paper to the CETP SRIA Renewable Technologies

Challenge 6

Bioenergy

Editors, Co-authors and Commenters of this Input Paper to the CETP SRIA:

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1 Introduction

The biofuels sector has struggled with an unclear political framework within the recent years, and currently different biofuels pathways are at various stages of maturity. For that reason, key barriers must be overcome for the deployment ranging from technology, awareness and capacity, cost finance, infrastructure and public acceptance in addition to policy and regulatory, institutional and administrative barriers. Biofuels in general, and with few and specific exceptions, cannot compete head-to-head with fossil fuels, such that the decarbonisation impact needs to be capitalized to a sufficient extent to make biofuels economically viable to produce at the scale foreseen.

2 Technology Status and Ongoing Research

Regarding the advanced biofuels, several value chains need to be developed, demonstrated and deployed. Elaboration and details to be added.
[https://www.etipbioenergy.eu/images/ETIP_SRIA_2018.pdf]

3 Technical Potential

In 2016, in the EU, about 67% of total primary energy production of renewable energy in the EU-28 is generated by biomass (solid, liquid and gaseous fuels) [Eurostat, last update January 2018], being the heat and power production, including in cogeneration plants. In the transport sector, the share of renewable energy in fuels consumption was 7,1%, mainly from biofuels with a large variation across different Member States.

Globally IEA scenario's reveal that bioenergy is crucial to realise the 2DS scenario, by providing nearly 17% of final energy demand in 2060, compared to 4,5% in 2015. Bioenergy will provide almost 20% of the cumulative carbon savings by 2060. According to the IEA Bioenergy roadmap[1] there is a need for a 4 times growth for bioenergy to about 150 EJ and within that scope a 10 times growth for fuels for aviation etc. There is also a growing need for biomass within the biobased industries for chemicals and products. It is expected that the potential growth in the EU28 will be much smaller and allow only for a 2-fold increase compared to a 4-fold global increase.

Globally this growth can be realised by biomass from MSW (~10 EJ), wood/forestry residues (~20EJ), agricultural residues (~70 EJ) and new production on un-used land (~50 EJ). Mobilisation of these feedstocks is a major effort, but not impossible and needs to be done, while ensuring or even improving sustainability (soil, water, biodiversity). Bioenergy can be part of the bioeconomy. It will result in an integrated approach (biorefineries) where additional biomass can yield additional products, while leaving part of the residues for energy.

Increased sustainable production may yield in additional 650 Mtons of biomass in the EU, but when demand is larger it may require sustainable imports from other regions in the world as well.

4 Economic Potential

Bioenergy is part of the bioeconomy and the growth of the bioeconomy is monitored by JRC in DataM[2]. The dataset with biomass flows[3] shows that in the EU about 1100 Mton biomass is produced of which 222 Mton is used for bioenergy. The same amount is used for biomaterials and the rest 650 Mton for food and feed. This bioeconomy has an turn-over of about 700 billion € and an employment of 17,5

[1] https://www.ieabioenergy.com/publications/technology-roadmap-delivering-sustainable-bioenergy/
[2] https://datam.jrc.ec.europa.eu/datam/public/pages/index.xhtml
[3] https://datam.jrc.ec.europa.eu/datam/mashup/BIOMASS_FLOWS/index.html

Mpeople[4]. Of this about 40.000 people are working on Bioenergy and Biofuels, and a similar amount on biomaterials. Main employment is in agriculture.

The growth of biomaterials and bioenergy in the EU would result in an additional demand for of biomass with an additional employment the biobased industries and an additional added value.

The Bio-Industry Consortium presents in its Vision 2050[5] the view that a circular bioeconomy can produce more biobased resources, sustainably and develop circular value chains to serve societal demands for food/feed/chemicals and energy and create jobs and contribute to the SDG's.

The know-how, developed in Europe on biobased materials and energy is also an export product for the global market through partnerships and collaboration.

5 Challenges

5.1 Challenge 1: Sustainable Carbon for the Globe

In the Circular Bio-Economy fossil carbon is left in the ground while aboveground biogenic carbon circulates without accumulating in the atmosphere - Biomass is the source of sustainable carbon, now and in the future. Circularity aims to maintain the value of products, materials and resources for as long as possible by returning them into the product cycle at the end of their use, while minimising the generation of waste. The Biosphere acts as both carbon absorber and becomes an important source of carbon. Carbon flows optimally provide societies with food, feed, carbon products energy and can result in climate mitigation. Lifecycle of carbon molecule can further be extended and upcycled with CCU. How to maximise the benefit of use and minimize impact at the same time; and even becoming carbon negative, is an important challenge? In addition to enabling smooth transition in energy system, biomass is a scarce resource and optimizing its energy use in combination to other primary uses maximising the value added is crucial. Biomass is also the only way to extract carbon from the atmosphere in scales relative to climate changes, putting it into a very unique position among other renewables also in the light of the European Commission Circular Economy Action Plan[6].

Overarching impacts

- Achieving full potential of circular bio-economy
- Helping to realize a fully sustainable (i.e., not only climate neutral) economy.
- Optimized and balanced use of biomass as constrained resource

Specific impacts

- Obtaining public acceptance and benefitting for the employment impact of biomass use:
- Supporting cost reduction by technology development in relation to ETIP Bioenergy SRIA[7]
- Ensuring the competitiveness of extension of carbon cycle and carbon negative solutions.

5.1.1 Subchallenge 1.1 Role of Bioenergy from Society (Public) Perspective

Rural development and job creation

Change from fossil resources to renewable resources

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[4] https://datam.jrc.ec.europa.eu/datam/mashup/BIOECONOMICS/index.html
[5] https://biconsortium.eu/downloads/joint-industry-vision-circular-biosociety-2050
[6] https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf
[7] https://www.etipbioenergy.eu/about-ebtp/the-role-of-etip-bioenergy/strategic-research-innovation-agenda-sria (2018)

Cleaner conversion with lower emissions

Convey the message to the public, the NGO's and the politicians

5.1.2 Subchallenge 1.2: Efficient Biomass Production

Lowering cost and balancing with soil and circularity demands - a shift up the value chain and away from competing with solar and wind.

Using crop residues for energy and other biobased uses while preserving soil quality.

Developing the crops and methods and technologies to use marginal and released land for production of fuels and biobased materials

Understanding and exploring the potential that intercropping and double cropping offers for producing biomass without causing ILUC (Indirect Land Use Change)

Current trend is to use lower value biomass fractions for energy and optimising the value added use. As this trend is seen to continue the increased technical requirements due to lower and more varying quality of marginal and residual biomass available for energy technologies need to be solved.

5.1.3 Subchallenge 1.3: Linking Biomass Resources to Markets in a Cost-Effective Way

Development of true commodities to link biomass resources to markets thereby lowering the transaction costs. Much biomass cannot link to a market. The economy of scale of biomass production is too small for the economy of scale of conversion systems.

This will require not only standardisation of intermediates but also the associated standardised logistical and conversion systems and market mechanisms and services standardised sustainability certification systems worldwide.

5.1.4 Subchallenge 1.4: Innovative Ways to Integrate Biomass to Circular Material World

The Circular Economy with the potential of digital technologies, can strengthen the EU's industrial base and foster business creation and entrepreneurship among SMEs. Innovative models based on a closer relationship with customers, mass customisation, the sharing and collaborative economy, and powered by digital technologies, such as the internet of things, big data, blockchain and artificial intelligence, will not only accelerate circularity but also the dematerialisation of our economy and make Europe less dependent on primary materials.

Biomass as a renewable resource needs to be integrated, both as renewable virgin material, as well as recycled material, and the optimum between virgin and recycled material needs to be determined for many markets (e.g. for cellulose for paper, the recycling is 7 times virgin material in the Netherlands).

Biorefineries for integrated processing for materials and energy.

5.1.5 Subchallenge 1.5: Providing Sustainable Carbon for CCU and Enabling Negative Emissions

Potential to increase carbon efficiency of circular systems with CCU and integrate other renewables to the carbohydrate hungry globe in different phases of transition.

Only significant scale opportunity to remove carbon from the atmosphere is to combine increase of biomass resources and sustainable biomass use together with end of life carbon capture and permanent storage, Bio-CCS also known as BECCS.

5.2 Challenge 2: Integration of Biomass to Future Sustainable Energy System

The global energy supply system is currently in transition from one that relies on fossil inputs to a system that relies on non-polluting and non-depleting inputs that are dominantly abundant and intermittent.

Optimising the stability and cost-effectiveness of such a future system requires seamless integration and control of various energy inputs. The role of energy supply management is therefore expected to increase in the future to ensure that customers will continue to receive the desired quality of energy at the required time.

In countries where wind and solar are expected to play a dominant role in the energy transition, integration of these intermittent energy sources with the power grid places significant pressure on the grid operators concerned how to balance the grid. Furthermore the renewable electricity from wind or solar is often provided in times when demand is low and the electricity has to be stored (e.g. in H2).or wasted. There is a huge market need to create solutions for industrial scale, with a cost-effective electricity storage capacity, and biomass could play a role.

Bioenergy is currently the major source of renewable energy in the world, while wind, solar and geothermal are the fast-growing alternatives. At best, the role of bioenergy can be very complementary with wind and solar in energy sector. Wind and solar electricity production will increase more rapidly compared to other renewable sources. However, bioenergy will continue to provide the bulk of heating and transport fuels for decades to come. Bioenergy, in its various forms, can eventually contribute to balancing the electricity grid, including as one form of solar energy storage.

Overarching impacts

- Securing a smoot, resilient transition to climate neutral Europe
- Helping to realize a fully sustainable (i.e., not only climate neutral) economy.

Specific impacts

- Achieving balanced, high value energy use for biomass for debottlenecking the energy transition;
- Making technologies suitable for the future energy system available
- Supporting cost reduction by technology development in relation to ETIP Bioenergy SRIA[8]
- Enabling tailored, flexible integration of bioenergy concepts with local infrastructure

5.2.1 Sub-challenge 2.1: Ensuring Benefits from Bioenergy in Enabling Smooth Transition

Bio energy can contribute to the transition is multiple sectors: energy, transport, process industry etc. in addition it has links to land use and food as well as links to environmental aspects of diversity and sustainability. Because of this it is extra important for bio energy to investigate its role and possibilities in the transition.

Establish the tools and knowledge needed for finding the role of bio energy in terms of sector coupling given the diversity and possibility of bio energy.

Collaborating with other enabling technologies to where bio energy can serve as a storage option and active technology for a cheaper smoother transition.

5.2.2 Sub-challenge 2.2: Increase Technical Suitability of Bioenergy for Future Energy System

References to set plan action 8 and ETIP SRIA on target setting

[8] https://www.etipbioenergy.eu/about-ebtp/the-role-of-etip-bioenergy/strategic-research-innovation-agenda-sria (2018)

6 Relation to Cross-Cutting Issues

- Circularity
- Digital transformation
- Social aspects/just transition/governance
- smart agriculture, efficient use of nutrients, water and soil
- Renewable electricity vs biobased applications in mobility and for heat and power
- Carbon negative solutions

7 System Level Challenges that Must be Solved to Realize the Potential

- Bring implementation policies in sync with scientific knowledge
- More integrated policies. Biomass production for energy in sync with agricultural and food policies.
- Carbon sequestration and bioenergy.
- Circular economy and bioenergy
- Governance of bioenergy

Challenge 7

Carbon Capture Utilisation & Storage

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1 Introduction

In 2019, the European Commission presented the European Union's new growth strategy –the European Green Deal, setting the target of reaching climate neutrality by 2050 within the European Union. Instrumental to the achievement of this objective are Carbon Capture, Storage (CCS) and Carbon Capture and Utilisation (CCU) technologies.

CCS and CCU technologies will ensure deep decarbonisation of European industrial and energy sectors, enabling Europe to reach climate neutrality by 2050 in a cost-efficient way. When applied to industrial processes and power plants, CCS and CCU can preserve and decarbonise existing energy-intensive value chains, which lie at the very core of the European economy and provide products that are the basis for our lifestyle. By preserving and also diversifying these value chains, CCS and CCU can help create and safeguard jobs and industrial activity and maintaining European industrial competitiveness in international markets, allowing European Industry to excel. This becomes even more important now as Europe deals with the aftermath of the COVID-19 health and economic crisis.

CCS technologies have been in operations since the 1980s, are scientifically proven and environmentally safe, and their mitigation potential is understood and acknowledged. Commercial CCS projects have captured and stored more than 260 million tonnes of CO2 emissions from human activity over 40 years, with an estimated 40 million tonnes of CO2captured and stored per year today[1]. In Europe, the Sleipner and Snøhvit CCS facilities are currently operating in the North Sea area, and they are expected to be joined in the 2020s by other CCS projects connecting from the Netherlands, Ireland, Belgium and the United Kingdom.

CCU technologies present different levels of maturity, depending on the final product. Life Cycle Assessments and further scientific evidence describing their climate mitigation potential will be needed to make a case for these technologies. In some cases, CCU applications have a limited potential for CO2 abatement at scale, yet they could provide a valuable means of incentivising investment in enhanced CO2 capture technology in the short term.

CO2 transport and storage infrastructure will enable Europe-wide clean, competitive and flexible energy and industrial sectors, early large-scale volumes of clean hydrogen, and negative emissions/Carbon Dioxide Removals (CDR) to balance residual, non-avoidable emissions.

The CCS and CCU technologies' potential for carbon emissions abatement and removal is scientifically proven and acknowledged by the Intergovernmental Panel on Climate Change (IPCC)[2] and the European Commission's Clean Planet for All reference scenarios.

In order to create the best opportunities for Europe to cost-efficiently reach climate-neutrality by 2050, during the next ten years there is a need to support early deployment of, and establish the foundation for, CCS and CCU to become investible technologies in order to scale up and support the EU transition – enable and support a just transition for European industry – preserving jobs, economic growth and diversifying supply chains into new industries – and thus develop Europe as a global leader in the clean, competitive industries of the future.

CCS and CCU technologies have the potential to play a key role to succeed in the transition, and R&I activities are crucial. Building industrial-scale CCS and CCU projects will identify many new challenges that can best be solved by undertaking R&I in parallel with large-scale activities: an iterative process is needed where R&I projects address specific challenges, with the results then implemented in large-scale projects.

[1] Global CCS Institute, 2019 Global Status of CCS, 2019

[2] IPCC Special Report on the impacts of global warming of 1.5°C

2 Technology Status

CCS technologies involve capturing CO2 produced by large industrial and energy (electricity and thermal energy) plants, transporting the CO2 and storing it permanently deep within rock formations. For CCU technologies, instead of storing, the CO2 is used as part of a conversion process, for the fabrication or synthesis of new products, or in non-conversion processes, where CO2 is used.

There are 20 full-scale CCS projects operating globally today with 31 in various stages of construction and development. In 2019, the operational projects injected more than 25 million tonnes of CO2[3]. When fully operational all the current proposed facilities will be able to capture and store at least 100 million tonnes of CO2 per year. CCS has been operational in Europe for over 20 years, with the Sleipner facility in Norway, having stored approximately 1 million tonnes of CO2 per year since 1996.

Carbon capture technologies can be applied to a variety of carbon dioxide emitting processes, where the CO2 is separated from process emissions by physical and chemical processes.

- Power generation, industrial processes (ammonia, iron and steel, cement, chemicals, ceramics, glass, petrochemical, fertiliser, natural gas etc.), low-carbon hydrogen manufacturing, net removal and permanent storage of CO2 from the atmosphere / carbon direct removal (Bioenergy + CCS, Waste-to-Energy + CCS, Direct Air Capture + CCS, etc.).

Transport of CO2 is primarily done by pipeline, but other modes of transport are also used, like ship, rail or road transport. There are over 5,000 kilometres of underground pipelines in North America, which have been successfully transporting CO2 for more than 30 years over long distances[4]. The development of shared CO2 transport infrastructure to connect industrial emission 'clusters' to storage locations is key to unlock economies of scale on a regional, national and European level. To meet decarbonisation targets across the EU, it will also be necessary to extend deployment of CCUS to small emitters (less than 0.5 million tonnes of CO2 per year) and to stranded emitters for which direct connection to pipeline transportation network infrastructure may not be feasible[5].

Permanent and safe CO2storage is achieved deep underground, using natural processes that trap CO2, similar to how oil and gas is trapped for millions of years. Oil and gas fields and deep saline aquifers have similar key geological features required for CO2 storage: a layer of porous rock to store the CO2 and overlying impermeable layers of cap rock which seals the porous layer underneath, trapping the CO2.

Utilisation is the process of using CO2 in industrial processes or products (CCU). The most common form of CCU is Enhanced Oil Recovery (EOR); a process where CO2 is injected into oil fields to increase the recovery fraction of oilfields. Such fields have been operating in Texas, USA since 1972. CCU technologies are more interesting to be used for a variety of other products, including building materials, synthetic fuel, chemicals, plastics, and for horticulture. To determine the climate benefits of each CCU application, full Life Cycle Analyses (LCA) are required and in some areas are becoming available.

CCS and CCU technologies are mature and have been operational for several decades at pilot, demonstration and industrial site scale. CCS is ready to be deployed at industry-wide scale, using shared CO2 infrastructure networks to permanently store CO2 emissions from power generation, industrial processes and low-carbon hydrogen production. CCS also enables the capture and net removal of CO2 from the atmosphere at scale. CCU technologies can be used in many new-products or industrial processes and will require full life cycle analyses to determine their climate mitigation potential. The CCU industry is young and LCAs are becoming available in some areas.

[3] Global CCS Institute, 2019 Global Status of CCS, 2019
[4] Global CCS Institute report
[5] ZEP, A Trans-European CO2 Transportation Infrastructure for CCUS: Opportunities & Challenges, 2020

3 Ongoing Research

Europe is an established global leader in CCS and CCU R&I activities. R&I is delivered by a broad range of organisations including industry, independent research organisations and universities. Key funders for European CCS and CCU R&I include ERANET-ACT, Horizon 2020, Mission Innovation and National Programs.

The 2018 Low-Carbon Energy Observatory CCUS Technology Development Report provides a useful review of projects funded by Framework Programs and Horizon 2020, illustrating the value delivered by connected projects that have progressed knowledge and delivered innovation thanks to sustained support over several years. These projects have been complemented by National Programs in many of the European Countries that are most interested in the development and deployment of CCS and CCU.

Current technical activities in CCS and CCU R&I consider Capture, Transport, Storage and Utilisation. Non-technical R&D – considering aspects such as economics/incentives, legal issues and public perception – also make important contributions. As CCS and CCU concepts move through the TRLs, there is typically excellent collaboration between research organisations and industry to ensure that 'blue skies' research is developed into technology that can be deployed effectively.

Today's CCS and CCU R&I include significant activities to use "building blocks" from both technical and non-technical research to develop effective and flexible low carbon energy systems (e.g. through level supporting the development of Carbon Neutral Clusters). Several projects and programmes are also exploring and developing key links between CCS/CCU and other important parts of low carbon energy systems (e.g. hydrogen and biomass).

4 Technical Potential

CCS and CCU are key technologies in the decarbonised future of the planet. CCS and CCU projects can capture emissions from many industrial processes, for which few alternative decarbonisation technologies exist, such as industrial emissions (cement, steel, refineries, fertiliser), flexible power generation in support of greater renewable penetration and fast ramp-up of cost-effective low-carbon hydrogen production. CCS and CCU are also amongst the few technologies that can remove CO2 that has already been emitted to the atmosphere.

The deployment of industrial scale CCS and CCU projects will enable the technology to be applied to many different applications, which in turn will accelerate innovation and improve technological efficiencies.

Carbon capture technologies currently capture up to 95% of the CO2 emissions, however it is technically feasible to achieve capture rates >95% with only minor (<3%) efficiency and financial penalties compared to a capture facility capturing at 90%. Capture rates above 99% are possible, and as technologies develop through continued R&I and deployment, capture technology efficiencies are expected to improve[6].

Net removal of CO2 from the atmosphere at industrial scale can be achieved with CCS, through the capture of CO2 from biomass sources, also known as BECCS. CO2 can also be directly captured from the air through Direct Air Capture (DAC) and the CO2 permanently stored, though this is a less mature technology. Net removal may also be achieved by utilising captured CO2 from biomass or DAC and permanently storing it through mineralisation (e.g. building materials). Many climate models have predicted that the net removal of CO2 from the atmosphere will be a vital component of future climate and energy systems to address residual emissions from other parts of the economy.

