3.2

ECS Key Application Areas

ENERGY

3.2 Energy

3.2.1 Scope

Change towards the carbon neutral society and challenges for ECS

Energy systems *supplying clean, affordable and secure energy* are the focus of *The European Green Deal*. To achieve this goal, the European Union set targets for a renewable energy share of 32 percent and a Greenhouse gas emission reduction of 55 percent by 2030. Renewable energies bring several benefits such as mitigating climate change, emission reduction as well as improvements in the European energy security[1]. Although the EU even surpassed its' 2020 target of 20 percent, sustained action with an accelerated pace is necessary to prepare the economy and society for the upcoming climate challenges. The drop in CO_2 emissions was overcome rapidly by the uneven recovery from the Covid-induced recession (Figure 3.2.1), which put a major strain on the European energy system with a rebound in coal and oil use[2].The power sector must be further transformed from fossil fuel-based to renewable generation and, at the same time, needs to grow in order to enable decarbonisation of mobility, industry, and thermal energy supply, and reach the climate targets. The recent change in the supply strategy in Europe to be independent of strategically critical gas or oil suppliers is a further boost for renewable energies and efficiency measures. The shortage of materials (e.g. batteries and other electronic equipment) has already had a serious effect on the R&D and direction of developments. Some materials are getting rarer or can contribute to conflicts. Furthermore, there is a growing shortage of skilled workers, which is a huge societal challenge and needs to be compensated by fast technological progress and innovation. Therefore, smarter components are needed to compensate the growing shortage of technical knowledge and skills.

Because of the increasing residual load, resulting from the local mismatch between decentralised renewable generation and load, a digitally controlled transmission and distribution infrastructure is required. Thus, electronic components and systems (ECS) are key to future energy systems being optimised in both design and operation, for high efficiency, low CO_2-emissions, cost, and security of supply. The development of energy systems is driven by action against climate change, booming decentralised renewable generation (solar, wind), digitalisation and AI technologies, as well as cyber security issues. The Energy Chapter highlights the Major Challenges in the changing energy landscape based on electrical energy generation, supply, conversion, and use. Highest efficiencies and highly reliable, secure solutions are required to achieve the change towards a carbon neutral society in 2050.

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1 European Environment Agency (2022). Share of energy consumption from renewable sources in Europe. https://www.eea.europa.eu/ims/share-of-energy-consumption-from

2 International Energy Agency (2021). World Energy Outlook 2021.

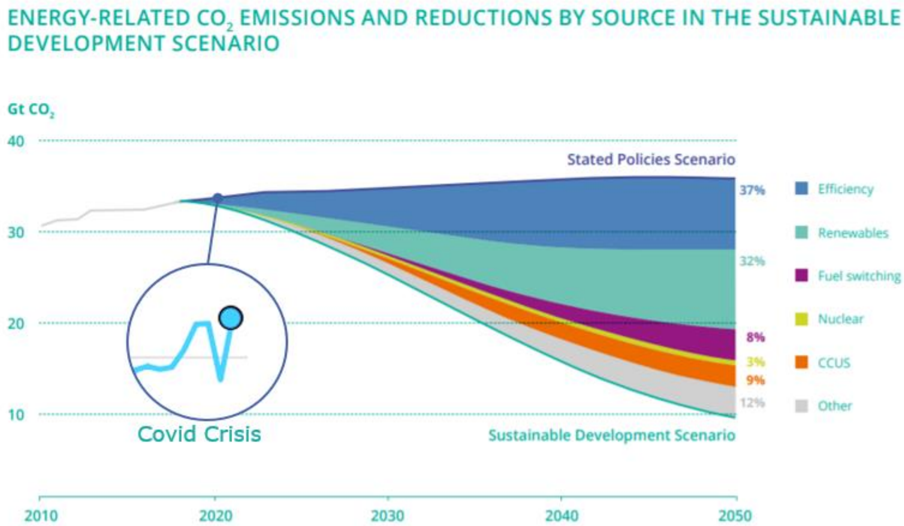

Figure 3.2.1 - Efficiency and renewables provide most potential for CO_2 emissions reductions. Source: IEA World Energy Outlook 2019. In the graph the impact of Covid in 2020 & 2021 is indicated, emission level is back on the levels from before the Covid crisis. Source: IEA Global Energy Review: CO_2 Emissions in 2021.

According to the IEA "CO_2 Emissions in 2023" report for the European Union the trend goes towards less emissions, main factors are an increased renewable electricity deployment and lower emissions in industry. The challenge is to accelerate that trend and manage the challenges coming up by local use and balance to integrate the decentralized highly variable supply into the grid:

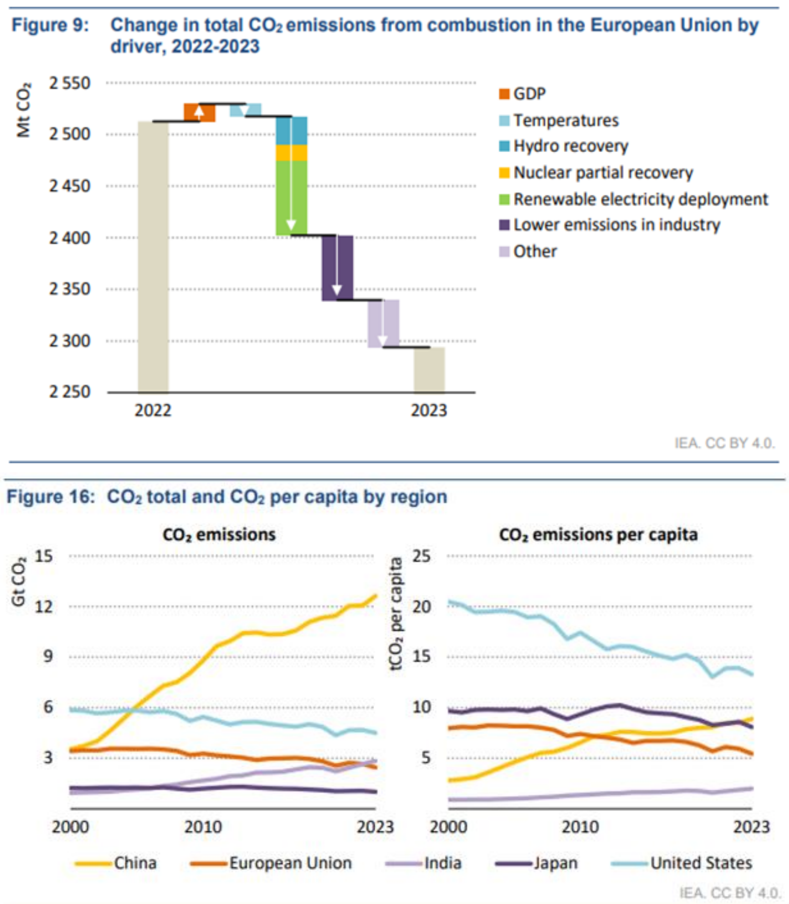

Figure 3.2.2 & 3.2.3 - Change in total CO_2 emissions in the EU & CO_2 emission globally – clear trend to less emissions and dominating factors relevant for less emissions in the EU visible. Source: IEA – CO_2 emissions in 2023: A new record high, but is there light at the end of the tunnel?

3.2.2 Application trends and societal benefits

Application trends

At present, 75 percent of total greenhouse gas emissions in the EU come from the energy sector. The energy world is undergoing a radical transformation: promoted e.g. by EU and national roadmaps, the globally installed capacity of renewable generation has doubled within the past 10 years. Europe alone expanded its renewable generation capacity by 6.4% in 2021. This increase is dominated by wind and solar energy being characterised by strongly intermittent, distributed generation. Altogether wind and solar energy made up one fifth of Europe's electricity generation in 2021 with plant capacities ranging from domestic solar (≤ 10 kW) via commercial solar and wind (≤ 500 kW) to power stations at utility scale (≥ 1 MW). At the same time, the levelised cost of electricity (LCOE) from photovoltaic (PV) sources dropped by 13 to 15%. However, the rise of renewables is still too slow - wind and solar generation growth must nearly triple to reach Europe's 2030 green deal target. In the long term, it enables the substitution of fossil fuel-based transportation, domestic heating, and commercial & industrial processes as well as address the strong economic growth of non-OECD countries. Since the pursuit of all economically viable opportunities for efficiency improvement can reduce global energy intensity by more than 3% each year, increasing energy efficiency may be accountable for 30 % CO2 emission-reduction by 2050 with current policy settings, but can be even increased up to 40 % if worldwide announced climate pledges are met. Energy supply to all sectors affordably and reliably needs to match the demand and availability as efficient as possible (Figure 3.2.4).

