Intelligent integrated energy systems

PowerWeb

PowerWeb is an interdisciplinary research platform of Delft University of Technology

TU Delft

PowerWeb: research on intelligent integrated energy systems

Our energy system is in transition. After 100 years of predictable development within the world of centralised topologies, clear roles, and fossil-fuel based generation, we are now entering a period of change. Various non-negotiable societal trends – most notably de-carbonisation, electrification of virtually all sectors including transport and industry, societal awareness, and digitisation – require an energy system to facilitate them in an efficient, secure and reliable way.

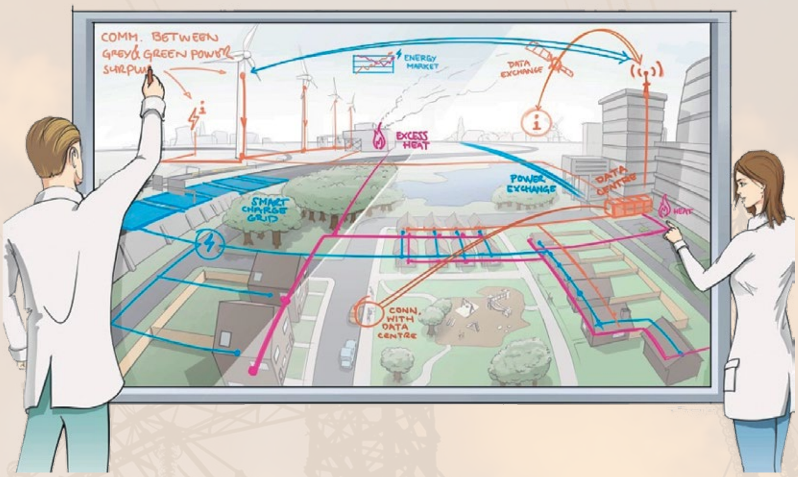
The assumptions that led to the development of our existing energy systems do not hold anymore: the load side is not passive but smart and even generates power; generation is not based on heavy rotating machinery but agile power-electronics; energy markets are no closed clubs for the big players anymore, we see bottom-up activities and empowered citizens who participate in the energy business. Centralised structures are replaced by self-organising cells on the physical, digital and organisational levels. Things get networked and integrated: there is a lively interplay between various energy carriers, between algorithms and data, and between business mechanisms.

This mandates better understanding of system dynamics, requiring new technologies, new technical and institutional structures, and new relations between the smart grid players.

PowerWeb is TU Delft’s platform for multi-disciplinary research on intelligent, integrated energy systems. A unique mix of research groups covers the entire spectrum from intelligent grid components up to regulatory mechanisms. It serves as a unified entry point for industry and authorities with trans-disciplinary questions on modern energy systems. A team of departments with a track record of successful projects and results coordinates researchers and students to work on new energy system design and operations with as main focus areas: **grid technology**, **intelligence and society**.

Energy transition

Somewhere between revolution and evolution we need substantial changes that do not ignore the assets and heavy investments that are already there. Two main domains that need such change are the hardware of the energy system itself and also its intelligence and how it interoperates with society.



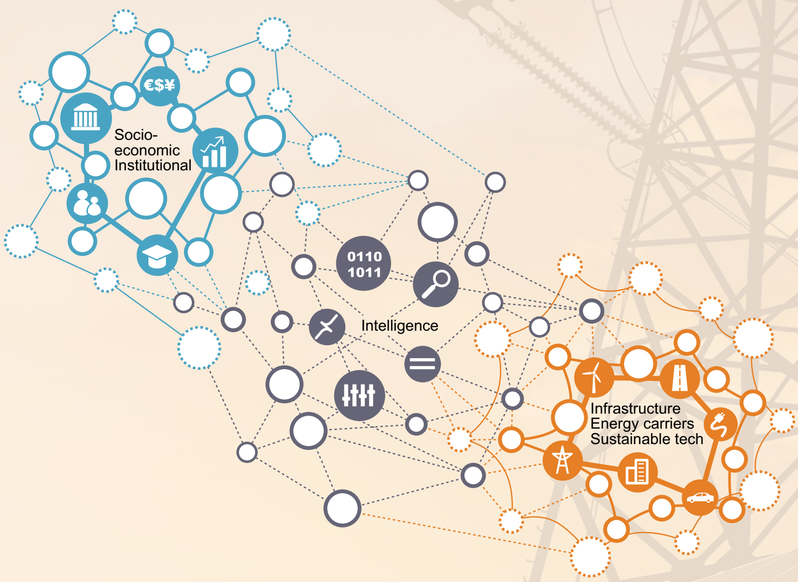
We identify the missing links in our future energy system: in technology, intelligence, and society.

