Digital Energy

- Topics for research and development

Contributions to the Norwegian Smartgrid Centre from

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December 2019

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Introduction

What research topics and challenges do you/your research group see under the heading "digital energy" that you think is relevant in the Norwegian context?

This question was a part of an invitation from the Norwegian Smartgrid centre to different national R&D communities in Norway This document is a compilation of the response.

What research topics and challenges do you/your research group see under the heading "digital energy" that you think is relevant in the Norwegian context?

SINTEF (Energy and Digital)

There are many research topics that are relevant in a Norwegian context. They have been grouped below into some bulk categories to structure them. There are overlaps between the categories, and also interdependencies. It is important in the assessment of each research topic to realize the dependencies this topic has on enabling technologies and other advancements needed to bring impact from the developments in any given field.

Decision support and automated processes:

Decision support and automated processes is an active field of research in many parts of the energy system. In this context it is particularly aspects related to power generation, transmission and distribution that are deemed central. Decisions needs to be made both with respect to long-term investment needs and shorter-term operational considerations. There are research challenges connected to both these aspects. Some exemplifications are mentioned below:

- Visualization of information, sorting/prioritizing events/alarms/messages to display the operationally relevant and critical ones in different contexts. This would largely support the daily operation of the assets connected to the grid such as hydro power stations and other generation equipment and the operation of the grid itself such as switchgear and cables.
- Shortening the gap between data gathering and decision making/makers by determining good processes or decision models. It is important that there exists good processes and decision models that allows the gathered data to be effectively translated into better decisions. Such as clear decision metrics and responsibilities.
- Exploiting analysed data as input to optimization methods, to provide efficient decision support in complex planning and management situations. Such situation could be building of new lines, upgrading of infrastructure such as transformers or the establishment of new reserve capacities.
- Investigate the possibilities and consequences of digitalization of control systems and processes to make operations more effective and reliable with respect to optimization of production in a more complex energy-mix with shorter market time-lines, effects on the grid from changes in the load pattern or to increase the flexibility offered by end-users.
- Develop solutions for automatic data collection, quality control, washing and formatting to a standardized format for utilization in data-driven processes

Data-driven methods and data analytics:

The developments in computing power, data availability and data driven methods is underlying the digitalization of the energy system. There are many research questions that arise as a consequence of this development, and some are given below:

- Investigate possibilities for applying machine learning techniques in a wide variety of applications such as for:
    - Flood forecast
    - Predictive grid fault detection

    - Load, generation and transmission capacity forecast
    - Asset management optimization or input to such
    - Technical state prediction (faults, degradation, …)
- Combination of machine learning techniques and domain knowledge into hybrid models in order to utilize the potential of these techniques in areas such as predictive maintenance, fault localization and operational optimization.
- Combination and standardization of databases on national/European level to provide statistical data sets large enough to do efficient training of data-driven models
- New analysis methods for AMS data gathered on a national level in order to enable for example better load-profiles (actual and forecasted), surveillance of the power quality, more effective interruption of supply detection and input to the DSOs knowledge of the state of the grid for their end-users.

System analysis, the combined effect of a large number of componentsand actors

The energy system is comprised of a large number of components, however there are also issues and research questions connected to the behaviour of these components as a system:

- Enable aggregation of flexibility from end-user up to the TSO level, finding efficient aggregation and disaggregation mechanisms and connected market solutions for the interplay between these.
- Facilitate for demand-response methods to be widespread deployed and study their effect on the energy system
- Investigate the interaction between different energy carriers such as electricity, district heating and gas on different geographical levels such as neighbourhood, city, region, national and European. By doing so the flexibility of combining energy carriers will be mapped and synergies between them identified. Multi-carrier energy solutions are expected to play a central role in city development, and this will have implications both on more local scale such as in neighbourhoods and on larger scales such as national and European.

Security aspects:

The ongoing digitalization of the energy system poses great opportunities, but also holds treats with regards to security and reliability that needs to be addressed in a structured manner:

- Ensure the robust and secure operation of the energy system (production, transmission, distribution and consumption aspects) given the treat of cyber-attacks while at the same time ensuring efficient operation and data exchange for the introduction of new services.
- Effects and possibilities of novel networking solutions (such as 5G) and data exchange platforms with respect to security.