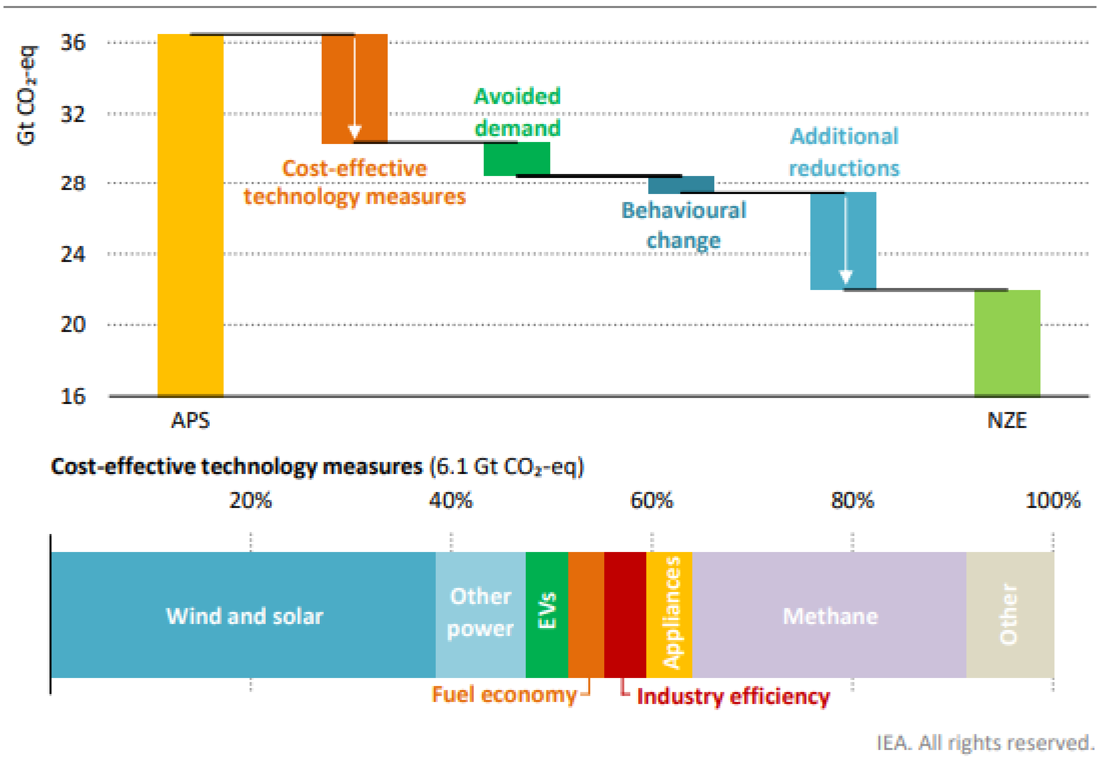

Figure 3.2.4 - Measures to reach the Net Zero pledge announced for 2050. Source: IEA World Energy Outlook 2021.

Thus, the power grid architecture developed for centralised, unidirectional, demand driven power generation will be transformed into a multi-modal energy system (MM-ENS) architecture (Figure 3.2.5). It will comprise distributed renewable generation, energy conversion units for sector coupling, transmission and distribution grids allowing bi-directional power flow, and energy storage for all modes of energy (electric, thermal, chemical). Energy management systems (EMS) will optimise ENS-operation. It will match load and demand at all levels ranging from the nanogrid (behind the meter, building level) and the microgrid (district or community level) to the regional distribution grid, which is connected to the cross-regional transmission infrastructure. Fossil-fuelled power plants, which used to operate on schedules orienting at the demand, will turn into back-up power supply facilities.

The overall reduction of energy consumption in addition to efficiency measures will be always a target, since all energy usage that can be avoided also implies reduction of emissions. This can be achieved by control elements for switching off energy use and zero power stand-by functionality or by transformation to new technologies as in the last decade the transfer to LED illumination had a high impact. Upcoming threats are energy consuming ICT technology related applications like blockchain, AI, data traffic, or digital currencies. The challenge will be to develop highly efficient algorithms and methodologies to decrease energy consumption despite the increased use of these new technologies. Between 2012 and 2018, the amount of computing power required for cutting-edge large AI models doubled every 3.4 months, amounting to a more than 300,000-fold increase [3] and this trend will hold until more research goes in efficiency. Quantum computing have in general the potential to decrease energy consumption for solving specific problems additionally. Already within the design and development cycle sustainability goals, energy efficiency and environmental legislation will need to be taken into account.

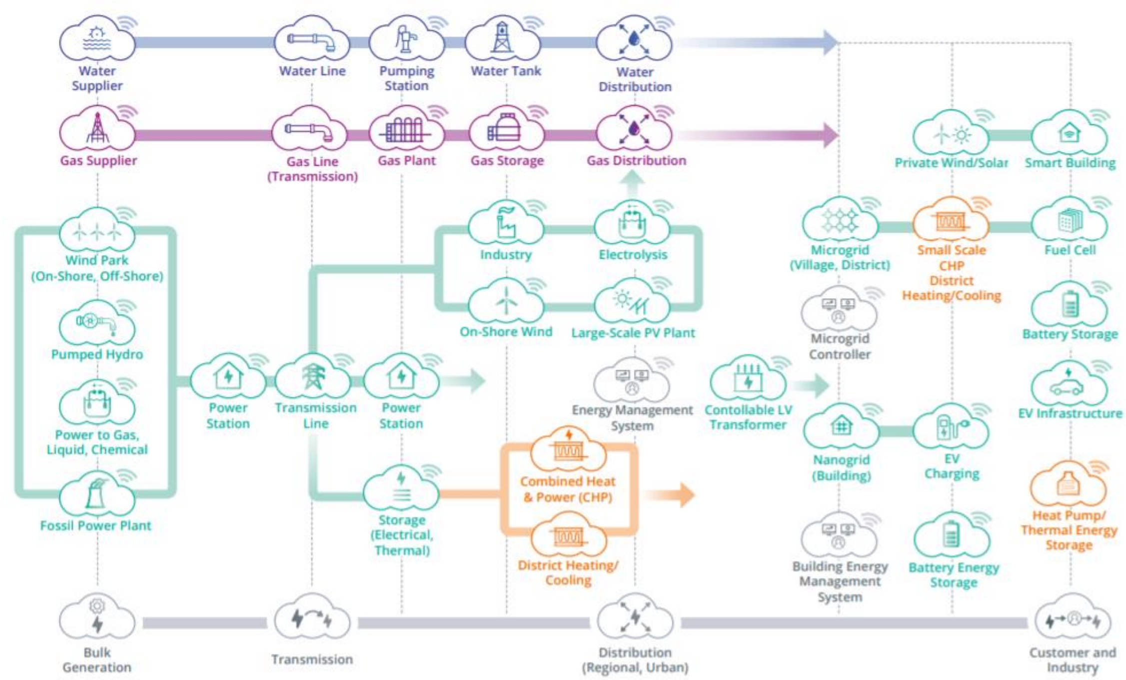

Figure 3.2.5- Interconnected Energy Infrastructure; Source: Siemens Corporate Technology

Key to these new energy applications will be smart sensors, networks of sensors, and smart actuators that enable status monitoring on each grid level as well as smart converters (for all voltage levels). The converters need to use highly efficient and fast semiconductor power devices and modules that enable real-time control of energy system components and grids for optimised operation based on forecasts of generation and demand but also in case of any critical

[3] "Are quantum computers really energy efficient?", Sophia Chen, Nature Computational Science volume 3, pages457–460 (2023)

event. The future grid operation requires a sophisticated information and communication infrastructure including cloud services, IT security, and AI technologies. Altogether, they will contribute to significant reduction of energy consumption and, consequently, CO_2 emission.

