VTT

Solutions to overcome bottlenecks in energy transition

beyond the obvious

Contents

Preface

Despite a few bottlenecks, the green transition is a gateway to endless possibilities

In the face of an inevitable transition within our energy system, there are several challenges to overcome. But it's also a moment of great significance that will define the future of the upcoming generations. The battle against climate change requires carbon-free ways of producing energy and more efficient ways of distributing and using it. As we move forth on the path towards a new energy era, remarkable steps have already been taken, fueled also by the recent global energy crisis. Companies are going full steam ahead towards the growth opportunities that the green transition creates for new technologies and solutions. Nevertheless, it is essential to acknowledge the existence of certain obstacles, bottlenecks as we say, that are momentarily impeding and slowing down the transition.

Solutions are on the way

At VTT, we are encountering the impediments of the energy transition. We have identified five major bottlenecks, and are now presenting three solutions for each of them. These solutions have been established due to our dedication to research and innovation, collaborating with our esteemed partners. To enable tangible change, we have devised concrete steps and a schedule for implementing these solutions, thereby facilitating their entry into the market. Through the continuous pursuit of research and innovation, we aspire to cultivate prosperity within society. We hope our ideas and endeavors will ignite inspiration also within you, guiding us all towards a brighter future.

Espoo, Finland, August 2023

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BOTTLENECK #1

New dynamics challenge the operation of the energy system

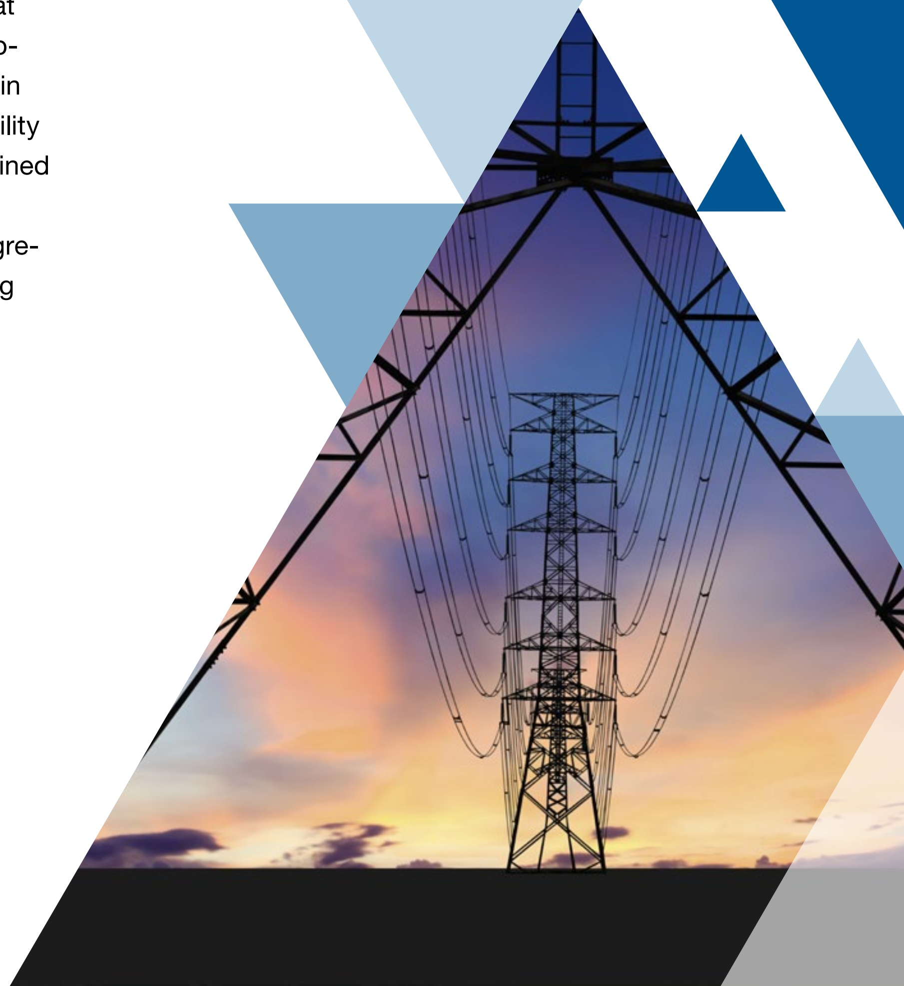
New dynamics challenge the operation of the energy system

The energy transition seriously challenges the prevailing energy system. With high shares of renewables, the generation side becomes more dynamic. At the same time, new kinds of dynamics are introduced on the consumer side through appliances like electric vehicles, heat pumps and batteries. These new solutions are distributed across different system levels, thus setting new requirements for system management. Cost efficient ways to match production and consumption of renewable energy enable to accommodate more renewable energy resources and to drive demand for renewable energy. In this new normal, solutions improving forecasting, monitoring, and controlling possibilities throughout the system are in high demand.