Energy systems

The system has to be re-imagined since market rules, generation technology, usage patterns and many other design factors have changed and continue to do so. There will be no ‘silver bullet’, but rather a smart mix of various principles and technologies. Centralised generation (such as off-shore wind farms) will interoperate with decentralised generation (such as roof-top photovoltaic panels). Regulated mechanisms will co-exist with free-market-based platforms. Changes in the energy system’s design principles are connected to massive investments. Careful analysis and robust scenario assessment are therefore goals of PowerWeb’s energy system re-design activities.

Energy operations

As important as an efficient, robust, and sustainable design are efficient, robust and sustainable operations. The dynamic interplay of market players, intelligent devices, fluctuating renewable generation, smart loads, storage, regulatory rules and energy system controls are complex and critical for a future-proof energy system. Roles and responsibilities in the power business are experiencing changes and new digital platforms enable innovative and green business ideas. The role of data, learning and analytics is growing. The human in the loop is also re-discovered. Many changes in the system make operations more difficult, but new technologies mitigate these risks and help to master the challenges of the future.



The three areas of PowerWeb activity are massively linked. Digitalization is the main glue between the individual aspects.

Area 1 – Grid technology: physics, energy carriers, infrastructure

Energy systems are becoming increasingly interconnected and interdependent. At the source of this transition is the global commitment to reduce the CO_2 emissions and increase the exploitation of renewable energy resources. Decommissioning of coal plants, unfavourable conditions for nuclear energy and intentions to phase out natural gas are all increasing our reliance on other means to ensure the security of our energy supply. Trends such as increasing connections between national energy carriers, increasing oversupply of renewable energy and increasing adoption of energy storage technologies are moving us towards a stronger integration of energy systems.

Design

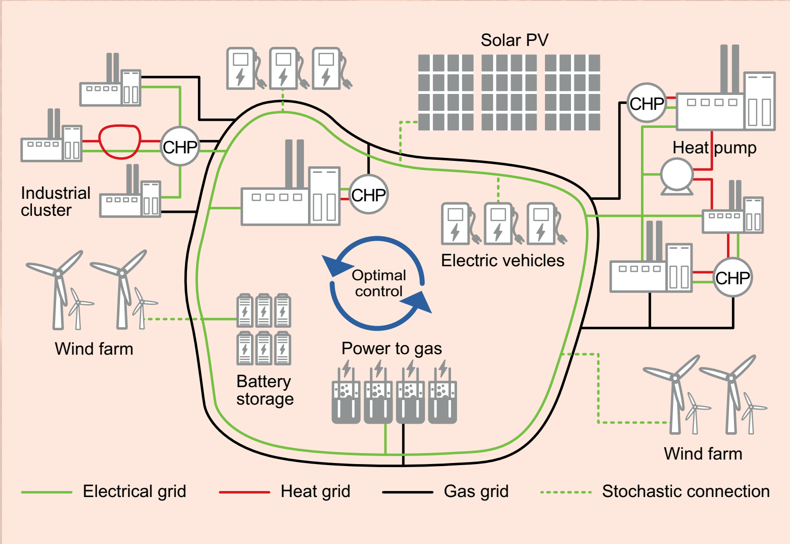
Each of the above trends requires a different approach and entails a different solution. Cross-country connections across the North Sea are exclusively achieved using the High Voltage Direct Current (HVDC) lines of large, GW-scale (Giga Watt) capacity. So far, these lines have been point-to-point lines. In the future, we can expect to see multi-terminal lines coming to existence. Conversion of excess renewable energy is typically imagined as power-to-hydrogen (although other forms of energy are also relevant such as compressed air and heat). In such a system, the electrolyser-fuel cell pair converts electricity to hydrogen and back. The first electrolyser-equipped wind turbines will be built soon while multiple studies show the viability of hydrogen-based economy in the Groningen province. To ensure warm homes, district heating systems are being set-up in the South Holland province. While such systems are generally harder to design and operate when compared to heat-pumps, they offer the benefit of lower stress on the electricity grid. Finally, local generation and usage of energy require enhanced communication and coordination systems between all stakeholders. Such systems should be accompanied by appropriate market designs.