To achieve the targets of the Green Deal and to have competitive advantages for European based technologies and solutions, research has to be performed in the following areas:

(1) Significant reduction and recovery of losses (application and SoA-related).

(2) Increase of power density and reduction of losses (e.g. through exploitation of new materials) and a decrease of system size by miniaturisation and smartintegration, on the system and power electronics level.

(3) Increased functionality, reliability, and lifetime (incl. sensors & actuators, ECS HW/SW, semiconductor power devices, artificial intelligence, machine learning, monitoring systems, etc.).

(4) Manufacturing and supply of energy relevant components, modules, and systems.

(5) Management of renewables via intermediate storage, smart control systems, share of renewable energies, peak control or viability management for the increase of energy flexibility. Grid stabilisation through e-vehicle charging.

(6) Energy supply infrastructure for e-mobility, digital live, and industry 4.0.

(7) “Plug and play integration” of ECS into self-organised grids and multi-modal systems, real-time digital twin capability in component and complete system design (to simulate system behaviour).

(8) Safety and security issues of self-organised grids and multi-modal systems through smart edge devices and high-level IT security (resilient communications and trustworthy AI).

(9) ECS for energy storage technologies: production, transportation, storage, distribution, combustion and energy conversion systems.

(10) Optimisation of applications and exploitation of achieved technology advances in all areas where electrical energy is consumed.

(11) Energy technologies in the circular economy approach: predictive and condition-based maintenance with repair, refurbish, reuse and recycle capabilities, LCA of ECS and reduction of environmental impact

(12) Aligning with standardisation of our energy systems.

(13) Manufacturing and world-leading technologies for energy relevant applications in Europe.

(14) Scheduling for cost-efficient energy consumption.

(15) Involvement of the consumer: traceable eco-footprint and incentives towards environmentally-friendly behavioural change.

(16) Design and development strategies of ECS that optimise the total environmental impact of energy solutions (e.g. trade-offs between environmental footprint and handprint, rebound effects)

(17) Innovation strategies for regulations-enabled energy markets and technologies.

External requirements and Societal Benefits

In alignment with the **Parisian Agreements**, the EU committed to substantial reductions of CO_2 emission. In particular, the EU aims to make Europe the first climate-neutral continent by 2050 (EU long-term strategy) while boosting the competitiveness of the European industry. Carbon pricing throughout the EU economy is going to be implemented more strictly. Further climate laws will be introduced and continuing policies will be clarified by the European Commission in 2022. The new policy regarding **"Clean energy for all Europeans package"** was completed by the EU in 2019 as a comprehensive update of its energy policy framework and updated with the new Green Deal in July 2021. It emphasises renewable energy, energy performance of buildings, energy efficiency, governance regulation, and electricity market design. Smarter buildings with more automation and control systems for effective operation shall be promoted. E-mobility infrastructure is going to be supported further. Energy efficiency targets and energy labels were tightened to encourage the industry to innovate.

Figure 3.2.6 - Energy from renewable sources: Wind turbines and photovoltaic (Source: © Mariana Proenca/Karsten Wurth – Unsplash)

To achieve the **Green Deal** goal of “clean, affordable and secure energy” in all sectors, new laws and regulations will be required. While subsidies and regulations will promote sustainable developments in all application domain of ECS (energy, industry, mobility, communication, consumer goods, and cities), the energy domain with targeted 40% renewables in the energy mix until 2030 is the foundation to all of them. Additional perspectives are given by the United Nation’s “**Roadmap 2050**” addressing sustainable development solutions and implementations towards a carbon-neutral global population.

Figure 3.2.7 - Electrification of the transport sector.

All these factors are considered for the roadmaps on research, development, and innovation of ECS for the applications in the energy sector. Potential targets comprise the implementation of electricity storage solutions (e.g. vehicle2grid, battery grid storage), the further increase in efficiency and the reduction in life cycle costs of energy generation from renewable sources (Figure 3.2.6), the electrification of transportation (Figure 3.2.7), and the thermal processes in industry as well as the development of secure, self-learning energy management systems for buildings and industrial sites. ECS as enablers support the EU and national energy targets to achieve sustainability (Figure 3.2.8) and are essential for a highly developed energy landscape towards a fair, democratic, healthy and prosperous society.

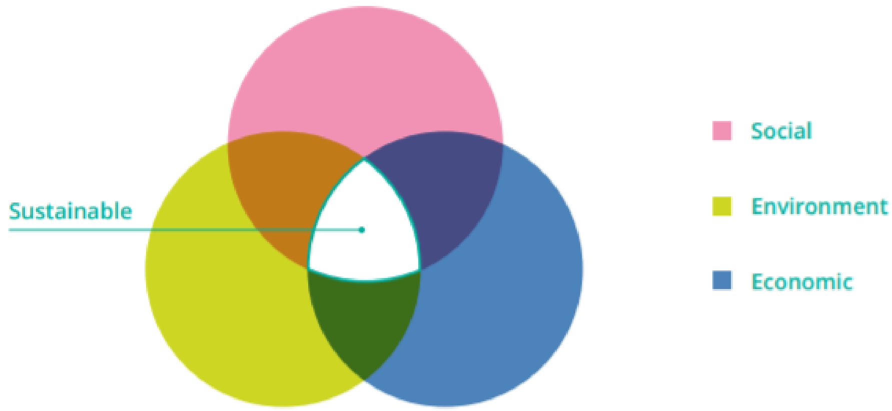

Figure 3.2.8- Three pillars of sustainability (Source: Purvis, Mao, Robinson 2018: Three pillars of sustainability: in search of conceptual origins).

Energy efficiency through ECS fosters economic development towards a circular economy and new employment opportunities. They will have a huge impact on job generation and education if based on the complete supply chain and fully developed in Europe. With more than 11 million jobs in the field of renewable energies[4] and indirectly involved technologies, this is a visible and significant factor for economic and societal stability. The capability of maintaining the understanding of the complete systems as well as the competence from small-scale solutions up to balanced regional energy supply solutions are key to the European competitiveness and success in the global market of energy solutions. Also the consumer itself can contribute its share, thus consumer empowerment to energy savings and efficiency should be taken into account for the development of energy systems. Societal benefits include access to knowledge, development of modern lifestyle and the availability of energy all the time and everywhere – with a minimum of wasted energy and a minimum of greenhouse gas emissions. Therefore, ECS and its application domains enable Europe to meet the needs of the present without compromising the ability of future generations to meet their own needs.

3.2.3 Major Challenges

Five Major Challenges have been identified for the energy domain:

- **Major Challenge 1**: Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems.
- **Major Challenge 2**: Energy Management from On-Site to Distribution Systems.

4 IRENA (2019), Renewable Energy and Jobs – Annual Review.

- **Major Challenge 3**: Future Transmission Grids.
- **Major Challenge 4**: Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply.
- **Major Challenge 5**: Cross-Sectional Tasks for Energy System Monitoring & Control.

3.2.3.1 Major Challenge 1: Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems

3.2.3.1.1 Status, vision and selected outcome

According to the IEA's Efficient World Strategy, digitalisation enhances energy efficiency gains in the transportation and industry sectors[5]. Smart and efficient energy systems are drivers of energy savings. Therefore, they are in full alignment with the Green Deal. Alternative ways of energy generation (hydro, photovoltaic, and wind) and the electrification within the industry, the transport / mobility, and the construction / building sectors result in the challenge of creating smart, efficient, and reliable energy generation, conversion, and storage components.

