Integrated SET Plan

CETP

Clean Energy Transition Partnership

Input Paper to the Strategic Research and Innovation Agenda

Storage Systems and Fuels

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

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1 Introduction to Storage Systems and Fuels

The European Strategic Energy Technology Plan (SET Plan) sets the reduction of CO_2 emissions by 40% within the year 2030 through the increased utilisation of renewable energies (up to 32% of the overall energy consumption) and improvements in the efficiency of energy use by 32.5%.[1] To achieve this, energy infrastructures (heating and cooling networks, electric grid, gas grid) have to be highly flexible to accommodate higher shares of renewable energy e.g., geothermal, biomass, concentrated solar power (CSP), photovoltaics (PV), solar thermal energy, hydropower and wind power in a secure and flexible way [1]. In this context, there are two major challenges: the compensation of fluctuating generation from renewable electricity sources as wind and solar (either electric or thermal), which rely on meteorological conditions, and the seasonal variations in demand. Figure 1 shows the Europe-aggregated demand for the different vectors (heat, transport/fuels and electricity)[2]. The integration of many new energy storage solutions is needed to tackle the related challenges, e.g., to prevent extreme price fluctuations and maintain security of supply and affordability of energy[3]. Also, radical improvement of existing technologies, as well as development and maturing of new ‘first of a kind’ technologies, will be required.

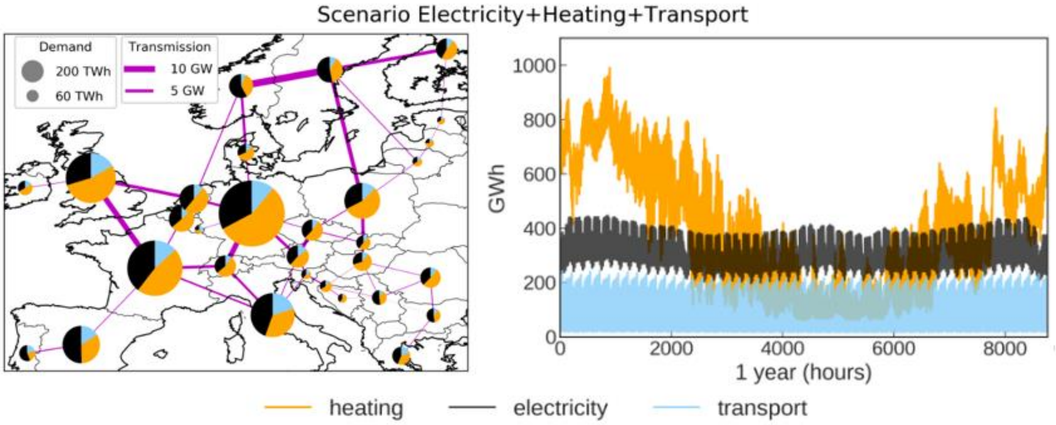

Figure 1: Spatial Plot Energy Demand per Sector and Country (left), Europe-Aggregated Demand for the Different Sectors (right) [2]

This thematic priority focuses on the development of cost-effective, integrated storage and fuel systems and will support solutions answering to various identified sub-challenges within this area. This includes sustainable, short- and long-term storage solutions at different system integration levels within technical areas such as electrical storage, electrochemical storage, material storage, thermal storage, mechanical storage, power to X and renewable fuels and the hybridization of energy storage technologies.

No optimal solution can be provided for Europe by a single technology. Rather a mix of various technologies providing high system flexibility at different time and integration scales as well as spatial ranges is required as indicated in Figure 2[4]. Spurring the efficient cross-sectoral development of energy storage and fuel technologies is absolutely crucial to support the SET-Plan objectives. Here a view on the system level is necessary to link and combine different storage options and other technologies to develop sustainable solutions.

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[1] EC, SET Plan delivering results: The Implementation Plans - Research & Innovation enabling the EU's energy transition, 21.11.2018

[2] M. Victoria, K. Zhu, et al., Energy Conversion and Management 201 (2019) 111977, DOI: https://doi.org/10.1016/j.enconman.2019.111977

[3] REPORT on a comprehensive European approach to energy storage (2019/2189(INI))

[4] S. van Gessel, “Large-Scale Energy Storage in Salt Caverns and Depleted Fields (LSES) – Project Findings” personal communication, August 25th, 2020

The proposed attempt requires a European approach and coordinated research, which has to be linked with various European platforms active in the field (e.g., BATTERIES 2030+, SUNRISE and Clean Hydrogen Alliance).

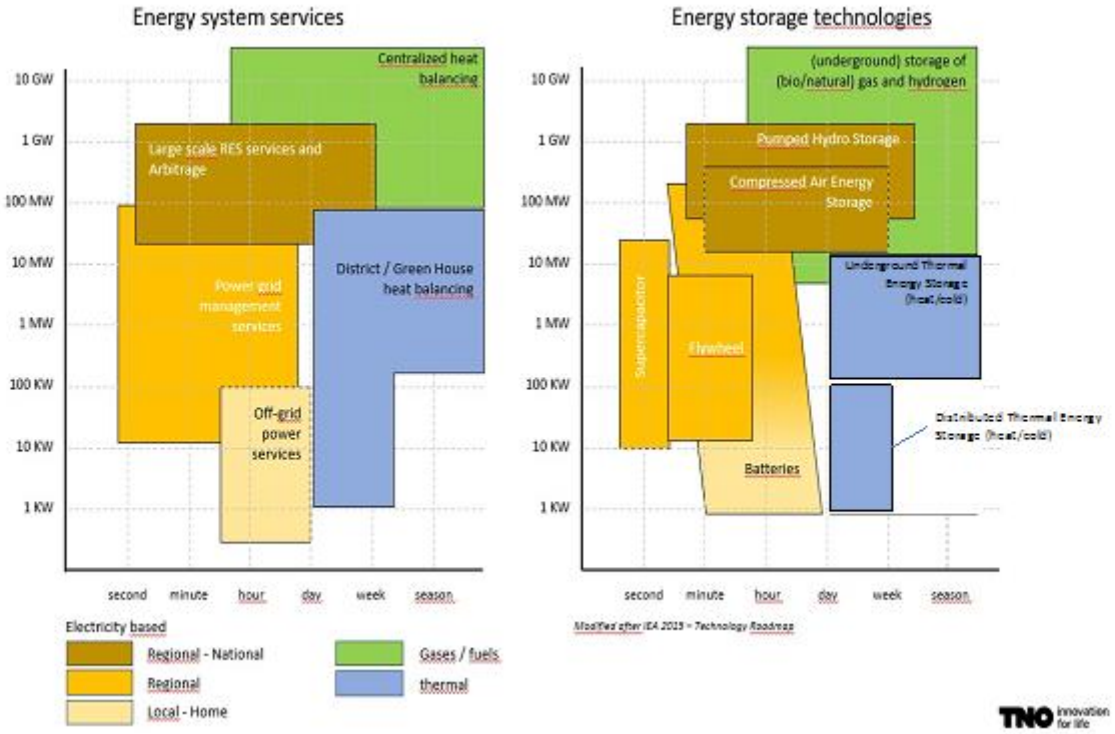

Figure 2: Storage Options for Various Timescales and Sizes; Logarithmic Scales based on van Gessel 2020 [4].