Operations

Operation of the future energy grids will require significant real-time coordination and fast-responding intelligence. Two-way power flow and increased usage of HVDC lines require re-design of protection schemes that disconnect faulty parts of the circuit. Since the conditions in the grid will change much more rapidly in the future, the coordination between protection units is the key to reliable operation. At the same time, the power electronic interfaces of renewable generation units will be able to provide much more than just simple electricity waveform conversion. These converters are expected to provide ancillary services such as synthetic inertia and frequency regulation, that would support the grid once the conventional generation is switched off.

Examples of research topics

Energy flexibility of industrial parks
Electrical systems require an exact balance in the supply and consumption of electrical energy. With stochastic variability coming from renewables, new solutions are needed to smooth out the variations. For industrial parks, ideas such as storage, demand-side management, energy conversion (in form of power-to-heat, power-to-gas, etc.) have been considered. Here, the different roles of electricity and heat can be distinguished, however with a higher intensity per actor than in domestic environments and thus with a higher impact on the intensity of the dynamics in the energy demand and supply.

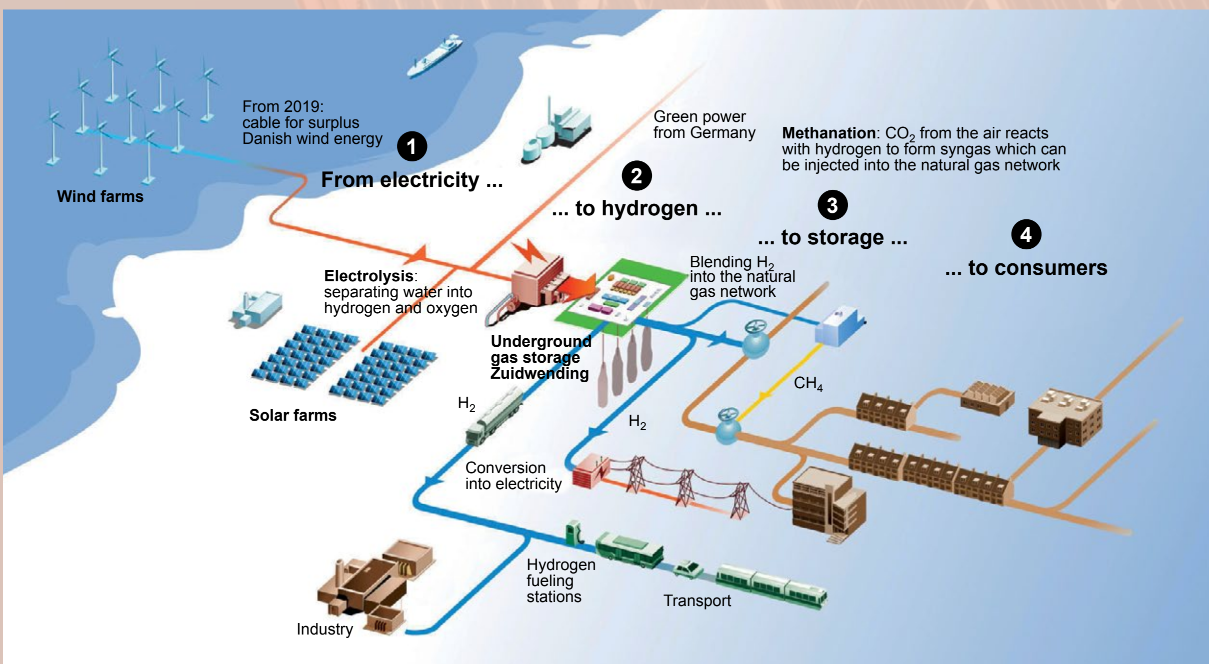


An example layout of an industrial multi-energy system.