Timing is everything

With the increasingly dynamic nature of energy systems, attention turns from traditional energy usage thinking more towards power behavior thinking. This means that in addition to mere energy efficiency, the timing of energy use becomes more important. While overall energy efficiency is definitely an important topic, and more efficient ways of distributing and using energy are needed, power peaks are eventually the events that can lead to blackouts and service interruptions. This has already led to an increase in the value of flexibility: for example, the ability to shift loads to suitable moments has gained clear value in the markets. New business models built around flexibility and the aggregation of distributed assets are developing fast at the moment.

Flexibility is the new efficiency.



SOLUTION #1

Sector integration provides better systemic efficiency and collaboration

Sector integration is a necessity and an opportunity

Sector integration is the new paradigm for future energy systems. It helps to optimize collaboration between various energy carriers, producers and consumers, improves flexibility and storage possibilities, provides better systemic efficiency and ties actors from different sectors closer together. Our future energy system needs to be able to dynamically utilize many different energy carriers, like electricity, heat, gas, and hydrogen. With sector integration, shifts across carriers take place at various levels of the energy system.

Co-operational models and exchange of information needed

Sector integration is, above all, a new way of thinking aimed at finding synergies and higher-level optimums across different sectors or infrastructures. The necessary technologies, for the most part, already exist and we can comprehensively use data that enables the cost-effective implementation of sector integration. The key challenges have more to do with the lack of common operating models than the technologies themselves: sector integration requires further development especially in terms of co-operational models and daily exchange of information. Business models and regulations also need to evolve in order to enable and even necessitate such collaboration across sectors.

The key challenges have more to do with a lack of common operating models than the technologies.

The number of interdependent actors will increase in the future

So far, sector integration has mainly been discussed in connection with the most energy-intensive sectors, like industry and transport. However, in the future, the sectors to be integrated will expand into all areas of society. Heat-electricity integration is already common in Finland. Buildings have great potential for sector integration, in terms of both producing and storing heat and electricity, as well as using energy in flexible and smart ways. Electric vehicle charging has great potential, currently through smart charging and later through Vehicle-To-Grid capabilities. Hydrogen offers additional flexibility of the energy system, because it enables the storage and transportation of renewable electricity.

What VTT can offer

While VTT is developing specific cost-competitive technologies and interfaces on all these topics, we are also working on a more generic level towards system architectures, business models and regulative frameworks that allow efficient and coordinated sector integration.

How to move forward

Now

Tuning in to new ways of thinking and collaborating across sectors: co-planning of new investments, sharing development plans or creating common awareness, for example. The question to be asked is "what does sector integration mean in my daily business?"

1–3 years

Improving data exchange and utilization, from long-term planning data to operational real-time signals between actors for planning and management.

1–3 years

Establishing new business models around sector integration, with VTT bringing different actors together in a test bed/regulatory sandbox.

3–5 years

Testing and piloting large-scale integration cases.

5–10 years

Extending the concepts across society.

SOLUTION #2

The electric rotary kiln offers significant demand flexibility

The industrial sector has major climate action potential when energy-intensive industrial processes are transformed to use carbon-free electricity and function as a part of the energy demand flexibility system. The electric rotary kiln tackles CO_2 emissions in many industries.

E-kiln technology offers a significant contribution to sector integration

The electric rotary kiln, E-kiln, is a technological solution for replacing fossil energy inputs in high temperature industrial processes for the treatment of solid matter. The E-kiln benefits from the rapid decarbonization of our electricity system and offers significant opportunities for precise process control and industrial-scale demand response. This means it can not only benefit, but significantly contribute to sector integration.

The cement industry is responsible for around 7% of the world's carbon dioxide emissions.

CO_2 capturing and utilisation made easy

In the electric rotary kiln, calcium carbonate decomposes to quicklime and carbon dioxide. With this solution, emissions from fuels are directly avoided. Furthermore, the unavoidable CO_2 from the raw material (calcium carbonate) exits the kiln at a very high concentration (95–100 vol.-%), which is easy to capture and utilize or store permanently instead of releasing it to the atmosphere. The calcination step directly serves industries such as lime, steel and cement manufacturing and pulp mills, however opportunities also extend to the processing of solid matter in numerous other applications, such as the asphalt or plastic recycling processes. The E-kiln also provides interesting possibilities for system integration and consequent further emission reductions. For example, at pulp mills, the availability of low-cost high concentration CO_2 improves the feasibility of lignin extraction.

How to move forward

1 year
Successful proof-of-concept for the improved E-kiln concept solving prototype challenges, ready to be scaled up with partners.

3 years
Construction of industrial demonstration of the pre-calcination step, together with partners, to prove technical and economic viability in an industrially relevant environment.

6 years
First-of-a-kind industrial-scale precalciner process commissioned and operational.

SOLUTION #3

Building-as-a-battery improves energy flexibility

The Building-as-a-Battery solution has great potential for improving energy flexibility

Buildings hold a great untapped potential when it comes to enhancing energy efficiency. Simultaneously, they form an extensive canvas for implementing diverse flexibility measures. The forthcoming wave of building services we provide energy efficiency, flexibility, resilience, optimal living comfort and indoor condition in an optimized way.