2 Overview of Challenges

Given the presently diverse nature of energy markets within Europe, including differing energy policies, meteorological condition (sunny regions, windy region, cold climate etc.), generation mixes and demands, energy storage solutions in different member states are likely to play different roles taking advantage of different technologies.

For such reasons, a deep knowledge of the energy supply and demand as well as the potential renewable electricity and thermal surpluses, is required to, e.g., develop and implement short-term to inter-seasonal storage. This entails knowledge about the magnitude of RES fluctuations, ramp rates, local infrastructure, loads, markets and regulations to exploit opportunities for transnational partnership, to fulfil the needs and take advantage of the potentials of different regions instead of working in isolation. Supporting the construction of transnational EU markets and partnerships to exploit the potential of each region will avoid, or at least minimise, the creation of costly, redundant infrastructures. Furthermore, storage sizing and location of the chosen technologies, including hybrid technologies, depend on applications and their characteristics (CAPEX, OPEX, cycling, lifetime, efficiency, interconnection with other energy carriers, environmental and social aspects (LCA)). Relevant drivers to determine the need and benefit of energy storage and fuel technologies are the following aspects:

- Spatial dimension: Transport of energy (including fuels), demand vs. supply location
- Consideration of different time frames:
    - short term storage (seconds to minutes up to some hours)
    - long term / seasonal storage (days, weeks up to months)
- Levels of system integration: decentralized, centralized

    - different needs at building, local and regional level
    - single or inter-sectoral integration
- Different application fields and corresponding business cases
- Corresponding technological characteristics as e.g. capacity, power capacity, storage duration, CAPEX, OPEX, round-trip efficiency and conversion efficiency, environmental impacts.

Short Description of Challenges

As stated before, this cluster focuses on the development of cost-effective, integrated storage and fuel systems supporting solutions answering to various identified sub-challenges. This includes sustainable, short- and long-term storage solutions at different system integration levels entailing various technologies (e.g., electrical storage, electrochemical storage, material storage, thermal storage, mechanical storage, power to X and renewable fuels and the hybridization of energy storage technologies).

The challenges in the field are identified and clustered alongside different energy storage technologies dealing with different energy forms and carriers (heat, electricity, natural gas, biomass and fuels, hydrogen, other chemicals) to understand and manage the complexity of the entire European energy system. Beside this more sectoral perspective, inter-sectoral and hybrid solutions as, e.g., Power to X are seen as a promising possibility for long-term and large-scale storage, making use of existing infrastructure (e.g., methane and oil infrastructure) to substitute fossil fuels in an efficient and environmentally friendly way. Although this type of technology is seen in close interplay with other storage solutions, new approaches to inter-sectoral and hybrid energy storage should also be explored. This leads to the following energy vector clusters considering the above-mentioned requirement dimensions in section 2 for Heating and cooling, Electric grids, biomass and fuels, cross-sectoral and hybrid solutions. Without a doubt, a holistic system approach is required to find optimal solutions and combinations of different energy storage and fuel technologies covering the different vectors. Topics such as system integration (Cluster 4) as well as cross-cutting issues (Cluster 6), environmental impacts, circular economy and digitalization are summarized in chapter 2.1 especially highlighted for those challenges where they are of high importance.

2.1 Challenge 1: Reliable and Cost-Effective Mid- to Long-Term Thermal Storage Systems

The development of thermal energy storage (TES) capacity and smart energy management systems is crucial for the clean energy transition. Advanced, reliable and cost-effective low, medium and high-temperature TES are needed. In fact, TES systems can match the heating and cooling demand profiles and supply profile fluctuations over various time-scales - from hour to seasonal - and size scales - from building to city level. The aim of this challenge is to develop advanced storage systems allowing to foster counter-seasonal integration of heat sources (seasonal surplus heat resources such as solar thermal, geothermal, heat from thermal treatment of waste or industrial surplus heat and seasonal surplus cold sources such natural cooling, industrial surplus cold or cold from LNG terminals) and other thermal storages that have a relevant role in the energy system.

The challenge is broken down in the following Sub Challenges (SC):

- SC1 - Development of large-scale underground TES
- SC2 - Development of cost-effective, large-scale TES in man-made constructions (tank- and pit thermal storages etc.)
- SC3 - Development of low temperature, mid- to long-term small TES
- SC4 - Large-scale day-to-month TES at temperatures > 120°C.

2.2 Challenge 2: Development of Efficient Storage Technologies for Electric Power Grids based on Renewables

Among the different tools available in the portfolio of network operators for real-time balancing of generation and demand, different technologies of storage will be crucial to support system stability. Energy storage technologies for energy and power applications seem to be still far from meeting technical and economic targets. The aim of this challenge is to optimise and demonstrate cost-effective and sustainable storage technologies able to cover seconds to minutes up to intra-week and seasonal modulation needs. This includes existing as well as radical new solutions for different application scenarios.

The challenge is broken down in the following Sub Challenges (SC):

- SC1 - Development of reliable and cost-effective electrochemical technologies for long term electricity storage
- SC2 - Increase the European hydro-power potential for energy storage
- SC 3 - Support of conventional power generators through storage technologies.

2.3 Challenge 3: Renewable Fuels

Renewable based liquid and gaseous fuels are an important flexibility option required to achieve a sustainable energy system. The provision of such fuels is crucial for industry, residential and transport sectors. Here, the major goal is to develop, improve, establish and launch technologies for the large-scale production of sustainable, renewable fuels, which are either compatible with the existing vehicle fleet and fuel infrastructure (replaceable, drop in) or possess better technical properties. Such new solutions have to be produced at lower costs for the needs of specific market segments (heavy-duty road transport, shipping, aviation, heat and power generation) and require a clear market entry strategy.