Smart Energy Systems

For operating smart energy systems, all the energy conversion and storage components need to be equipped with smart actuators and sensors for status and health monitoring as well as optimisation of grid operation. The integration of sensor, connectivity and edge processing in supplementary/additional parts will enable the creation of intelligent facilities by retrofitting. The creation of secure electronic control units requires development of specific hardware and software. Scalable modular renewable energy supply with seamless installation capability brings in or scales up renewables from single households to larger installations.

Consequently, smart control units need to be developed for all types of energy production, conversion, and storage components comprising smart electronic converters, actuators, sensors, security systems and reference communication interfaces. They shall have plug-and-play functionality and real-time digital twin capabilities in component and complete system design to simulate system behavior for evaluation of its' health status.

For offshore energy generation, such as windfarms and tidal energy generators, fibre optical sensors is an emerging technology beneficial for online monitoring of metal fatigue and excessive turbulences. This technology is currently being developed for such monitoring in aircraft wings and ship masts.

Conversion

Electrification of industry is one of the main implications to reach the 2050 decarbonisation targets, mainly via the conversion from fuel-based heating processes to electro-heating solutions.

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5 IEA (2019), Energy Efficiency.

In addition, direct electrification of industrial production processes (such as electro-synthesis of chemicals or electrolysis) is also crucial for replacing present CO2 emitting solutions. In the case of Heating, Ventilation, and Air Conditioning (HVAC) systems, significant reductions in consumption can be obtained by optimizing the system that handles all the processes of energy management or by changing the use of the Machine-to-Machine (M2M) technologies. For both strategies, efficient ECS are required to obtain optimal control functionality based on sensing, collecting, processing, and evaluating device related data. DC power supply requirements based on advanced semiconductor power devices will provide lower power consumption and thus, feature higher efficiency of the increasing ICT energy consumption (i.e. through data centres) . Investments in the next-generation computing, storage, and heat removal technologies will be required to avoid a steep increase on energy demands and to minimise the implications of unavoidable data centre energy use on the global climate. In data centres and 5G/6G networks, photonic ICs can route information streams from fibre to fibre without conversions into electronics in between. This will be highly efficient and save energy. The advanced features of 5G/6G will innovate the use of the technology (Figure 3.2.9), but as consequence of larger data rates and through-puts, cost and energy demand will increase substantially. Therefore, energy harvesting capability of sensors and devices in the 6G environment will be one of the crucial aspects towards a green and cost-efficient technology landscape[6].

Figure 3.2.9 - 5G as enabler of an interconnected smart network. Source: European Commission, Towards 5G.

Power electronics circuits based on semiconductor power devices are used in all conversion processes. Silicon based power devices are approaching their ultimate limits in terms of breakdown voltage, current, switching frequency and temperature capabilities. Next generation power

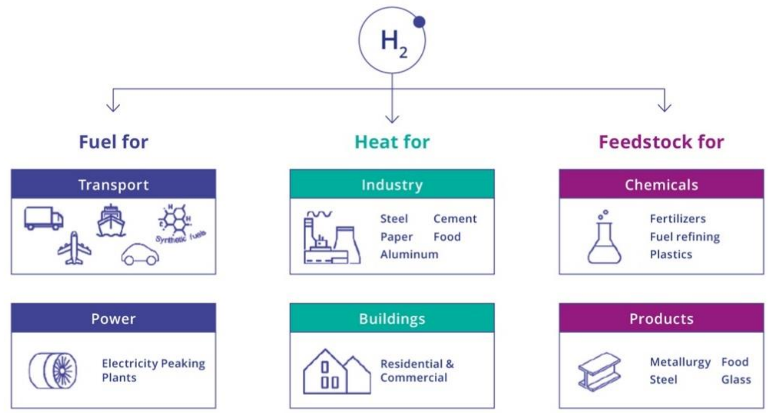
6 Routray (2016), Green initiatives in 5G, 2nd International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB), Chennai: 617-621.

semiconductor devices will rely on Wide Band Gap (SiC, GaN) and Ultra WBG (diamond, Ga_2O_3) technologies. The integration of ultra-wideband gap (UWBG) semiconductors presents a transformative opportunity for power electronics. With thermal conductivities far surpassing those of traditional materials, UWBG semiconductors such as diamond offer unparalleled heat dissipation, enabling the creation of more compact, efficient, and high-performing power modules. Their capacity to handle extreme voltages further enhances device robustness and energy efficiency. As a strategic initiative, prioritizing research and development in UWBG materials could catalyze breakthroughs in power electronics, paving the way for advanced technological solutions that align with the goals of miniaturization, efficiency, and long-term reliability.

Due to this unstoppable trend, research on device reliability, packaging and assembling methods suitable for very high electric fields and high temperature, is strongly required. A focus also needs to be set on the medium voltage grid (< 45 kV) , as the power rating of applications will increase beyond 1 MW (EV charging, BESS, hydrogen electrolyzers etc.) and will be preferably connected directly to the medium voltage. Here, the case of solid-state transformers based on medium frequency transformers will become a cost-effective alternative in the near future and consequently help to reduce the material spending for standard grid frequency transformers. As many concepts rely on a modular approach using power electronics building blocks (PEBB) aspects of coordinated system controls, reliability based on redundancy need also to be investigated.

Storage

Energy storage deployment provides energy system flexibility. Looking at further storage possibilities, different options for various capabilities need further efficiency improvements. As an example, optimised converters, sensor solutions for monitoring, and battery management systems need to be developed for storage options, all including ECS. In power generation, hydrogen with its many uses (Figure 3.2.10) is one of the leading options for storing renewable energy. Hydrogen can be used in gas turbines to increase power system flexibility. In combination with fuel cells, it is also a great vector of clean energy since it allows to produce electricity directly onboard of EV or in areas, which are cut off from the power grid. With declining costs for renewable electricity, interest is growing in electrolytic hydrogen. ECS will be employed in electronics for electrolyzers, fuel cells, as well as power management and health monitoring.



F.X *The many uses of hydrogen (Source: ECS-SRIA 2021 Draft)*

Figure 3.2.10 - The many uses of Hydrogen, source: Bloomberg NEF.

3.2.3.1.2 Key focus areas for increased efficiency and smart energy generation, conversion and storage components

- Increased efficiency at all levels:
  - Power conversion and wide-bandgap semiconductor power devices.
  - Power supply.
  - Energy harvesting.
  - Energy management.
- Residential, commercial, and industrial demand side management (scheduling and load adaption):
  - Sensors, actuators, drives, controls and innovative components.
  - Full monitoring in adaptive and controlled systems.
  - High efficiency electric drives, heat pumps, cooling, HVAC, data centres and other consumers of electricity for variable load operation.
  - Solutions for increasing power demand of 5G/6G systems.
- Development of Energy Management Systems including:
  - Optimisation module.
  - Demand and generation forecast.
  - Customer preferences.
  - Weather forecasts.

  - Price/tariff information/forecast for scheduling controllable loads and generators.
  - Smart sensor network: internal and external physical parameters that influence energy conversion efficiency.
  - Resilient and smart communication and edge devices.
  - Deployment of Trustworthy AI.
  - Fiberoptic sensors for fatigue detection.
  - Converters for power quality improvement (e.g. electronics filters to manage resonances).
  - Sensors and controls for the management of decompression and compression and leakage detectors for methane, hydrogen, and other gases.
  - ECS for the coupling of processes in the chemical and electrical industry.
  - Traceability and labelling of green energy.

- Conversion of industrial processes:
  - "Industrial electrification" (Replacement of CO2-emitting processes by others based on "clean" electricity).
  - Electric drives for commercial & industry applications.
  - Industry 4.0 with combination of Cyber-Physical Systems (CPS), Internet of Things (IoT), Artificial Intelligence (AI).
  - DC subsystems for industrial production / data centre applications and DC distribution grids.
  - Photonic routing in data centres from fibre to fibre without conversion to electronics.
  - Carbon capture technologies compensating production emissions (up to negative emissions).

- Development and application of storage optimised for residential, commercial, industrial utilisation:
  - Control, interfaces to batteries, fuel cells, hydrogen storage electrolysers.
  - Integrated battery driven applications (e-car charging, PV – system local storage).
  - Power Storage to "buffer" net fluctuations and to avoid long distance transmission.
  - Smart storage technologies from low to medium voltage.