Better monitoring and control through digitalization

Digitalization empowers buildings to undergo enhanced monitoring and control, thereby effectively addressing the need for improved power performance within energy systems.

VTT has developed digital twins for buildings, alongside an extensive suite of energy management solutions and tools at the building level. Furthermore, VTT has successfully created Energy Management Agents and multi-market optimization systems for this purpose.

To effectively harness the potential of buildings as integral components of the energy system, it is imperative to establish cost-efficient and scalable frameworks. This necessitates the implementation of automated data management and harmonization capabilities, empowering building flexibility while facilitating seamless data streaming from diverse building automation and hardware vendor systems.

Buildings hold an extensive capacity for implementing diverse flexibility measures.

Buildings offer a huge volume for various flexibility actions.

An ultra-scalable Building-as-a-Battery solution under development at VTT

At VTT, we are at the forefront of developing ultra-scalable Building-as-a-Battery solutions. Our innovations encompass model predictive control of buildings, coupled with advanced physics- and data-based modelling. Through real-time optimization of building energy systems, we unlock the true potential of flexibility, enabling us to monitor the available resources and the consequential impact of their utilization. Our ultimate objective is to streamline energy flexibility management across a vast array of buildings, circumventing the need for intricate and expensive engineering endeavors.

How to move forward

1 year
Ensuring a good level of digital capabilities in buildings, including data management and harmonization capabilities that enable basic building flexibility.

1–3 years
Proof-of-concept of Building-as-a-Battery with an existing and connected building fleet.

3–5 years
Scaling up the solution platform and aggregating buildings as larger entities into the markets.

BOTTLENECK #2

Conflicts between sustainability impacts

Conflicts between sustainability impacts

Climate change is the biggest challenge of our times. In many cases, the actions that mitigate climate change are good for other environmental and social systems as well, but this is not always the case. Sometimes the impact can be very contradictory and mitigating one problem may cause severe harm for other systems. The loss of natural habitats has been emphasized in recent times. Other environmental harms are also causing severe impacts on our environment and societies. Ecosystem destruction, degradation, and fragmentation due to anthropogenic demands for energy, food, fiber, water, and land have increasingly driven global biodiversity loss over the past century. As an example, reducing fossil fuel use with bioenergy plantations can help with climate change, but simultaneously lead to a biodiversity loss in that area. Electrification can also help mitigate climate change, but the mining of critical materials for electrification might cause increased local pollution near mines. Balancing these impacts in multicriteria decision-making is certainly needed to assess whether the side effects offset the initial goal, but some so-called ‘no regret’ options that advance all aspects towards a positive direction can certainly be identified.

SOLUTION #1

Transport system model 3.0 – how to change the ways people and goods move

Improving the energy-efficiency of the transport system

A greater number of vehicles leads to more kilometers travelled, which in turn translates into more energy spent on moving people and goods around. This trend needs to be reversed. The energy-efficiency of the transport system must be improved by reducing the amount of energy used to transport people and goods. In addition to developing and deploying more energy-efficient vehicles, we need solutions that encourage mode transition from personal vehicles to active modes (i.e. walking and cycling) and public mass transport.

Measuring what is relevant

To move towards better energy efficiency, we first have to be able to measure it in meaningful ways. Developing accurate and representative metrics for the energy efficiency of the transport system is one of the actions needed immediately. At the system level, the focus should be on how much energy is used to move one individual or unit (person/piece of goods) rather than a specific number of kilometers. When the appropriate metrics are in place, more accurate modeling and monitoring of the transport system can be performed. In order to get people to change their mobility habits, it is important to develop alternatives that are affordable, sufficiently comfortable and easy to use.

Appropriate metrics allow more accurate modeling and monitoring of the transport system.

Digital technologies, automated and shared services

The adoption of digital technologies also plays a key role. Multi-party data ecosystems and open transport system interfaces make the development of handy end-user applications possible.

New alternative mobility solutions can also provide tools for the transport energy transition. Multi-modal mobility-as-a-service concepts, vehicle and ride sharing, automated buses and taxis, delivery robots and drones as well as electric micro-mobility all still require both technological and business development to reach their full potential in improving the energy efficiency of the transport system.

The solution is to develop an improved and more comprehensive understanding of the current state of our transport system, its components and their interdependencies. This transport system model 3.0 will describe the impacts of daily mobility and transport choices at a systemic level, combining them with a deep understanding of alternative energy sources. The goal is to create systemic change in the ways people and goods move from one place to another in our society.

How to move forward

1–3 years
A more accurate transport system modeling and monitoring tool, developing metrics to measure transport performance from energy consumption perspective.

1–3 years
Real-life pilots to facilitate the deployment of alternative mobility solutions.

3–5 years
Deployment of national mobility data spaces, larger pre-deployments of alternative mobility solutions such as tailored MaaS services, automated buses and taxis, delivery drones and robots.

5–> years
Large-scale deployment of new mobility solutions and MaaS services, automated vehicles and drones in daily use.