The challenge is broken down in the following Sub Challenges (SC):

- SC1 - Production of advanced biofuels/bioenergy from sustainable biomass
- SC2 - Integrated biofuels and bioenergy production solutions with Power to Gas (e.g., biogas upgrading) and CCUS
- SC3 - Thermochemical Solar Fuels
- SC4 - Electrochemical Solar Fuels (sunlight direct conversion).

2.4 Challenge 4: Development of Cross-sectoral and Hybrid Energy Storage Solutions

The interplay of several generation, fuel conversion and storage technologies on different system levels is the precondition to achieve a clean energy transition. ‘Cross-sectoral‘ storage solutions will promote the efficient inclusion of high shares of renewable and excess energy sources into the energy system. Developing and demonstrating such solutions is urgent. Examples include Power-to-X (P2X); and the combination of different storage technologies. The integration of such solutions will also require advanced digital techniques to optimise system performance. Challenge 4 aims to obtain carbon-free, breakthrough technologies for integrated hybrid solutions covering multiple time scales and sectors, allowing an optimal exploitation of renewable energy sources.

The challenge is broken down in the following Sub Challenges (SC):

- SC1 - Development of Hybrid energy storage solutions
- SC2 -Development of reliable and cost effective P2X technologies for fuels and gas
- SC3 -Development of integrated decentralized energy storage solutions.

2.5 Challenge 5: System Integration and Cross-Cutting Issues for Energy Storage

The robustness and resiliency of the European future energy system will increasingly depend on the flexible response of energy production, transport, conversion and consumption to each other in the short and long term. Technical solutions such as storage, energy conversion technologies (e.g. P2X), sector coupling, demand-side management and distributed generation need to work together seamlessly. This requires a high degree of systems integration across all of its dimensions. The integration of energy storage and fuel technologies plays a crucial role in this systemic perspective. As such, it is covered in detail in the input paper for "System Integration - Cluster 4" covering issues as integrated operation of infrastructures, market design and regulation, modelling approaches and network operation.

There are several cross-cutting issues that are highly relevant to achieve a sustainable, reliable and resilient energy system that are tackled in the frame of the input paper "Crosscutting - Cluster 6". These factors are also highly relevant for energy storage and fuel technologies and require a wide set of multidisciplinary approaches covering several technological, techno-economic, socio-technical and environmental research dimensions.

Some of the named aspects are joint for a number of individual technologies. Naturally, some might be more crucial for certain technologies and have to be stressed where necessary in the challenges.

The challenge is broken down in the following Sub Challenges (SC):

- SC1 - Assessment of the potential solutions for energy storage and fuels in a holistic approach for a CET
- SC2 - Optimized lifespan of storage systems and the failure modes, including stochastic cycling profiles, CAPEX, OPEX, efficiency and environmental impact.

3 Detailed Description of Challenges

3.1 Challenge 1: Reliable and Cost-Effective Mid- to Long-Term Thermal Storage Systems

The development of thermal energy storage (TES) capacities and smart energy management systems is crucial for the clean energy transition. TES can match the heating and cooling demand profiles and balance fluctuations over various time-scales - hourly to seasonal - and size scales - from building to city level. Also, thermal storage can contribute to balancing the electricity grid when high levels of intermittent renewable electricity sources are introduced. Finally, thermal energy storage can optimise opportunities for utilisation of industrial and other excess/waste heat and cold.

An integrated approach implies better exploitation of the potential of TES. The cost-effectiveness of all types of TES, including combined storage, long-term and seasonal solutions, should be identified and unlocked. Thermal energy storage techniques include storage of sensible heat, latent heat, and thermochemical processes, for both heating and cooling. TES can provide many services to the energy system, such as peak generation and peak shifting, security of supply, storing surplus electricity, and many more. This will prove crucial in an energy system that includes a high share of RES.

Concrete challenges for TES are defined at various temperatures, storage sizes and typical applications. Typically, 'large scale' refers to a block of buildings and up, while small systems are at a level of single residences. Overall, the critical challenges are:

- Reliable and cost-effective underground large-scale seasonal thermal energy storage for temperatures between 0-120°C
- Cost-effective largescale seasonal storage for temperatures between 0-130°C in man-made constructions (pits, vessels, tanks etc.)

- Cost-effective small systems for mid- to long-term thermal energy storage at building level for space conditioning and domestic hot water.
- Cost-effective and reliable largescale day-to-month storage systems for temperatures > 120°C for industrial applications and power production.

3.1.1 Sub-Challenge 1 (SC 1): Development of Largescale Underground TES

Large-scale, underground thermal storage systems can provide significant storage capacities, typically 1-20 MW and 0.1-25 GWh. Targeted research and development activities should develop underground storage solutions for a broader range of temperatures and a broader range of geologies than available today. Underground TES (UTES) includes aquifer TES, borehole TES, and mine TES - in abandoned mines. Pit thermal energy storage is part of sub Challenge 2 here. Demonstrating cost-effective and robust solutions that operate essentially trouble-free for tens of years is still a need. Also, Europe has a significant and underutilised potential for seasonal heat and cold storage, where heat pumps are used for alternate extraction of heat and cold, while replenishing these storages for future use, e.g., in other seasons. Recovering thermal energy from the storage is cheaper than the heat or cold production from the original source. Crucial here is integration in the system, with and without heat pumps, and with more than one source of renewable energy.

Geological conditions vary considerably across Europe and are crucial for UTES. UTES needs proper low-cost characterisation methods. This is for some technologies more critical than for others. Also, improved subsurface modelling to predict performance of UTES technologies is relevant.

Technical challenges vary per UTES technology, but can be summarised as low-cost drilling, improved efficiency, improved operational strategies, reliable subsurface pumps, low cost materials and implementation, water treatment optimization, new and low cost monitoring technologies. Overall key performance indicators: temperature range, response time and ability to provide peak demand, power range, energy capacity range, efficiency, installation footprint (in relation to impact on environment and society) and lifetime.

Market challenges also vary per storage technology as they also have different CAPEX/OPEX ratios and different applications. So next to bringing cost down it is of high interest to stack revenues through expanding applications served by these technologies and new business models. Smart integration is a very important target, also considering that the storage is allowing other assets in the system to be optimised. Smart controls are crucial there.