[6] IEAGHG, Further Assessment of Emerging CO2 Capture Technologies for the Power Sector and their Potential to Reduce Costs, 2019

The deployment of CCS and CCU technologies at industrial scale will accelerate innovation and technological development. Capture rates have scope for improvement reaching close to 99% for some processes. CO2 removal from the atmosphere using DAC and BECCS technologies will be key to enable the net CO2 removal required in the net zero energy and climate systems of the future.

5 Socio-Economic Potential

CCS technologies offers one of the lowest cost routes to transform and decarbonise energy intensive industry and power generation towards climate neutrality. A well-developed CCS industry could reduce the global cost of the energy transition by USD 4 trillion[7].

CCS and CCU are vital technologies to safeguard many thousands of jobs in hard to abate industries in the energy transition. Additionally, CCS will require skills currently employed in the oil and gas sector, such as working in the subsurface, handling high pressure fluids and managing large-scale projects.

Shared CO2 transport and storage infrastructure will attract clean sustainable investments for industry activities, energy applications, carbon dioxide removal and the hydrogen economy. Access to sufficient volumes of blue hydrogen will attract industrial investments and pave the way for the development of green hydrogen.

CCS is crucial to the development of the hydrogen economy as the transport and storage infrastructure supports the development of blue hydrogen, thereby securing timely availability of large-scale volumes of clean hydrogen, nationally and globally. The hydrogen economy will not only reduce carbon emissions but can also build a potential global market worth up to USD 2.5 trillion per year in 2050[8].

CCS and CCU are key technologies as part of a cost-efficient energy-transition. Large scale demonstrators together with further R&I will decrease the cost of abatement and accelerate the growth of decarbonised product markets.

6 Challenges

In order to create the best opportunities for Europe to cost-efficiently reach climate-neutrality by 2050, during the next ten years there is a need to support early deployment of, and establish the foundation for, CCS and CCU to become investible technologies in order to scale up and support the EU transition – enable and support a just transition for European industry – preserving jobs, economic growth and diversifying supply chains into new industries – and thus develop Europe as a global leader in the clean, competitive industries of the future.

Specific challenges for CCS and CCU for the coming years to make this possible:

- Getting the commercial framework right
- Accelerating timely deployment at scale of CCS and CCU technologies
- Driving costs down – through R&I, learning by doing and economies of scale
- Enabling rapid scale-up to deliver on the climate goals
- Enabling EU citizens to make informed choices regarding the benefits that CCS and CCU bring.

Challenge 1 - Getting the commercial framework right

Making CCS and CCU investable technologies for industry and energy stakeholders requires an appropriate legal framework that provides long-term predictability for private investments and a reliable

[7] Global Energy Transformation – Irena 2018
[8] Hydrogen Council Roadmap

business model. The standardisation and regulatory issues, such as incentives for innovative technologies and the harmonisation on reporting mechanisms, coupled with support for capital expenditure and operational costs, will be crucial for the development of CCS, CCU technologies in Europe. Other barriers – such as legal challenges, liabilities related to storage and social acceptance, etc. – also need to be explored in R&I activities.

These challenges are further articulated in 6.3.6 and 6.3.7 below.

Challenge 2 - Accelerating timely deployment at scale of CCS and CCU technologies

Early deployment of industrial-scale CCS and CCU projects as well as accelerated development of European cross-border CO2 transport and storage infrastructure is vital to connect CO2 emitters and capturers in "remote" clusters with CO2 storage sites, collecting CO2 from various sources with variable composition Europe-wide.

R&I activities supporting the mapping of CO2 sources and investing in CO2 storage appraisal, mapping and development are vital to develop European CO2 storage capacity, to reduce costs of CO2storage and evaluate risks associated with storage.

These challenges are further articulated in 6.1, 6.2, 6.3.4 and 6.3.5 below.

Challenge 3 - Driving costs down – through R&I, learning by doing and economies of scale

To ensure the development of industrial-scale CCS and CCU by 2030, R&I activities to reduce cost of current CCS/CCU technologies (both CAPEX and OPEX) are essential. R&I activities are also vital to support new, innovative technologies for CO2 capture with higher capture rates at industrial sites and power plants, including Direct Air Capture. The role of CCS and CCU technologies are crucial and must be considered when assessing the potential for clean/low-carbon hydrogen production, carbon dioxide removals (upon a thorough carbon accounting and LCA) and for clean flexible power generation.

6.1, 6.3.1, 6.3.2 and 6.3.3 provide areas for further R&I on CCS and CCU technologies.

Challenge 4 - Enabling rapid scale-up to deliver on the climate goals.

For Europe to lead on clean, competitive industrial and energy sectors, it is crucial to undertake R&I activities in parallel with large-scale activities as iterative processes. Combining existing datasets with specific analyses of industrial areas or plants, supported by the use of artificial intelligence, is recommended. Priority research topics best addressed through R&I range from CO2 capture at industrial and power plants, to CCU technologies, CO2 storage and regulatory issues.

The R&I activities associated with this challenge are further detailed under point 6.3 below.

Challenge 5 - Enabling EU citizens to make informed choices regarding the benefits that CCS and CCU bring

It is crucial to bring all societal actors on board and to showcase the benefits of CCS and CCU technologies not only for the European society as a whole but also for the European citizen in day-to-day life – e.g. domestic heating, cooking and transport/travel. Social sciences, humanities and AI can help engage EU citizens in a positive dialogue around the need for technological solutions to fight climate change and a narrative that focuses on the most advantageous consumers' choices. Developing public awareness, creating confidence in these technologies is vital.

R&I topics associated with this challenge are listed under 6.3.7 below.

6.1 Development of Industrial-Scale CCS and CCU

The early deployment of industrial-scale CCS and CCU projects remains a key priority for Europe. The level of deployment by key milestones, e.g. 2030, must be consistent with reaching net-zero GHG emissions by 2050. Europe should enable widespread application of CCS and CCU for all industrial sectors.

- Industry: Adaptation of current capture methods to new areas as well as development and deployment of higher TRL capture
- CCU technologies at commercial scale to achieve carbon circularity
- The role of CCS in enabling clean hydrogen, including the role of blue hydrogen as bridging technology for the introduction of green hydrogen
- The role, feasibility and scale of Carbon Dioxide Removals (negative emissions)
- Flexible Power Generation, developing low-carbon power generation facilities to support the deployment of increasing renewable power.

6.2 Development of European CO2 Infrastructure

The development of a European CO2 transport and storage infrastructure, including regional CCS and CCU clusters, enabling cross-border cooperation across all European regions is crucial for the possibility to reach climate neutrality by 2050. CO2 infrastructure is deployable today and already operational in Europe, although challenges remain, which is why further R&I is needed. Recommended focus areas are:

Projects of Common Interest (PCI)

Economic instruments that can support the deployment of CO2 infrastructure are critical. The TEN-E Regulation/ CEF/ Projects of Common Interest (PCI) remain very important tool and should be updated:

- The full range of transport modality options, e.g. barge, ship and rail, should be utilised.
- CO2 storage infrastructure should be included.
- PCIs should be extended to also connecting member states without North Sea coastline to ensure that all European regions with potential can plan CCS and CCU infrastructure – the number of PCIs should be consistent with the development of the CO2 infrastructure.

Reviews of infrastructure re-use (pipelines, wells, platforms from hydrocarbon industry) for transport and storage should identify those assets of strategic importance to PCIs and wider member state plans for CCS.

European CO2 storage assets

A Europe-wide storage atlas will strongly support the strategic planning of activities to develop CCS.

A European CO2 storage development programme

A range of priority CO2 storage appraisal activities should be supported to ensure that the required CO2 storage resources are provided for CCS deployment. This should include:

- Appraisal of storage regions which would include pre-competitive evaluation of storage options to encourage subsequent commercial project uptake.
- Detailed characterisation of storage sites across Europe to define the contingent storage resource and to provide storage hubs for CO2 capture projects. This could include the testing of new formations to assess their feasibility for storage.
- Assessment of long-term and post-closure storage liabilities (technical risk and uncertainty) and the development of technical, regulatory, policy and commercial solutions.

- Innovation to reduce costs of CO_2 storage operations, including reducing risks and uncertainties, reducing development and operational costs through e.g. innovative monitoring, drilling and asset management.

European CO2 sources/utilisation opportunities and longevity

- CO2 sources and utilisation capacities across the EU should be mapped and assessed.
- Inventory of pre-commercial and/or industrial demonstration scale level CCU projects.

Both regarding CO2 sources and storage, further exploring the use of big data and artificial intelligence is recommended.

6.3 Areas for CCS and CCU Research

Building industrial scale CCS and CCU projects will also identify many new challenges that can best be solved by undertaking R&I in parallel with large-scale activities. An iterative process is needed where R&I projects address specific industrial challenges, with the results then implemented in large-scale projects. A recommended approach would combine existing datasets with specific analyses of industrial areas or plants, supported by the use of artificial intelligence. Priority research topics include the following areas and are best addressed through R&I at a range of scale from laboratory to pilot:

6.3.1 CO2 Capture in Industrial Clusters and Energy Applications

- Integration and synergies with other sectors and renewable solutions
- Process intensification, including utilisation of waste heat
- Retrofitability, part-load operation and flexibility
- Part-load operation and flexibility
- Buffer storage and shared transportation infrastructure
- Treatment of waste products from capture plants
- Degradation and life span of capture technologies
- Flexible electricity production
- Hydrogen applications (e.g. fuel switching, chemical conversions)
- Business models.

6.3.2 Cost Reduction of CO2 Capture Technologies

- High-TRL CO2 capture technologies (from TRL 5-6 to TRL 7-9)
- Next generation CO2 capture technologies
- Modularisation of capture technologies, compact capture technology
- Carbon removal technologies
- Fuel flexible combustion systems.

6.3.3 Technological Elements for Capture and Utilisation

- Flexible, modular and energy efficient capture and purification technologies considering specificities of the downstream application
- Novel reactor design for efficient integration of capture and conversion stages

- Intensification for reduced energy consumption (including waste heat valorisation) and waste generation
- Novel and cost-effective materials (membranes, adsorbents, absorbents) with high durability and recyclability for increased capture rates
- Catalyst and material development for conversion technologies into fuels and chemicals (electrochemical, photoelectrochemical, thermochemical)
- Increased uptake of CO_2 during carbonation of primary and waste materials for the production of building materials (mineralisation)
- Increased direct uptake of CO_2 for polymer production
- Synthetic biology for increased conversion efficiencies in biological conversion and efficient downstream product processing.
- Artificial photosynthetic systems for efficient and direct conversion of solar energy to fuels and chemicals.

6.3.4 CCS and CCU Transport Systems

- Value chain analyses (full chains, H_2, ammonia and liquid organic H_2 carriers)
- New CCS and CCU chain concepts and transport networks (including hubs, buffers)
- Impact of CO_2 composition and impurities
- Safety assessments and engineering design tools
- Non-pipeline transport of CO_2 (e.g. ships, rail, trucks, etc.)
- Injection of fluctuating CO_2 flows, particularly into low pressure reservoirs
- Improved understanding of thermophysical properties of CO_2 and CO_2 mixtures.

6.3.5 CO2 Storage

- Develop experience with site conformance monitoring and assessment
- CO_2 flow behaviour near valves and chokes
- Storage optimisation through development of a range of injection strategies including in highly depleted reservoirs
- New geophysical techniques for examining and characterising legacy wells
- Deeper understanding of induced seismicity
- Effective prediction of CO_2 plume evolution under geophysical and geological uncertainty
- Dynamic storage capacity; understanding pressure responses, pressure-connected volume and pressure management techniques
- Storage of small volumes of CO_2 and scale storage if needed
- Storage appraisal to provide de-risked storage capacity to meet net-zero targets across Europe from a range of technologies
- Risk mitigation for storage value chain (financial, technical, regulatory)

- Strategic storage planning to optimise use of the deep subsurface, including interactions with other users.
- Innovation in monitoring technologies including, inter alia, use of robotics, autonomous machines, permanent monitoring, shared monitoring infrastructure, use of machine learning, continuous monitoring and large datasets.
- Effective simulation of CO2 storage at semi-regional scale (several sites in communication) to enable optimisation of safe subsurface pore space utilisation
- Cost-effective ways to repair legacy wells.

6.3.6 Standardisation and Legislation Issues

- Standard CO2 specifications
- Incentives for carbon negative solutions
- Incentives and market-pull mechanisms for low-carbon products
- Methods for measuring biogenic/fossil CO2ratio
- Data on emissions from CO2 capture technologies
- CO2 stream composition, including technical considerations such as pressure, temperature and physical state and MMV
- Harmonization of legal standards / regulations relevant for the development of a European CO2 transport- and storage-network.

6.3.7 Social Science and Humanities

- Computational tools in process engineering & intensification (e.g. AI-driven process control, machine learning for catalyst development)
- Harmonised guidelines for life cycle sustainability assessment
- Public awareness and social acceptance of technology solutions towards achieving climate neutrality goals.
- Engaging communities in local projects through development of participatory monitoring programmes.

This list of proposed R&I activities summarises some of the most important and overarching areas for continued research efforts in the coming years. The list is non-exhaustive and new areas will be identified as CCS and CCU technologies are deployed.

7 Relation to Cross-Cutting Issues

Integration into a single European energy system

- Energy system modelling and developing scenarios based on the results, to understand the scale, timing, options for and optimisation of CCS and CCU deployment to enable and support the transition in industrial decarbonisation and energy provision, including hydrogen and flexible electricity production and carbon dioxide removals.

Legal, policy and regulatory framework and market design (See under 8 below)

Fair and inclusive transition

- Just transition – Shared Europe-wide CO2infrastructure will ensure that CO2 emitters in all European regions can connect to permanent CO2 storage.

Circularity

- CCS and CCU technologies are by definition introducing circularity. LCA including end of life impact together with real carbon accounting should be the basis for all energy technologies.

Digitalisation

- There is already a great variety and big volumes of data available. Explore the use of big data and artificial intelligence.

Technology acceptance and energy citizenship

- Public perception in parts of Europe, especially where onshore storage is considered – Inclusion of stakeholders in cities/regions is an enabler: Engaging communities in local projects through development of participatory monitoring programmes (co-design, co-ownership, co-decide, co-monitor); understanding stakeholder needs and opportunities to support transition through policy alignment (e.g. clean air and hydrogen economy); public awareness campaigns.

8 System Level Challenges that Must Be Solved to Realise Potential

Crucial to set the European focus on GHG/CO2 mitigation/removal

- Align all relevant policies with the European commitment to reach climate neutrality by 2050
- Take on a technology neutral approach and focus on clear CO2 (GHG) thresholds – solve overlapping and contradicting policies.

An enabling policy framework, making it economically feasible for companies to invest in the whole value chain of CCS/CCU

- A functional and relevant carbon price – a robust EU Emissions Trading System
- In the short term, incentives to support timely large-scale deployment of all parts along the CCS/CCU value chain
- An Innovation Fund that can support the whole CCS/CCU value chain
- Coherent and coordinated EU and national funding programs
- Use national long-term strategies and National Energy and Climate Plans (NECPs) to track EU's progress towards climate neutrality and coordinate national and European research and innovation programmes. An early assessment of the NECPs shows that 13 Member States participate in European research initiatives aimed at accelerating CCS technology (including under the SET-Plan, ERA-NET CoFund ACT and EEA-grants 2014-2021)[9].

[9] IOGP

Input Paper to the CETP SRIA Renewable Technologies

Challenge 8

Ocean Energy

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1 Introduction

The oceans have huge potential as sources of renewable energy. Ocean energy describes both the energy contained within the seas – in kinetic, chemical and thermal energy – and the technologies under development to harness that energy to power human activity. These technologies are tidal stream, wave, Ocean Thermal Energy Conversion (OTEC), salinity gradient and tidal range.

It is technologically challenging to develop these devices. They must operate in harsh environments with a wide range of challenging conditions – e.g. meteorology, temperature, salinity, depth and remoteness. The challenges outlined in this report focus on tidal stream and wave energy given their high market potential for Europe, commercial maturity, and Europe's current leading position in this sector [1].

Ocean energy is part of the solution to decarbonise Europe: electricity production in 2050 will need to be emissions-free, low cost and flexible. To reach that objective, we will need demand-side management, storage and most importantly, all flexible renewables at our disposal – whether established already or still innovative today such as ocean energy.

2 Technology Status

TIDAL STREAM – on the verge of industrial roll-out

Tidal stream turbines harness the flow of ocean currents, like underwater wind turbines. Tidal stream turbines can be mounted directly on the seabed or floating, moored to the seabed. The method for extracting energy from tidal streams is approaching design convergence. Successful designs generally comprise two- to three-bladed **horizontal-axis turbines**. Alternative designs include **vertical axis turbines** and **tidal kites**. Technologies are approaching commercialisation, with the deployment of full-scale devices in relevant conditions at sea, as well as an increasing number of pilot farms.

WAVE – several promising designs in development

Wave Energy Converters (WECs) harness energy using the movement of the waves. WECs can be deployed both on, near or further away from the shoreline. Wave energy technology remains at an earlier stage of development than tidal stream technology, with novel device prototypes – both scaled and full size – undergoing testing at sea. Wave energy is comparatively further from technological convergence. Unlike tidal, wave energy may converge to several different designs, each tailored to extract energy most efficiently from different local conditions. Wave prototypes are currently found in three main forms: **point absorber**, **oscillating wave surge converter** and **oscillating water column.** WEC developers are currently improving the performance of their devices through design improvements. This will allow proving of the technology at higher TRLs, and subsequent commercialisation.

Other ocean energy technologies

Aside from wave and tidal stream, three other technologies are under development, at a range of maturity levels:

- Ocean Thermal Energy Conversion (OTEC), including Sea-Water Air Conditioning (SWAC), exploits temperature differences found at different ocean depths.
- Salinity gradient exploits the osmotic pressure between seawater and fresh water.
- Tidal range harvests energy from the difference in sea level between high and low tides – just like hydropower

Ocean energy technologies have reached different stages in their development:

- **Wave energy is at full-scale prototype stage**
- **Tidal energy is already at demonstration stage with first pilot farms**
- **OTEC and salinity gradient are at R&I stage, and tidal range can be rolled out.**

3 Ongoing Research

3.1 Tidal Stream

Tidal stream has reached a relatively high Technology Readiness Level (TRL) of between 6 and 8, depending on device type. Devices and their auxiliary technology are expected to reach competitive cost levels following around an estimated decade of further research, development and real-sea deployments. With appropriate support mechanisms, array-scale deployment is possible in Europe today.

The rated power of existing tidal turbines ranges between smaller-scale devices of 0.1-0.25 MW, and larger scale of 1 and 2 MW, with scope to increase larger devices by 50% or more in the coming years. Tidal stream's progress in recent years is demonstrated by the operating hours accumulated, capacity deployed and electricity generated. Since 2010, over 26.8 MW of tidal stream has been deployed in Europe. 11.9 MW of this is currently operating, and 14.9 MW has now been decommissioned.

An industrial supply chain is growing out of both existing practices, modified to suit the requirements of this technology, and the creation of new supply chains specific to the needs of tidal technology.

The first evidence of tidal stream's balancing role in future electricity systems is being demonstrated. Tidal stream's predictability has important grid-balancing benefits and places the technology in a strong position relative to alternative renewable energy sources. The periods between tides are always short, so the addition of small volumes of storage can deliver 24/7 power and extra flexibility to electricity systems.

Nova Innovation's Shetland Tidal Array has an integrated battery pack that can accommodate the full power of the array, for applications like load balancing. Sabella's single turbine uses storage to balance the power fluctuations.

EU-funded projects driving progress

European-funded tidal stream prototypes are found in bottom-fixed turbine, floating turbine, and kite form.

Within the EnFAIT project and operated by Nova Innovation, an array of three turbines is deployed. The array will soon be doubled in capacity from 0.3 MW to 0.6 MW. The bottom-fixed array has achieved over 24,000 hours generating power to the grid.

Sabella's D10 turbine, partly funded by the EU's regional funds, was France's first tidal turbine to connect to the national electricity grid.

Operating within the FloTEC project, Orbital Marine Power's floating 2 MW turbine achieved 12 continuous months of operation, generating more than 3.3 GWh of electricity. This testing in real-sea conditions validated the technology, studied Operation and Maintenance (O&M) costs and demonstrated value to the potential market.

The NEMMO project aims at improving performance and reliability by improving blade survivability and performance testing based on Magallanes Renovables' tidal turbine in modelled harsh conditions.