State-estimation:

Knowing the state of the energy system at large and specific portions of this in particular is key to efficient asset management and systems operations. This is an active area of research that has great potential:

- Continue the maturation of the use of digital twins based on models and sensor data. Presently there exists piecewise solutions for parts of the energy system such as grid models and some component models, but the potential for extending this coverage and combing existing twins is large. Additionally, there is a large potential in making the twins run faster

than real-time to give predictions on future behaviour of the power system, building scenarios on a range of assumptions. This could be applied to network users and major components in the power system, including wind turbine systems, hydro-power generators and utilities, buildings and distribution grids to name a selection.
- Remaining lifetime assessments of generation and grid components based on physical, hybrid or purely data-driven models. Alongside this work to assess the validate the models towards observations to assess their usability as well as physical experiments both to build the models and to validate them.
- Utilization of data from different sources to enhance the understanding and certainty of the operational state and remaining life-time of components such as rotating machinery, switchgear and lines. This could include meta data on a given asset, the load profile of the grid the component is connected to, the weather in the area and projections on the expected usage of the given component.

Effects of digitalization:

It is expected that the digitalization of the energy system will have effects on many aspects of the system. Some trends that are assumed to be significant include changes in the energy market and the behaviour of the actors in the various existing and emerging markets, the introduction of new energy generation techniques is expected to increase and change the energy-mix considerably, changing loads and end-user behaviour is expected to be dependent on and facilitated by digitalization and the increased interconnectivity and decentralization of energy production will be closely linked to digitalization efforts.

- Investigate the effects of different tariffs such as capacity-tariff. Both with regards to social aspects and with respect to consumer behaviour and impact on the grid and energy usage.
- Investigate possible market design and balancing needs in the context of changed tariffs.
- Market design aimed at achieving the emission reduction/zero-emission targets

Social aspects

The energy system is ultimately in place to provide social welfare, it is important that this aspect is not left out of the R&D agenda:

- Study the effects of changes due to digitalization in a social context to ensure that the development of the energy sector digitalization results in socially acceptable solutions.

Norwegian University of Science and Technology, NTNU

Department of Electric Power Engineering (IEL), Department of Information Security and Communication Technology (IIK), Department of Mathematical Sciences (IMF) and Department of Computer Science (IDI)

Reliable real-time communications

The research focus is on modelling and simulation of next generation communication networks architecture and their characteristics.

- Changes in communication network architecture are affecting both local area networks, which will increasingly be based on software-defined networks that offer more flexible and feature-rich environments, but at the same time make characterizing their operation including quality of service more challenging.
- Similar changes also arise for wide-area networks, particularly where reliance on dedicated proprietary networks is reduced. This requires advanced techniques for modelling and simulation of such networks and their characteristics.
- Beyond operator errors and faults, moreover, deliberate attacks may also target such communication network infrastructure and require in-depth studies on their prevention and detection.
- Changes in communication network technology such as penetration of 5G networks offers the ability to substantially enhance the number particularly of sensors and measurement frequency in power systems even with real-time characteristics, but also at the cost of increased complexity of the network itself; a clear understanding of network structure, performance and resilience also in the presence of faults and attacks
- Smart grid distribution networks are also anticipated to be tightly integrated with smart city environments, necessitating research on the ability to exchange large volumes of data with heterogeneous trust relationships also transitively and utilizing this information for optimizing the network and decision support. These activities can be partly analyzed in laboratory environments, which can also serve as a test bed and model validation environment.

Robust operation; monitoring and control systems

Research focus is on securing intelligent transmission systems, wide-area and distributed monitoring, as well as control architecture and algorithms for transmission and distribution systems. A common theme across the areas is timing and real-time behavior and its impact on security guarantees, a fundamental modelling problem in information security that has seen limited research, for which power systems are an outstanding example, and where model validation is important.

- Securing Intelligent Transmission Systems increasingly including power electronics facilitating flexible alternating current transmission system (FACTS), but which require monitoring and active control as well as integrating high-voltage direct current (HVDC) links places far higher requirements on the reliability, robustness, and security of the monitoring and control system of transmission networks than was the case traditionally. An important R&D challenge is how to coordinate all the new controls, and further to integrate the controls with on-line used of system-wide monitoring and security analysis tools.