SOLUTION #2

Negative emissions

Negative emissions through CO_2 capture technologies

The role of carbon sinks is emphasized in climate change mitigation –in the long term, they are as necessary as emission reductions. In addition to this, negative emissions allow the mitigation of emissions in hard-to-abate sectors and the compensation of historical emissions. This will reduce dependency on certain critical technologies that might pose significant environmental or societal harm due to, for example, excessive need of critical raw materials.

Creating carbon sinks

In addition to natural sinks, there are technical solutions to create carbon sinks, either based on sustainable biogenic carbon flows, bioenergy with carbon capture and storage (Bio-CCS or BECCS) and biochar, or based on atmospheric carbon through direct air capture (DAC). To create technical carbon sinks, the captured CO_2 needs to be permanently isolated from the atmosphere, either by permanently storing it in geological formations or binding it into long lifespan products, for example through mineralization. Moreover, these measures need to be supplemented with the current processes taking place.

Technological solutions exist, but what we are missing is certainty in the business landscape.

There are a number of technologies that can provide both permanent and additional CO_2 removal. Bio-CCS is one of the potential moderate cost options, and it is especially relevant for Scandinavian countries with large sustainable biomass resources and industrial use of these carbon flows. The opportunity is closely connected to forestry and existing

biomass uses, as sustainable biomass is a constrained resource. A technical option with no similar limitation is to capture CO_2 from ambient air. This technology is more expensive than capturing CO_2 from large point sources and requires more energy, but it can be done in every geographical location and at various scales, from small applications improving indoor air quality to large industrial-scale capture facilities, potentially integrated with renewable energy production. Permanent storage is essential to create these sinks, and currently the only large-scale alternative that reaches the required scale is geological storage of CO_2. However, binding CO_2 into products, such as construction materials, with a long enough lifespan is a promising future option.

What we are missing is certainty in the business landscape of CO_2 removal methods: who is going to pay for what and for how long? If we do not make a decision, the future of inaction will be more expensive.

How to move forward

Now

Creating an initiative for the Finnish context to determine the role of biogenic carbon and direct air capture in climate change mitigation and initiate national carbon sink saving program based on technical carbon sinks.

1–3 years

Proof-of-concept for a direct air capture concept related to mineralization, for example storing CO_2 in construction products.

3–5 years

Industrial demonstration of Bio-CCS with technical carbon sinks based on capture from industrial point sources using novel technology, for example storing the CO_2 of pulp and paper mills in million-ton-scale geological storage.

SOLUTION #3

Urban neighborhoods that restore biodiversity

Protection of biodiversity is critical for addressing climate change

Climate change and its impacts on ecosystems around the world pose a critical threat to biodiversity. Concomitantly, biodiversity supports ecosystem services that contribute to both climate change mitigation and adaptation. Thus, the conservation, protection, restoration, and sustainable management of ecosystems and biodiversity is critical to effectively address climate change.

Densification doesn't necessarily compete with green space

Densification of urban areas is widely recognized to combat climate change through, for example minimized land consumption and reduced transport emissions via organization of efficient public transport systems. Long-held beliefs around urban densification versus the provision of urban green space are being challenged by recent research demonstrating that urban neighborhoods can be designed to both accommodate more dense human populations as well as maintain or restore ecosystem integrity.

Green infrastructure offers short- and long-term benefits

Green roofs, green walls, and other green infrastructure solutions provide capacity to adapt to climate change in the longer term, and in the shorter term, confer resilience to climatic extremes. During the last four decades, storms, heatwaves and floods accounted for economic losses of approximately 500 billion euros across Europe.

Additional innovation in building materials, methods and standards are required

In order to enhance the structural and functional connectivity of urban ecosystems and achieve the European and national targets, additional innovations in building materials, methods and standards are required to support the systematic integration of green roofs, walls and other features that are biologically diverse and comprised of species that are consistent with the natural communities of vegetation within the design, as well as retrofits of buildings across all climate zones. In addition, there is a critical need to embed green infrastructure design requirements within urban development and land use planning to ensure ecological connectivity and facilitate the movement of species within urban areas.

Fundamental need for evidence-based decision-making tools

In order to deliver biodiversity benefits within a broader portfolio of activities, there is a fundamental need for evidence-based decision-making tools that systematically and simultaneously consider impacts to all elements of an urban socio-ecological system, including environmental, social, political, legal, economic and technological factors.

How to move forward

Now

Integrated, cross-sectoral dynamic system modelling of urban ecosystems, including explicit consideration of biodiversity, to gain a holistic view of urban social-ecological systems.

1–3 years

Integrated diagnostic tools that utilize Big Data analytics to integrate and synthesize existing heterogeneous data regarding, for example, land use and land cover, ecosystem integrity, extant biological diversity, and related parameters to derive coherent inputs.

3–5 years

A tailored, integrated, holistic framework comprised of diagnostic and decision-making tools.

5–10 years

Embedding integrated decision-making processes within governance frameworks.

BOTTLENECK #3

Integration and complexity are challenging our energy resilience

Integration and complexity are challenging our energy resilience

In the modern society, we are reliant on uninterrupted access to energy services. The resilience of our energy system faces increasing challenges, further compounded by globalization and foreign local crises. We keep encountering new and unforeseen threats that have implications for our energy infrastructure. Moreover, the changing climate introduces a new dimension of risk, as we grapple with the consequences of weather-related hazards and the aftermath of natural disasters.