Innovative Power Take-Off (PTO) designs are undergoing sea testing at full- and reduced-scale under the TiPA and PowerKite projects. The TiPA project tested a 'direct drive' turbine that does not need a gearbox. The PowerKite project saw the deployment of a 500kW device off North Wales.

OCEANERA-NET COFUND is investing EU and national / regional research and demonstration funding in 5 projects developing key enabling areas for cost reduction, including foundations, moorings, blade technology and pitch regulation.

3.2 Wave Energy

Currently, wave technology development is estimated to be at TRL 7. Only onshore designs such as the OWC Mutriku Wave Power plant in Spain have demonstrated consistent power production and can be placed at TRL 8. Since 2010, 11.3 MW of wave energy has been installed in Europe. Of this, 2.9 MW is currently in the water and 8.4 MW has been decommissioned. Research continues into geographical resource profiles and potential markets.

An industrial supply chain is growing, with suppliers focused on both requirements specific to wave technologies and adapting their existing services to cater to these new technologies. Knowledge and experience of survivable materials can potentially be found in other sectors, such as offshore wind or oil and gas.

The development of wave energy device prototypes has reached a more sustainable pace: phased development has helped mitigate the risk of large-scale prototype testing.

EU-funded projects driving progress

European programmes are funding investigations into a number of areas important for the progression of wave technology. Several WECs have been progressed to full-scale demonstration stages, following successful reduced-scale testing in recent years.

The WaveBoost project developed and validated an innovative Power Take-Off (PTO) technology that improved reliability and performance of CorPower Ocean's point-absorber buoy.

The OPERA project, coordinated by TECNALIA, improved IDOM's MARMOK-A-5 wave energy converter. This project, completed in 2019, validated and de-risked innovation in wave energy development and increased TRL by deploying an Oscillating Water Column device in open-sea operating conditions and sharing the resulting data.

Innovative Power Take-Off (PTO) designs are undergoing sea testing at full- and reduced-scale. An example of this work is the repurposing of aerospace technology for novel PTOs, such as Umbra Cuscinetti S.p.A.'s EMERGE project. Umbra's Electromechanical Generator PTO was integrated into real-sea scale testing of the EEL Energy tidal device.

The SEA-TITAN project, coordinated by Wedge Global, is designing, building, testing and validating an innovative second-generation Direct Drive PTO that will maximise energy generation while protecting devices in extreme conditions.

OCEANERA-NET COFUND is investing EU and national / regional research and demonstration funding in 4 projects which support development of wave devices (SPhorcis and Wedge Global, anchoring and mooring systems and integration into local energy systems).

3.3 Other Ocean Energy Technologies

OTEC is being demonstrated at plants in EU overseas territories. OCEANERA-NET COFUND has funded a project aimed at the development of advanced non-corrosive materials which will improve the survivability, durability and reliability of ocean thermal energy converters. The technology can also be harnessed to deliver SWAC and desalination.

Salinity gradient technology requires further development of membrane materials. Commercial plants require very large quantities of membranes, so more economic and efficient membranes need to be developed at large scale. Countries around the world are developing and testing this technology – the Netherlands and Mexico are key participants.

Generation of power using **tidal range** began back in the 1960s. European annual generation from tidal range is 500GWh, by La Rance Tidal barrage in France.

Tidal stream is on the verge of industrial roll-out and tidal technologies are approaching commercialisation, with the deployment of full-scale devices in real sea conditions, as well as an increasing number of pilot farms.

Wave energy technology remains at an earlier stage of development than tidal stream technology, with novel device prototypes – both scaled and full size – undergoing testing at sea.

OTEC is being demonstrated at plants in EU overseas territories and salinity gradient technology requires further development of membrane materials.

4 Technical Potential

Ocean energy has the potential to deliver 100 GW of capacity by 2050 – equivalent to 10% of Europe's electricity consumption today – all along the Atlantic coast from Portugal to Norway, along the Baltic sea and the periphery of the Mediterranean. With almost 45% of Europe's citizens living in coastal regions, ocean energy can be readily delivered where it is needed.

Ocean energy is flexible and predictable, and it will play an important role in balancing Europe's electricity grid. Regulated by the constant cycles of the moon, sun and earth, tidal stream is 100% predictable. Waves follow a different pattern from wind and solar. Wave works particularly well with wind – the waves are built up by the wind, so when the wind dies down, wave energy can step in to maintain power production. Combined, wind and wave together produce an overall power output that is smoother, and more reliable. Ocean energy will reduce the need for storage and make the electricity grid more efficient, more reliable, and more cost effective.

Ocean energy will deliver large volumes of the renewable energy that Europe needs, delivering 100 GW of capacity by 2050 – equivalent to 10% of Europe's electricity consumption today.

5 Economic Potential

European companies lead the world in ocean energy. In tidal stream, the world's first offshore array is located in Europe, as is the world's largest tidal array, and the world's largest tidal turbine. In wave energy, Europe remains the world leader with the largest amount of full-scale wave energy devices and 1,250 kW of capacity installed per year since 2010. 66% of tidal energy patents and 44% of wave energy patents are held by Europeans.

Europe has a chance to consolidate this lead and dominate a new global high-value market, estimated at €53bn per annum by 2050. Ocean energy can create 400,000 jobs by 2050, all along the supply chain and across Europe. These jobs are created at a local level, revitalising the coastal communities that historically served for shipbuilding, fishing and the oil and gas sector. They are also created where the supply chain is, in countries such as Austria, Germany, Sweden and the Czech Republic.

Europe has a chance to consolidate its leadership in ocean energy and dominate a new global high-value market, estimated at €53bn per annum by 2050 with the creating of 400,000 jobs by 2050.

6 Challenges

The following Challenge Areas represent a set of R&I fields that the ocean energy sector has identified as most worthy of investment during the next period of 4-5 years.

Ocean energy industry and research professionals agree that the **Design and Validation of Ocean Energy Devices** is the most urgent and crucial area to focus on. Addressing this area is the most important step to bring ocean energy to a level where private investment can gradually replace public supported projects in financing the further development of ocean energy. This is reflected in the larger number of 'high priority' projects in this Challenge Area.

The rest of the Challenge Areas focus on specific aspects of ocean energy systems, such as the **Foundations, Connections and Mooring, Logistics and Marine Operations and Integration in the Energy System.**

6.1 Challenge 1: Design and Validation of Ocean Energy Devices

This challenge encompasses the **research, design, development, demonstration and validation of ocean energy devices and their subsystems**. The primary focus of this challenge is demonstration of wave and tidal energy technologies.

Design and validation of ocean energy devices involves **extensive testing – from tanks in laboratory to deployment of scale and full-size prototypes in real sea conditions, as well as first pilot farms**. There is currently widespread research infrastructure in place, but specific funding is required to develop and operate the devices that are deployed in these testing facilities. Ocean energy devices need to be deployed in real sea conditions to validate and optimise key performance metrics. This will allow validation of the next generation of ocean energy technologies. The continued refinement of sub-systems improved operational procedures, reduced risk through demonstrated performance and economies of scale will drive down cost and increase the bankability of ocean energy projects.

Focusing on one or several sub-systems will significantly improve the overall reliability, energy yield, availability, operating cost and lifetime costs of complete ocean energy devices. Simultaneously, **integrated design approaches to the control system** within a device and other aspects of the device design will contribute to higher performance, reduced fatigue, simpler and more cost-effective maintenance and improved survivability. Transition to the **highest level of circularity will be achieved by considering a system approach** in the design of ocean energy technologies.

Innovative designs together with real operational experience will reduce existing uncertainties and risks, thus increasing the **reliability, availability, maintainability and survivability** of devices. Survivability is particularly important as ocean energy technologies need to withstand extreme weather conditions and loads. Reliability is fundamental for all ocean energy technologies, as project life cycles are long (target deployments are 20/25-year) and the environment they operate in is challenging. Maintenance operations can be very costly and difficult to perform. Devices are also subject to marine growth which increases maintenance needs.

Data and reports from demonstration projects are currently available, but **knowledge exchange should be promoted while respecting the protection of company IP**. Information should be made easier to find, access and reuse, in order to support technology development. Collaborative working, knowledge exchange, good practices, successful approaches and generic problem-solving techniques will accelerate the commercialization of the sector.

Finally, **demonstration of ocean energy technologies will build on Europe's global lead** in this sector by accelerating commercialization of the Europe's world-leading ocean energy technologies, companies and projects.

Research and innovation areas (more information in [2])

- **Demonstration of ocean energy devices to increase experience in real sea conditions.**
- **Demonstration of ocean energy pilot farms.**
- **Improvement and demonstration of PTO and control systems.**
- **Application of innovative material from other sectors.**
- **Development of novel wave energy devices.**
- **Improvement of tidal blades and rotor**
- **Development of other ocean energy technologies (OTEC / Salinity gradient)**

6.2 Challenge 2: Foundations, Connections and Mooring

This challenge refers to device **mooring** and **foundation (floating or bottom-fixed)**, **offshore structures** other than the device itself, and **connections**. **Non-electrical power transmission** such as hydraulic lines or pipes are also included.

These aspects share many similarities with those of existing marine structures for coastal defence, offshore wind and offshore oil and gas. However, **ocean energy imposes novel functional requirements** for which optimised solutions must be developed and thoroughly tested at sea.

Many aspects of this challenge cannot be addressed in isolation and **should be considered together with the demonstration of devices**. Aspects related to **improving installation should be considered together with the challenge on Logistics and Marine Operations**.

Optimising design for foundations, connections and mooring will **reduce cost of components and installation and increase energy yield, thus reducing CAPEX**. Operating experience will reduce OPEX by improving installation, operation and maintenance, reducing uncertainties and risks and improving reliability, availability and survivability.

Research and innovation areas (more information in [2])

- **Advanced mooring and connection systems for floating ocean energy devices**
- **Improvement and demonstration of foundations and connection systems for bottom-fixed ocean energy devices**

6.3 Challenge 3: Logistics and Marine Operations

This challenge includes technology development and demonstration of **marine operations related to installation, operation, maintenance and decommissioning**of ocean energy devices or arrays. Due to the limited number of devices and projects deployed to date, ocean energy does not yet have a dedicated and specialised supply chain. In addition, and particularly for wave energy, the variability in designs makes the development of generally applicable procedures difficult.

Ocean energy devices typically need to operate for a lifetime of at least 20 years, so **operation and maintenance significantly impacts cost of energy**.

Demonstration projects will **generate valuable learnings and improve logistics and marine operations**. This will in turn reduce cost of installation, maintenance and decommissioning for upcoming commercial projects.

Research and innovation areas (more information in [2])

- **Optimisation of maritime logistics and operations**
- **Instrumentation for condition monitoring and predictive maintenance**
- **Marine observation modelling and forecasting to optimise design and operation of ocean energy devices**

6.4 Challenge 4: Integration in the Energy System

This challenge includes actions that will assist and speed-up the integration of ocean energy arrays into the European energy system. The research focus will differ between farms connected to the national grids and those feeding into smaller grids, such as islands deployment. The actions within this challenge should evaluate electricity system-balancing benefits of ocean energy deployment in both grid types and for other renewables such as solar and wind energy.

Research and innovation areas (more information in [2])

- **Developing and demonstrating near-commercial application of ocean energy in niche markets**
- **Quantifying and demonstrating grid-scale benefits of ocean energy and synergies with other renewables**

7 Relation to Cross-Cutting Issues

7.1 Environment

Analysis of the lifecycle environmental impact of ocean energy and comparison with other renewables should be continuously updated as the technology evolves. Research, dissemination and enforcement of good practices will reduce or eliminate individual negative environmental impacts. It is important to also focus efforts on enhancing the **overall positive environmental impacts** of ocean energy developments. **Monitoring equipment and field work such as seabed observation** and samples are costly and will significantly impact the economics of initial ocean energy projects, so they may be a particularly suitable target for R&I activities.

Available **job creation studies** suggest that employment created by ocean energy will be a decisive benefit of these technologies. These studies must be updated with new data from real deployments, especially first arrays and near commercial applications, in order to provide reliable numbers to policy makers. Practices that enhance or reduce the job creation potential of ocean energy should be identified and documented for application in upcoming projects.

7.2 Circularity

The implementation of previous challenges should be driven by a **systemic innovation approach** that contributes to a clean and circular economy. Transition to a higher level of circularity in the economy requires fundamental changes in the value chain, from product design and technology to new business models and new ways of preserving natural resources. Future technology developments in ocean energy should respect as far as possible these wider principles of sustainability. and the **design of devices should consider lifecycle environmental impacts** in a circular economy perspective

7.3 Digitalisation

Accelerating development of ocean energy by means of digitalisation requires some degree of **sharing data** and experience but fostering competitive European companies in the emerging supply chain requires intellectual property and some confidentiality, so the **optimal balance between open data and confidentiality** must be found. Previous EU-funded projects, such as the OPERA project [http://opera-h2020.eu/], have shown that with the right planning and dialogue, it is possible to enrol private companies to participate in public-funded projects and deliver valuable open data while respecting their existing IP and confidentiality requirements. This experience on sharing data is highly recommended for research and demonstration projects supported by public funds.

It is difficult and time-consuming to find, access and process the data necessary to design and improve ocean energy devices and operation. This adds costs, slows down design improvements and constitutes an important barrier for new entrants. **New technologies allowing better collection, analysis and processing of large datasets are an important opportunity for ocean energy**. Activities should be coordinated and should avoid redundancy with existing repositories such as the WTKN (Wave and Tidal Knowledge Network) or WES knowledge library.

8 System Level Challenges that Must Be Solved to Realise Potential

Ocean energy is not making a massive contribution to the European energy system yet. However, in view of a much higher contribution in the medium-long term, some challenges should be addressed now with two main focuses: integration of ocean energy farms connected to the national grids and ocean energy installations feeding into smaller grids or off-grid applications.

Ocean energy's variability is correlated and out-of-phase with that of wind and solar power. This is a major advantage for managing high penetration of renewables on the European grid. For **farms that feed into the national grid, the challenge is to quantify the benefits of the high predictability of tidal power and, for wave power, its complementarity with wind and solar power**. This means less requirements for storage, transmission and demand-response which are starting to take up a significant share of the investment needed for the energy transition. Quantifying this benefit of ocean energy will require multi-annual, system-wide grid simulation including weather and climate variability, similar to those that are conducted for solar and wind power integration.

In smaller grids such as island deployments, wave and tidal farms may contribute to a significant share of generation. Their deployment will be accompanied by storage and demand-response roll-out, and their potential to complement solar and wind power must be assessed. These integration assessments for island deployment are one very promising pathway for ocean energy commercialisation. Another field to be explored for wave and tidal technologies are **off-grid applications** such as aquaculture, remote monitoring systems or desalination plants in which wave and tidal can contribute with local and accessible power.

The **predictability of tidal energy** coupled with the possibility of ensuring almost 20 hours of generation per day, has led to exploratory projects where electricity that cannot be used by the grid is directed towards the generation of hydrogen as an energy storage. Possible markets for **wave energy include the desalination market**, powering remote areas (diesel displacement) and powering offshore oil and gas platforms.

9 References

[1] SET-Plan Temporary Working Group Ocean Energy, *SET-Plan Ocean Energy Implementation Plan*, 2018.

[2] Strategic Research and Innovation Agenda for Ocean Energy. May 2020. ETIP Ocean.

Input Paper to the CETP SRIA Renewable Technologies

Challenge 9

Hydropower

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Executive Summary

Hydropower (HP) is the largest renewable energy source (RES) in Europe, adding up to about 36% of the electricity generated from renewable energy sources in the EU and 10% of the entire generation of energy in the continent. Worldwide, hydropower generates more than 60% of the electricity originating from renewable energy sources. Currently a cornerstone of the energy sector in the EU, HP is far from exploiting its entire potential in terms of energy generation, capacity, storage, and flexibility provided to the system. Innovative solutions and industrial development are needed to utilize this potential. Thus, many workplaces will have to be implemented.

To cope with the challenges posed by the transition towards a climate neutral Europe, further research, development, and innovation are crucial. HP will not only be an enabler for other renewable energy sources (RES) in the energy mix, but it also has the potential to balance a renewable energy system both on the short and on medium to long term. However, phasing out traditional energy sources while increasing the amount of variable RES will increase the strain on the HPP, changing the normal operating patterns.

Many are the areas of research currently investigated by researchers in HP. Increasing the flexibility of hydropower plants, the expansion of HP's storage capacity and the environmental design of HP plants are only a few among the topics that need to be addressed. To effectively ensure that HP will continue to provide the system the flexibility and adaptation capacity it needs, research in all domains ranging from technological aspects to social acceptance is needed today more than ever.

Research developments will not only remain confined to HP plants and related activities but will also provide a positive impact to other fields of research. Increased research on the impact of HP on the environment will mitigate its effects on climate and organisms populating water streams and bodies, increasing biodiversity, and reducing the impact on local hydrology. In addition, HP can provide a high level of circularity thanks to the potential recyclability of its components and the low levels of greenhouse gas emissions correlated to its production processes. Furthermore, research on the application of digital processes would bring HP a step further in terms of capacity, flexibility, and responsiveness to extraordinary situations. Modelling can also improve construction planning and plants design, reducing the cost of energy and increasing the lifespan of current and future plants.

The potential for further research activities in HP is large, creating a strong case for increased efforts in the field and providing a strong backbone for other, more volatile sources of renewable energies.

1 Introduction

Hydropower (HP) is the largest renewable energy source (RES) in Europe. In 2019, the electricity production from HP in Europe was 653 TWh/year[1] (334 TWh/year within the EU[2]). This means that hydropower generates about 36% of the electricity generated from renewable energy sources in the EU and 10% of the entire generation, contributing significantly to achieving EU targets for energy and climate[3]. The capacity of European HP is 251 GW, including pumped storage.

The European HP industry has a long history spanning more than a century back, and the world leading manufacturers, i.e. hydraulic turbines and the corresponding electromechanical equipment, are based in Europe with European ownership. Research finance through public and private partnerships during the

[1] International hydropower association. (2020). 2020 Hydro Power Status Report: England, IHA

[2]EUROSTAT. (2020). Electricity generation statistics 2020. https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_generation_statistics_%E2%80%93_first_results#Production_of_electricity

[3] EURELECTRIC and VGB Powertech. (2018). Facts of Hydropower in the EU. https://www.vgb.org/hydropower_fact_sheets_2018-dfid-91827.html#:~:text=So%20far%2C%20hydropower%20is%20the,to%20achieving%20the%20EU%20targets.

last two decades has played a significant role towards developing several technological solutions for hydropower, enabling flexible energy storage and supply.

In 2015 the HP sector in Europe directly and indirectly provided more than 100,000 jobs and an annual value creation of €39 billion, with an estimated potential of reaching €90 billion by 2030[4]. Strengthening the technology base through research and innovation can create further growth, more jobs, and ensure the leading position in the global market. As the policies of many countries currently strive to move towards a carbon neutral energy sector, such products, technologies, and services are expected to be highly demanded export goods.

HP as a renewable energy source has several unique capabilities. Hydropower plants (HPP) offer highly flexible generation, high output capacity, rapid ramping, and unmatched storage capacity. HP is therefore expected to be an enabler for an increase of other renewable energy sources (RES) in the energy mix, as the other RES are lacking these capabilities. HP has the potential to balance a renewable energy system both on a short term (seconds to minutes) and on medium to long term (months or even years). The seasonal energy storage provided by storage HPP (with artificial lakes called reservoirs) is of particular importance to balance the generally higher demand in winter. Phasing out traditional thermal energy sources while increasing the amount of variable RES, will however increase the strain on the HPP and change the normal operating patterns. To cope with these changes in requirements, further research, development, and innovation are crucial. As HP can deliver much more to the electricity system than just energy, further research into new market models and pricing of services that award services such as ramping and grid balancing are required.

HPP are often part of integrated water management systems tackling flood protection, draught management, and freshwater provision. As the climate changes, these services will become more important. More extreme weather conditions will increase strain on dams and water systems, and a sound understanding of these impacts is necessary to ensure both safety through resilient infrastructure and a sustainable water management.

Many HPP were built in a time when there was limited knowledge and environmental and social impact were not a priority. To ensure that HP is a renewable energy source on the long term, i. e. sustainable, it is important to increase the knowledge about the impacts on the affected ecosystems and how to mitigate these. Sustainable solutions may offer win-win situations for both the environment and from an operational perspective, e.g. regarding reservoir desilting techniques.