- Current practice in power systems is to consider contingencies, but more complex interactions in power networks requires new methods particularly for sequential “n-1-1” contingency modelling and mitigation.
- The wider adoption of PMU measurements offers opportunities to greatly enhance the accuracy and timeliness of state estimates, ultimately allowing more robust and efficient management of power networks, but require secure and trustworthy measurements as well as robust, reliable real-time communications. There is a need to develop better state estimators and (PMU-based) wide-area monitoring and control systems in order to make optimal use of generation as well as demand flexibility in maintaining power balance at all times.
- Interactions within and with the distribution network are more fine-grained than in transmission networks, with larger numbers of entities interacting and on different trust levels. Resilient distributed monitoring and control architectures and algorithms are therefore a research challenge to guard against errors, but also against deliberate attacks.
- Smart distributions grids, particularly where electric vehicle penetration is increasing, must rely on intelligent and secure demand management and response as dimensioning of the power network would otherwise be un-economical; this must take into account load characteristics as well as the state of the distribution network up to islanding.
- Closely related to this is the integration of storage and local generation into management of power networks, which may be critical to maintain stability of distribution networks.
- Securing such systems in all operating modes, and determining anomalous behavior that may indicate compromise in realistic operating environments requires modelling of cyber-physical system behavior and adversarial activities to ensure that effective and efficient control is retained; this is particularly pertinent to digital twin systems relying heavily on the ability to model and match the target system’s behavior based on state estimators. The ability to co-emulate interactions with the power network allows the study of models and adversarial interaction that would otherwise be difficult to replicate in a purely static or simulated environment.

Combination of data sources, stochastic modelling

The research focus is on understanding and correctly handle the uncertainties connected to the different part of the electricity system, both on the consumer and the production side.

- Understanding electricity consumption is the key in optimizing the future electricity grid and production. Stochastic modelling allows to account for several data source, with different degree of accuracy, availability and spatiotemporal detail; for example, smart meter data, official energy consumption statistics, district heat data and meteorological data. All these data sources can be combined to study consumption patterns and their spatiotemporal variations. Better knowledge of consumption patterns can help utilities to optimize their current power generation and identify flexibility in the electricity grid.
- Forecast of consumer needs is also a key feature, accurate short-term forecast would allow the system to adjust to the consumer need. Given the large amount of data available, and the need to continuously update the forecast, it is important to develop computational methods that allow models to be update fast.
- On the production side, renewable energy sources, like wind and sun, are characterized by high spatiotemporal variability and high degree of uncertainty. Understanding such variability is essential for planning an optimal electricity grid. Stochastic modeling of the most relevant weather variables, like temperature, precipitation wind and solar radiation is a challenging task as one needs to consider the spatiotemporal patter of each variable but also the covariance between the different variables.

- Producing accurate and reliable forecasts of wind, solar and hydro power production, is essential to optimally integrate renewable energy into power systems and new and better models are needed. Fully probabilistic forecasting allows also to quantify the forecast uncertainty in a correct way.

Microgrids, Digitalization in Power Distribution and Digital Control of Power Electronics for Cyber-Physical Systems

The research focus is on modern power system operation and control; unlocking the potential of power electronic converters in electric grids through advanced control schemes enabling monitoring, coordination, and integration among different electrical subsystems. Important research areas are research activities/tools/technology/methodologies for:

- Design and analysis of microgrids, and digitalization in control and operation of power distribution networks.
- Dynamic modelling and simulation of power systems with a high share of power electronic devices, such as applied in microgrids and smart distribution grids.
- Integration of distributed generation such as photovoltaic (PV) systems, and more electrical vehicles and energy storage systems.
- Design, analysis and control of complex power systems; integrating ICT, power electronics and conventional power grid components.
- Application of information technologies (such as blockchain) in operation and trade of electric power and energy.
- the role of digitalization in improving productivity, efficiency, stability and sustainability of electrical energy conversion systems
- digital control algorithms (e.g., model-predictive control, adaptive controllers) and their implementation on digital platforms (e.g. FPGAs, high-speed digital signal processors and System-On-Chip integrated circuits)
- optimized control techniques for emerging power converter topologies
- control coordination for large-scale interconnected power grids and cyber-physical systems.
- Laboratory work, including design, control, implementation, and validation of power electronics applications for the grid integration of renewables and energy storage.
- Real-time simulators with hardware-in-the-loop testing.