3.1.2 SC 2: Development of Cost-Effective Largescale TES

Development of Cost-Effective Largescale TES in Man-Made Constructions (Tank- and Pit Thermal Storage

District Heating and Cooling (DHC) operators have the challenge of covering a very high difference in heating or cooling demand between the seasons. The low demand for heating in summer leads to an increase in operational costs. The integration of large TES in DHC systems not only helps to balance this seasonal difference but also enables the better integration of different renewable and excess heat sources. The state of the art for large-scale TES is given mainly in Denmark, where large-scale pit thermal energy storages with volumes up to 200,000 m^3 are in operation, and several new Pit Thermal Energy Storage (PTES) are in planning with volumes of 500,000 m^3. This successful Danish practice can be applied to other geographic regions when the concept is modified to the different geological and market conditions. The R&D challenges in this field are materials development to enable better temperature resistance and durability, novel concepts for the construction of the walls, bottom and lid, improved building processes, concepts to enable or integrate cold storage and concepts that enable small overpressure of the storage, enabling storage temperatures up to 130°C.

3.1.3 SC 3: Development of Low Temperature, Mid- to Long-Term Small TES

Large parts of the buildings are not connected to a heating or DHC grid and therefore need local solutions for maximising the renewable share for heating and cooling. Part of the housing stock can be catered with heat pumps, but as these are electrically driven, they will add to the high load of the electricity grid in winter. This has to be balanced by technologies that move the surplus of renewables in summer to cover the demand in winter. On local level, phase change (PCM) or thermochemical (TCM) storage technologies can provide this long-term storage of heat. The system can be charged with either (solar) thermal heat or with renewable electricity. The state-of-the-art systems for PCM are based on water/ice, salt hydrates and paraffines and for TCM based on solid sorption or on hydration, some systems demonstrated on small scale. An added value of the TCM systems is the possibility of providing cooling. The R&D challenges are cost reduction of the components and the storage materials on the short-term and development of novel storage materials on the longer term.

3.1.4 Sub-Challenge 4: Largescale day-to-month Storage at Temperatures > 120°C

Thermal storage systems are highly relevant to industrial process heat applications. Specific developments are needed for different temperature ranges. Here, the development of suitable thermal storage systems based on latent heat (phase change materials, PCM) and on thermochemical materials (TCM) have the potential to substantially boost the commercial deployment of these (solar) systems in the industrial sector, thus contributing to its decarbonisation.

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. At the same time, these can contribute 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.

3.2 Challenge 2: Development of Efficient Storage Technologies for Electric Power Grids based on Renewables

Among the different tools available in the portfolio of grid operators for real-time balancing of generation and demand, different technologies of storage will be crucial to support electric power system stability by providing a wide set of power (e.g. ancillary services, power and quality management) and energy-based services (e.g. seasonal storage, peak shaving). Energy storage technologies for energy and power applications seem to be still far to meet technical and economic targets. For example, while present storage technology is proving its effectiveness in fast balancing services and intra-week power production thermally driven, there is still a strong need to optimise, develop and demonstrate improved storage technologies able to cover the intra-week and seasonal needs. Moreover, the total cost of storage systems, including all the subsystem components, installation, and integration costs need to improve its cost competitiveness with other non-storage options available to electric utilities. Storage still lacks a proper valorisation in many scenarios and context, thus limiting the unlocking of its full potential. Principal challenges to be addressed by the RD&I activities are:

- Identify use cases of storage in the various services that may be provided to the grid, individually and in multiple or “stacked” services, where a storage system has the potential to capture several revenue streams to achieve economic viability.
- Cost competitive energy storage technology - Achievement of this goal requires attention to factors such as life-cycle cost and performance (round-trip efficiency, energy density, cycle life, degradation, CRM, etc.) for energy storage technology as deployed. Long-term success requires both the cost reduction and the capacity to realise revenue for all grid services storage provided.
- Validated reliability and safety - Validation of safety, reliability, and performance of the proposed energy storage is essential for users ´ confidence.

- Equitable regulatory environment - Value propositions for long-term grid storage depend on reducing institutional and regulatory hurdles to levels comparable with those of other grid resources.
- Reduce the cost of all energy storage solutions contributing to the minimisation of the overall system costs.

3.2.1 SC 1: Development of Reliable and Cost-Effective Electrochemical Technologies for Long Term Electricity Storage

Existing electrochemical storage technologies can supply appropriate storage for the hourly to daily (Lithium Ion batteries) and weekly (Redox Flow Batteries) energy storage. However, the most significant challenge to overcome is the compensation of seasonally fluctuating generation from renewable energy sources. Since the early 1970s hydrogen has been proposed as the solution for the needed energy storage to grant a stable energy supply over days, weeks and even years.[5] In this challenge, radically new energy carriers beside batteries and hydrogen should be explored and evaluated and, possibly, implemented in a relatively short period of time to meet the targets proposed by EC.

Such new technologies are electrochemical energy storage technologies based on reactive metals, i.e., metals which oxidation potential is below that of hydrogen (e.g., Al, Zn, Fe, Na, Ca, Mg). The optimum exploitation of reactive metals can be achieved through an efficient combination of different energy conversion paths and existing processes for metal production. With this approach, excess energy from renewable resources is used for reactive metal production. The metals can be stored for long-term or even be kept in, e.g., the molten state, additionally acting as thermal storage media. Upon request, the chemical energy stored in the reactive metals can be converted back to electrical energy, by means of chemical and electrochemical processes, independent from environmental conditions.

Such metal-based systems can overtake the mentioned challenges of seasonal fluctuations as they can be used for: (i) short- (if necessary) and in particular for long-term energy storage in power generation, heat and transport sectors and (ii) encourage a circular economy through the incorporation of secondary materials in their life cycle.[6] Specific targets are to develop seasonal storage solutions via reactive metals, that offer a high volumetric and gravimetric energy density, including high round trip efficiencies of >50%, low cost and zero emissions.[7]

Besides technological solutions, long term storage itself still lacks a proper valorisation in many scenarios and context, thus limiting the unlocking of its full potential. Feasible applications are not available up to date due to missing business cases for long term storage. The cost of corresponding LT technologies has to contribute to the minimisation of the overall system costs and has to be proven in theory as well as on a demonstration level.