3.2.3.2 Major Challenge 2: Energy Management from On-Site to Distribution Systems

3.2.3.2.1 Status, vision and expected outcome

The distribution grid comprises commercial scale renewable generation as well as private smaller renewable power generation units, conversion between different energy modes, storage, control and protection systems for the grid infrastructure together with all kind of consumption.

Autonomous Control Systems

In the future distribution grid, generation and consumption by power electronics systems will surpass the share of synchronous generation. This leads to potential grid instabilities due to lack of inertia. Therefore, autonomous control systems need to be implemented to control the high demand loads. These control systems should be organised hierarchically to adjust the heavy loads according to the actual local production and storage capabilities so that import or export of power is minimised. Price control systems such as TOU (Time of use) can help to prevent grid violations. Storage devices, such as local community storages or e-Vehicles, can be charged when the price is low and discharged when the price is high, to provide flexibility as well as to ensure stability and reliability in the grids.

For industry or larger groups of buildings, control methods increase the flexibility of the total system and can be set up using hierarchical and intelligent control methods to minimise costs and to provide peak-shaving (Figure 3.2.11). For larger power production facilities, hybrid generation and storage solutions are also discussed, which integrate the power production facilities with storage devices to have the best arbitrage cost. Novel grid architectures for manufacturing strive to increase topological and energy flexibility within production cells to enable adaptive production optimisation. Also, blackouts and their consequences need to be prevented, since for example for large industrial electrolyzers they result in serious safety and cost issues.

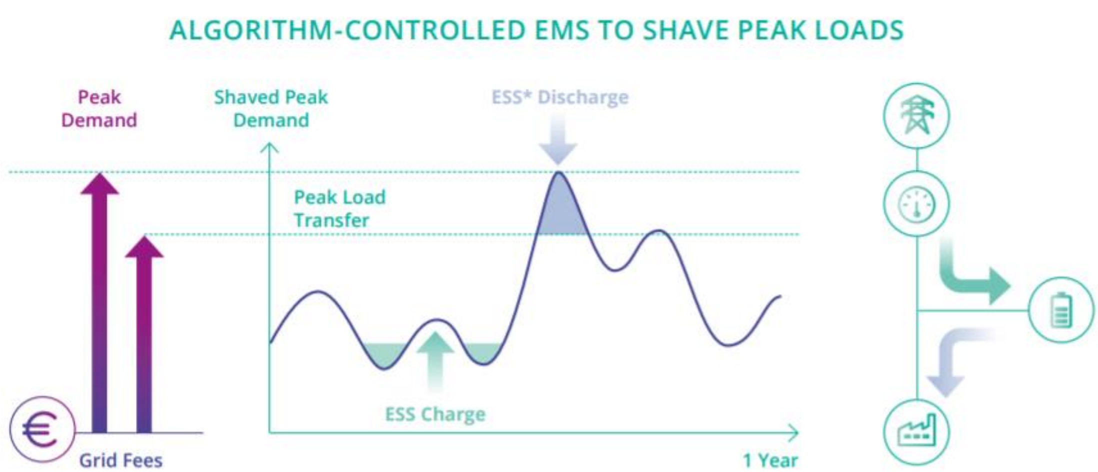


Figure 3.2.11: Visualisation of an algorithm-controlled energy management system to shave peak loads. An energy storage system predicts load peaks and charges/discharges a battery accordingly. Source: EDF Renewables.

Security, Reliability and Stability of Energy Systems

For stable, resilient on-site energy systems, multi-modal energy management systems allowing integration of electricity, heating & cooling, molecules, and transport (e-vehicle charging incl. Vehicle-2-Grid) will be developed. Their features comprise high level IT security, energy trading via local energy market platforms, renewable energy certification, development of solutions for low voltage electronic systems that are easy to setup, as well as support for self-learning against evolving needs.

Energy Management Systems for industrial and residential customers include optimisation module, demand and generation forecast, customer preferences, weather forecasts and price/tariff information/forecast. They require beyond-state-of-the-art techniques for scheduling controllable loads and generators, and to forecast the weather to produce accurate generation profiles. Furthermore, the interface to the grid might be used for additional power quality services based on power electronics converter technologies beyond state-of-the-art reactive power compensation (e.g. virtual inertia and balancing).

3.2.3.2.2 Key focus areas for on-site or behind the meter systems

- Security, reliability and stability of total energy system:
    - Automation of grids.
    - Storage of data.
    - Trustful AI and ML for optimised operation of the grid.
    - Machine-learning based forecasting algorithms for generating accurate generation profiles of expected power production and consumption.
    - Deployment of sensors and edge computing devices to health-check grid assets to increase lifetime and optimise operation.
    - Converters for power quality improvement (e.g. electronics filters to manage resonances).

- Stable and Resilient On-Site Energy Systems:
    - Integration of electricity, heating & cooling, molecules, and transport (e.g. Vehicle2X).
    - Coupling with energy trading systems, e.g. local energy market platforms.
    - High level IT security.
    - Renewable energy certification.

- Hybrid solutions:
    - Integrating power production facilities with storage devices.
    - Arbitrage cost, keeping level of production according to market bid.

- Virtual markets:
    - Flexibility in demand & supply.

    - Aggregation of Energy consumption and production.

- Electric energy supply for manufacturing:
    - Higher uptime using novel industry grids and UPS.
    - Stable power supply using novel electronics converter technologies.
    - Blackout prevention.

- Plug-and-play capability for components, self-learning:
    - Integration of low voltage systems using flexible planning rules.
    - Cost effective solutions to minimise set up-time and manual parametrisation.
    - Reduced physical size and weight of individual transformer stations with equivalent power ratings.
    - Development of solid-state transformers with:
        - New functions for the operation of power systems.
        - Avoidance of infrastructure extensions caused by increasing share of distributed generation.

3.2.3.3 Major Challenge 3: Future Transmission Grids

3.2.3.3.1 Status, vision and expected outcome

New grid challenges

Future transmission and distribution grids will remain an integral backbone of energy systems. Coupling of different domains like electricity, thermal, gas etc. will enable new business opportunities which require new technological solutions for high power electronics, combined with sensors and ICT for monitoring, intensive control and prediction.

The energy generation and energy consumption pattern will drastically change as the industry and society at large will be highly electrified. Base industries such as the chemical industry, steel and cement production will completely change production technology to enable fossil free production and will require extreme amounts of electric energy. New industries such as giga volume battery production factories are planned in several places in Europe7. This together with a massive expansion of supercharger station for private passenger cars and heavy trucks with individual charge capacity of more than 1 MW will put severe challenges on the grid capacity in both networking and electronic components to manage highest possible efficiency. Therefore, further ECS R&D needs to work towards improvements of the grid capacity with the highest possible efficiency (Figure 3.2.12). Thus, continued development of components for HV transmission for 1.2 MV or even higher voltages are needed to roll out an efficient energy

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7 Maisch, M. (2020). Europe’s Gigafactory Boom in Full Swing with Another Plant Announcement. PV Magazine.

transmission over Europe. In addition, new business models must be developed for the electric energy market enabled by the smart grid technology.