Digital Power System Protection (and Control)

The research topic is relay protection and wide-area protection, including relay planning and testing, real-time simulation and the use of phasor measurement units in power system monitoring, protection and control.

- While traditional relay protection today is mostly based on digital technology, there are significant research challenges; in particular related to the increasing amounts of renewable and distributed generation. As more and more generation (and consumption) is connected via power electronics converters, the entire grid protection philosophy needs to be revised.
- New measurement and communication technologies must be fully utilized, such as made possible by Phasor Measurement Units (PMUs). The vast amount of high resolution time-stamped measurements that becomes available must be turned into useful information. This can be applied for system protection and control purposes, where the overall aim is to

maintain the security of supply and avoiding large scale blackouts in a power system that is rapidly changing.

Power system planning and optimization

Power system operators and planners are facing a system that is exposed to larger and more frequent variations as well as uncertainties in generation and demand. Thus, flexibility is needed on all levels to maintain stable and secure operation of the interconnected power systems. The research focus is on the role of digitalization in improving power system planning, operation and control, efficiency and stability.

Related to system planning and market design, there is a need to further develop system optimization and design tools that fully incorporate the challenges and changes needed towards the realization of a 100% renewable electric power system in Europe and world-wide. To this end, there are numerous research challenges that need to be addressed:

- As the power system complexity is increasing, there is a need for improved continuous prediction of power flows and voltage fluctuations in the grid. Fast and accurate computation techniques for optimal power flow, taking into account short-term uncertainties are needed for on-line operation.
- New types of loads and generation such as EVs and PVs needs better forecast techniques, which could be based on physical load/weather models, reinforcement models or a combination.
- Battery energy storage and demand-side flexibility is expected to play a vital role in smart grids. New algorithms and computational techniques are needed for optimal operation of these in multiple market and for different grid services.
- With more distributed renewable energy sources owned by many small actors such as households and small enterprises, there is a growing interest for new ways of selling the energy. This can be through local markets, peer-to-peer solutions, through aggregators, directly to the main power pool, and by the use of long-term contracts. To optimize and plan generation and loads in each of these market mechanisms is a challenge of its own, with respect to the best utilization of available resources. It is even more complex to operate in several of these markets, and may not be tractable for traditional optimization models. Alternative techniques based on Machine Learning and Artificial Intelligence should therefore be exploited.

Digital twin technology

IEL is presently active in the application of digital twin technology particularly for two key components in the power system: electrical machines and circuit breakers. Some research topics and activities in this regard are:

- For an electrical machine, it could be smaller subsystems (or internal processes) like a bearing model, a ventilation model, a thermal model, a mechanical (eccentric) model, an electromagnetic model or even a larger multiphysics model. Relevant fields of study in electromechanical systems includes:
  - Digital prototyping in the design process of a system.
  - Learnt lessons of operation for identification of possible improvements in the design stage.
  - Online prediction of thermal capacity and thermal expansion for overload operation of machinery for optimal control and utilization of all components.

  - Tracking of machine health by monitoring of insulation characteristics, electromagnetic vibrations, etc.
  - Tracking of maximum efficiency during different modes of operation.

- The reliable operation of circuit breakers is a key requirement for optimum operation and control of future power grids. The circuit breakers are exposed to different stresses and degrade gradually. The main research activities and needs in this regard are related to development of a holistic dynamic degradation model (digital twin) for the circuit breaker,where different condition monitoring techniques applied to the operation mechanism of the circuit breaker (e.g. analysis of the coil current, motor current and vibration) or to the current interruption chamber (e.g. contact erosion and nozzle ablation), are combined with the actual stresses applied to the circuit breaker to virtually estimate the dynamic condition of the circuit breaker.
- The developed model is continuously refined based on the measurements, and is in close interaction with the other components in the network. In this context, a collaboration with the Center for Technology Innovation – Energy within the Hitachi Research and Development organization has been planned. The main focus of this collaboration, commencing in August 2019, will be the feature extraction based on advanced mathematical methods for the purpose of early stage prediction of failures in operating mechanism of circuit breakers.