The recent energy crisis has exposed the geopolitical risks entangled with our reliance on fossil energy. Numerous reserves are situated within politically complex regions, intensifying the challenges we confront. However, the energy transition, characterized by the substitution of fossil fuels with renewable sources, is revolutionizing the status quo of energy geopolitics. The former dependency on fossil fuel resources is now paving the way to novel forms of interdependencies.

The growing complexity and integration of future energy systems pose significant challenges in ensuring resilience. Digitalization brings new risks, such as dependency on information and communications technology (ICT), malfunction, cyberattacks, other criminal activities, and misuse of existing device features. However, wireless communication offers the faster setup e.g. after a natural disaster.

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SOLUTION #1

Resilient districts support recovery from abnormal incidents

The energy resilience of a district can be defined as the ability to sustain energy services during abnormal incidents, such as natural disasters, technical malfunctions, or even hostile man-made damage, and the ability to recover from these.

Resilient district energy system design includes an emphasis on longer-term abnormal incidents and the prioritization of end uses and energy resources, so that a minimum level of energy services can be provided without the escalation of negative events in the society

The electricity system is the most vulnerable part of our society

Urban energy services in Finland rely on critical infrastructure composed of both the district energy system, used to heat and cool the buildings in cities, and electricity services delivered via the grid for various end uses. The most vulnerable part of our society is the electricity system. If electricity is lost, the heating and cooling in buildings stops simultaneously, due to the lack of power for the pumps, controls and fans that deliver energy and indoor climate services in buildings. This is critically important, especially during the subzero extremes of winter.

Deeper interaction between buildings and district systems needed

Today, the security of the energy supply is managed by the district energy systems and the electricity grid, which both have measures for back-up production, redundancy in the delivery systems and a stockpile of fuels. The lacking part is the deeper interaction between buildings and district systems. Currently, the buildings and district energy systems are not designed to support each other during an incident in a way that allows co-operation between both systems.

Energy efficiency, distributed resources, integrated control, and new business models

VTT focuses on the Positive Energy District solutions and the 4th generation district heating and cooling systems, which both contain the supporting technical elements for energy resiliency. Typical supporting elements that increase energy resiliency in these solutions include increased demand side energy efficiency, resulting in longer time constants of the system in heating and cooling; distributed local energy resources, reducing the dependency of the centralized production; integrated control of the overall district energy system, and new business models that support the financial viability of these new solutions.

VTT's research focuses on supporting technical elements that improve energy resiliency.

How to move forward

1 year
Completion of the concept for energy resilient building and district solutions that enable habitability and survivability during long wintertime failures of the energy infrastructure.

1–3 years
Development of deep digital integration between buildings and district energy systems, so that the operation during district energy outages accounts for both priority and equal provision of energy services to end users.

3–5 years
Demonstrating the resilient district and building solutions in a real-world environment, for example 1 or 2 block-level solutions in the urban environment.

SOLUTION #2

Supporting energy system stability through grid-connected storages

Grid-connected storages support energy system stability

Energy system flexibility and resilience will increasingly benefit from, but also require, grid-connected storage that provides various services. Stationary electrical and electro-chemical grid-connected storages, such as batteries, will play an increasingly important role in short-term grid support needed to secure energy system stability. Sufficient storage capacity also reduces the risk of curtailment of the increasing renewable power generation.

Electric vehicles to be used as mobile energy storages

As the electrification of transport progresses beyond cars to commercial and heavy-duty vehicles, the growing electric vehicle (EV) fleets have a great potential to be used as mobile energy storages and for balancing demand and supply in the electricity grid through bidirectional charging devices and capability. Examples of benefits include behind-meter optimization and resilience, islanded operation, energy arbitrage for charging and EV operations, as well as various grid services for producer-consumers. V2G enabled vehicles can also be used in crisis situations. In the case of a power outage, electric vehicle and fleet owners can deploy V2X-equipped mobile assets and connect them to return power temporarily.

Improved performance and sustainability with next-generation batteries

Next-generation battery technologies for mobility applications will show improved performance and sustainability in terms of energy density, power density and circularity. For stationary applications, technologies beyond lithium-ion batteries can include 2nd life use of EV traction batteries, new inexpensive chemistries (such as Na-based batteries), as well as flow batteries. Future solutions can also include hybrid storages consisting of several technologies, optimized for providing several stacked grid services.

VTT's research on energy storage concentrates on bringing new emerging technologies to system-level readiness and validating their performance, designing and optimizing single-technology and hybrid storages for mobility and stationary applications, as well as optimizing the use of these storages in their intended end use cases, including smart grid connection of EV's.

Energy system flexibility and resilience will increasingly benefit from, and also require, grid-connected storages.

How to move forward

1–3 years

As bidirectional functionalities are implemented and adopted by the OEMs, their value in the low-cost mass market is demonstrated. Optimization schemes for battery systems for mobility and stationary applications become available. Next generation battery systems under development.