3.2.2 SC 2: Increase the European Hydropower Potential for Energy Storage

Hydropower is the largest source of renewable energy worldwide and in Europe. Reservoir hydropower is largely used for both baseload generation and for storage and balancing at timescales ranging from seconds to seasons and years. Europe has about 170TWh in hydropower storage capacity (more than 90 % of European grid-connected storage today). Most of the European hydropower fleet are quite old and requires refurbishment in the coming years. This is an opportunity to redesign many hydropower plants to meet increased demand for flexibility, to retrofit cascading reservoirs with pumping capacity, to upgrade mitigation measures for environmental impacts and to potentially increase both capacity and generation by including more inflow. However, the retrofitting of hydropower plants with pumping capacity poses several design challenges related to both the huge number of design constraints related

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[5] National Hydrogen Association; United States Department of Energy: The History of Hydrogen, see. hydrogenassociation.org. National Hydrogen Association. p. 1. Retrieved 17.12.201

[6] Bergthorson, J. M. Recyclable metal fuels for clean and compact zero-carbon power. Prog. Energy Combust. Sci. 2018,68, 169-196, doi:10.1016/j.pecs.2018.05.001

[7] Baumann, M.; Barelli, L.; Passerini, S. The Potential Role of Reactive Metals for a Clean Energy Transition. 2020. Advanced energy materials, p. 2001002. doi:10.1002/aenm.202001002

to the old plant design and to the need of facing new operating problems (cavitation in pumping mode) due to the added pumping capacity.

A major aim is to identify ways to enhance pumped storage capacity by more flexible pump turbines (variable speed, stable operation at part-load), ternary groups with hydraulic short circuit, using new technologies and sites (sea water, underground and under water pumped storage, exploitation of particle-laden flows), and hybridization with other renewables and storage options (batteries, flywheels, etc.) in order to provide regulation services supporting the grid stability.

Upgrading and extending existing facilities are among the best options, since Europe still has about 40 % (about 400TWh) of its hydropower potential unexplored. With modern mitigation measures to safeguard ecosystems (see protocol such as the Hydropower Sustainability Assessments) and with the introduction of Artificial Intelligence and digitalization, it is possible to harvest some of this potential in a sustainable way.

3.2.3 Sub-Challenge 3: Support of Conventional Power Generators through Storage Technologies

Integration of energy storage systems with conventional power generators, such as cogeneration, hydropower, thermal plants to increase their flexibility and improve operation (incl. effectiveness and load hours of combined heat and power).

Thermal Power Generation, at all the network levels, lack an integrated coordination with non-programmable RES which needs to be rapid, reliable and efficient and guarantees the lowest possible emission level. Fuel flexibility is not realised to its full extent, i.e. the capacity to switch between renewable-based fuel as well as conventional ones, including different rates of mixtures, depending on the availability of carbon-neutral synthetic fuels like synthetic methanol or methane, hydrogen, ammonia, biomass derived from waste, etc. Seasonal storage capabilities of the gas network, via Power-to-gas technologies will also be developed and extensively used.

Flexible operation could impact negatively on the equipment and components life, with increased maintenance and repair costs; innovative solutions will, therefore, be developed to reduce out-of-service and failure rates. Power-to- Gas and Power-to-Liquid options are needed to allow increasing synergies between Power and Transport sectors.

Suitable tools will be developed to optimize the different flexibility resources, assessing their availability, the retrofitting technologies, the operating (and external) costs, both under a planning point of view. Improved combustion systems for CO_2-neutral fuels (including renewable “green” hydrogen/ natural gas mixtures) will be demonstrated, with particular attention to efficiency and reliability, as well as faster thermal generation ramping down and up and start-up/shut down. Energy storage systems such as batteries, hydro reservoirs, hot water tanks, molten-salts thermal storage, cooling systems storage, storage for CO_2-neutral or free gases, integrated with power generation plants, will be demonstrated via pilot experiences. New technologies and operational methodologies will be developed and demonstrated to increase hydropower and pumped hydro-storage plants flexibility.

Additionally, it is also possible to refurbish conventional gas or coal power plants introducing thermal storage systems based on molten salts (already commercially used in CSP plants) feed with the PV and Wind dumped electricity, which cannot be used or stored by other technologies.

The penalty in the efficiency of converting electric to thermal energy can be compensated by the important CAPEX saving in the reusing of existing power plants with the additional benefit of replacing gas or coal by renewable energies to the steam production to feed the corresponding turbine. Specific research is needed here to consolidate and demonstrate the feasibility of this concept.

Storage systems and Energy conversion technologies are key factors in ensuring a high degree of flexibility to the energy system as a whole, as well as guaranteeing the deep de-carbonization requested. Storage still lacks a proper valorisation in many scenarios and context, thus limiting the unlocking of its full potential. P-to-X technologies need extensive R&I activities, followed by a suitable demonstration at different scales to achieve the following objectives:

- Ensured knowledge that power generation –including for existing generation capacities is ready to optimally use the gases generated under novel Power-to-Gas concepts, where alternative fuels are provided.
- Optimized operation of power generation through storage, for instance by bridging between stop and restart of a generator or by providing the needed time to achieve optimal ramp-up/-down, allowing fast load changes to be met.
- Increase the cost effectiveness of thermal energy storage for electricity production. 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. The development of thermal storage systems for $T > 600$ºC is then needed to allow the implementation of supercritical steam Rankine cycles, while thermal storage for $T > 750$ºC 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.
- Techno-economic feasibility assessment of retrofitting existing assets for low-carbon flexible power generation, including the re-use of natural gas infrastructure for decarbonized gases such as hydrogen.

3.3 Challenge 3: Renewable Fuels

Development, improvement, establishment and launch of technologies for the large scale provision of sustainable, renewable fuels contributing to store renewable energy as long term solution must be either compatible with the existing fuels market (vehicle fleet, fuel infrastructure, heat generation, etc.) or possess better technical properties, and produced at low cost for the needs of specific market segments (heavy-duty road transport, shipping, aviation, industry, heat generation, etc.). This challenge is seen in close interaction with the **European Clean Hydrogen Alliance**.

The aim of this challenge is to provide a clear market entry strategy demonstrate the possibility for dynamic response and contribution towards renewable energy storage as renewable liquid and gaseous fuels within the core production process.