Multi-energy models are key enablers to assess the impacts of demand-side management and energy conversion technologies. Over decades of development, simulation software has been fine-tuned and solvers optimised to analyse particular energy domains. However, with the need to couple domains (inter-energy and energy-communications) to enable development of new methods and techniques for energy flexibility analysis, combined simulation ('co-simulation') has emerging as a preferred method.

Transmission and storage options for the hydrogen economy
The use of offshore wind energy from the North Sea is to be maximised by exploring options for its storage and transmission to the mainland. The existing power cable networks can be used to bring the electricity to a nearby major gas network facility where it could be converted into hydrogen using electrolysers.

Alternatively, the electrolysers could be located on offshore wind-park sites, and the hydrogen fuel could be then shipped on-shore. Existing gas storage facilities and the national gas pipeline network (power to gas) will be unlocked to absorb the fuel. Local businesses will provide H_2 distribution via road transport in the Netherlands and the western part of Germany.



Conversion of excessive offshore wind electricity into hydrogen.

Area 2 – Intelligence: ICT, algorithms, data, digitisation

Because of the intermittent and uncertain generation of power from renewable sources, matching loads with generation becomes much more complex. For efficient operation, providers and aggregators need to optimise their use of (heterogeneous) flexible demand under uncertain prices and uncertain consumer behaviour. Where traditionally deterministic models using mathematical programming could be run once a day to decide on the operation of large generators, the number of controllable generators as well as of flexible loads are drastically increasing. This, in turn, exponentially increases the time needed to solve such problems. On top of this, renewable generation adds to the uncertainty, increasing the need for including a wider range of alternative scenarios, and for more frequently (re)solving the problem whenever new information has been received. Existing methods cannot adequately deal with these scalability issues

Distribution service operators

The energy transition, with the advent of controllable flexible loads, demands a more active involvement of distribution network operators in the daily operations of the grid. This gives rise to new algorithmic challenges. The use of flexible loads for balancing increases the simultaneity of loads and may create congestion where this previously was not a problem. The challenge for distribution network operators is to avoid unnecessary network reinforcement by getting involved in this demand-side management to resolve congestion and voltage quality issues. This involves the computation of complex power flows to compute losses and, more importantly, limitations of the distribution network, dealing with stochastic information regarding other loads, local generation, many more agents than in traditional energy market, and interaction with wholesale markets.

Fast simulation

Smart grids are fast grids. The dynamic behaviour of renewable generation and active loads require fast decisions. Ideally, such decisions are based on or verified via numerical models. As existing simulation packages are too slow for complex and large grids, TU Delft developed new tools that outperform the state of the art. The main ingredients of the new tools are: better algorithms based on mathematical insights, suitable to be used on modern hardware. The new hardware is based on graphical cards. These machines can be a factor 10-100 faster; however, this can only be reached if the algorithm has been adapted to this hardware.

Examples of research topics

Optimising power flows

Power flow problems are becoming more and more important now that solar and wind energy allows many (smaller) energy producers. To bring all this energy from producers to consumers, an optimisation problem has to be solved: Optimal Power Flow. Solvers rely on simulation methods, so a speedup of these methods directly influences the quality and performance of the optimisation algorithm. Researchers at TU Delft are working with Alliander to simulate a distribution network with 2 million nodes. The introduction of the power flow model and replacement of the traditional solver by a much faster one, will enable a better distribution of the electricity generated by solar and wind energy.

Example of a national electricity network showing overhead lines, underground cables and HVDC lines.