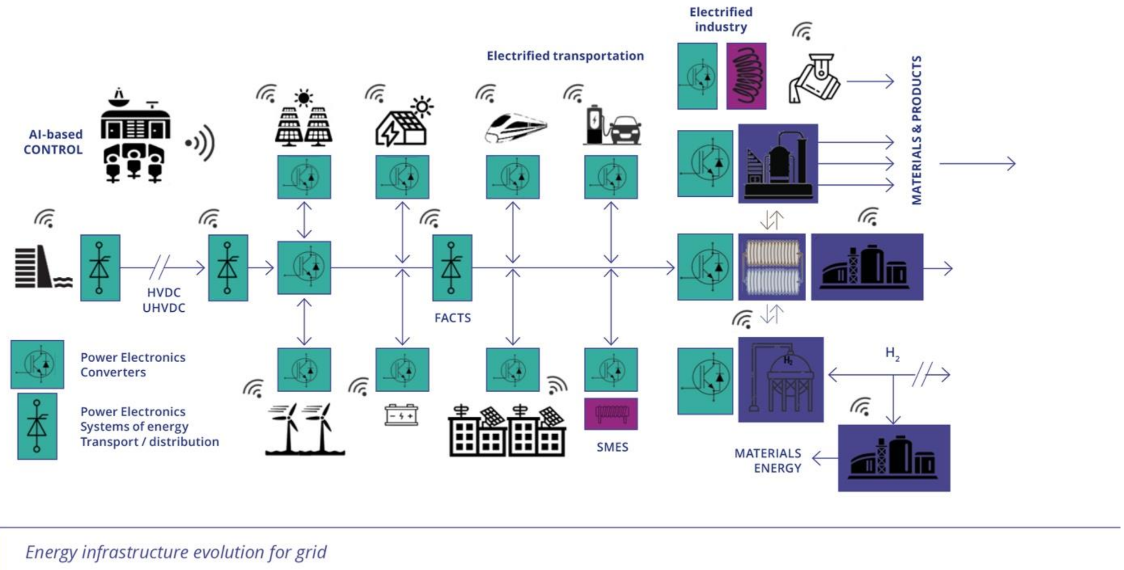

Figure 3.2.2: Power ECS at each point of the future transport and distribution grid. Source: CSIC Scientific Challenges: Towards 2030, Volume 8.

Resilience

To account for adverse conditions caused by climate change, the new national and transnational grids must include autonomous electricity generators based on fuel cells or local storage systems for communications and network information management as well as water-resistant components or modules. Also, sensors need to be placed at critical points to immediately alert authorities in case of unexpected incidents. To be able to quickly react to an electricity line fault, the system will benefit from powerful switches and AI to successfully reroute the systems. Additionally, predictive maintenance (e.g. with digital twins) of the energy supply sensors provides further safety and resilience. Due to the weak tectonic movement in most of the parts in Europe, transmission grids could become much more resilient and loss-less when buried in the ground. Thus, extra isolation technology needs to be considered and critical points equipped with smart ECS for monitoring, control, and prediction.

3.2.3.3.2 Key focus areas

- Grid stability during the industrial transition:
  - Efficiency increases.
  - Development of smart medium voltage grid.
  - Development of components for HV transmission for 1-2 MV or even higher voltages.
  - New solutions for high power electronics, combined with sensors and ICT for monitoring, control and prediction.

  - Development of new simulation and business models to foster innovations regarding grid stability.
- Development of a Trans-European energy infrastructure:
  - Secure, cross-regional transmission infrastructure.
  - Multi-terminal HVDC systems connecting remote energy generation sites.
  - Interaction between distribution systems on community and district level.
  - Development of components for HV transmission for > 1.2 MV.
  - Minimise Losses.
- Requirements on ECS by disruptive changes in transmission and use:
  - Flexibility in system design and operation.
  - Water-resistant components/modules.
  - Autonomous electricity generators based on fuel cells.
  - Modelling, sensing and forecasting weather conditions and thus, supply and demand.
  - Intelligent power devices, systems, and switches.
  - Status-/health-monitoring (e.g. ice sensor/detection) for transmission lines.
  - ECS for multi-modal energy systems.

3.2.3.4 Major Challenge 4: Achieving Clean, Efficient & Resilient Urban/Regional Energy Supply

3.2.3.4.1 Status, vision and expected outcome

A 40% renewable energy share in the electricity sector in Europe by 2030 needs additional decentralised, intermittent energy sources, bi-directional grid and storage for energy supply in transport, industrial and smart cities applications.

Multi-energy Systems (MES)

MES help to achieve optimised energy management. All sectors are integrated to maximise overall system efficiency. Energy flows between sectors and their storages ensure the highest use of renewable energy while balancing fluctuations.

Heating supply uses district heating, supported by heat-pumps and boilers, using thermal storage in the district heating system (Figure 3.2.13). Integration with industry makes use of waste process energy using heat pumps to boost from low (40-50 deg) to high temperatures in the pipe (80-90 deg). Electrolyzers add to the gas system or transport. Water treatment uses excess power from renewables adding further flexibility.

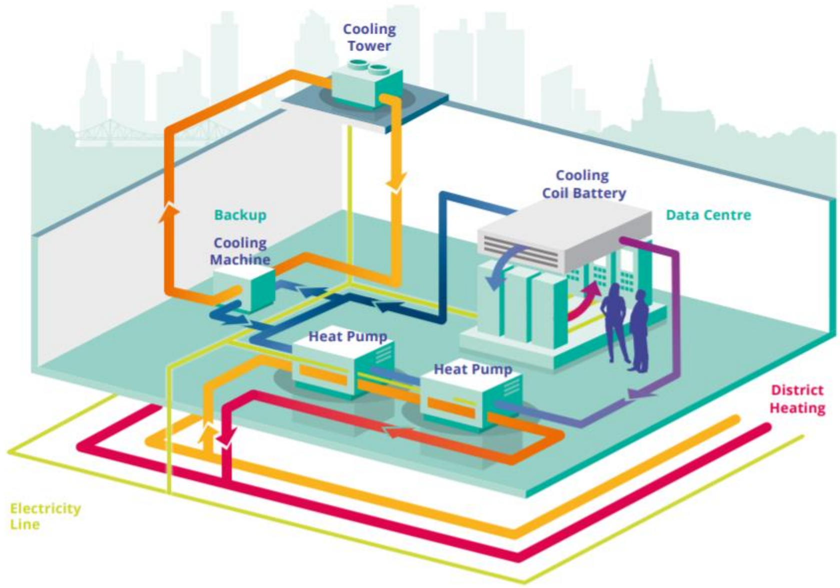

Figure 3.2.3: A Combination of heat pumps and district heating. Source: IEA HPT.

Local communities use MES concepts on regional level. Different local inputs are gathered for an overall aggregated control for the larger regions as well. Autonomous controllers are used behind the meters to support overall control. A clear hierarchical set up, control structure and knowledge of market interactions are necessary.

> Complex integrated control systems use AI, machine learning and comprehensive communication grid/IoT platforms (including edge computing) to get all data for control and optimisation. Risk and security analysis provide resilience and ensure stability of MES.

Urban Transformation

> Emission free cities use electrification and decentralised storages to improve efficiency and reliability. ECS as indispensable components ensure efficient management of data and data storage. AI approaches and the ECS supply chain for integrated applications in energy are key enablers for smart power grids. Electrification of urban mobility supports individual and public transport (incl. utility EV) and furthermore, contributes to the stabilisation of the grid. The first needs household and public charging, the latter uses well defined charging points on (bus) lines or at terminals. Powers vary from 10 kW (LV) to 600 kW (MV). Reservation and optimisation are based on ICT.

Other, crucial aspects of emission free cities are an efficient urban energy infrastructure, low carbon and smart residential and service buildings, low carbon mobility, smart water systems and smart waste management. Even the shift to LEDs without any smart functions can result in energy savings of ~50% in an industrial setting[8]. Carbon capture technologies will add another dimension to the energy systems.

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8 Muneeb A, Ijaz S, Khalid S, Mughal A (2017) Research Study on Gained Energy Efficiency in a Commercial Setup by Replacing Conventional Lights with Modern Energy Saving Lights. J Archit Eng Tech 6: 202.

Storage Solutions

In households, battery energy storage devices can used to increase self-consumption. Some regions will use heat/cooling storage. Algorithms/models for optimal use of storage (community/private/ industrial) are based on technical parameters, demand and generation forecasts, customer preferences, in order to reduce power peaks and to support integration of RES into existing infrastructure.
MES in larger communities with different kinds of storage possibilities (electrical, thermal, gas, water etc.) play an important role. V2X is used as huge distributed electrical energy storage. Systems with electrolyzers might use storage tanks for gas production. Thus, development of grid-supporting control algorithms and supporting regional energy management for communities (e.g. P2P trading via storage systems, self-consumption optimisation) are needed.