3–5 years

The value of the aggregated flexibility element in the energy system has been demonstrated. Storage systems based on next-generation battery technologies and hybrids are being demonstrated. Market-based functionalities and services have been established for impacts to be visible at system level.

5–10 years

The large-scale deployment of electric vehicles and smart charging ties the transport and energy sectors together in a synergic interplay is taking place, improving both energy flexibility and resilience. Diverse storage technologies are in synergic hybrid use with optimized usage and value proposition.

SOLUTION #3

Interoperable and cyber-secure architectures improve energy system security

Interoperable and cybersecure architectures for a more coordinated and secure energy system

Energy systems rely increasingly on digitalization and connectivity across different energy system levels. Information and communications technology solutions are an important enabler of a more intelligent and coordinated system. In particular, new monitoring and forecasting capabilities will be valuable in the increasingly dynamic energy system. Through open interface development, system solutions are becoming modular, so that even small players can provide some subsets of bigger systems. This development supports the diversity of system provider markets and reduces the risk of vendor lock situations.

Architectures combine cloud and edge level intelligence

Digitalization can also support the better coordination of different actors through new ways of sharing data, enabling common situational awareness or co-planning functions. Data sharing platforms will also open possibilities for third-party service providers to develop new data-driven services. The overall architectures combine cloud and edge level intelligence: most time-critical functions are likely to be more local or far-edge, whereas longer-term functions are taken into the cloud level, utilizing wider data beyond the local system on the cloud–edge continuum.

Open interfaces and architectures are the base for building new models

To assure interoperability across all systems and actors, it is important to develop common open interfaces and architectures, based on which new models can be built. At the same time, such wide connectivity and interface options can present serious cybersecurity concerns. As the energy system is a truly critical part of our infrastructure, reliable cybersecurity must be ensured in all situations, including during abnormal events or system disturbances. This requires combining technical cybersecurity and social engineering solutions, but also adequate awareness of all actors involved in the energy system operations.

Through open interface development, system solutions are becoming modular, so that even small players can provide some subsets of bigger systems.

VTT's testbed for recognizing cyber-security and connectivity-related risks

VTT tests various cybersecurity and connectivity-related risks in a realistic environment utilizing our IntelligentEnergy Testbed, which combines real distribution automation with a variety of different connectivity options, including commercial wireless networks, extended with real-time simulation capabilities and advanced quality-of-service wireless network measurement system.

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How to move forward

1–3 years
Ensuring research and development platforms for cyber physical systems, their interoperability and resilience under varying conditions. Bringing together experts from the energy and cybersecurity sides to define next-level solutions. Closely involving companies and their latest products in such platforms.

3–5 years
Achieving a safe and transparent method for exchanging operational data between different sectors, without concerns relating to safety or privacy aspects. This will pave the way for sector integration and synergies between actors.

3–5 years
Evolving towards a system structure in which more stand-alone system cells can be dynamically formed for better reliability. Realizing the web-of-cells type concepts for better robustness of the system.

BOTTLENECK #4

Limited availability of critical raw materials slows down the green transition

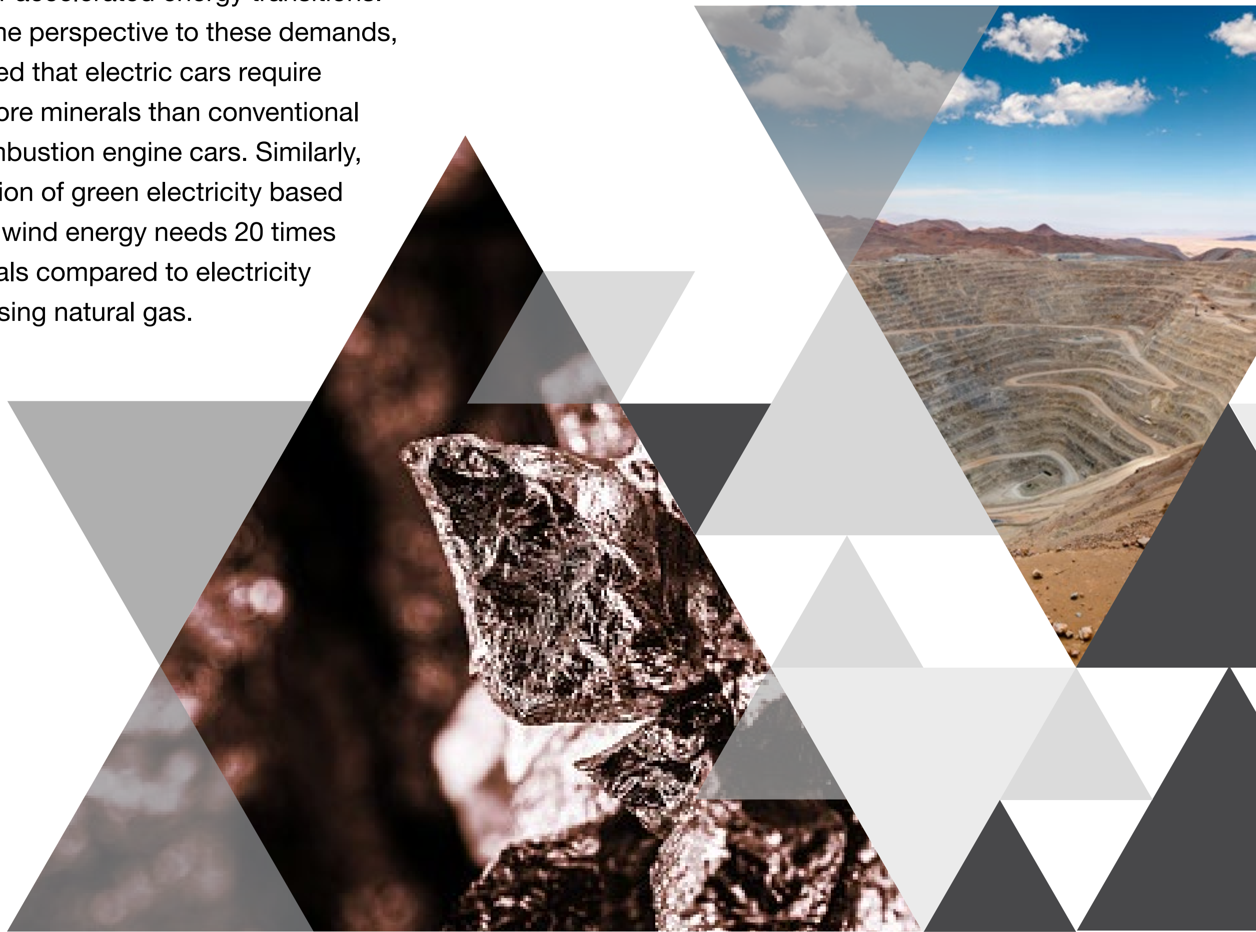
Limited availability of critical raw materials slows down the green transition