For many municipalities, regions and countries, HP is an important source of revenues, both directly through payments of the HPP operators to the authorities (water rights fees, royalties) and indirectly through the economic contributions of HP to the local trade and infrastructure.

HP, if modernised appropriately, has the potential to be the backbone of the future carbon free European energy system, providing resilient infrastructure, clean electricity and contributing to mitigate the global challenges posed by climate change.

Hydropower provides sustainable, reliable and secure energy supply at affordable prices. Through its flexible production (quick response to demand fluctuations and up to seasonal storage) hydropower is a key enabler for Europe's energy transition.

[4] DNV GL. (2015). The hydropower sector's contribution to a sustainable and prosperous Europe: Germany, KEMA Consulting GmbH

2 Technology Status

Today HP is the most flexible source of renewable energy, i.e. the source of energy which can be best regulated to meet the demand and the production of the other RES at any time. Besides energy production and storage, it also serves to stabilize the electricity grid (system services and balancing abilities). HP technology has been developed over more than a century and is still being improved. Its flexibility, lifetime, performance, efficiencies and ecologic footprint are outstanding – some HPPs are more than 100 years old and still in operation: turbines with 96% efficiency and generators with efficiencies above 99% are some examples. HP is an indirect way of using solar power, i.e. making partly energetic use of the hydrological cycle of evaporation and precipitation driven by the sun. Compared to other RES, HP is outstanding with respect to energy-payback ratio, life-cycle assessment, greenhouse-gas emissions, water footprint, and more. Adding to that, HP schemes have the highest energy-conversion efficiency and the longest operational life.

Both in Europe and worldwide, an increased amount of unregulated power from new RES, i.e. wind and solar, are introduced. Hence, the market demands for flexibility and dynamics such as energy storage and fast response are rapidly growing. HP has potential to provide the required services, e.g. high ramping rates. However, energy markets are subject to strong regulation[5] and due to the large range of political and socioeconomic concerns the HP industry is highly regulated[6]. Future changes in climate and impacts on water resources will directly influence the HP industry[7]. Simultaneously, the high number of upcoming revisions of HP licenses[8] and implementation of the EU Water Framework Directive (WFD) introduce uncertainty in the HP industry. This uncertainty calls for knowledge-based solutions that optimise the trade-offs between HP production, market opportunities and local environmental impacts[9,10] and address the societal concerns[11]. The HP development in Europe took place mainly between 1950 and 1990. Hence, the hydropower sector faces challenges related to ageing equipment and components of HPP. Lack of targeted research on new HP technology over time has become a barrier for utilize new opportunities. Putting new solutions to work, in cooperation with industrial partners, will ensure future value creation.

European research for the hydropower sector will have to focus on technology, power markets, operation & maintenance, regulatory frameworks, social acceptance, and environmental impacts.

3 Technical Potential

The technical capacity and generation potential of HP in Europe are 338 GW and 1174 TWh/year[12], respectively. This technical capacity is calculated using the capacity factor of the existing HPPs in

5 R. Bardazzi et al., «Enhancing European Energy and Climate Security: Eastern Strategic Partners, Unconventional Sources and Public Policies.» i European Energy and Climate Security, Springer International Publishing, 2016.

6 Jamasb et al., «Electricity Market Reform in the European Union: Review of Progress toward Liberalization & Integration. Report CEEPR» University of Cambridge, UK, 2005.

7 I. Hanssen-Bauer et al., «Kunnskapsgrunnlag for klimatilpasning oppdatert 2015» Norsk klimaservicesenter, 2015.

8 J. Sørensen et al., «Vannkraftkonsesjoner som kan revideres innen 2022.» 2013.

9 H. Jager et al., «Sustainable reservoir operation: Can we generate hydropower and preserve ecosystem values» River Research and Applications, vol. 24, pp. 340-352, 2008.

10 T. Forseth et al., «Handbook for environmental design in regulated salmon rivers» NINA Special Report 53, 2014.

11 F. H. Koch, «Hydropower—the politics of water and energy: introduction and overview» Energy Policy, vol. 30, nr. 14, pp. 1207-1213, 2002.

12 International Energy Agency. (2012). *Technology Roadmap: Hydropower*. Paris: IEA.

Europe, which is currently approx. 0.35[13]. It is highly uncertain whether future new or refurbished HPPs will have such a high capacity factor, and capacity to balance volatile RES seems to represent a more profitable business case than the generation of baseload-like electricity. This means that the technical potential for capacity can be even higher than 338 GW if the capacity factor is intentionally reduced. This reduction will come by lowering the time of operation, and since the energy generated from HP is limited by precipitation on the long term, the power rating of the installations is increased. This freedom to decide on the capacity to meet the needs of the electrical energy system represent a technical potential by itself, and refurbishment projects can significantly increase the capacity compared to the current installations.

Many HPP and installations are old, and limitations that existed at the time of construction may no longer be present. As technology is developing, operational limitations are also lifted and will make HP an even more flexible and valuable asset to the European grid. HP is considered a key enabling technology for the renewable electrical system in the coming years, providing services that extend far beyond or complement other technologies needed for the green energy transition. In refurbishment projects, the annual generation is expected to slightly increase due to higher turbine efficiencies and potentially lower energy losses in the power waterways.

Factors limiting the realization of the hydropower technical potential are numerous. Adding to the abovementioned issues based on environmental and social concerns, technical limitations also exist. Phenomena due to Fluid Structure Interactions are limiting the range and its continuity imposing operational limitations, and numerical tools are not yet accurate enough to capture dynamic phenomena in an engineering phase. Sediment erosion is reducing the lifetime of units, and even without sediment erosion the assessment of remaining lifetime of units and hydraulic system is not accurately described.

The flexibility of hydropower is largely due to the energy storage provided by upper reservoirs retaining water. Many of the existing reservoirs have a potential for increased energy storage by increasing the height of the dam. The futuristic technology of flexible operation will allow hydro turbines to operate at off-design loads, without causing heavy fatigue damage and allowing for an optimisation of available energy storage.

- **Hydropower capacities can be chosen where water storage is available.**
- **Hydropower can be used to balance and enable more new volatile renewables.**
- **Upgrading of the existing hydropower fleet reveals optimization potential.**

4 Economic Potential

Today, 53% of the European technical potential has been developed[14]. Calculating using an electricity price of 0,2€/kWh, each percentage of new developed potential represent more than €2.3 billion[15]. Some development further increasing this number is realistic, but there is a limitation to how much can be developed, based on several factors such as environmental effects and water management issues. Even if such issues are not limiting, there must be an economic intervention to trigger the development. This economic potential is difficult to assess, as it includes a multitude of elements, most importantly regarding future revenues and the need for investments. Hydropower plants are designed to last for several decades and the revenues are distributed over many years, making them sensitive to future uncertainties regarding market situations, etc. Hydropower investments are large, and developments are

[13] IPCC 2011 Renewable Energy Sources and Climate Change Mitigation

[14] IPCC 2011 Renewable Energy Sources and Climate Change Mitigation

[15] 1% of potential is 11,74 TWh (11.74 10^9 kWh), times 0.2 €/kWh, is 2.348 10^9 €

capital intensive. The economic potential envisioned today might not present itself in the future. On the other hand, potentials which are invisible today might appear suddenly, caused by both new human-created and environmental conditions.

It is estimated that the economic potential of HP will not be fully realized in the current market conditions. It is suggested to implement market design changes so that the true needs of the system are economically mirrored and give an incentive for investment. HP can respond to those needs much easier and cheaper than many other technologies if the appropriate incentives are set and targeted research is getting the appropriate attention. This will lead to a greater realization of the potential of other new RES in Europe, like on- and offshore wind and photovoltaics.

Both large technical and economic potentials for HP are seen in other parts of the world, particularly in Africa and Asia. Europe's proximity to Africa and Asia, the strong European hydropower technology and outstanding engineering consultants are good prerequisites to take a leading role in the HP development also outside of Europe.

- **With measures to maintain the competitiveness of hydropower in changing market conditions, it is expected that hydropower continues to contribute substantially to generating incomes in both the private and the public sector**
- **In 2050 45,000 – 60,800 (estimate, 10% of the wind CETP projections) jobs related to hydropower are expected**
- **In 2050 global contracts awarded to European Hydropower Technology industries are expected to be around 100B€ annually**

5 Challenges

5.1 Overview

To solve the challenges from enhanced energy system requirements, it is proposed to focus the future research in the HP sector on strengthening the capabilities of the HP fleet, i.e. power, energy storage, availability and ramping rates. Most countries in Europe are now in a situation in which new strategies for energy security and reliability must be developed like discussed in Manso et al.[16] and Bucher[17]. To give the future HP fleet the flexibility required to serve the market demands, transmission and distribution systems, new materials and advances in turbine and generator design, tunnel systems and penstocks must be utilized. This includes research in tunnel systems enabling quick response, increased dampening of surges, cost efficient large-scale water tunnels, intake and reservoir design adapted to new tunnel systems, powerhouses constructed for flexible solutions, and reconstruction of dams and reservoirs[18].

Flexibility is a requirement inherent in all power systems, and in recent years there has been an increasing focus on how to manage flexibility. Large organizations such as IEA, NREL and EURELECTRIC have launched initiatives to quantify future requirements for flexibility in order to permit increased inclusion of variable RES, while maintaining a secure power system[19,20] A general

[16] Manso et al., «Adaption of Swiss hydropower infrastructure to meet future electricity needs» Bordeaux, 2015.

[17] Bucher, «The role of pumped-storage in a pan-European supergrid» Bordeaux, 2015.

[18] Vereide et al., «Surge Tank Research in Austria and Norway» Wasserwirtschaft, vol. 105 (1), 2015.

[19] International Energy Agency. (2014). *The Power of Transformation: Wind, Sun and the Economics of Flexible Power Systems*. Paris: IEA.

[20] EURELECTRIC. (2011). *Flexible Generation: Backing up Renewables*. EURELECTRIC.

conclusion of their studies is that HP, due to its quick response and good ramping capabilities, represents an important asset for the system operator. Improving the ability of HPPs to provide system services will increase their value and permit increased integration of variable renewable energy into the power system. Despite already being one of the most flexible and versatile renewable power sources, several organizations have pointed out that further increasing the flexibility of hydro turbines will increase the value of HP in a future energy system[21,22,23]. HP in combination with modern electronic power converter technology may not only provide better balancing in the grid, but also a set of other ancillary services, such as frequency control, reactive power compensation, oscillation damping and increased transient stability of other units in the power system.

The European HP industry is a worldwide leader due to its excellence. To maintain this competitive advantage, the industry needs to develop continuously and offer the best technologies. The development of HP technologies that will provide operators with more flexible operation will contribute to keep the European HP industry as the world leader in the global market.

Targeted R&I support will keep the hydropower industry as the world leader in the global market.

5.2 Increased Flexibility from Hydropower Plants

A paradigm shift in design and operation of the HPP is possible by introducing electronic power converters. Reversible pump-turbines will operate smoothly, ramping rates will be faster, efficiency will be higher, and the operating range of hydro turbines will be wider when introducing variable speed turbines and generators[24]. By introducing converter-fed synchronous machines, the dynamic capability will be strengthened due to “synthetic inertia” and decoupling the generator from the grid frequency during starts and stops [25]. Variable speed operation allows a new degree of freedom[26].

Areas of research

- **Variable speed operation of hydropower- and pump storage-plants**
- **The economic value and cost of flexible operation of hydropower plants**
- **Evaluation of lifetime reduction on technical installations in the hydropower plants due to flexible operation**
- **High ramping rates and virtual inertia**
- **New power station electrical layouts, generator rotor and magnetization systems and power electronic converter control for increased flexibility and strong grid support.**

[21] The Norwegian Research Centre for Hydropower Technology (2019). *www.hydrocen.no*

[22] International Energy Agency. (2012). *Technology Roadmap: Hydropower*. Paris: IEA.

[23] Hydro Equipment Association. (2013). *Hydro Equipment Technology Roadmap*. Brussels: Hydro Equipment Association.

[24] G. D. Ciocan et al., «Variable speed pump-turbine technology» UPB Sci. Bull. Series D, vol. 74, pp. 1454-2358, 2012.

[25] P. Steimer et al., «Converter-fed synchronous machine for pumped hydro storage plants» Pittsburgh, USA, 2014.

[26] “Trending research”, interview with R&D director for hydraulic development and risk management at Alstom, International Water Power and Dam Construction, 2015

- **Mitigation of negative environmental effects from flexible operation of hydropower plants**
- **Social acceptance of flexible operation of hydropower plants**
- **The merging of old power plants with restrictions and new technology being integrated in these old power houses**
- **“Hybrid” power plants, combining hydropower, other storage e.g. Battery storage for fast response, other generation e.g. floating solar panels**

5.3 Utilization and Expansion of European Hydropower’s Storage Capacity

Today’s storage capacity in the European HP reservoirs exceeds 185 TWh. Thus, storage HP is the largest battery available, and serves as an energy storage system for other RES. Further expansion introduces technological and regulatory challenges and will affect power ramping rates and downstream flow conditions. Flexible operation will benefit from more precise inflow modelling that will reduce operational risk and increase the revenue potential.

To increase the seasonal storage capacity of HP, new medium- and high-head HPP may be implemented mainly in regions of retreating glaciers, where new reservoir areas in unpopulated areas and additional elevation differences become available [27]. In the Alps, several such projects are under planning.

At existing medium- and high-head run-of-river HPP downstream of retreating glaciers it is recommended to check the feasibility of new reservoirs serving as a headwater storage, ideally for several HPP along a river (hydropower cascade). At existing low-head run-of-river HPP, operational optimizations may be implemented to slightly increase the exploitable head (elevation difference) by moderate variations of the headwater level (dynamic water level control).

A further option is to extend existing reservoirs by moderate heightening of their dams [28]. This has been successfully done already in multiple cases. Because of the typical shapes of the valleys, a slight increase in dam height results in an over-proportional gain in storage volume.

Additional HP capacity may be realized by implementing new pumped-storage facilities. Such developments are particularly attractive in places where two reservoirs with a suitable elevation difference of several hundred meters exist close to each other. Further options for new pumped-storage are underground caverns in the low-lands, potentially in the vicinity of larger cities, where heat storage might be combined[29].

Besides physically creating more reservoir capacity, the existing active storage volumes may be exploited more efficiently through improved real-time modelling and forecasts of inflows, operation, and demand.

It is recommended to pursue all options to increase HP storage, also for multiple reasons like irrigation and downstream flood protection or mitigation of natural hazards in general (glacier lake outbursts, droughts).

[27] Ehrbar et al., "Hydropower Potential in the Periglacial Environment of Switzerland under Climate Change", *Sustainability* 10, 2794; 2018.

[28] Felix et al., "Ausbaupotential der bestehenden Speicherseen in der Schweiz (‘Potential of extending existing storage lakes in Switzerland’). *Wasser, Energie, Luft* 112(1): 1-10 (in German); 2020.

[29] Pikl et al., "Underground Pumped Hydro Storage - A versatile forever asset for a sustainable energy future". Hydro Porto, 2019.

Areas of research

- **Flexible utilization of existing reservoirs**
- **Increasing the production flexibility by adding new reservoirs or operational optimizations to existing run-of-river power plants**
- **Increasing the production flexibility through extensions of existing reservoirs by dam heightening**
- **Develop new multi-purpose storage hydropower schemes particularly in regions of retreating glaciers**
- **Develop pump-storage power plants for example between existing reservoirs**

5.4 Markets and Services for Hydropower's Capabilities

The European HP system is in a state where the need for rehabilitation is increasing and large re-investments are required the next 20 years. At the same time the energy markets are developing rapidly, where changes in policy and alternative technologies create uncertainty in future profitability. Challenges are associated with uncertainties in the development of market mechanisms, prices in multiple markets and stochastic inflow depending on climate development. To support HPP operators and developers in taking appropriate decisions on future investments; new methods for investment analysis need to be developed that include both new market perspectives and technologies.

Areas of research

- **Modelling of expected revenues for future power systems.**
- **Develop methods and tools for the estimation of the remaining lifetime of hydropower plant components. (replicate in digitalisation)**
- **Develop tools to support assessment of the long-term hydropower resources and its associated risk in river basins with multiple water users under present and future climate situations**

5.5 Environmental Design

Water resources are important for several socio-economic benefits in addition to production of climate-neutral energy[30]. This comprises flood protection and control, security of supply and balancing services etc. In addition, essential ecosystem services such as irrigation, drinking water, biodiversity and recreation[31] are stakeholders in water management- and usage. Implementation of the European Water Framework Directive (WFD), new national legislations[32] and new regulatory requirements exert pressure on the hydropower industry by establishing targets for environmental conditions in regulated rivers, potentially at the cost of energy production along with other beneficial effects from water regulation. While hydropower is generally accepted as a resource efficient source for renewable energy,

[30] European Parliament, «Renewable energy directive» European Parliament, Council of the European Union, 2009

[31] MA, Millennium Ecosystem Assessment. Ecosystems and human well-being synthesis., Washington, DC: Island Press, 2005.

[32] Nature Diversity Act, «Relating to the Management of Biological, Geological and Landscape Diversity» Ministry of Climate and Environment, 2009.

there has also been substantial societal opposition to hydropower developments[33]. These drivers and pressures call for knowledge-based solutions that optimize the trade-offs between hydropower production and other socioeconomic benefits vs local environmental conditions[34] and accommodating societal concerns[35,36].

Hydropower operations/regulation can cause environmental challenges, such as decreased habitat quality and quantity, in rivers as well as reservoirs. By altering water flow, water flow patterns and temperature aquatic ecosystems are likely to be heavily influenced and disrupted (biodiversity). Freshwaters provide important aesthetic, cultural, economic and provisioning ecosystem services and these systems are experiencing declines in biodiversity far greater than most other ecosystems worldwide. The most common impacts of hydropower on the environment are disruption of hydrological connectivity, changes in the natural discharge dynamics, changes in suspended solid and nutrients dynamics, flooding of areas for water storage and disruption of the biosphere especially during the construction phase of the plant. The methods for assessing these impacts should be improved and adapted to the new regime of future hydropower operation and climate, in particular by introducing digitalisation processes to optimise production and minimise environmental impact.

An assessment of the advantages of storage infrastructure to use water resources in an efficient way and stabilizing the electricity grid through smart usage of large reservoirs and pump storage operations will lead to solutions on how hydropower can efficiently produce electricity with minimal negative impact on the environment including effects from climate change and alterations in the energy market. Ideally, the operational regime of regulated watershed gives the possibility to simultaneously produce hydropower, secure landscapes and biodiversity and protect the society from flood and draught.

Fish management and conservation in regulated rivers is often hampered by HPPs. The main risks associated with the presence of such structures include blocking or delaying of up- and downstream fish migration, and damage or mortality of fish when passing turbines, weirs or spillways. Although upstream fish passage technologies are well developed, downstream fish passage still poses challenges to scientists, engineers, authorities and HPP operators due to the lack of design standards and related basic information on behaviour of various fish species. There are many fish protection technologies available for fish downstream migration. However, most of them have been developed for salmonids and applied in North America. Therefore, more research on region-specific fish passage designs and development of new technologies based on the local species requirements is still needed.

In order to avoid and mitigate possible negative consequences of new hydropower plants, the International Hydropower Association (IHA) developed the Hydropower Sustainability Assessment Protocol (HSAP, https://www.hydrosustainability.org/). In most hydropower plants across EU member states, the HSAP is nowadays applied to minimize negative impacts and assure sustainable and clean energy production applied across EU member states. The HSAP provides a holistic framework to tackle this challenging task. The HSAP is composed of 26 topics addressing the sustainability of hydropower that has been established in a joint collaboration between leading power developers, financial institutions, and non-governmental organisations. Nevertheless, recent research has demonstrated that specific impacts of hydropower can be highly complex and interdisciplinary, requiring innovative and cross-sectoral solutions. This is especially challenging in large watersheds where data availability is scarce and environmental monitoring is difficult.

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[33] Huber et al., «Hydropower, Anti-Politics, and the Opening of New Political Spaces in the Eastern Himalayas» World Development, 2015.

[34] T. Forseth et al., «Handbook for environmental design in regulated salmon rivers» NINA Special Report 53, 2014

[35] H. Koch, «Hydropower—the politics of water and energy: introduction and overview» Energy Policy, vol. 30, 2002.