(Digital) Solar PV Systems

The research topic focuses on the integration of solar PV systems into the electrical grid and power markets. Some relevant fields of study may be:

- The use and relevance of PV in a Norwegian/Northern context
- Data acquisition and analysis for PV systems (real time, historic, forecasts)
- Integration of PV in off grid systems, grid connected systems, microgrids and picogrids
- Characteristics of different types of PV cells and modules
- Protection of PV systems – e.g. diagnostics and measurement methods, typical error mechanisms and faults on solar cell modules and systems, power loss resulting from partial shading and mismatch loss, behaviour at fire
- Normal operation of PV systems, mode of operation, Maximum power point tracking (MPPT), network services
- Design and simulation of PV systems – e.g. expected energy production, sizing of a stand-alone or integrated PV systems, performance characteristics, connection criteria, simulation software, adaption of inverters
- DC power grids in buildings (data centres, LEDs, valves, power windows, batteries)
- PV integration in buildings (BIPV) and infrastructure (IIPV) – e.g. commercial buildings with cooling, integration in roads, noise protection, tunnels and other infrastructure
- Challenges with the operation of PV – e.g. grid quality, market models for the future power system, design of solar parks, interactions with battery systems, integration in buildings
- Business models for PV owners, participation at the energy market, interactions with DSO or local grids
- PV integration in energy autonomous electronic systems – e.g. cars, planes, boats

Electrical Energy Informatics - Blockchain Technology and Artificial Intelligence for Electricity Markets and power system operation

The research focus is on the deployment of Blockchain (BC) Technology, Artificial Intelligence (AI) and Big Data (BD) for Electricity Markets and Power System Operation. Considerations regarding Cyber and Information Security should be integrated in all research topics.

- For wide-spread acceptance of BT and AI in the electricity sector and consequent extensive deployment, conceptual frameworks need to be systematically developed, followed by simulation-based evidence to design architectural support for the possible design alternatives, further leading to field testing and demonstration through prototype deployments (small- and large-scale).
- For deployment in the electricity sector, the Blockchain technology design's feasibility with a view to scalability, extensibility, interoperability, and energy efficiency of computational resources is also an underlying research theme.
- Flexibility and transactive energy mechanisms in the electrical energy trading processes (wholesale markets, local markets, and peer to peer trading of green electric power)
- Better integration of renewable energy resources using smart contracts, and creation of new power grid management tools.
- Investigating transmission and distribution system operator related innovations by exploiting the complementarity between BT, AI and BD
- The impact of big data, artificial intelligence, machine learning, and blockchain technology on the shape and structure of the electrical energy sector of the future.

Vulnerability of digitalization (cyber security)

- Like other infrastructures power system operation and control is increasingly dependent on digital information and communication systems. Thus, the vulnerability of the digitalization itself, and the interplay with the power system, is an important subject for further research.

University of Oslo, UiO

Energy related research at the Department of informatics is concerned with how to exploit and improve state-of-the-art ICT methods, tools and techniques to achieve sustainable energy generation and use.

Electrification of transport

There is a need to develop better solutions for EV charging towards a more optimal use of *all* charging resources (private, public, home) with the goal of reducing queueing time, reduce peak loads, and avoid overload of local transformers. Relevant research topics include:

- Novel business models beyond time-of-use electricity pricing, to incentivize off-peak charging and manage peak loads, respectively including business models for EV-to-grid and EV-to-EV (in general, EV2X) which are not presently available.
- Electric energy sharing and trading methods for local/neighborhood energy production (mainly PV) and with local storage including EVs as mobile energy storage.
- Optimized use of a (super) fast charging infrastructure for nation-wide electric mobility. The research should address issues of the expected continuously shifting demand pattern for EV charging over time (underutilization in periods, long charging queues in other periods due to peak demands), and the resulting challenge of making commercial chargers economically profitable.
- Real-time data acquisition from electric vehicles and charging stations, while ensuring security and privacy, to enable optimized use of the charging infrastructure. The research will need to take current and emerging regulations into account (e.g., GDPR), and resolve issues of data ownership and usage, data quality, data protection and privacy, security and liability.
- Interoperability of EV charging infrastructures among different provider solutions: A significant number of companies and organizations, from global corporations to innovative start-ups, are developing services for EV-drivers, deploying charging infrastructure, and overall, working on products and services that will make driving and electric vehicles as convenient as its petroleum-powered counterpart. However, interoperability among these actors is a key challenge for a nation-wide (and beyond) charging infrastructure and, if left unresolved, will be a counter-incentive to further uptake of electric driving.
- Digital vulnerabilities in the charging infrastructure are seldom studied in the research community and need to be strengthened. When connected to the Internet, such vulnerabilities may easily spread from individual EVs and from the charging infrastructure itself, to the electric power grid. Attacks may lead to grid instability and even black-outs. Solutions are needed for trustworthy EVs and charging infrastructures.