Aquifer thermal energy storage

Smart energy systems often represent a typical common pool resource problem. Here, uncertainty plays a key role, distributed data-driven decision-making approaches are sought, and self-organisation principles can be applied successfully by utilising a supporting communication infrastructure.

As an example of a common pool resource problem, aquifer thermal energy storage (ATES) concerns the storage and recovery of seasonal thermal energy in the subsurface. ATES is often applied to provide heating and cooling to buildings in densely populated urban areas.

Thermal interference between ATES systems near Utrecht train station. Left: Master plan based on analytical calculations. Right: Groundwater model simulation of 75 years of operation.

Area 3 – Society: institutions, markets, policy

Technology and society are strongly interrelated in smart energy systems. Policy, markets and institutions strongly determine technological designs, and vice versa. A successful realisation of smart energy systems depends on their societal acceptability, market dynamics, regulations and the support of different stakeholder groups. To facilitate the introduction of flexibility sources like storage, demand-side response, flexible clean generation and interconnections between different power systems, different socio-technical designs have to be considered. Insights into the possible consequences of design choices and operational modes can be provided by advanced modelling and optimisation techniques, but at the same time alternative governance structures, institutional designs, and ethical considerations should be taken into consideration.

Design and operations

Sustainable energy systems are complex socio-technical systems with a social network of many players that contribute to the development, operation and maintenance of the technical infrastructure. No single player controls the system, but actions are coordinated through a range of different coordination mechanisms, including informal and formal rules, societal norms and values, regulations, contracts and prices. As the control is distributed among actors, the overall system behaviour (at different time scales) emerges from operating practices and characteristics, from (dis)investment decisions and from other aspects of the actors' strategies. Essential aspects of the overall system behaviour or structure might be misunderstood or even overlooked if only traditional methods continue to be applied. In other words: methods which examine the connections between the heterogeneous parts and the whole system of systems are needed to analyse the (European) energy system in transition.

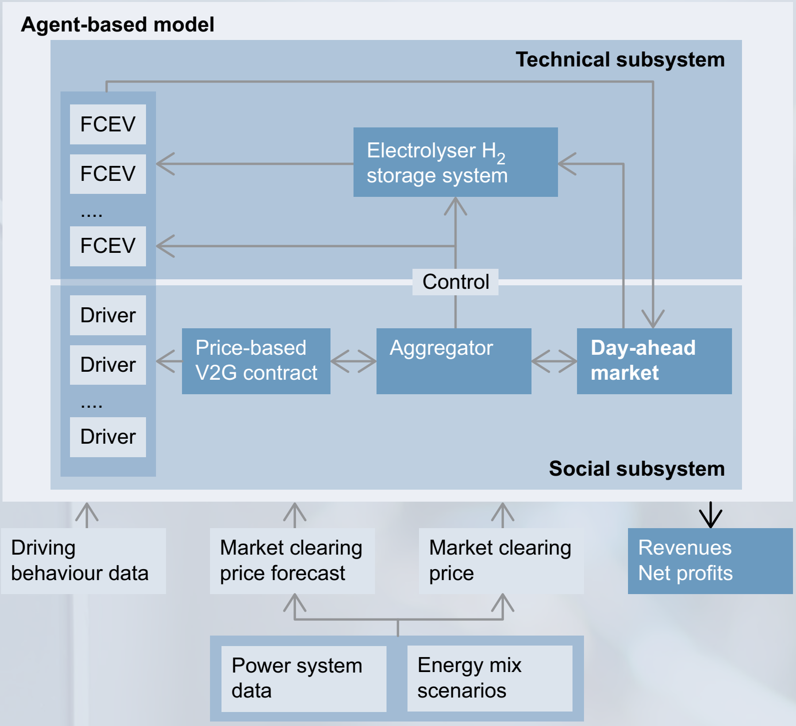
Multidisciplinary research

Multidisciplinary research comprising engineering science, economics, political science, behavioural science and ethics is indispensable to meet ambitions. On the power generation side, it includes real-market functioning, decentralisation, variability and uncertainty as well as behaviour of private and public actors covering the deployment of innovative technologies. On the demand side, it includes the behaviour of individuals and communities of actors, public acceptability and defining (monetary and social) incentives to reduce household fossil-energy use. Moreover, the integration of energy sectors (electricity, heating/cooling and gas) and the electrification of other sectors like transportation and heating can provide opportunities for cross-sector synergy.