[36] B. Köhler et al., «Decision making for sustainable natural resource management under political constraints – the case of revising hydropower licenses in Norwegian watercourses» Civil Engineering and Environmental Systems, vol. 36, 2019

Areas of research

- **New concepts to mitigate negative environmental impacts from hydropower installations and operation**
- **Development of fish passage technologies in regulated rivers with hydropower plants**
- **Environmental design for multiple interests under future flexible hydropower operation.**
- **Water resources availability under changing conditions.**
- **Guidelines to include environmental constraints in hydropower operation and scheduling models.**
- **Climate adaption of production planning and regulation.**
- **Optimization of existing hydropower infrastructure to changing climatic conditions due to climate change.**
- **To develop two-way fish passages for multiple species.**
- **Development of tools for estimating and compensating lost ecosystem services and biodiversity in rivers and reservoirs.**
- **Investigation of the interplay between climate change and environmental impact in regulated rivers.**
- **Optimization of storage of water resources (pumps storage technology, large reservoirs, discharge fluctuation mitigation installations, etc) in the frame of a changing energy market.**

5.6 Sediment Handling

Sediment handling specifically addresses these issues aiming to accumulate new knowledge required to guarantee sustainable and efficient global hydropower development. In regions with large hydropower potential such as the Alp region in Europe, Himalaya in Asia, and Andes in South America, different sediment transport processes, e.g. sedimentation, are core challenges that need to be addressed and amended to ensure sustainable hydropower development. Sedimentation processes have proven to be technically, economically and socio-ecologically challenging (e.g. reduction of reservoir lifetime or impacts on downstream ecosystems). Additionally, climate change is projected to cause increased sediment catchment yield, affecting the operation and maintenance of the hydropower plants and hence energy production. In order to address these challenges, it is essential to develop cost-effective methods for sediment handling. Implementation of such findings will reduce downstream social and ecological impacts in a sustainable way.

Moreover, sediment (bedload) transport across dams should be re-established if possible, to prevent negative effects of sediment accumulation and to maintain active storage volumes on the long-term. This requires a holistic sediment management approach at HPP. Solutions to mitigate negative environmental effects of HPP exist, but further research is required to optimize them and make HP more ecologically compatible.

Areas of research

- **Design of hydraulic structures, flushing techniques, and sediment bypass systems**
- **Quantification of sediment erosion - Develop models on how to estimate sediment erosion with respect to velocity, size, shape, and mineral**
- **Sediment monitoring systems**
- **Development of green metals for manufacturing of turbine components to reduce heavy metal content in water due to erosion.**
- **Identification of environmental impact downstream the rivers due to flushing of sediments from hydropower dams and/or sediment catchments**
- **Assessment of challenges related to sediment handling and erosion for flexible operation of hydropower.**
- **Novel technique to reduce sediment deposition in the reservoir and the intake system.**

5.7 Social Acceptance

The new role of hydropower as flexibility provider in a renewable energy system requires new forms of governance and policies that include environmental and socio-economic perspectives and valuation of costs and benefits on different temporal and spatial scales. Increased flexibility will change the physical conditions in rivers. Even if mitigation technology will succeed in dampening some of the hydrological and ecological effects, increased flexible operation of hydropower plants may still modify rivers in ways that conflict with local community interests.[37,38] Hence, the implementation of the suggested flexible hydropower operation even with mature technological solutions will depend on public support facilitated i.e. by respective mitigation measures, as well as citizen and stakeholder participation in decision-making processes. Environmental, economic, and social concerns on different societal scales must be considered. Hence, it is important to address the social acceptance in new or modified hydropower schemes in order to give guidelines for future and flexible hydropower production.

Areas of research

- **Investigate social acceptance of flexible operation of hydropower schemes.**
- **Assess factors promoting social acceptance and improved public engagement**
- **Investigate the uptake of hydropower in consumers` energy portfolios (e.g. the role of eco-labels)**
- **Investigate public knowledge, attitudes, perceptions and responses to hydropower**

[37] P. Garrone & A. Groppi, Siting locally-unwanted facilities: What can be learnt from the location of Italian power plants. *Energy policy*, vol. 45, 2012.

[38] A.M. Mayeda & A.D. Boyd, «Factors influencing public perceptions of hydropower projects: A systematic literature review» *Renewable and Sustainable Energy Reviews*, vol.121, 2020.

- **Develop strategies to reduce negative and promote positive socio-economic impacts of hydropower**
- **Investigate strategies for effective public and stakeholder participation**
- **Investigate policymaking practices and how policymakers, developers and experts engage with and construct publics**

5.8 Basic Hydropower Sciences

Hydro turbines are large rotating machines operating under extremely high loads for many years. Little is known about the fatigue of the used materials. To allow HPP operators and owners to better estimate the remaining lifetime of important components such as the turbines, further knowledge about the materials and the effects of fatigue should be acquired. With the fast developments in computer sciences, more advanced numerical simulations become possible. We know that the hydro turbines undergo moderate to high amplitude pressure loading during the flexible operation. Although hydro turbines are expected to operate seamlessly during flexible operations, the resulting pressure amplitudes are so significant that they take a toll on a machine's operating life. The amplitudes cause fatigue to the blades and initiates material damage, which gradually propagates in the blade and results in catastrophic failure. Understanding of the mechanism of crack propagation in blade materials and the fracture mechanics are extremely important to find out root cause of failures.

In mountainous regions, sediment particles in the turbine water leads to erosion on the turbines. As a result, some HPP have high maintenance costs and suffer from reduced efficiency. To better cope with turbine erosion, improved prediction models and countermeasures such as high-strength coatings of turbine parts and switch-off turbines during high sediment loads shall be developed. This also applies for the management of sediment in general and the handling of driftwood and floating debris at dams and reservoirs.

During flexible operations turbines are expected to change load frequently. That means impact from the rotor stator interaction is substantially different from that of the traditional consequences. Understanding of fluid mechanics at basic level is crucial to relate how vortex shedding from the guide vanes influence the pressure amplitudes on the blades. Another important factor is stochastic loading on the blades from the variable-speed operation of the turbine. Flow field around the blades behave completely different during load change and speed variation. This behaviour is related to the boundary layer separation and detachment from the blade leading edge. Credible understanding of this mechanism will allow us to improve the existing design concepts and provide smooth operation of turbine, especially during load change. During flexible operation, hydro turbines often undergo unexpected resonance condition, due to high density of water, effect of added mass is substantial and cannot be ignored. Very limited knowledge is available how turbine/blades behave during such situations. Stronger resonance lead to blade crack and premature failure. Basic research is needed to investigate the mechanics of water and blade interaction to reduce the risk of turbine failure.

Areas of research

- **Improved understanding of material that has endured high fatigue loads over many years.**
- **Development of numerical tools for analysis of turbine parts**
- **Development of materials/coating to reduce sediment erosion**
- **Understanding the mechanism of blade crack propagation during flexible operation.**
- **Understanding of coupling mechanism associated with cavitation, speed of sound, level of pressure amplitudes, crack propagation rate.**
- **Understanding the rate of sediment particle settlement (and suspension) with respect to flow velocity and pressure in the dam.**
- **Develop innovative technique to settle sediment particle before the turbine intake – understand physics of interaction between flowing water and sediments**

6 Relation to Cross-Cutting Issues

6.1 Environment

Despite the many favourable aspects of HP mentioned in section **Error! Reference source not found.**, HP development has impacts on aquatic environments, which need to be mitigated to fulfil the necessary legal requirements. Such impacts can range from local scale to catchment scale, are site-specific, and strongly depend on (i) the climate and watershed setting, (ii) the organisms (fauna and flora) present, and (iii) the HPP characteristics and operation[39]. Environmental impacts of HPPs can be divided into three major groups, namely interruption of longitudinal connectivity, discharge reduction between water abstraction and restitution, and artificial rapid fluctuations in discharge ('hydropeaking) and temperature ('thermopeaking') [40].

On the local scale hydropower may additionally lead to disruption of hydrologic connectivity, changes to the natural discharge dynamics and changes of the suspended solids and nutrients dynamics. Globally, the most significant impact occurs during the construction phase, disrupting the biosphere, generating emissions, and altering the local hydrology. These impacts are particularly harmful for the migration and habitat of different kinds of fish. It is therefore of highest importance to clarify how fauna and flora in general and fish, in particular, is influenced by hydropower and to develop tools and methods that can be used to reduce the effect of hydropower. These issues become in particular, challenging with an increase in the regulation of hydropower and with a changing climate.

6.2 Circularity

Hydropower plants are generally operated for many decades, even centuries. With adequate measures regarding sediment management in reservoirs, their storage volume can be maintained on the long term, i.e. HP deserves to be called a sustainable energy source. Because HP schemes are operated during many decades, the specific grey energy used for the construction of their civil structures is relatively low.

[39] Poff, N.L.; Hart, D. (2002). How dams vary and why it matters for the emerging science of dam removal. *BioScience* 52(8), 659-668.

[40] Weber, C. and M. Schmid (2014). Wasserkraftnutzung im Wasserschloss Schweiz: Herausforderungen aus ökologischer Sicht ('Hydropower use in Switzerland: challenges from an ecological perspective'). *WSL-Berichte* 21: 15-23 [in German].

Many components of HPP, e.g. the turbine parts, are recyclable and are treated as such. As progress has been made on turbine bearings, contamination of water by machine oil is no concern anymore.

HP is unbeatable as to the so-called recovery factor or Energy Return on Energy Investment (EROI) of primary energy, which is obtained by the ratio of the total energy produced to the total expense of non-renewable energy (direct and indirect) during a lifetime to operate an installation[41]. For storage HPP with reservoirs created by dams, the EROI amounts to 78, while for run-off-river power plants it is 58. These numbers clearly exceed those attained by nuclear power (12) and other RES (e.g. photovoltaics 4 to 8, wind 18 to 20 under Swiss conditions). Regarding the recovery factor for electricity storage technologies, the so-called Energy Stored on Energy Invested (ESOI) parameter is currently 186 for pumped storage, while technologies such as power-to-hydrogen-to-power, lithium-ion batteries and lead acid batteries have values of 23, 7 and 1, respectively [42].

Recent life-cycle analyses (LCA) confirm that HP can reduce Green-House Gas emissions (GHG) significantly, even by developing only a part of the remaining economically feasible HP potential. Recent studies revealed that for HP the equivalent CO_2 emission is extremely small compared to other electricity generation technologies; there are only small emissions due to the material production required for construction and maintenance [43,44](Frischknecht *et al*. 2012; Bauer, Hirschberg *et al*. 2017).

6.3 Digitalisation

Digitalization in the hydropower sector is still very young, and therefore the experience and knowledge are limited. Operators are now actively developing strategies to digitalize their new horizons of productivity and allow the industry to fully realise its enormous potential. Digitalisation will create new economic opportunities for hydropower operators, by reducing the costs and increase the income for the entire lifespan of hydropower assets. Innovative digital technologies will also improve turbine yields and productivity while driving down costs in design, operations and maintenance, thereby reducing the cost of energy. Digitalisation is primed to make a valuable contribution to wind energy at a crucial time for renewables. As the ongoing energy transition triggers an increase in distributed power generation, new data-related challenges are emerging. Digitalization builds a cross-cutting function between other renewables such as wind, tidal and solar technologies. From this perspective, one of the biggest challenges is how to integrate the expertise of professionals from different disciplines.

To exploit digitalization's potential influence, the hydropower producers must build processes that can utilize information from parallel business areas. An example is maintenance of power plants, where we can expect that digitalization will change traditional maintenance processes from regular manual inspections, to monitoring and surveillance of components resulting in a shift from time-based and scheduled maintenance to condition-based and predictive maintenance. By integrating this optimized maintenance with optimization for production planning there is an even larger potential for value creation.

Generation changes in the work force, long system lifetimes and the low personal count in hydropower plants, gives an opening for digital tools to ensure the transition of the knowledge base to new maintenance personnel. Advanced condition monitoring tools together with machine learning promises

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[41] Schleiss, A.J. (2000). The importance of hydraulic schemes for sustainable development in the 21st century. Hydropower & Dams 7(1): 19-24.

[42] Steffen, B., Hischier, D., Schmidt, T.S. (2018). Current and future energy performance of power generation technologies in Switzerland. ETH Zürich, Switzerland.

[43] Frischknecht, R., Itten, R., Flury, K. (2012). Treibhausgas-Emissionen der Schweizer Strommixe ('Greenhouse gas emissions of the Swiss electricity mixes'). Studie im Auftrag des Bundesamtes für Umwelt (BAFU). ESU-Services Ltd.: Uster, Switzerland [in German].

[44] Bauer, C., Hirschberg, S. (eds.), Bäuerle, Y., Biollaz, S., Calbry-Musyka, A., Cox, B., Heck, T., Lehnert, M., Meier, A., Prasser, H.-M., Schenler, W., Treyer, K., Vogel, F., Wieckert, H.C., Zhang, X., Zimmermann, M., Burg, V., Bowman, G., Erni, M., Saar, M., Tran, M.Q. (2017). *Potentials, costs and environmental assessment of electricity generation technologies*. PSI, WSL, ETHZ, EPFL. Paul Scherrer Institut PSI: Villigen, Switzerland..

to detect component weaknesses. The training of these machine-learning codes with limited data represents a challenge in the development, long time before failure, and each unit being individuals and different from all other units.

In today's market, the flexible power offered by hydropower is restricted by conservative limitations set to the operating range of the generating units. This is in place to safeguard long service life of these units. By allowing more versatile exploitation of the generating units, more flexible power can be offered. The versatility comes at a cost that needs to be known if this strategy is to be employed. A key question here is if digital twins of generator and turbines can lead to a breakthrough in calculations of the reduced remaining life of new operating patterns?

Concerns over cyber-attacks against hydropower plants have increased in recent years. IT systems in hydropower plants are less regulated than, for example, their counterparts in nuclear power plants. An intruder could do significant damage by manipulating the plant's dam gates. There has been a study of a hypothetical scenario where an attacker opens all gates of a hydroelectric dam and causes rapid and massive flooding downriver as well as damage to the turbines and power station.

Digitalization also shows opportunities in field of social aspects. Digital workforce management and especially Know-How management in terms of maintenance and operation are a crucial topic today. Knowledge based databases and virtual realities could act as a pathfinder in this direction. To realize the potential for value creation form digitalisation, industry must have willingness to accept and trust new technology.

Areas of research

- **Digital twins for all parts of the hydropower plant**
- **Machine-level technological aspects**
  - **Surveillance technology**
  - **Evaluation of the surveillance data**
  - **Installation and management of monitoring systems.**
  - **Quality assurance and harmonization of data.**
  - **Digital twin of turbine and generator.**
  - **Develop methods and tools for the estimation of the remaining lifetime of hydropower plant components.**
- **System-level technological aspects**
  - **Virtual power plants supporting ancillary services.**
  - **Security and prevention of cyber-attacks.**
  - **Benchmarking of methods for big data.**
  - **Interface towards other digitalization initiatives.**
  - **Predictive maintenance on component and system level**
- **Economic aspects**
  - **Cost-effective operation and maintenance.**
  - **New business models from digital platforms.**

- **Environmental aspects**
    - **Improving water inflow models from new available data.**
    - **Model verification based on satellite monitoring**
    - **Image processing for identifying fish behavior**
    - **Improved models and tools to predict the interplay between the flow in the rived and biodiversity**
    - **Mitigation measures in reservoirs and rivers with flexible operational regimes**
    - **Development of new innovative concepts for fish passage for multiple species (two-ways, combine with sediments, etc.)**
    - **Investigations of the interplay between climate change and environmental impact in regulated rivers**
- **Social aspects**
    - **Acceptance of existing and new technology.**
    - **Mitigation of increased complexity from cross-discipline collaboration.**
    - **Knowledge Management in terms of maintenance and operation**

Input Paper to the CETP SRIA Renewable Technologies

Challenge 10

Solar Thermal Heating & Cooling

Editors, Co-authors and Commenters of this Input Paper to the CETP SRIA:

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1 Introduction

Nowadays, the final energy consumption in Europe is composed as follows: electricity is 20%, transport is 30% and heating and cooling is almost 50%, hence **heat is half** of the total energy consumed. Furthermore, the heating and cooling sector is responsible for 40% of the energy related CO_2 emissions[1] and solar thermal is among the renewable technologies which can substantially improve decarbonisation in this sector. With 389 GW_{th} installed worldwide, in 2019, solar thermal systems produced 479 TW_{th} which shows the potential of this technology.

In Europe, more than 10 million systems are currently installed, demonstrating how this technology is mature and is among the best options to reduce energy costs and boost decarbonisation.[2] During the last decade, solar district heating applications rapidly grew, and today more than 200 cities in Europe use solar thermal. The market for solar heat for industrial processes (SHIP) has also doubled in sized in the last few years, with record size installations coming up on a yearly basis.

Solar thermal has always been among the most acknowledged renewable energy sources by European citizens. This is because of several reasons:

1) Solar thermal is a no regret option, not producing emissions and easy to combine with several power and heat solutions (both renewables and fossil-based).
2) Its components are either reusable or recyclable, making these systems almost completely sustainable[3]
3) It combines a low levelised cost of heat (LCoH) with short energy and carbon pay-back periods, stressing its relevance as a sustainable solution.

Solar thermal has experienced for decades a continuous increase in total installed capacity in Europe, reaching as of 2019, more than 36 GW_{th} of solar thermal collectors installed in Europe (corresponding to more than 50 million m^2), and representing an estimate energy generation of 26 TWh_{th}[4]. Such high value shows how concretely solar thermal is already contributing to EU's energy supply. And even though year-on-year sales have reduced in recent years, along with other heating and renewable heat solutions, the solar thermal market faced a rebound in the last two years, with market growth both in 2018 and 2019.

Furthermore, solar thermal has a good track record in terms of quality assurance. European solar thermal companies joined hands with research institutes to create the first quality mark for a renewable (or heating product) based on EN testing standards, the Solar Keymark. Thanks to this, solar thermal is a highly trustable technology, with many skilled local installers thanks to widespread training programs across the EU.

Today, strategies to achieve carbon neutrality emphasise the need for electrification, but such a path will require costly upgrades to distribution networks. While for mobility, this may be unavoidable, a fully carbon-neutral H&C sector is possible without increasing the electrical peak load by using currently available thermal renewable technologies.

A clear advantage of solar thermal in this context is that solar heat does not rely on the use of external network by providing thermal energy storage, both diurnal and seasonal. This technology can therefore

[1] https://www.iea.org/reports/renewables-2019/heat
[2] https://www.iea-shc.org/solar-heat-worldwide
[3] Recent studies, like the one by JRC on "Critical Raw Materials for Strategic Technologies and Sectors in the EU", highlight that 100% of components used for solar heat are recyclable.
[4] Solar Heat Markets in Europe Trends and Market Statistics 2018, Solar Heat Europe, 2020

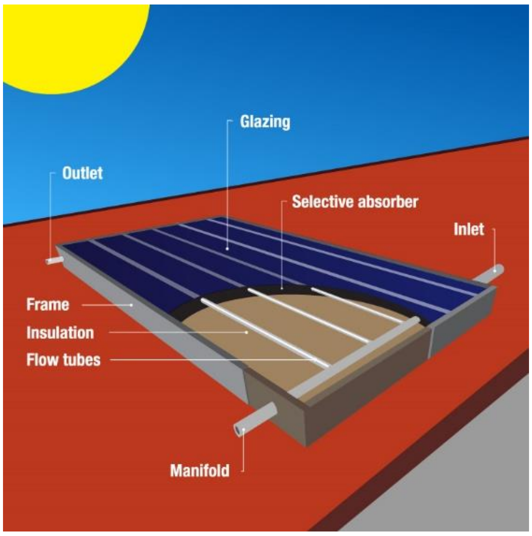
support the decarbonisation of the power supply. For these and other reasons, solar thermal should be further deployed and new solutions using solar thermal for heating and cooling developed.

Solar thermal technologies will play a key role in the future energy system and significantly reduce energy costs and emissions. These applications are generated on-site and have the highest efficiency of all renewable technologies.

Most of the solar thermal systems installed in Europe are also manufactured in Europe and can provide both households with hot water at 60°C and industrial sites (such as breweries, paper mills or textile industry) with process heat (air, water or other fluids, steam) with low and medium temperature (reaching up to 400°C) solutions.

By reducing the cost of heat and by reducing CO_2 emissions, solar thermal is making living in a green world easier. The purpose of the input papers is to identify high-level RDI challenges to further deploy the potential of this promising technology.