The green transition has led to a heightened demand for critical raw materials like rare earths and lithium. Current production of many of these minerals is more geographically concentrated than that of oil or natural gas. These materials not only play a crucial role in green technologies but also for instance in the security and defence sector, and in various digital applications. While electrification presents an efficient energy utilization method with existing technological options, the availability of critical raw materials poses a significant bottleneck.

This bottleneck not only increases the cost of solutions but also hinders the widespread adoption of new technologies, thereby presenting challenges from both environmental and societal perspectives.

Huge gap between the demand and supply

Current supply and investment plans are not yet ready for accelerated energy transitions. To offer some perspective to these demands, it is estimated that electric cars require six times more minerals than conventional internal combustion engine cars. Similarly, the production of green electricity based on offshore wind energy needs 20 times more minerals compared to electricity produced using natural gas.



SOLUTION #1

Power to X

Power-to-X for a cost-efficient route to sustainable fuels and decarbonization

Power-to-X (P2X) refers to a process where CO_2 and hydrogen produced using clean electricity is converted into hydrocarbons through a synthesis process. These hydrocarbons can be either used to replace fossil components directly or as feedstock for the chemical industry to produce, for example, plastics or even proteins. This will provide a cost-efficient and resource-saving route to decarbonization and energy transition, as it can be very quickly deployed without bearing the full cost of instantly replacing end-use infrastructure completely.

Climate-friendly hydrocarbons with P2X and clean electricity

Our current energy and industrial system infrastructure is designed and built to use hydrocarbons, and the transition to replace these assets will take time. With P2X we can produce climate-friendly hydrocarbons with clean electricity and supply this infrastructure rather quickly with carbon-neutral solutions without limitations set by the renewal pace of the end-use applications (for example ships or airplanes). This will decrease pressure to exploit the most challenging critical raw material reserves and buy more time to develop alternative materials and other solutions to electrify societies. For example, with sustainable aviation fuel produced from clean hydrogen and CO_2, we can decarbonize aviation faster than by waiting for other solutions and switching the entire global fleet to a new technology that is not available today.

Sustainable aviation fuel produced from clean hydrogen and CO_2 decarbonizes aviation faster than waiting for other solutions.

VTT's solution for efficient P2X process

VTT develops integrated high-temperature electrolysis and synthesis processes to increase P2X process efficiency significantly.

How to move forward

1–3 years

Demonstrating new, cost-efficient production routes, for example based on integrated high-temperature electrolysis and synthesis processes to increase process efficiency significantly.

3–5 years

Industrial-scale integrated demonstrations, developing system concepts with superior efficiency and increased ability to operate flexibly.

5 years

Developing electrolyzed system manufacturing solutions and upscaling manufacturing capacity to decrease cost and increase deployment pace multifold.

10 years

First-of-a-Kind industrial-scale plant producing sustainable aviation fuels.

SOLUTION #2

Circular economy reduces the need for virgin raw materials

The circular economy is one way to reduce our dependency on primary raw materials and to ensure secure and sustainable access to metals and minerals. Critical raw materials (CRMs) have a key role in renewable energy technologies, so their efficient use is a pre-requisite for a successful energy transition. The circular economy aims to maintain the value of materials, for example by keeping materials in use whenever possible, recycling the materials and using recycled and secondary raw materials to prevent waste generation and the loss of valuable elements, like critical raw materials.