3.2.3.4.2 Key focus areas for achieving efficient community and regional energy management

- Electric Energy Supply for urban mobility:
    - Development of household and public charging infrastructure.
    - Creation of HV (wireless) charging points along the (bus) line or at fleet terminals, for public transport.
    - Reservation and optimisation services implemented with ICT solutions.
- Electric Energy Supply for urban life:
    - Increase share of renewable generation, self-consumption (mainly heating/cooling and EV) and building optimisation.
    - Local DC-coupling of various technologies for fast charging at home.
- Regional Energy Distribution infrastructure:
    - Communication infrastructure to support self-organised local energy communities.
    - Sustainable off-grid supply with power electronics-based grid forming capabilities.
    - Virtual power plant functionality optimizing match between generation and demand.
- Operation of connected energy systems:
    - Connectivity, Security, Integrity, Resilience, Variability.
    - Interoperable platform for energy management
- Storage systems:
    - Development of grid-supporting and peak-shaving control algorithms.
    - Support for regional energy management for communities.
    - Peer-to-peer trading by using storage systems.
    - Self-powering systems for small IoT nodes.
    - Local energy harvesting to substitute battery powered devices and eliminate the high demand of energy for the battery manufacturing and distribution logistics.

3.2.3.5 Major Challenge 5: Cross-Sectional Tasks for Energy System Monitoring & Control

3.2.3.5.1 Status, vision and expected outcome

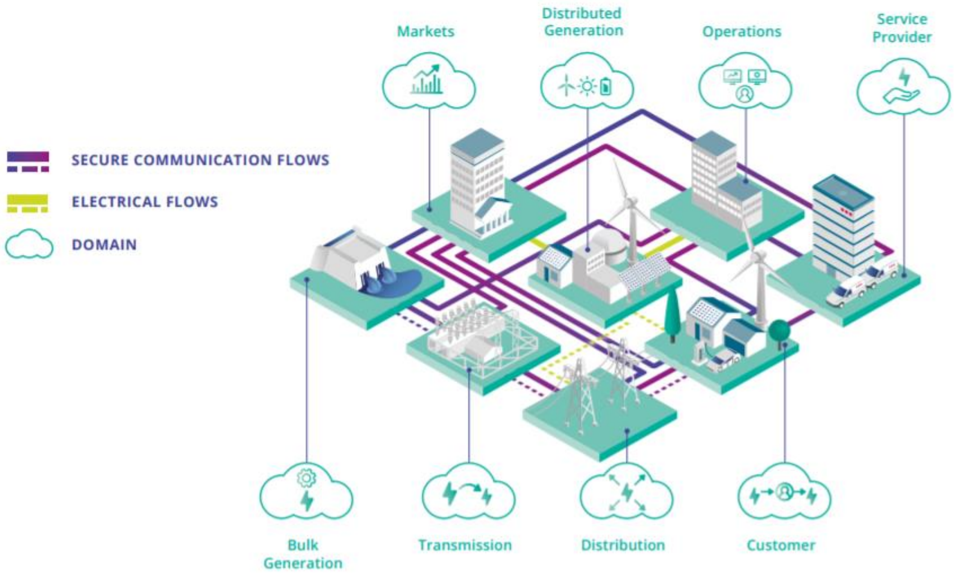

Figure 3.2.4: Interaction of actors in different Smart Grid Domains through secure communication flows and electrical flows. Source: NIST Framework and Roadmap for Smart Grid Interoperability Standards.

Focusing on current energy management platforms, they still have shortcomings in terms of automation, interaction and intelligence. Thus, when the traditional energy grid is evolving into a smart grid, it needs to integrate ICT and power electronics massively. The ECS empower the electrical utilities providers and consumers, improve efficiency and availability while constantly monitoring, controlling, and managing the demands. The huge complex networks need cross-sectional approaches for monitoring and control to achieve efficiency, security and reliability of the communication and electrical flows (Figure 3.2.14) - all based on new ECS technologies.

Optimisation in Monitoring and Control

To ensure security, reliability and stability of the total energy system, it is important to know the current state of the system at all times. Therefore, observability and state estimation together with forecast of expected production and consumption play an important role. This requires automation of the grids, use of sensors at different levels, storage of data, AI and machine learning to operate the grids in an optimised way and at the same time obeying data security and GPDR. Data collection within the grid needs to be limited on chosen parameters to avoid unnecessary costs and complexity. The IoT technology as application in the smart power grid can help to achieve sustainable energy, low latency, and reliability.[9]
Machine-learning used for forecasting energy demand in smart grid environment contributes to medium-term and long-term prediction of consumption and production and is able to solve energy management

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9 Jaradat, M., Jarrah, M., Bousselham, A., Jararweh, Y., & Al-Ayyoub, M. (2015). The Internet of Energy: Smart Sensor Networks and Big Data Management for Smart Grid, *https://hdl.handle.net/10356/81241*

issues through improved accuracy of prediction[10]. It allows administrators to optimise and plan their resources and manage energy inconstancies and variations.
Nevertheless, security concerns and vulnerabilities need to be identified in today's electricity grid and sufficient solutions implemented to reduce the risks to an acceptable secure level.[11]

Energy Management Platforms for integrated energy systems

The European electrical power system is undertaking a transformation process driven by targets towards renewable energy sources. A challenge will be that all different energy infrastructures (electric, thermal, molecules) will be interconnected on high, mid and low power/voltage scale but all have completely different time scales of response. Different energy sources from different operators can be managed through ML, algorithmic trading, agile transformation, etc. In this way, challenges of current and future applications like the energy transition and the digital revolution can be faced appropriately.[12]
Energy Management Systems (EMS) are required to enable efficient and combined operation of multiple energy systems and components. Within a study that quantitatively examined 98 scientific papers dedicated to EMS in buildings and households, the identified focus areas were mostly the reduction of energy costs or peaks, as well as the increase of comfort. Results show that high computation time is a significant weakness of current EMS. A possible solution to that could be heuristic algorithms. Furthermore, the study suggests that stronger focus on high uncertainties and robustness is needed in order to transfer EMS with operational management and scheduling into practice. The integration of forecast methods also needs further attention. Regarding sector coupling (e.g. heat and electricity), major challenges exist due to great complexity and uncertainties over longer optimisation horizons. Moreover, multi-level EMS in combination with cloud computing offer exciting approaches for new research questions.[13]

Hardware

Electrical grids aim to become more distributed, smart, and flexible to meet the increasing electricity demand. For new grids, the trend is to design energy generation and consumption areas together, in distributed form. Therefore, especially power electronic devices play a crucial role to regulate distributed generation and dispersed energy-storage devices together and into the grid. Future power converters also act as edge devices actively contributing to a stable grid either in grid forming devices, virtual inertia and other functions. Hence, the intensive use of power electronic converters in the microgrid brings their control methods to the forefront, which should meet good dynamic response and high reference tracking characteristics[14]. The domain of combining low power and high-power components does require fundamentally new HW solutions. It necessitates heterogeneous integration

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10 Ahmad, Chen 2018: Potential of three variant machine-learning models for forecasting district level medium-term and long-term energy demand in smart grid environment.
https://www.sciencedirect.com/science/article/abs/pii/S0360544218313811
11 Aloul, Al-Ali, Al-Dalky,Al-Mardini,El-Hajj 2012: Smart grid security: Threats, Vulnerabilities and Solutions.
12 Camponesci et al. (2020). ENEL Energy Management Evolution in a growing complexity of the Italian market context. https://ieeexplore.ieee.org/document/9241132
13 Schminke (2021). Overview of the current state of research on characteristics and algorithms of energy management systems in households and buildings. https://doi.org/10.1002/er.6738
14 Bayhan, Abu-Rub (2020). Smart Energy Mangement System for Distributed Generations in AC Microgrid. Quatar Environment and Energy Research Institute, Hamad Bin Khalifa University; Texas A&M University at Qatar, Doha, Qatar.

at the highest and most diverse levels, which leads to unprecedented EMC and thermo-mechanical concerns. It may open the door to developments possible in no other application field. Exemplary, while sensors (e.g. for self-monitoring) placed directly into power switches controlling the energy flow to an entire city, two heterogeneous worlds meet (e.g. kV and pW, MA and nA). The sensors must be able to withstand strong magnetic field changes and temperature fluctuations (300 degrees +), thus requiring research and innovation.