2 Technology Status



Solar thermal systems convert solar radiation into heat through an absorber, and then exchange this heat via a transfer medium. This transfer can be done in air, water or a mixture of water and glycol and, for higher temperature needs, with pressurised water or oil. The thermal energy produced is transferred to a storage tank, which is always a built-in feature of solar heating and cooling systems, regardless of their size and geographical location.

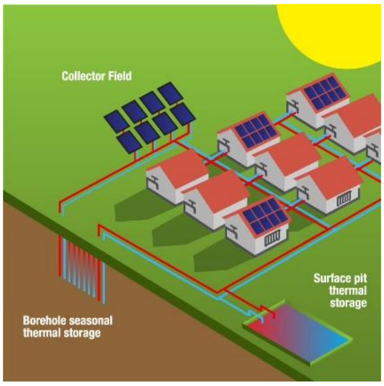
Indeed, solar thermal technologies are extremely flexible and can be used to warm up swimming pools and sanitary hot water, for space heating of both residential and non-residential buildings, or even for higher temperatures to decarbonise industrial heat processes with temperatures up to 400°C. These solutions range from small domestic systems (1.4 kW_{th} or $2m^2$) to medium-large large industrial plants (12 MW_{th} already existing), up to very large district heating installations (largest in Europe reaching 110 MW_{th}).

Furthermore, components of solar thermal collectors are of EU origin, and can almost entirely be reused or recycled. Considering that heat production through solar thermal does not produce emissions nor hazardous substances and consequently does not represent a risk for health or environment and since solar thermal can be combined with a myriad of other solutions (power or heat), solar thermal heat is clearly a *no regret* option.

Worldwide, most solar thermal systems are used for domestic hot water (DHW) production. However, the market has experienced a constant and robust increase of solar heat for industrial process (SHIP) plants and solar-assisted district heating (SDH) networks. Additionally, solar thermal at individual and large-scale level is easily compatible with other solutions, for both heat and power production.

Currently, typical applications of solar thermal technologies are:

- Domestic hot water preparation for single- and multi-family houses: these applications are usually done with thermosyphon or forced circulation systems, with t ypical solar fractions between 40-90% (meaning that solar energy covers these shares of the total heat demand). Temperature levels are between 40-60°C

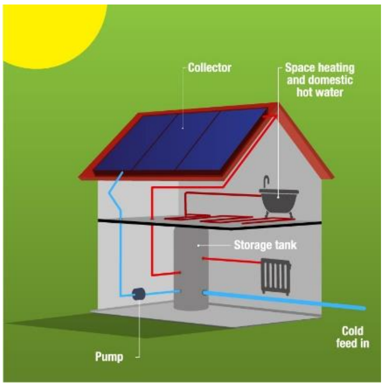


- Space heating for single and multi-family houses with typical solar fractions between 15-40%, and for non-residential buildings and temperature level around 40°C
- Combi systems: combining DHW and space heating for single or multifamily houses
- District heating, with solar fractions going up to 50%, depending on the type of storage (seasonal to cope with summer-winter fluctuations, or storage for shorter periods) temperatures are usually between 40-100°C
- Low, medium, and high temperature heat for industrial process applications (through both solar heat and concentrated solar heat). Temperature can range from 40°C up to 400°C depending on the process
- Other applications, as Solar Thermal for swimming pools, Solar Active House, and Solar cooling applications.

The fact that solar thermal solutions do not produce polluting emissions contributes clearly to the reduction of greenhouse gas emissions and the improvement of air quality. For example, thermosyphon systems (e.g. individual solar collectors at building level) in Greece can save up to 1.5 tons of CO_2 per year which in Europe is the equivalent of the annual emissions of a combustion engine car.

Large-scale solar thermal applications have experienced a strong growth over the years:

- solar heat for industrial process (SHIP) is an expanding niche market with large potential for cost reductions in manufacturing. In 2018 alone, more than 100 industries installed solar thermal systems and the market already reached an annual installation rate of 0,5 GW. The industry sectors with the highest number of realized SHIP plants are the food and beverage industry and textile and pharmaceutical manufacturers[5].
- solar district heating systems with and without large seasonal thermal energy storage represent over 1 GW_{th} of installed capacity in Denmark and new projects have been extending geographically over Europe, with new systems in Central Europe or even South-East Europe.
- large commercial and residential systems, ranging from collective systems used in multi-family homes, and applications in key segments such as hospitals, schools, and hotels.



Harvesting direct solar energy for heating of individual buildings has a very long history too, as part of the building architecture. As referred before, solar energy is today also extensively harvested in solar collectors for thermal uses, being the most common heating,

[5] www.ship-plants.info

though there are also relevant solutions for solar assisted thermally driven cooling.

Concentrating solar thermal uses solutions also used in CSP (such as Fresnel or parabolic trough) to produce higher temperatures, either for industrial uses, for cooling processes or even in district heating. Furthermore, combining PV with solar thermal in PVT (photovoltaic thermal) collectors[6] is today an increasingly attractive option. PVT collectors convert solar radiation into usable thermal and electrical energy.

By combining electricity and heat generation within the same component, these technologies can reach a higher overall efficiency than solar photovoltaic (PV) or solar thermal alone.[7] PVT technologies can differ substantially and be suitable for different temperature applications.

Compared to other technologies, solar thermal has some key specific strengths, as it:

- Is easy to integrate with other RES heating and electrical solutions, or with incumbent fossil systems, making it an enabler of sector integration and a facilitator of renovation processes.
- Can be considered as an energy efficiency measure since it always results in direct energy saving and faces similar challenges (e.g.: upfront investment, provide cost-savings rather than a direct return).
- Is a *no regret* infinite source of energy since it does not produce emissions and is easy to combine with other sources.
- Creates local jobs along the value chain (including distribution, planning, installation, and maintenance of solar systems).
- Is a scalable solution, deployed in all European member states and efficient in all types of climate and for different applications.
- Has no exposure to the volatility of energy prices (gas, electricity) and does not cause an increase of electricity demand, instead it helps to shave peak power demand.
- Allows a real self-consumption and increase both security of supply and energy independence.
- Provides a viable and reliable solution for direct renewable heat, decreasing the need for high exergy sources (electricity, gas) to be diverted to low exergy uses (space and water heating), hence reducing the burden on additional investments in infrastructure, being it for power or gas.

Solar heat provides clear benefits for local economies. In the European internal market, 90% of available solar thermal products are manufactured in Europe with European components. This solution not only produces clean energy locally, but it also creates new business and new jobs (including job-reconversion) at local and regional level. Furthermore, the European solar industry is an exporting sector, with annual net exports surpassing at times 1 billion Euros.

3 Ongoing Research

Previous and ongoing research on the solar thermal sector was focusing on three main segments: Solar Active Houses (SAH), Solar Compact Hybrid Solutions (SCOHYS), and Solar Heat for Industrial Processes (SHIP).

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[6] See IEA SHC || Task 60 || Application of PVT Collectors, 2018

[7] Zenhäusern, Daniel, Evelyn Bamberger, and Aleksis Baggenstos. 2017. «PVT Wrap-Up: Energy Systems with Photovoltaic-Thermal Solar Collectors». Rapperswil, Switzerland: published by EnergieSchweiz. http://www.spf.ch/fileadmin/daten/publ/PVT_WrapUp_Final_EN.pdf

SAH projects were focusing on building and in particular façade integration of solar thermal, and its development pathway was mainly enhanced by national projects. A high number of SAH projects included a strong emphasis on different thermal energy storage solutions.

Solar Active Houses are available in the market but are not a standardised solution. Several projects[8] are addressing topics that are relevant to improve SAH, such as storage or components (collectors, heat exchangers, façades) but an integrated approach into the overall SAH concept is still lacking and projects are not enough to promote the aimed standardization. Public funding is focused on generic nZEB concepts and private funding is scarce, with limited engagement and ambition from the main heating industry actors on this market segment.

In what concerns SCOHYS, several projects[9] showed that such solutions are available in the market, covering both single- and multi-family houses for both domestic hot water (DHW) and space heating or DHW only. In this context, systems for multifamily houses represent a relay of growth and create interesting LCoH values (€0,07/kWh for Austrian conditions). SCOHYS projects also address new thermal energy storage solutions (PCM, thermochemical, etc.), seasonal storage or optimization, and can have a positive impact on the sector.

Regarding SHIP, one key issue regards competitiveness with low fossil fuels prices, the availability and/or cost of land near relevant industries and lack of data on existing systems. The Solarbrew project reached €210/m² with a solar fraction of 19%; whilst for medium temperatures, Fresh NRG reached €412/m². Considering the technical lifetime of the systems, the target of 3-6 €cent/kWh for low temperature applications and 4-7€cent/kWh for medium ones can be reached under certain conditions. The main barrier is that the economic lifetime expected by companies which is much lower. This can improve trust on solar heat applications, more large demonstration projects and new business models promoting this switch.

New technologies, such as high vacuum flat plate collectors are also providing new options for applications in higher temperature ranges, which can bring prices closer to target in applications. IEA SHC Task 55 is dedicated to large solar thermal systems including district heating as well as SHIP systems. New large SHIP projects in Europe are expected to provide values between 2.5-3.5 €cent/kWh (with subsidies). These include commercial projects and demonstration projects (SHIP2FAIR).

Initiatives such as INSHIP can provide additional opportunities for R&I investments in this area. Solar energy's applications to the industrial sector, including refrigeration as well as water and wastewater management, are being investigated. Interest towards solar cooling applications for the civil sector is also increasing after the break during recent years and is focussing especially on sunny countries (the so-called Sunbelt Regions). Additional information are available from the project Solarpayback.

There was also an important number of projects addressing components, such as collectors (polymer, air, PVT, etc) or other components (heat exchanges, controls, etc). These are also potentially relevant for different pathways, though with a more indirect impact.

Additional ongoing research includes:

Research on new concepts and materials is contributing to increased efficiency and reduced costs. All the components in a solar collector can be improved and the production cost and environmental load of production can be reduced substantially. New advancement in e.g. nanotechnology is being applied

[8] THERMALCOND, SCOOP, SolSys, COMTES, HP-LP-SOLAR-FAÇADE, ECOSS, SARTEA, STAID, UniSto, Tes4seT had arelevant relation to SAH. Projects HeizSolar (DE) and ECOSS (FR) had a more direct contribution to the standardization goal, while projects such as HP-LP-SOLAR-FAÇADE (EU), Tes4seT (AT), SCOOP (EU) contributed to the cost reduction goal.
[9] PROSSIS2, SAM.SSA, MERITS, TESSe2b, WPSol, COMTES, UniSto, Tes4seT, SySTHEff, iNSPiRE, SYSTHEFF, MACSHEEP, HP-LP-SOLAR-FAÇADE. A few R&D initiatives focusing on cost reduction can be noted, such as TEWISol (DE), Task 54 (DE) and Zeosol (EU) and SunHorizon

to the solar materials. New concepts are being developed jointly by entrepreneurs and research institutions. Some examples are new systems using vacuum as isolations, new design for concentrators, and novel concepts for thermal storage.

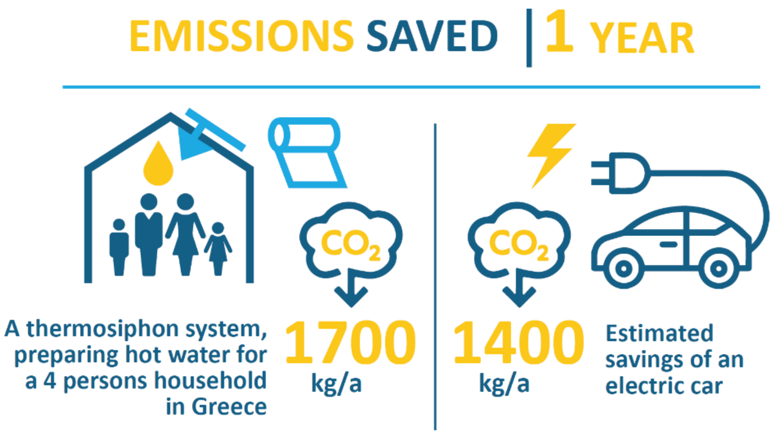
Improved business models are developed that offer "heat as a service". The customer, normally a city or a heat intense industry like a papermill or a brewery, is offered lower energy cost and CO_2 emission free heat without the need of making large investments. It will significantly contribute to reducing initial investment costs for end users. Those business models will also trigger efficient integration of solar thermal technology into the existing heat generation and distribution systems, making sure that return temperatures from the heating system to solar collectors are as low as possible. Feed-in of thermal energy in thermal networks shall be correctly valorised, among others by setting rules regarding feed-in temperatures, continuity of supply, minimum amount of purchased energy, certificate of renewable origin.

Increased number and average size of large-scale systems (solar district heating and solar industrial process heat systems) will increase experience and lead to reduced planning and implementation periods. Design rules and thumb rules will be further developed and spread, particularly focussing on integration points. Commissioning rules of large-scale systems should be improved and further tested. Best practices in the field of industrial symbiosis via DHC networks will enable a better exploitation of available area and limit the risk connected to delocalization. Advanced concepts to support a sustainable and healthy use of land around cities and industrial areas for solar thermal energy shall be introduced. There is a large potential for further cost reduction in the same order of magnitude that has been seen in the wind and PV industry.

Public and reliable solar irradiation maps and forecasting algorithms and methods need to be available to simplify the feasibility and the design process and, afterwards, operation and control of the solar installations. Research is ongoing in this field.

Sector coupling opportunities offered by solar thermal heating and cooling technologies will allow to dramatically reduce the need for new transmission grids compared to an unlikely highly-electrification scenario. This will also unlock additional economic benefits (flexibility services) for solar thermal and other renewable technologies, both at product level (hybrid systems) and system level. Research activities somewhat related to sector coupling focus on PVT systems for the HVAC sector and on material and component development for Thermal Energy Storage. Other ongoing research activities are related to the **planning level** (Solar Neighbourhood Planning), to **integration in new and retrofitting of buildings including historical buildings** (considering the huge amount of ancient buildings in whole Europe) and to **standards and certification** of solar collectors and solar systems.

4 Technical and Economic Potential

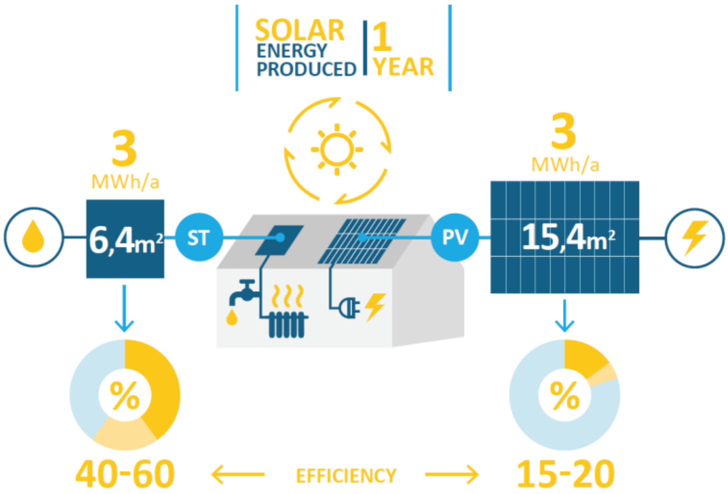


By effectively addressing the challenges listed in the following paragraph, solar thermal technologies will have a strong impact on the adoption of solar thermal technologies across different applications and a total solar energy supply equivalent to 31 000 toe[10] will be reached by 2040. An electric car can avoid approximately 1400kg CO_2/y

[10] In average this can converted into 504 651 MW_{th} and 720 930 233 m^2

compared to a single solar collector of 2.5m^2 size that can save up to 1700kg CO_2/y.[11] Such great impact will be reached if enough research and demonstration efforts will be directed to this technology, which is strongly acknowledged by the public as one of the 100% renewable heating technologies and is predominantly manufactured in Europe.

In a carbon neutral 2050 energy mix, renewable heating solutions are expected to take a prominent role. In fact, the decarbonisation of the heating and cooling sector will not be achieved without solar thermal, which in Europe is expected to cover at least 50% of the final energy demand for this sector. The European market is showing positive trends, and initial estimations for 2020 (pre-COVID) indicates strong growth rates in some of the largest markets and this is expected to continue in 2021.[12]



Solar thermal is the most efficient renewable energy sources. It converts the inexhaustible solar resource with an efficiency up to 70% (40-60% in most collectors), meaning that it is able to convert into thermal energy 70% of the solar energy received in the surface of the collector. As a reference, solar PV panels have an efficiency between 15 and 20%. The comparison with other heating solutions, such as heat pumps, presenting a COP from 1 to 5 (for ground-source heat pumps), would show an even larger difference, as a solar thermal system primary energy consumption (electricity for running the water pump) would lead to COPs of 60 and above.

Currently there are 36 GW_{th} of solar heating capacity in Europe, with an estimated generation of around 26TWh_{th}. This represents over 10 million systems installed in Europe, with most of applications ranging between 40-70°C for domestic hot water and space heating for both residential and commercial buildings.

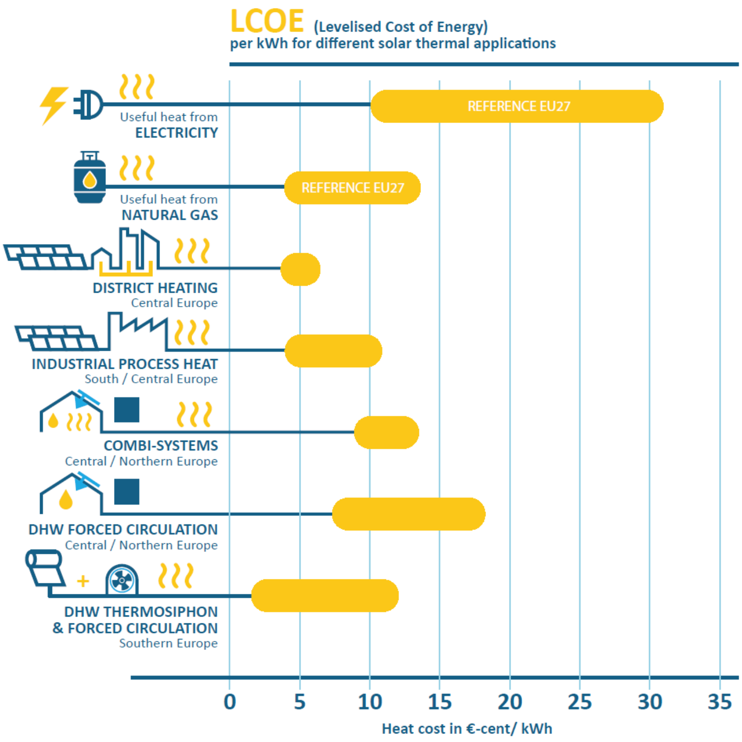
Nevertheless, solar heat can be used for a variety of applications: for example, solar-assisted district heating systems are commercially available, can reach sizes over 100 MW_{th}, and are particularly developed in Central and Northern Europe. The largest solar assisted district heating in the world is in the Danish city of Silkeborg where the solar thermal plant covers 100% of the summer heat demand of the city and 20% of the winter load, thanks to large seasonal thermal energy storage capacity.

As mentioned before, solar district heating (SDH) networks are an innovative and promising solutions which is more cost-effective than gas-based systems. However, the potential for this application is still underestimated and limited mostly to areas supplied with natural gas networks. In this context, the integration of solar heating and cooling with other renewable sources (be it for electricity or heat production) can also be an effective solution for peak shaving, especially when coupled with seasonal thermal storage.

[11] In average a solar thermal collector avoids 675 Kg CO_2/m^2 year and an electric car avoided 120 gr/Km[11]. Comparing a single solar collector of 2.5 m^2 and a car with a Kms/year of 12000 km: 1 collector avoids 1688 Kg CO_2/collector year, and an electric car avoids 1440 Kg CO_2/year. Data from IEA SHC 2020

[12] https://www.iea-shc.org/Data/Sites/1/publications/Solar-Heat-Worldwide-2020.pdf

Another growing reality is the one of solar heat for industrial process (SHIP), which shows already good results especially in areas as the food and beverage industry (breweries, dairies, etc), mining and textile processes.[13]



These solar thermal systems show great potential and are well suited for generating process heat, with good economics, but there is still a need for promoting further demonstration projects and feasibility studies.