Some examples of actions required:

- Sustainable biomass sourcing (technical, economic and sustainable sourcing potentials; storage & logistics, combining decentralised production of high quality biocommodities (intermediates) for more central production of advanced biofuels/bioenergy
- Appropriate logistics to ensure year-round supply for biorefineries etc. Development of methods to facilitate market acceptance of liquid and solid intermediates by improved handling, storage or performance properties or by improved user-friendliness (e.g. pelletization, torrefaction, contaminant extraction, stabilization, water removal)
- Integration with Power to Hydrogen: biogas upgrading (CO2/H2 methanation)
- Development of novel processes and technologies for low cost and sustainable e-fuels and solar fuels (direct sunlight conversion)
- Integration with CCUS to mitigate environmental impact

3.3.1 SC 1: Production of Advanced Biofuels/Bioenergy from Sustainable Biomass

A main issue regarding the viability of bioenergy plants lies in the development of reliable, integrated biomass supply chains from cultivation, harvesting, transport, storage to conversion and by-product use across Europe. Secure, long-term supply of sustainable feedstock – often by local supply chains -is essential to the economics of bioenergy plants and their integration to the energy networks in to contribute to renewable energy storage. Consequently, it is necessary to foster development of regional biomass supply and value chains, as well as to assist in overcoming the barriers of feedstock and economics of bioenergy production vis-à-vis higher capacity plants and assess and develop the integration with renewable energy power plants and other energy vectors (power to X). This can be done by increasing efficiency in the biomass conversion to intermediate bioenergy carriers analogous to coal, oil and gaseous fossil energy carriers and thus creating the sustainable bio-crude energy feedstock basis that could be further refined to final bioenergy products (e.g. integrating green hydrogen). The conversion solutions can be based either on local feedstocks or in large scale and long transportation distances on low-cost bioenergy carriers.[8]

3.3.2 SC 2: Integrated Biofuels and Bioenergy Production Solutions with Power to Gas (e.g. Biogas Upgrading) and CCUS

Renewable electro-fuels (such as renewable hydrogen, methane, methanol etc.) are increasingly seen as suitable storage media for excess electricity generated by wind and solar power, facilitating the renewable uptake and integration of the power, transport, industry and heating sectors. They are thus likely to become more widely available, also as renewable fuels for transport in the medium and long term. The use of renewable hydrogen and other renewable liquid and gaseous fuels (Biomass-to-liquid, renewable Power-to-Gas including hydrogen and renewable Power-to-Liquid) could play an important role not only in decarbonizing transport, but also in enabling the cross-sectorial integration of surplus renewable electricity and realizing a fully renewable energy supply linking the electricity, heating, transport and industrial sectors. These technologies could prove indispensable in the scenario where low-carbon renewable electricity needs to be stored either in large quantities or over very long-time (inter-seasonal storage). In addition, renewable hydrogen can also be used to increase the output of biomass, allowing for additional synergies.[9]

Large demonstration projects are needed in order to support the energy transition:

- Demonstrating the possibility for dynamic response and contribution towards renewable energy storage as renewable liquid and gaseous fuel (in synergy with hydrogen partnership) within the core production process
- Demonstrating the feasibility of the integration of biofuels and bioenergy production with phytoremediation (combining soil remediation, industrial reconversion and sustainable energy transition)
- Exploiting the integration of biofuels and bioenergy production with Power to Hydrogen to Power processes (reversible process): e.g. biogas upgrading via CO_2/H_2 methanation, injection into the NG network and power generation (when needed to balance the renewable energy intermittency); hydrogenation processes for upgrading pyrolysis oil and HTL; syngas yield increasing (H_2 in gasification processes).
- Fostering the integration CCUS processes in advanced biofuels production routes to guarantee environmental sustainability

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[8] ET-Plan Key Action 8 Renewable fuels and Bioenergy Implementation Plan, June 2019

[9] SET-Plan Key Action 8 Renewable fuels and Bioenergy Implementation Plan, June 2019

3.3.3 SC 3: Thermochemical Solar Fuels

Fuels, defined as any chemical compound that can react with oxygen releasing energy, can be produced using concentrated solar energy (Solar Fuels) to provide high-temperature process heat as the necessary energy source for the performance of endothermic thermochemical reactions for the production of chemical substances. These can be used downstream in the chemical industry for synthesis of liquid hydrocarbon fuels or ammonia or stored/transported and used for off-sun electricity production when and where needed. So far, these solar-driven processes 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, current 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. Indeed, the full process value chain from solar-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. Nevertheless, no such process has been so far demonstrated at the several hundred kW level and relatively long-term operation so far.

Some examples of actions required are:

- Proof-of-concept operation of solar fuels production reactors, comparable to “traditional” chemical industrial plant operation
- Demonstration of solar-to-fuel conversion efficiencies ≥ 15 %, with the integration of heat recovery
- Development and construction of custom-made solar fields capable of achieving the high temperatures required on high-efficiency receivers/reactors

3.3.4 SC 4: Electrochemical Solar Fuels (Sunlight Direct Conversion)

Research on photo(electro)chemical technology is still at the laboratory stage, but it bears important promises. The integration of all components into a single device can lower the total system cost and provide greater flexibility in the design. Compact, integrated devices that are independent of the electrical grid allow for a decentralized production of fuels and chemicals. The main targets are to develop novel light-absorbers and photocatalytic materials for integrated photo(electro)chemical systems and to increase solar-to-product efficiency beyond current levels. Photo(electro)chemical devices may operate as a solid state ”monolith” (buried junction cells or photoelectrochemical cells) or as a liquid phase suspensions of photochemical systems (photocatalytic nanoparticles or supramolecular assemblies). Approaches hybridizing solid state and molecular active components (catalyst and light-absorber), including biological molecules extracted from living cells (bio-molecular systems) are also a promising route.[10]

Some examples of actions required are:

- Hydrogen production using photoelectrochemical cell devices
- Hydrogen via buried-junction photoelectrochemical cells
- Direct photoelectrochemical ammonia synthesis

3.4 Challenge 4: Development of Cross-Sectoral and Hybrid Energy Storage Solutions

Beside sectoral storage solutions, intersectoral and hybrid solutions as Power to X as generic technology are seen as a promising possibility for long-term and large-scale storage on all time scales, making use of existing infrastructure (e.g., methane and oil infrastructure) to substitute fossil fuels in an efficient

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[10] https://sunriseaction.com/wp-content/uploads/2020/06/Roadmap_February_2020_withannexes.pdf

and environmentally friendly way. Basic feedstock consists of CO_2, nitrogen and water, whilst renewable electricity provides the source of power for conversion. Although this type of technology is seen in close interplay with other storage solutions, new approaches to inter-sectoral energy storage should also be explored. This entails the identification of synergies that can be used among other technologies beyond P2X (e.g. battery storage and super caps, hydrogen with SMES, etc.). Such hybrid storage solutions increase the cost but enable the coverage of different storage scales, increasing the efficiency and lead to additional resilience. P2X as well other hybrid storage technologies need extensive R&I activities, followed by the suitable demonstration at different scales.