3.2.3.5.2 Key focus areas in the cross-sectional tasks

- Self-adaptive control based on Artificial Intelligence / Machine Learning:
  - Data driven analytics (descriptive, diagnostic, predictive, and prescriptive) in smart grid.
  - Fraud detection.
  - Design, development, and application of deep learning in smart grid.
  - Artificial intelligence in advanced metering infrastructure.
  - Predictive and condition-based maintenance concepts resulting in reduced maintenance costs and increased lifetime for equipment and infrastructure.

- Algorithms for status, prediction & demand:
  - Multiobjective optimisation algorithms in smart grid; e.g. forecasting of generation and consumption.
  - state-estimation based on measurement values, simulation values, trained models (machine learning).
  - optimal utilisation of storage systems (community storage, private storage, industrial storage systems) based on technical parameters, demand and generation forecasts, customer preferences.
  - Short/long-term demand and generation forecast algorithms for different energy domains (electricity, warm water consumption, etc.) and integration into overall systems.
  - New theories and applications of machine learning algorithms in smart grid.
  - Data management, weather forecast, energy use forecast with a time horizon of 24 hours and with resolutions of at least 15 minutes (prevalent use of renewable solar, wind, hydroelectric sources according to demand profiles and use cases).

- Flexibility in management of energy supply and price offers to control the demand and avoid grid congestion
- Technologies for an open distributed energy market

- IT security, connectivity, integrity:
  - Artificial intelligence techniques for security.
  - Smart, secure edge devices for secure data management and control.

    - Energy management systems for low-power/low-cost devices.
    - Smart edge computing and AI for autonomous energy control.

- Hardware Innovation:
    - H-bridge quasi-impedance source inverter (qZSI) for PV Systems.
    - Three-phase back-to-back inverter for Wind Energy Conversion Systems.
    - Ultra-capacitor with high efficiency (95%) and high-power density.
    - New generation of Smart Meter.

3.2.4 TIMELINE

MAJOR CHALLENGE	TOPIC	SHORT TERM	MEDIUM TERM	LONG TERM
		2024–2028	2029–2033	2034 AND BEYOND
Major Challenge 1: Smart & Efficient - Managing Energy Generation, Conversion, and Storage Systems	Topic 1.1: smart electronic control systems for energy conversion and storage	High efficiency converters, smart actuators & sensors, Plug- and Play Functionality, Real Time Digital Twin, Integrated Security System, Status & Health Monitoring, Integrated reference communication interface, self-powering systems for off-grid operation	Further development of intelligent power devices and electronic control towards higher system energy efficiency, lower system costs and integration or newly developed device technologies - 55% GHG emissions	Getting closer to zero emissions (due in 2050)
	Topic 1.2: optimised storage possibilities	Control interfaces to batteries, fuel cells, electrolizers; Optimised converters Sensor solutions for cell and module monitoring Battery management systems Self-powered electrochemical energy storage systems (SEESs)	Grid Integration Further development based on the needs and opportunities by larger volumes	Development of excellent storage possibilities to balance energy generation volatility; efficient energy distribution and usage
	Topic 1.3 electric drives for domestic, commercial & industry application	Heat pumps, cooling devices, HVAC development, innovation and installation	Supplying clean, affordable, and secure (made in Europe) energy to these applications	"In all cases, the 2050 target is to electrify these [...] processes with technical solutions based on renewable ("clean") sources." (Green Deal)

Major Challenge 2: Energy Management from On-Site to Distribution Systems	Topic 2.1: stable and resilient multi-modal energy management systems	Distributed Generation, Interconnectivity: Renewable energy sources and grid connection	Integration of electricity, heating, cooling, and transport Virtual power plant functionality optimzing match between generation and demand; Secure gateways allowing energy trading, Coupling with energy trading systems (e.g. local energy market platforms) Renewable energy certification (labeling	Efficient energy distribution and usage; cost efficiency; high level IT-security
	Topic 2.2: energy management systems for industrial and residential customers	Development of beyond-state-of-the-art techniques for scheduling controllable loads and generators, and to forecast the weather to produce accurate generation profiles Handle uncertainties at industrial sites through ECS	optimisation module, demand and generation forecast, customer preferences, weather forecasts and price/tariff information/forecast; Demand side management for buildings Virtual Energy Market	Energy Management Systems optimizing operation of components for lifetime &revenue
	Topic 2.3: autonomous control systems	Control of high demand loads for efficient energy distribution	Price-control systems Storage devices provide flexibility, stability and reliability in the grids	Minimise costs, provide peak-shaving; hybrid solutions; novel grid architectures for manufacturing to enable adaptive production optimisation

Major Challenge 3: future transmission grid	Topic 3.1: Grid stability during the industrial transition	Development of components for HV transmission for 1-2 MV or even higher voltages New solutions for high power electronics, combined with sensors and ICT for monitor-ing, control and protection	Further improvements on grid capacity with highest possible efficiency Development of business models that encourage new technological solutions	European Energy tran-sition to zero-carbon emissions
	Topic 3.2: Resilient systems for the European transmission grids	Water-resistant compo-nents/modules Autonomous electricity gen-erators based on fuels cells Modelling Intelligent power devices, sys-tems, and switches	Modelling, weather forecast, sensing data Digital twin ECS for multi-modal energy systems (cooling with excessive energy, use thermal capacities)	Multi-Modality across Europe
Major Challenge 4: Achieving Clean, Efficient & Resilient Urban/ Regional Energy Supply	Topic 4.1: Regional energy distribution infrastructure	Secure Cross Regional Trans-mission Infrastructure communication infrastructure to support self-organised local energy communities	Sustainable off-grid supply with power electronics based grid forming capabilities	Energy flows between sectors and their stor-ages ensure the high-est use of renewable energy while balancing fluctuations
	Topic 4.2: Electric energy supply for urban life and mobility	Development of household and public charging infrastructure; charging points on bus lines or terminals Reservation and optimisation services implemented with ICT solutions. Bi-directional charging and grid stabilization solutions	Increase share of renewable generation, self-consumption (mainly heating/cooling and EV) and building optimisation Local DC-coupling of various technologies for fast charging at home Sector coupling of large energy users (e.g. harbours, airfields) with urban users (electric cars, households,	Emission free cities with electrification and decentralised storages to improve efficiency and reliability

	Topic 4.3 Storage systems for urban communities	Development of grid-supporting/forming and peak-shaving control algorithms Battery energy/ heat/ cooling storage devices for households Integration of fuel cells and electrolyzers	Peer-to-peer trading by using storage systems; Self-consumption optimisation	Support for regional energy management for communities

Major Challenge 5: Cross-sectional Tasks for Energy System Monitoring & Control	Topic 5.1: AI, machine learning and algorithms for status, prediction and demand	Data driven analytics and deep learning in smart grid; AI in advanced metering structure; smart sensors with improved data processing; stream processing for real time application	Innovative approaches ensuring clean, secure and affordable energy for EU citizens; multiobjective optimisation algorithms in smart grid; optimal utilisation of storage systems; short-/long-term demand and generation forecast algorithms for different energy domains	Safe and interconnected smart grid netword; cross-sectional approaches for energy monitoring and control; integrated energy systems; optimal match between generation and demand; energy flexibility
	Topic 5.2: IT security, connectivity, integrity	Smart, secure edge devices for secure data management and control	Artificial intelligence techniques for security	Eliminate security vulnerabilities as best as possible
	Topic 5.3: Hardware	Improvements in robustness of HW devices to withstand strong magnetic field changes and temperature fluctuations	Good dynamic response and high reference tracking characteristics of power electronic converters; new HW solutions to combine low power and high power components	Optimal regulation of distributed generation and dispersed energy-storage devices; robust devices able to control high energy flows