Overall, large-scale systems need project finance and bankability tools, which implies, among other issues, standardisation, system validation and risk assessment procedures. In the last few years SHIP plants kept growing in Europe. From 2018 to 2020 they passed from 2MW$_{th}$ to reaching the record size (in Europe) of 12MW$_{th}$. These plants were made by European companies for different industrial customers, from the agri-food sector to pulp and paper one.[14]

Large-scale solar thermal systems can produce heat at a cost of around 20 to €30/MWh, compared to €28-35/MWh which is the full cost range for generating heat through gas boilers.[15]

5 Challenges

The European Solar Thermal Technology Panel (ESTTP), part of the European Renewable Heating and Cooling Technology and Innovation Platform (ETIP RHC), identified a set of priorities which will enhance the role of solar thermal heating in the EU energy framework, providing a significant contribution to the energy demand for space heating, domestic hot water heating, industrial process heating and district heating and cooling.

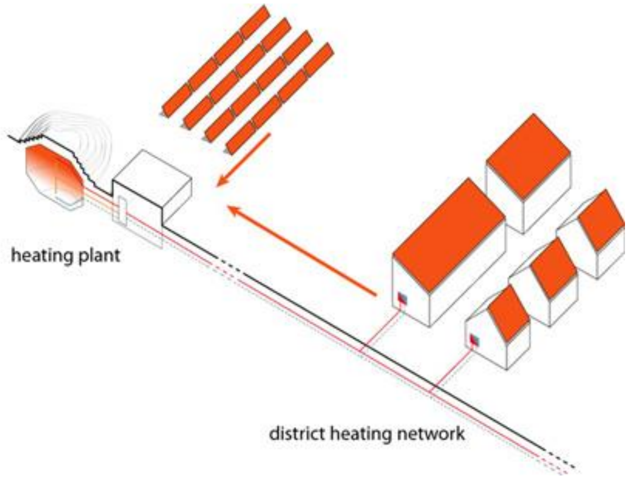
Main advantages of solar thermal systems include the exploitation of locally available solar irradiation, the integration with thermal energy storage and the consequent opportunity of exploiting storage capacity to provide flexibility to the power grid. Solar thermal is widely manufactured in Europe and has always had excellent acceptance among European citizens as one of the 100% renewable technologies.

There are currently more than 10 million solar thermal systems in Europe, corresponding to an installed heat generation capacity over 36 GW$_{th.}$ and thermal energy storage capacity equivalent to 180 GWh$_{th}$.

[13] During last years the largest plant in Europe grew from 2 MW up to 12 MW
[14] More information http://www.ship-plants.info/
[15] Solar Heat Worldwide 2019 – Global Market Development Trends in 2018 https://www.iea-shc.org/Data/Sites/1/publications/Solar-Heat-Worldwide-2019.pdf

5.1 Challenge 1: Solar District Heating (SDH) networks

District heating and cooling is a powerful vector to integrate renewable and excess heat/cold and use it to supply homes, offices and even industries. The potential of solar thermal in district heating (DH) is clearly being demonstrated in some 200 SDH systems across Europe. The demand on district heat that can be covered by solar heat combined with seasonal storage is by far the biggest untouched potential for use of solar heat.



Large storages can store thermal energy from summer to winter. With the installation of seasonal storage pit solar thermal can provide the base load heat for many of the 6000 heat networks in Europe – from Helsinki to Leipzig and Madrid. Drake Landing in Canada is an example on how communities can have 100% of their heating from solar thermal using seasonal storage.

District cooling is currently at a low level of distribution only at rather few cities but with a great potential for expansion. Cooling is emerging massively by climate effects and increasing comfort demands. While today most district cooling systems are powered by waste heat or environmental heat combined with electric driven heat pumps, solar heat is today only used on campus level in cold water grids.

What this technology needs for a full take-off in all European countries includes:

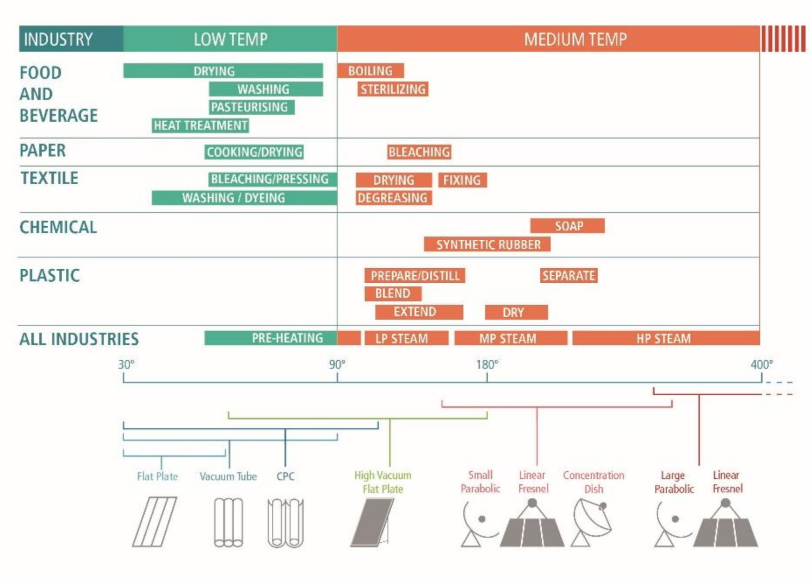
- **Integration of large solar thermal systems and storages** in medium and high temperature DH networks in large (often coal-fired) and medium size (often natural gas CHP) DH systems as well as in DH clusters. Storages shall be developed, designed and used both for short term (balancing heat between day and night) and on seasonal base (shifting summer to winter).
- **Developments in system components**, involving performance, price, and reliability. Improved technical aspects related to the design and operation of large SDH systems, with emphasis on hydraulic optimisation, improvement of network control and optimisation of thermal storage capacity.
- **Changing district heating systems** from single source boilers with controllable fuels to multi renewable supply systems with volatile sources and storages by AI, digital twins, and predictive controls as well as lowering supply and distribution temperatures in the DH grids.
- **Tackling non-technical issues**, including environmental impact assessment, improvements in the fields of area screening and development, availability of land close to the district heating systems secured and supported by regional energy planning, elaboration of multi-use concepts for ground mount systems combining solar heat with agriculture or valuable biodiversity, multi-coding of areas, participation, and innovative business models.

5.2 Challenge 2: Solar Heat for Industrial Process (SHIP)

According to IRENA[16], industrial process heat accounts globally for more than two-thirds of total energy consumption in industry, and half of this process heat demand is low- to medium-temperatures (<400°C). Solar thermal can therefore cover part of that energy demand by exploiting locally available solar irradiation. As such, it should be considered as a key technology in future regulations affecting energy supply in industry (e.g. minimum RES shares in industry).

Solar heat for industrial processes (SHIP) is at an early stage of development but is considered to have huge potential for solar thermal applications. Currently, concentrating solar heat systems (CSH) reach temperatures of 400°C and even above. They may directly supply steam systems by injection. 635 operating solar thermal systems for process heat are reported in operation worldwide. The total gross area of the 301 documented systems which are larger than 50 m² is 905,000 m² gross and the thermal capacity is 441 MW_{th}.[17]

Continuous process management, which can be achieved through innovative process technology and which makes the use of renewable energies at low temperature level possible, would lead to further significant reduction of the energy input and can be defined as a future long-term goal. In Europe, the size of SHIP (solar heat for industrial process) installations, is growing every year. Until 2018, the largest SHIP plant in Europe was 2MW, since then new plants became operative and reached 12MW.



The reasons for the low growth rates are mainly commercial and market related issues, namely the need for demonstration of the technology in diverse industrial heat processes, as a way to gain confidence from industrial clients and demonstrate the performance and reliability of such solutions.

In addition, alternatives for the future carbon neutral industrial heat supply, such as hydrogen or power-2-heat, are substantially more expansive. While the named solutions are of utmost importance for total decarbonization SHIP has lower costs for specific decarbonization for suitable solar shares.

Some essential developments needed for an increased deployment include:

- **Standardization and modularization.** Today SHIP systems are still tailor to the largest extend tailor made for each specific application. While the collectors only make up around 1/3 of total system costs the major share of the costs refer to peripheral components (hydraulic, electric, control) and engineering costs. Standardization and modularization allow to reduce the costs of both components and labour costs. In standardized solutions it is easier to achieve larger

[16] https://irena.org/-/media/Files/IRENA/Agency/Publication/2015/IRENA_ETSAP_Tech_Brief_E21_Solar_Heat_Industrial_2015.pdf
[17] https://task49.iea-shc.org/Data/Sites/1/publications/IEA-SHC-Technology-Position-Paper--Solar-Heat-Integrations-Industrial-Processes--May2020.pdf

component quantities and thereby achieve lower specific costs and in addition the time for engineering is cut drastically. R&I improvements in this context will result in overall lower system costs for SHIP applications.

- **Integrated solutions for processes below 100°C**: solutions for processes below 100 are widespread, they come with better cost-performance ratio, better solar production rates, and can be accomplished with simpler systems such as stationary flat plates and vacuum collectors. However, solar thermal collector fields are still relatively small. The development of integrated solutions, combining low temperature solar process heating systems with other technologies (e.g. heat pumps, waste heat recovery, large thermal storages, solar-trackers, heat driven processes, e.g. absorption cooling, power-2-heat, PVT) allows to increase the solar fraction and thereby achieves greater contribution to decarbonization.

- **Integrated solutions for processes between 100-400°C.** The development of integrated solutions, combining high temperature solar process heating systems with other technologies (e.g. heat pumps, innovative high temperature storages, heat driven processes (e.g. absorption cooling / ORC turbines), power-2-heat, biomass combustion) allows to increase the solar fraction and thereby achieves greater contribution to decarbonization. The economy of scale due to larger solar shares will lead to lower specific costs.

- **Demonstration projects for high temperature projects (>400°C).** While solar process heating for industrial processes has been applied the number of demonstration plants at industrial scale in key sectors and key countries is too small – hampering the market development due to risk aversion of industrial end-users. Implementing industrial scale demonstration projects (>1 MW_{th}) in key sectors (e.g. chemical, pulp and paper, water treatment) and countries. Demonstration projects for high temperature SHIP applications will accelerate the market uptake of solar thermal solutions.

- **Foster sector coupling.** With increasing shares of renewable electricity in the grid sector coupling becomes more important. Due to the comparatively low costs of thermal storages power-2-heat can provide flexibility to the grid and industrial companies to balance loads and thereby reduce costs. Solar process heating systems already come with large thermal storages and thereby provide attractive services. To maximize the potential suitable hybrid storages (supplied by various heat sources at different temperatures) and sector specific measures of thermal load shifting needs to be developed. The promotion of sector integration through research and development will increase grid stability and reduce dumping of green electricity, whilst increasing the solar thermal share for process heating and cooling.

- **Integration of SHIP urban planning** concepts, processes and guidelines and local energy roadmaps, assuming the sustainable energy supply of industries (and industry districts) as fundamental. R&I support for the integration of SHIP in the urban design will improved framework conditions for solar process heat and boost a quicker uptake and larger solar shares.

- **Long term, third party verified performance data projects.** One major lever to accelerate the uptake of solar process heating are so-called “heat purchase agreement”. While such projects have already been implemented for non-concentrating collectors none has been done for high temperature projects with concentrating collectors. For the later there are greater uncertainties, namely a) uncertainty of direct normal irradiation larger than for global horizontal irradiation, b) substantially lower number of plants and greater technical complexity increase risk-premium for investors. Concentrating collectors allow to achieve a greater solar share and are thus essential for deep decarbonization. Yet, despite their importance they mentioned uncertainties prevent investors to engage. Thus, long term, third party monitored performance data for solar process heating projects are required to unlock the market for heat purchase agreements for that technology.

- **Thermal collector and storage development:** To reach higher solar ratios in largescale industrial projects, also new storage technologies will continue to be an important research topic to realize large scale storage capacities on an economically feasible scale. New collector developments will further focus on the medium temperature level, with a focus on little collector weight, simple installation procedures, and economic realization potential.

- **Emerging process technologies:** Research concerning the integration of solar thermal energy in industrial process will focus on new process technologies. On the one hand, it will focus on new technologies that provide the usage of low temperature heat (e.g., thermal driven separation technologies - membrane distillation), and on the other hand, a more integrated research approach connecting collectors and process technologies will be decisive.

Proving commercial and financial viability will unlock additional market shares for heat purchase agreements with concentrating solar thermal collectors.

5.3 Challenge 3: Solar Thermal Applications in Buildings

In EU households, heating, and hot water alone account for 79% of total final energy use. 84% of heating and cooling is still generated from fossil fuels while only 16% is generated from renewable energy sources. Around 70% of the EU population lives in privately owned residential buildings.

Solar thermal are a 100% renewable energy (RE) solutions both in existing and in new individually heated & cooled buildings (residential and others) that are not possible to connect to district heating and cooling (DHC) grids due to limited existence (e.g. some southern European countries) or are difficult to connect to DHC grids, e.g. due to either its remoteness (in rural areas), or due to its low energy demand (new, low-energy buildings or passive houses).

Solar thermal systems used at building level, either residential or commercial, cover space, water heating, and solar cooling applications. These are the most common solar thermal systems, ranging from thermosyphon solar water heaters of 1.4 kW_{th} very common in Greece, or more efficient compact and forced solar water heaters in South Europe, to combi-systems for space and water heating between 7 and 14 kW_{th} in single family houses, popular in central Europe to larger systems (up to 500 kW_{th}) in multifamily houses or even bigger ones for commercial uses. The integration into buildings and nZEB/Passive-house concepts, the combination with other solutions in hybrid products and the use as enablers of sector coupling are functionalities that will be important for the development of such solutions, for which improvements at component level are also relevant.

Some of the challenges related to this topic are:

- **Hybrid solutions,** including new thermal energy storage concepts and combination with other technologies, such as air- and ground-source heat pumps or biomass boilers, and photovoltaic thermal collectors (PVT). Developing cost-competitive compact solar hybrid heating units currently, with the complexity of combining solar thermal with another heat source is confusing for customers and installers. The development of easy to install and operate compact solar hybrid heating units, combining the solar thermal and back-up heating system into one, will make solar thermal heating and cooling more attractive.
  R&D is needed to identify the most energy-efficient and cost-efficient hybrid (and compact) system designs. Assessment criteria must be developed considering economic and ecologic aspects both from a short-term and from a long-term perspective.

- **Improved hybrid collectors, such as PVT** (photovoltaic and thermal) and new collectors with temperature-controlled performance. Research activities must focus on further improving the performance of these panels. At present, adding up the thermal and electrical performance, covered PVT collectors are already among the most efficient (with 70% in the thermal part + 18% in the electrical part totalling 88% efficiency). New specific regulations need to be developed for hybrid solar panels, along with standards and certifications since currently these systems must comply with some PV standards that are incompatible with the search for maximum thermal efficiency. Overall, all the challenges identified can be implemented with PVTs (not in the cases of high temperature) managing to produce electricity and heat in the same occupied surface.

- **Improved retrofit solutions and renovation technologies**, including enhanced and simplified integration with other heating solutions (both new and traditional, like underfloor heating). This work requires the adaptation of new concepts and learnings from the hybrid solutions development, from optimised controls, to increase standardised solutions with self-modulating capacities to reduce complexity, malfunctioning risks and work time related to the installation. Besides the ease-of-installation, solar thermal systems shall add smartness capabilities to the retrofitted space and/or water heating system.

- **Developing prefabricated multifunctional solar façade systems**. Most buildings in Europe will be retrofitted within the coming years to reduce their energy demand significantly. Solar thermal systems integrated in multi-functional façade systems could become a cost-effective solution for refurbishing the building stock and allow a solar fraction above 50%. R&D is necessary to develop solar thermal collectors as an integral element of the façade, to meet the challenges of incorporating the hydraulic system and combining the solar collector with other functional systems such as insulation, ventilation and heat distribution. The objectives are easy maintenance, reduced risks of system failures and, by combining solar thermal collectors with other elements of the façade system, to fulfil the aesthetical expectations of architects and homeowners with different surfaces and colours. Generally, façade collectors must comply with building regulations such as statics, as well as weather and noise protection. The multi-functional solar façade system could be a part of a multi-functional building system as well, which includes the solar façade collectors on the outside, a heat distribution system on the inside and a heat store in between, integrated in the wall.

- **Developing smart systems based on simplified design**, cost-efficient components, and optimised control strategy, which provide good system efficiency at lower costs and improved reliability on installation and operation. The development of standard hydraulic and electrical connections between all components is one measure which will help towards reducing installation costs, allow inter-changeability and increase reliability due to fail-safe installation (plug and function).

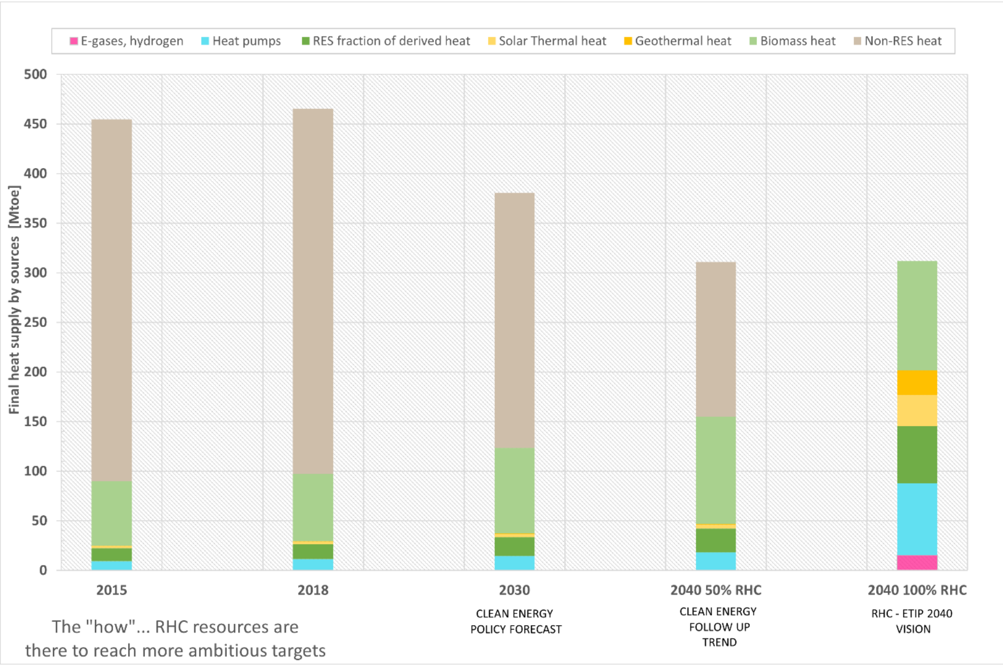
- **Developing 'Solar-Active-Houses' with high solar fraction**. R&D is needed to develop cost effective and reliable solar thermal systems with high solar fractions. In addition to improved key components, other relevant factors include: an optimized system design to facilitate low-cost high efficiency; effective adaptation of the solar thermal system to the individual building characteristics and to the location; well-designed integration of collectors into the building envelope and of storage into the building structure; as well as high reliability and ease of operation of the system. New system concepts must, therefore, be tested and evaluated, and planning and design tools as well as standards developed.

- **Maintenance and performance through reliability, data gathering and IoT.** The reliability of solar thermal systems must be increased by the integration of smart control, monitoring and self-detection functionalities through data gathering and IoT (Internet of Things). Simplicity of installation can be increased based on intelligent controls for system surveillance and diagnosis. Predictive and preventive maintenance programs for buildings would be developed based on such functionalities.

- **Increase simplicity of installation** with intelligent and cost-efficient components (pumps, storages, controllers, pipes, and valves.) and intelligent controllers for system surveillance and diagnosis. More **integrated systems** (first for large facilities) using solar thermal energy both for heating in winter and cooling in summer through on side generation.

5.4 Challenge 4: Financing and Business Models for Solar Thermal

Solar thermal applications need a substantial scale up in size, to make a clear impact in the upcoming renewable energy mix. Applications such as large scale (1-100MW) Solar District Heating (SDH) and Industrial Process Heat (SHIP) can replicate the successes of Solar PV utility scale, provided they can profit of advanced project financing tools and methods, much the same way they have been deployed in large scale PV. This technology is expected to provide a substantial contribution in the future energy mix as showed in the graph below, but additional financing tools and new business models are need to achieve this goal.