Some examples of actions required are:

- Development of hybrid solutions combining different energy storage systems
- Knowledge and results among member states for storage operation and its implementation and development of pan-European or regional solutions
- Development of business models and analyse how they impact the levelized cost of electricity (e.g. seasonal storage, intersectoral solutions)
- Assessment of environmental performance and the systemic benefits of storage and fuels from RES

3.4.1 SC 1: Development of Hybrid Energy Storage Solutions

The need and potential for hybridization of storage technologies arises from the requirements stemming from a certain application that cannot be covered by one single technology. In this sense, hybridisation can be seen as the combination of two or more inherent features of two combined technologies to meet these specific needs. The development of hybrid storage systems is a problem driven task to solve specific issues and not a purpose on itself. The major challenge is to identify the synergies between different storage are required and how synergies can be used among them to increase overall performance for specific applications. Examples for such potentials among storage technologies are to e.g. extend life time of a storage unit (e.g., superconducting magnetic energy storage systems or supercapacitors in combination with batteries or hydrogen) to minimize overall LCOE. However, studies for storage flexibilities in operation of electrical grids (including Microgrids) are required including: storage sizing and location (also hybrid technologies) depending on applications and their characteristics (CAPEX, OPEX, cycling, lifetime, efficiency, interconnection with other energy carriers, environmental and social aspects (LCA).

3.4.2 SC 2: Development of Reliable and Cost-Effective P2X Solutions

Power to X technology (P2X) is regarded as a key enabler of energy system integration and the linking of the electricity and gas sectors. There is a high potential of hydrogen, especially green hydrogen, as base for synthetic methane and biomethane for seasonal energy storage in high volumes. Additionally, it can be transformed further into other types of gas, such as methanol and ammonia. All these different products can serve as feedstock for energy-intensive industries, and as a sustainable fuel for several modes of transport.[11] Naturally, activities are closely linked to the European Clean Hydrogen Alliance.

Major challenges are the further up scaling of P2X technology, to stimulate investments in the production of green hydrogen and thus to create a market, a solid infrastructure and harmonised technical standards are essential. The possibility to make use of existing grid pipelines should be considered before contemplating the construction of a separate grid to transport hydrogen. The co-location of consumption and production is also regarded as a challenge to develop P2X markets were geo-specific solutions will be required.

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[11] REPORT on a comprehensive European approach to energy storage(2019/2189(INI))

Large demonstration projects are needed in order to support the energy transition and the establishment of a proper context to stimulate a P2X European supply chain and harmonising codes, standards, business models, etc.:

- Citizen energy communities (stand-alone buildings, living quarters and small and medium sized businesses and industries) supplied by renewable generation, sector-coupling and storage components (P2Hydrogen, P2Gas, P2Heat, P2Fuels involving carbon capture), P2chemicals and vice versa; flex control of P2Heat conversion, with energy management systems for local multi-energy streams operation.
- Pilots demonstrating the techno-economic value of Long-Term (weekly to seasonal) energy storage systems (from pumping hydro to other alternative solutions as P2X). Validated tools and platforms enabling effective sector coupling as tested in large demonstration project.
- New technology developments to enhance the flexibility of commercial RES (CSP, hybrid systems solar biomass, etc).
- Assessment of capabilities, performance and constraints of conversion plants (P2X: heat, gas and or hydrogen) within the electric system as validated in pilot projects. Assessment of capabilities, performance and constraints of storage potentials laying within other energy sectors as validated in pilot projects.
- New business models (like multi-vector bids) and new markets design (like coupling market).
- Optimized coupling of the gas, heat and electricity networks and adaptation to the flexibility challenge connected to the increased penetration of variable renewable energy sources in the system.
- Leveraged flexibility on the generation side to enhance the integration of variable renewable energy sources in the electricity system, but also for heating and cooling and carbon-neutral gas systems.
- Support the effective penetration of the novel Power-to-Gas concepts, where alternative green fuels are provided

3.4.3 SC 3: Development of Integrated Decentralized Energy Storage Solutions

The role of decentralised energy storage by consumers will increase. Private households can store the energy that they produce, for example from photovoltaic panels, in-home batteries or in thermal form through heating pumps for their own later use.[12] Such integrated decentralized storage solutions provide flexibility to the system, and are crucial to achieving climate and energy targets. Relevant technologies are e.g. residential battery storage, domestic heat storage, vehicle-to-grid technology, smart home energy systems, that enable in a wider sense demand response and sector integration.

These help to cut consumption peaks, provide flexibility, and are playing an increasingly important role in ensuring that the energy grid is efficient and integrated. Major challenges are early standardisation of new devices, consumer information and transparency of consumer data. Also, well-functioning electricity markets providing easy access for consumers will be key to achieving this. It is crucial to consider the role of active customers and citizens' energy communities in the energy transition process and to promote them adequately. Such concepts have to be proven on a demonstration level and require a high form of hybridization.

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[12] REPORT on a comprehensive European approach to energy storage (2019/2189(INI))

3.5 Challenge 5: Cross Cutting and System Integration Issues for Energy Storage

The transition to a net-zero greenhouse gas economy requires an affordable and cost-efficient energy transition away from a system based largely on fossil fuels towards a highly energy-efficient climate-neutral and renewables-based system. Technical solutions such as storage, energy conversion technologies (e.g. P2X), sector coupling, demand-side management and distributed generation need to work together seamlessly. This requires a high degree of systems integration across all of its dimensions.