The role of blockchain technology and machine learning

Blockchain technology and smart contracts are being considered as very promising for many applications, including decentralized (P2P) electric energy markets, billing, and for trustworthy energy-related IoT (including metering). However, there are several issues with current technologies for their use in the future electric grid (in particular lack of scalability to handle huge amounts of micro-transactions, and trusted smart contracts). Machine learning techniques are considered important for a wide range of applications in the future electric power system. Research topics include:

- Performance studies and evaluations of emerging blockchain and smart contract technologies to assess their suitability for various purposes in the energy sector.
- Novel business models and mechanisms for community level intelligent energy management enabled by blockchain technologies and computational intelligence.
- Scalable and energy-efficient blockchain consensus protocols suitable for the energy sector. We believe tailored solutions for the energy sector must be sought for as “no size fits all”.
- Trusted and confidentiality-preserving smart contract systems.
- Improvements of optimization and machine learning methods are needed to handle realistic energy-related learning and optimization problems at large scale and in real time.
- Investigations of novel use of machine learning techniques in a local energy neighborhood context, including prediction of demand, end-user and aggregated flexibility at community level, and end-user and community level aggregated energy generation and storage.

Data acquisition and management

There is a need for research focusing on methods for trusted data collection and controlled usage in light of increased level of cyber-attacks and new regulations like GDPR. Research topics include:

- Solutions for secure, trusted and privacy-preserving data collection, quality control, storage, and use.
- Data-driven methods and data analytics, both of data-at-rest and data-in-motion (off-cloud computing).
- As the electric grid will be more and more intertwined with other city infrastructures there is a need for research on trusted mechanisms for sharing, protecting and merchandizing data among diverse stakeholders for optimizing resource usage and creating innovative services.
- While emerging networking technologies, like 5G and beyond will be key enablers for data acquisition, research is needed to understand how network, data and computing resources can be efficiently orchestrated in a scalable manner to support real-time applications, and how diverse infrastructure across multiple domains can be effectively managed by various tenants when providing communication services with different requirements.

Green computing

Cloud computing and large data centers have severe impact on the worldwide energy demand and calls for integrating alternative power sources in order to progress towards carbon-free cloud infrastructures. Research topics in this area include:

- Reducing the (peak) energy demand of data centers through optimal resource utilization.
- Optimization of data center operations taking into account the (predicted) availability of renewable energy (sun, wind…) and data center work load, while ensuring *service-level agreements* (SLA) associated to the third-party services hosted by a data center.
- Data centers as a source of demand flexibility.

Security and privacy

This is a cross-cutting research topic that concerns all parts of the electric power system infrastructure. In addition to related research topics on security and privacy mentioned above, we would highlight the following:

- Digital vulnerabilities in local/community level electric energy markets and resulting from emerging third-party energy management service providers. New players appear on the scene with a resulting increase in attack surface. Research activities would include identifying novel attacks opportunities (ethical hacking), analysis of their potential consequences, development of techniques for their detection, and mechanisms for how they can be protected against.

Norwegian University of Life Sciences, NMBU

At NMBU, the research topics and challenges that have the most focus under the heading “digital energy” are:

- Better prediction models for forecasting PV and wind power output, including machine learning methods
- Data driven methods for synthetic inertia from solar cells and wind turbines.
- Data driven approach for fault detection and / or prediction in solar power plants
- Hyperspectral imaging of PV solar cells for a digital and non destructive way of characterizing the solar cells, thus improving the production methods and hence reduce the costs
- Effect of variable energy sources on power stability (harmonics, voltage level, frequency)
- Smart charging of electrical vehicles
- Vehicle to grid (V2G) - use of batteries in electrical vehicles to reduce peak loads from private homes and / or commercial buildings
- Better interaction between the electrical and thermal system.
- Technologies for energy storage.