The key elements to be able to use project finance tools are, among others:

- Risk assessment tools, namely:
  - Technology risks – e.g. risks of system/component failures, lower than expected performance.
  - operational risks – e.g. system ordinary and extra-ordinary maintenance, frequency of stops, uncertainties on capacity factor.
  - Counterparty risks – e.g. energy Offtaker's creditworthiness, possibility of user ending production, plant relocation.
  - Country risks – e.g. political stability, public acceptance, currency risks
  - Weather/Climate risks – e.g. long-term availability and reliability of irradiance data
- Risk management tools:
  - Public funded – financial risk mitigation facilities
  - Insurance and re-insurance policies

- Worldwide/EU wide monitoring and data collection/validation on existing and new solar thermal plant, with full disclosure on performance data, failure rates, OPEX

To stimulate and facilitate investment, project developers and investors should be attracted to this new renewable energy asset class, the solar thermal plant, and there is a need for:

- Contract templates, to be elaborated or adapted for HPA (Heat Purchase Agreements), In the case of use PVTs the contracts could be for Heat and Electricity Purchase.
- Friendly legal framework for obtaining construction permits, and to protect investors interests in case of financial stress of the energy off-taker/user.
- Performance Certification and Guarantees, covered by insurance policies
- Data collection and validation by accredited third parties, which also entails transparency and access to performance data.

There is today an immense amount of liquidity on the financial market, desperately seeking for good investments and above average returns. Such liquidity has its rules of engagement, especially when it comes to infrastructure investments, such as renewable energy.

Some of the tools outlined above are already available on the market, because they have been developed for general purpose investments (for example weather risks can be covered with specifically developed insurance policies, while client's creditworthiness is the base for bank lending). Some other need to be developed from scratch, much the same way it has been done with solar PV.

It is crucial that an alliance is formed among the institutional and industry players, in order to deploy technical assistance resources, and attract insurance and re-insurance players to help build these risk management tools, and above all determine their costs. The size of the market for solar thermal infrastructure projects is too small today for such a process to be initiated spontaneously. Projects are too few and too small. This creates a vicious circle where no tools are created to deploy new large-scale investments, because there is no finance for such investments, and there is no finance because the tools are not there.

Breaking this circle will be possible when solar thermal players, Manufacturers, Developers, Large users, Utilities, ESCOs, will present themselves with unity of intents towards the financial community, backed by a solid long-term policy framework. Different technologies, hydraulic integration concepts and typologies of clients (B2C, B2B), available incentives are therefore to be considered, which calls for innovative and differentiated business models (BM), taking into consideration:

- Better identification and parameterisation of risks for large scale solar systems, enhanced certification processes, facilitating contractualisation and guarantees.
- Innovative BM exploiting demand-response mechanisms on the electricity grid and the certified origin of renewable heat

Improved investment decision-support-tools available on the market and used by investors, integrating LCoH calculations using standardised and simplified rules for the calculation of operation and maintenance costs, residual value, auxiliary energy consumption, among other parameters.

6 Relation to Cross-Cutting Issues

Research and innovation are a key factor for large scale deployment of solar thermal applications. Technology advancements will lead to radically lower costs, higher efficiency, better system design and integration, enhanced operations, and increased security of supply.

The challenge of digitalisation

Among the cross-cutting issues relevant for the solar thermal sector, digitalisation will play a key role. The future energy mix will be based on the interaction of different technologies and this will lead to strong interdependencies and require smart monitoring and control for an efficient interaction. Digitalisation can be an enabler of this: it will allow an optimum use of energy sources and promote a deeper sectoral and technological integration.

However, especially for small and medium enterprises the digital transition can be a heavy burden, and ad hoc support will be needed for SMEs which are at the heart of the solar thermal sector and overall, of the EU industry. The internet of things (IoT), domotics and the integration among power and thermal sectors are expected to have a deep impact in making grid and off-grid solutions smarter.

In this context, an integrated approach is needed, carefully considering all relevant actors. Future energy systems will enable solar district networks to fully exploit their operations (also in cooperation with other sources) and while empowering the end users. The impact of digitalisation will also be particularly relevant in the industrial sector since current industrial processes are design for a single technology. Digitalisation will more integrated energy management systems.

The key role of thermal energy storage

From the beginning, thermal energy storage (TES) technologies were part of solar thermal systems, enabling the use of solar heat at night, in a period of less sunny days and in winter seasons. With thermal storage, the effective use of solar thermal increases.

The main technology used for TES for solar thermal in practice is sensible thermal storage with water as the storage material. In the fields of very large storages for district heating or industry at low temperatures (<120 °C) the technology can be further improved, while for other application fields other, novel TES technologies need to be developed and demonstrated. These application fields are medium and high temperature industrial solar heat and concentrated solar power generation and long-term or seasonal thermal storage.

The TES technologies capable of delivering these services are compact thermal energy storage technologies, using either phase change materials (PCM) or thermochemical materials (TCM). Through their capacity of storing and providing heat at a fixed temperature, PCMs are suited for applications in which a constant temperature is preferred, like heat pumps, comfort temperature control and steam generation. TCMs are specifically suited for long-term storage applications, as the heat losses are virtually zero, and for applications in which the available volume for TES is limited. The development challenges for TES in relation to solar thermal are materials development and improvement, component development and optimisation and system integration.

7 System Level Challenges that Must be Solved to Realize the Potential

Awareness raising and training needs are still two of the challenges that need to be solved to realise the full potential of solar thermal solutions. To achieve a future-proof energy mix, it will be key to educate new solar thermal professionals and have a qualified and highly skilled work force. This will enable the reconversion of workers from sectors dominated by fossil technologies and incentivise the uptake of renewable heat solutions such as solar thermal. Schemes to support these actions should be implement at national level but can also be promoted through EU programmes such as Horizon Europe in coordination with the CETP. Therefore, it will be key to define the right training strategies to avoid insufficient skills/education of all stakeholders from heating companies to planners, installers, and end-users. R&I policies need to align speed of technology implementation and speed of deploying training strategies and tactics on the new technologies at all professional levels. This will also ensure consumers affordable and free choice between renewable heating technologies.

Another major barrier to the deployment of solar heat is the unbalanced situation competition with fossil sources. Solar thermal, like other renewable solutions in the heating and cooling sector, is facing an unfair competition with natural gas and fossil fuels. Nowadays, also because of the Covid19 pandemic, natural gas is extremely cheap and easily available all over Europe. To counterbalance the negative externalities that fossil solutions bring in the market, an EU-wide carbon tax must be implemented. This is the only way to further promote renewable direct heat sources which are lacking behind their competitors in the power sector. The revenues of this tax should return to lower income households through social benefits or be reinvested in key sectors like hospital, schools, and climate-friendly public infrastructures.

A similar approach should be applied to the industrial sector, which is among the hardest to decarbonise. Europe should implement a system of obligations and incentives to promote the use of onsite renewable heat to decarbonise industrial processes and allow an easier access to finance for those businesses which are supporting the energy transition.

New investments on locally generated renewable heat should be financially supported and coupled with a binding requirement for a minimum share of RES in the industrial production. Most of solar thermal solutions present in the internal market are manufactured in Europe, with components of EU origin. This fact provides additional advantages for local economies and job creation and creates competitive gains for the industrial competitiveness of European companies at global level.

Other policy measures which would accelerate decarbonisation would be a clear streamlining legislation at EU level, to be implemented at national and local level, to facilitate and incentivize the use of available surfaces (rooftops, industrial and commercial buildings, industrial ground surface, reclaimed areas, etc.) to install solar thermal solutions. New district heating systems should enable the use of different renewable energy sources, and R&I can facilitate the integration of RES also in already existing networks. A Guarantee of Origin should also be established for thermal energy generated by direct renewable heat.

8 Conclusions

Solar Thermal technology is well established in Europe and in most countries worldwide. It is very common in the residential sector for the production of domestic hot water, this being a relatively constant heat demand throughout the year, but it is also used for space heating and can be applied to cooling production through sorption chillers. Besides the residential sector, solar thermal is used as well in industrial applications for process heating and cooling. Solar plants cover a wide range of sizes, from few kW_{th} to hundreds of MW_{th}, and across almost any climate condition, from Mediterranean to north European countries.

For solar thermal to heavily increase installed capacity in the future, thus reducing Europe’s dependence on fossil fuels and meet energy efficiency targets, efforts are needed especially on the system integration side. This will widen the possible applications and increase current solar fractions, the share of energy demand that a solar plant can cover in a specific application.

Most promising segments are industrial processes industries and district heating networks. Hundreds of systems are already operating in Europe and worldwide, but the potential is enormous and largely untapped. SHIP and SDH projects are typically larger compared to residential projects, because of more demanding demand profiles (load, seasonality, temperature range, pressure). Buildings, which are historically the main market for solar thermal, keep being very relevant and, again, call for innovative system integration, such as combination with other renewable technologies, façade integration and enhanced system's smartness factors.

Technological improvements will enable a wide diffusion of solar thermal only if boundary conditions will be adapted to the changing requirements. From a financial perspective, business models need to be tailored on renewables, and especially solar thermal, aiming at reducing upfront investments. But efforts are also needed to identify areas for solar collectors' integration to ensure enough space is available and that land is used in a healthy and sustainable way, being correctly integrated in the urban context.

Solar thermal will certainly play a key role in the future energy system, exploiting locally available, 100% renewable solar irradiation. It will dramatically reduce pollutants and greenhouse gas emissions, will be suitable for most energy-consuming sectors and applications and will be affordable thanks to innovative business models, among others based on thermal energy storage as the key device for sector coupling, with huge benefits on peak electricity loads shaving.

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Input Paper to the CETP SRIA Renewable Technologies

Challenge 11

Integrating Climate Neutral Technologies

Editors, Co-authors and Commenters of this Input Paper to the CETP SRIA:

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1 Introduction

Putting the enabling technological to work in an optimal way is the as building blocks of the climate-neutral energy system is the key challenge in the energy transition. It is necessary to look beyond the traditional energy carrier electricity, and rather look at the combination of enabling technologies spanning multiple energy carriers, storage options combined with multiple end products and services when considering the climate-neutral and sustainable energy system. Although definition of the research challenge for the enabling technologies is the main contribution in this paper some other important transition challenges regarding application and role of the specific technologies are summed up here in section 2.

If enough resources are put into it the energy system can be made neutral, but the transition challenge is about doing this in a way where low energy cost and high energy system reliability goes hand in hand with new industrial possibilities and a just development for all regions in Europe. The challenge of designing a joint energy market and levelled playing field for energy vectors of generation, consumption and energy infrastructures is described in section 3.

Operation of an energy market requires digitalization on many levels from the digitalisation of the technology to communication and security and resilience. The joint energy market will greatly benefit from a full utilisation of digitalisation but must take special care to use digitalisation to develop the energy citizenship and support the needed consumer empowerment needed for a social and economic feasibility of such a marketplace. The digital market infrastructure also has strong relations to the aspects of cyber security and crisis mitigation. This is further elaborated in section 4.

2 Impact from proposed R&I

The challenge of a climate-neutral energy system will help the CETP partners to deliver on the policy goals for greenhouse gas emission as decided by the EU Parliament. This is and needs to be a moving target as knowledge about the consequence increases and new technology options reach TRL needed for implementation.

The target for a low greenhouse gas emission energy system in 2050 is <85% (ref.1990) has existed for some time while the 2030 targets are currently being discussed with the aim of increasing the ambition for greenhouse gas emission reduction by 2030. This is a very important discussion because accumulated greenhouse gas emissions have a high impact on the resulting global temperature rise, and different pathways to 2050 will lead to differences in accumulated greenhouse gas emissions on the road to 2050.

Closely connected to this ambition is the goal of a zero-GHG-emission power system in 2050. One way to reduce accumulated GHG emissions towards 2050 is to archive this objective sooner than 2050. A strong focus on power alone will reduce the possibility to see the complete picture of the transition to a climate-neutral energy system. The possibilities that rest in combination of energy production, energy infrastructures and energy demand (including energy citizenship) deserve an approach that embraces and combines the different options and how they together can result in a climate-neutral energy system and on the way create new technologies, services and green jobs.

Impacts where the research of the CETP can contribute to regarding a climate-neutral energy system are:

- **Improved energy security of supply**. From a political angle this means that Europe should utilise its own energy potential and depend less on imports of resources from the outside. From an operational perspective this means a robust energy system in terms of operation and resilience to uncertainty from climate variations, natural disasters, and cyber security. As a citizen, an industry, and a public service provider you should experience high quality energy services when and where you need energy and the service energy can provide.

- **Affordable/competitive energy.** The impact from the partnership is to decrease the cost of energy supply from the different technologies in the framework of circularity. This encompasses material use, investment and construction, operation, refurbishment, and re-use of input factors. The focus of the partnership is not limited to a low-cost, climate-neutral energy system in 2050, it is also a low-cost transition to the optimal 2050 energy system. It follows from this that the energy system must stay competitive in a global setting throughout the transition and that the cost of energy must be affordable for all citizens in Europe.
- **Fair and inclusive energy transition.** The transition towards the climate-neutral energy system must embrace that it takes more than reliable and affordable energy to transform the system. The interaction between stakeholders in the energy sector must be experienced as fair by all parties and the transition needs the inclusion of the stakeholders to succeed. It is important that the CETP can contribute to fact-based decisions and debates, but it is just as important that the technical and practical implementation of the transition must be able to include the mechanisms that makes "fair and inclusive" possible.

To succeed in reaching these impacts and requirements of a climate-neutral energy system three main research challenges for the energy transition are suggested:

- Integrating the enabling technologies, with challenges a mentioned above in chapter 2.
- Market design, the energy market challenge
- Digital market infrastructure, operating the energy market, driven by end-user empowerment

The proposed challenges for these areas are further elaborated in the following section.

3 Integrating Enabling Technologies

Enabling technologies are the building blocks of the climate-neutral energy system. In the climate-neutral energy system where power is expected to play a larger role through electrification of processes that currently results in greenhouse gas emission technologies for renewable energy production will of course be very important. The challenge is that generation technologies to different extent are delivering variable weather dependent output, the exception being biomass, hydropower, and to a degree CSP. As a result, there is need for flexibility and storage which makes technology that aggregate and release flexibility on the consumer introducing another group of enabling technologies, these are covered more thoroughly in other partnerships (Smart Cities, Smart Buildings etc.) Then there will be different energy infrastructures that link energy generation and energy consumption: power grid, heat networks, gas networks, battery electric vehicles, bulk transport etc., these are also enabling technologies in a climate-neutral energy system. Then there are the conversion technologies such as power2x and x2x that connects the different energy infrastructures. Finally, but not least important there are the technologies that can provide CO2 reductions that may be needed for deep decarbonisation.

Given an integration perspective it is necessary that:

- these technologies are further developed, not only with respect to their costs but also with respect to how their flexibility capabilities can be enhanced or better used and how the capabilities can be combined in a common energy market to provide affordable and secure energy for the European society.
- that services are developed that facilitate that the technologies are integrated to their full capability in the European energy system as the home market but also enables the technology to compete on the global market and provide export related green jobs.

A detailed description about the challenges for specific enabling technologies can be found in the individual technology papers.

Technology challenges:

- How can the joint flexibility of enabling technologies be used in the energy market as the transition progress?
- What flexibility and energy services are needed to ensure energy system operation and energy citizenship at different stages in the energy transition?
- How can the emission footprint for the different technologies be reduced and become as low as possible?
- How can the technology be developed into a competitive delivery with respect to both energy, technology and services?

4 Market Design

Joint research is needed to investigate and generate new knowledge about an energy market design that can facilitate a climate-neutral energy system. A joint energy market that works across different energy infrastructures and carriers will be a completely new innovation that needs to be developed to cover the principles outlined in section 5. These objective for a common energy market can be formulated as:

- Contribute to a fast completion of a climate-neutral energy system
- Result in affordable energy prices for industry, citizens and public sector
- Facilitate an energy independence by using European resources
- Work in line with the objective of a just and fair transition

Such a joint energy market must be a levelled playing field for the enabling technologies if it shall be able to use competition to drive the development in the energy system towards decarbonisation with the lowest possible cost resulting in affordable energy and an energy-vice competitive Europe and industry-vice new technology and services that can be exported worldwide and transform fossil jobs in Europe into new green jobs.

In practice an energy market that drives the decarbonisation means a transition to generate energy from renewable sources which to a large extent is variable. This is a transition from a system where it was possible to stockpile fuels to a system where flexibility in demand and different types of energy storage has to work hand-in-hand with the enabling technologies to balance energy production. The marginal cost in the system will to a larger extend reflect the capital cost for production technologies, not the fuel cost as today, which is a situation known from hydro- and nuclear power.

A functioning energy market must value not only the kWh but also the services that ensure operability of the energy system such as flexibility and storage. The energy market for a climate-neutral energy system must comprise different services and the relation between these services, e.g. if all generation capacity is used for energy delivery there is no capacity left for reserves. Such services are flexibility, reserves, storage with different time horizons etc.

A major question therefore is: How to value different types of flexibility and energy storage in the energy market to get the right investment levels and ensure enumeration to the stakeholders?

The climate-neutral energy system must be fair to different energy infrastructures and also respect the connection between the common energy market and the distribution infrastructures. The transition should enable Europe to use the available resources, also local and regional, and this means that energy system and the market design must enable use of regional resources and look beyond a mare competition and towards a fair and inclusive transition.

The climate-neutral energy system must fulfil the following criteria:

- is affordable
- is efficient
- internalise
    - nature use
    - emissions
    - circularity
- ensure investment level
- fairness to different energy infrastructures
- local, regional and European policy goals

In this broad holistic picture of an energy market there is many challenges that can be solved both for the enabling technologies and for improving innovation, integrating the energy system in society, increase efficiencies and more. Some challenges are important for getting started and for increasing the speed and success of the energy transition:

Market design challenges:

- How to design a single energy market over large geographical area for different energy sources, energy carriers, and energy infrastructures?
- How to design for the interdependency for different energy products within each energy carrier and between energy carriers?
- What is the best approach to reach one energy market? Is it: top-down, bottom-up, or both simultaneously?
- How to ensure that the emission targets are reached and measure the progress?
- How to internalize externalities in the design and operation?

The technical aspects of the energy system, stability, security co-operation of the energy infrastructures is more thoroughly covered in the paper on system integration.

5 Digital Marketplace

With the enabling technologies operating together in a competitive energy market that delivers the products and services needed in a reliable and affordable energy system the third challenge is to make the market platform operational, transparent, and efficient. This is a big challenge for a small market and a much bigger challenge for the European Member States. There are no examples of joint markets on energy system level that can be used as a blueprint but there are use-cases from the power system, examples from local energy communities that we can learn from. To make an energy market work across Europe new novel methods and approaches must be established. The success of a joint energy market starts with joint competence and knowledge building research addressing how digital technology can be used to construct and operate an integrated European energy market. The objectives of the research on digital energy market platform are:

Contribute to an energy flexible European industry in terms of demand and technologies

- Implement "empowerment" for European citizens
- Develop energy flexible public sectors as front movers
- Improve security and resilience of the energy system

Digitalisation a key enabler for the ambition to establish a platform for operating the joint energy market. Digitalisation is an important element for the communication between different components in the energy system, e.g., electric cars, battery packs, demand side management systems, for managing infrastructures and especial parallel infrastructures such as: electricity, heat, gas etc., and for setting up automated control systems that allows empowerment while improving living conditions and life quality at the same time.

A digitalized market platform opens new possibilities to improve the efficiency of the energy system and must allow new services to be implemented in the energy system. An example is the aggregator role in the power system facilitating small sources of flexibility to become important flexibility assets for operating the climate neutral power system.

Attacks on digital platforms are an increasing problem with huge damage potential. Attacks with the aim of getting information can lead to economic losses, but we also see attacks on public infrastructures with the aim of controlling policy processes. An attack and possible breakdown of the operation mechanisms of the energy system will have extremely large consequences for the society and longer breakdowns will be dangerous for European citizens. Cyber security of a digital marketplace must be adequately handled, and the system must have built-in security that allows the system to operate analogue without the digital platform.

Research challenges for the digital marketplace:

- How should the digital market infrastructure be designed and operated?
- How can digitalization be used and managed to ensure openness and transparency of the energy market platform?
- How can a digital marketplace support empowerment for citizens, the industry and the public sector?
- How to use digitalization to ensure operation of the energy system in case of natural disasters and robustness in case of cyber-attacks?
- How can the innovations in the digital marketplace result in new products and services that can create values and jobs in Europe as well as export possibilities?