Examples of research topics

The role of electrical vehicles
Electric vehicles (EVs), including plug-in EVs and fuel-cell electric vehicles (FCEVs), have a huge potential to play an important role in future energy systems. They can be used, when parked, to discharge electricity to the grid. When aggregating the power of a large number of vehicles, they can function as dispatchable power plants. Plug-in EVs can adapt their charging behaviour to the needs of the power system operator. Similarly, they can act as storage, for example by charging their batteries when there is a surplus of renewable energy.

The role of EVs in wholesale markets deserves more attention as the penetration of sustainable energy sources in electricity systems continues to increase. Although focus for EVs still remains largely on ancillary services, new possibilities can be opened through a wider view by considering both wholesale and reserve markets. For this type of studies, inclusion of the driving needs and the actual availability of cars should be taken into consideration just as the challenge of managing and agreeing upon the availability of cars. Different types of contracts between drivers and aggregators can be designed to optimise their market-driven operation.



Agent-based model of fuel-cell electric vehicles (FCEVs) as part of the energy system.

Value-sensitive design
Responsible innovations in smart energy systems are determined by their ability to serve different societal values, including economic efficiency, technical reliability, distributional justice and sustainability. These societal values can already be considered in the design of smart energy systems.

This value-sensitive design approach enables planners of smart energy systems to consider and anticipate possible value conflicts of different technical and institutional designs in advance. Certain value conflicts might be resolved by technical or institutional innovations, others might be unavoidable given the state of technological development and s ocietal preferences. This provides different fundamental choices for the socio-technical development of smart energy systems.

Smart responsible technologies help cities become more sustainable.

Research expertise at TU Delft

PowerWeb is a multi-disciplinary collaboration of researchers at 6 faculties of TU Delft: Electrical Engineering, Mathematics & Computer Science, Technology Policy & Management, Mechanical, Maritime & Materials Engineering, Industrial Design Engineering, Architecture and Applied Sciences. Together, they cover the following expertise areas:

Grid Technology

Smart grids

Smart thermal and power grids, Smart homes, Distributed energy, Smart charging, Microgrids, Occupant behaviour and comfort, Electric vehicles as power plants

Renewable energy sources

Photovoltaics technology, Electrochemical devices, Hydrogen energy systems, Fuel cells, Batteries (Li-ion, Mg, Na, Li-S), Materials science, Electrochemistry, Thin-film deposition

Energy systems

High voltages, Networked cyber-physical systems, Power electronics, Power quality, Robust controller design, Insulation system, Monitoring and diagnostics

Intelligence

Energy management

Distributed energy management, Energy system robustness & resilience, Self-organisation in energy systems, Local demand/supply management, Algorithms for planning and scheduling, Bottom-up energy systems, Critical infrastructures, Data-driven decision making, Energy system diagnosis at the building level

Modelling

Grid resiliency, Optimisation methods, Time integration methods, Load flow computations, Co-simulation of integrated energy systems, Hardware-in-the-loop power system simulations, Optimal power flow, Modelling of renewables for stability, Real-time digital simulation

Digitisation

Cyber security, Internet science, Network optimisation, Network resilience, Computational intelligence, Artificial intelligence, Smart energy, Digital platforms for energy, Internet of Things

Society

Policies

Responsible regulation, Assessment of energy policies for the building stock, Building regulations, Housing quality, Public acceptability, Modelling energy systems as socio-technical systems, Energy access to poor communities

Markets

Market design, Sharing economy, P2P energy trading, Demand-side management, Game theory for the energy market

Institutions

Designing institutional arrangements for energy systems, Data-driven energy policies in buildings

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