Additionally, the properties of emerging technologies entering into a socio-technical system are not given beforehand, but they co-evolve with interactions occurring upon their development, implementation, adoption and broader use. Considering this, there are several cross-cutting issues that are highly relevant to achieve a sustainable, reliable and resilient energy system, which are tackled within the frame of Cluster 6 Crosscutting. These factors are also highly relevant for energy storage and fuel technologies and require a wide set of multidisciplinary approaches covering several technological, techno-economic, socio-technical and environmental research dimensions. Some examples are:

System integration aspects:

- Identification of new business models (e.g., stacking of services)
- Minimization overall system cost
- Resilience of the grid
- Market integration: regulation and market design for energy storage and fuels

Crosscutting issues:

- Validate the safety, reliability, and performance and focus on degradation and failure mechanisms and their mitigation, accelerated life testing and monitoring
- Social Aspects / technology acceptance
- Policies, governance, regulation and markets
- Energy flow optimization
- Sustainable materials choice and extraction
- Environmental performance / Life cycle assessment
- Resource efficient and sustainable energy technologies based on circularity (end of life treatment, critical raw materials, closed loop recycling etc.)

Some of the named aspects are joint for a number of individual technologies. Naturally, some might be more crucial for certain technologies and have to be stressed where necessary in the following challenges.

3.5.1 SC 1: Assessment of the Potential Solutions for Energy Storage and Fuels in a Holistic Approach for a CET

The progressive decarbonisation of the energy system relies on the deep integration of variable renewable energy sources. A paradigm shift is needed in the management of the energy system in front of all uncertainties, to guarantee the stability and efficiency of the system at all time and geographical scales. All sources of flexibility must be employed along the entire value chain.

The present demand-related technologies, market models and integrated energy system policies do not provide sufficient features and incentives to the customer/prosumer, to engage in DSM and DR programs and market initiatives.

There is also a lack of knowledge about customers behaviour and motivation to involve them in the energy market.

Power systems need to be increasingly flexible to accommodate rising shares of distributed, non-controllable renewable generation. Demand side flexibility in this context refers to enabling final customers/prosumers to become active in the market but also to enable system operators to make best use of flexibility in order to ensure low-carbon, secure, reliable, resilient, accessible, cost-efficient, and market-based system operation at affordable costs. There is a need to assess, in a reliable way, the full potential of flexibility to be addressed in different contexts and to simulate the effects of different technical and economic measures.[13]

Suggested R&I actions:

- Multi-carrier hybrid storage systems, including their economic benefits in comparison to single storage units, their application to power to Heat for balancing and storage, dynamic interaction between heat and electricity, their application at building level, dynamics of the coupled energy system considering the inertia of thermal loads (electricity-heating-buildings)
- Optimally located, sized and coordinated hydro, gas and chemical thermal and chemical storage for seasonal needs.
- Models for demand flexibility provided by integrated energy-intensive industries (e.g. steel production) and bulk energy storage (P2G, CAES, LAES, etc.)

CETP – Expected Benefits

- Accelerated availability of market based sustainable flexibility services for the grid.
- Increased market participation of a wide range of flexibility products, both short and long-term, through remuneration in multiple balancing / flexible markets.
- Improved market conditions of flexibility products at both supply and demand sides to ensure balancing and ancillary service provision in the markets.
- Increased flexibility investments for business in electricity sector to other energy vectors and their networks and businesses.
- P2X solutions enabling DER entities – connected to distribution grids – to become more and more active, allowing new service portfolio for the whole energy system beyond electricity.
- Fully integrated (in the electricity market) storage and multi-service (stacking concept).
- Developed and validated multi-energy markets considering flexibility resources.
- A complete set of rules, standards and guidelines for classification, test procedures, labelling, uniform test parameters and performance/diagnostic tests, including standardization of communication protocols for data exchange with storage systems.
- Finalized assessment on the quantitative contribution and potential benefits to the electric system of sector coupling.
- A full assessment of regulation, market and operational barriers.

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[13] ETIPSNET-IP21-24

3.5.2 SC 2: Optimized Lifespan of Storage Systems and the Failure Modes, including Stochastic Cycling Profiles, CAPEX, OPEX, Efficiency and Environmental Impact

The power system will be progressively operating under increasing constraints: managing and balancing the system under the extreme variability linked with the integration of renewables will imply higher frequencies of equipment load cycling, temporary overloads, working conditions closer to the design limits. Moreover, climate changes impose increasing mechanical, electrical, thermal, environmental stresses to all system components. Asset management approaches must evolve to ensure the level of reliability of the system.

Asset management is one of the most important chapters in the operation of the energy system. Identifying critical components deserve a specific attention in view of the overall system availability, balancing the necessity to minimise the OPEX and fulfilling the requirements of continuity and quality of supply is an important step towards a reliability or a risk-based operation. Selecting the most adequate monitoring and diagnostic quantities to be used in conjunction with well proven degradation and end-of-life mathematical models is the rationale on which to build the asset management policy: this must be complemented by sensors, monitoring systems, ICT, data, information and knowledge management tools (data analytics and big data). Critical assets must be managed based on risk and optimization, to reduce OPEX, while increasing network flexibility and ensuring adequate power quality. Finally, lifetime extension of existing power system components, based on improved monitoring and measurement of their health state and residual lifetime is key to optimise CAPEX.

There is a strong need to develop and validate tools that address the life-cycle management of energy system components. They must span from the study of performance degradation laws to components and systems diagnostics and monitoring. Maintenance approach and residual life evaluation must be addressed at the light of the threats deriving from the radical changes in operation cycles and environmental constraints.

The challenge addresses the advanced management of assets in the energy system along their entire life-cycle, from the commissioning to the end-of life covering the identification of the degradation phenomena and the indicators of the failure development, the sensors and methods for diagnostic and monitoring, the setting up of maintenance policies and end-of-life decision making at the light of the progressive advancement of data acquisition and management techniques.

With the onset of observability solutions and IoT utilization, systems and components can be constantly monitored through intelligent systems capable of offering improved operational regimes and advanced sensing capabilities that can offer accurate usage of installed infrastructure. Together with the pre-specified capabilities of installed equipment and systems by the manufacturers, maintenance decisions can be more accurate and in time to safeguard flawless operation of the system. This can be of real value to operators and R&I in this direction can offer a family of solutions that can improve operation and maintenance practices.[14]

R&I actions aim to achieve the following objectives:

- Cost-efficient and highly effective approaches for increasing system reliability through enhanced equipment maintenance and lifetime extension of existing power components based on improved monitoring, measurements and models to determine their health and remaining lifetime in the future.
- Best practices and guidelines for scaling-up and replication of coordinated asset management techniques.

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[14] ETIP SNET-IP21-24