Circularity along the refuse and reduce thinking

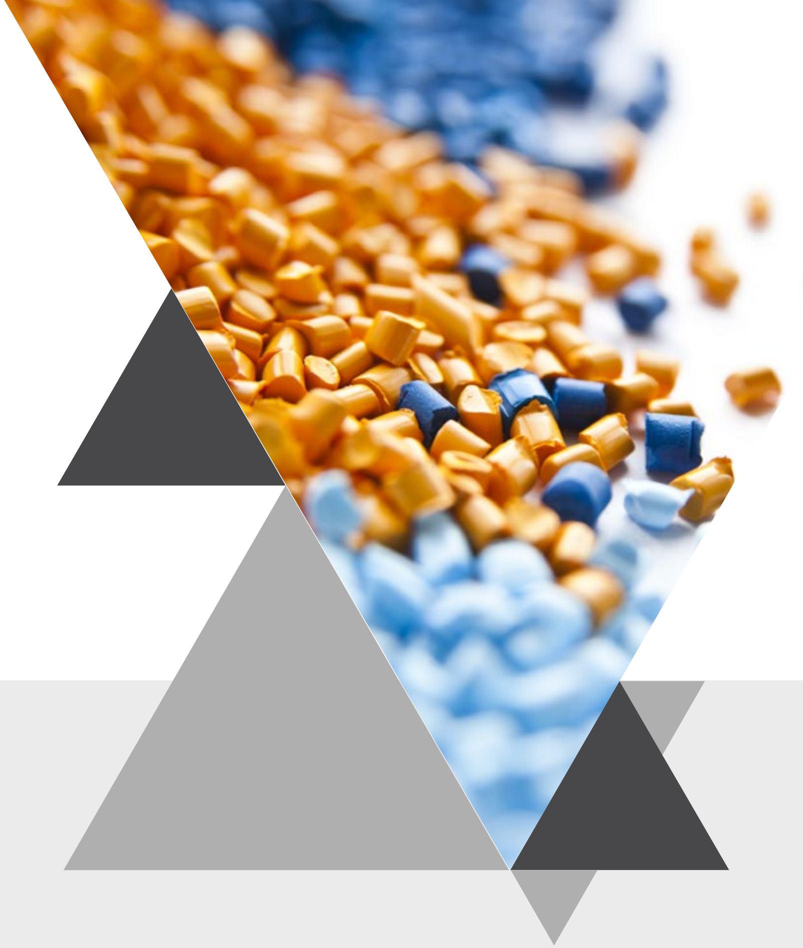
The goal of the current state-of-the-art circular strategies, often referred to as R-strategies, is to offer a framework for circular design, and to support the supply security of critical raw materials. This means not only the ability to circulate materials in existing products, but also designing products to facilitate circular use. The largest benefits are obtained if sustainability innovations are considered early on in the production chain. Lifetime extension strategies, like reuse and repair, as well as recycling and recovery strategies, directly influence the need for and availability of the critical raw materials in their value chains. Utilizing secondary resources and end-of-life recycling strategies reduce the need for primary production of critical raw materials from ores. This also increases the security of supply for primary products. On the other hand, ‘refuse, rethink and reduce’ strategies can radically change the game and reduce the need for raw materials through alternative materials and substitution. Digitalization is seen as an important enabler in the circular transformation, and the introduction of digital technologies throughout the production chain has potential to reduce resource use and facilitate circular systems. Novel processes are needed for materials to meet circularity targets, e.g., powder technology related to additive manufacturing, direct recycling, and hydrometallurgical recovery technologies.

The circular economy is one way to reduce our dependency on primary raw materials and to ensure secure and sustainable access to metals and minerals.

Products, materials, processes, and business models need to be redesigned

Clean energy targets require more renewable energy, thus increasing the amount of critical raw materials that will be bound to long-life assets. Today, only 9% of the used raw materials are cycled back to the material loop. To ensure resource sufficiency, we need to redesign products, materials, and processes, as well as business models, to support the circular economy.

VTT develops a portfolio of technologies and digital tools that respond to the challenges of the circular economy through the smart traceability of materials and intelligence inside materials. VTT aims to demonstrate digital product passports that enable technologies to support digital raw material circularity.



How to move forward

1–3 years

Digital materials design through a proof-of-concept of a materials acceleration platform (MAP) for digital material screening and design to support circularity of especially critical raw materials.

1–3 years

Life-cycle management by proofing substitution, life-time extension and smart maintenance, as well as hydrometallurgical recycling concepts with supported digital track and tracing.

3–5 years

Direct recycling to maintain the added value of materials and more sustainable lifecycles. Developing direct recycling and material reuse technologies that makes it possible to keep materials in use without breaking them to their elements.

SOLUTION #3

Alternative materials

VTT is developing new alternative material solutions to secure the supply of raw materials.

Alternative materials to ease the shift from a fuel-intensive to a material-intensive world

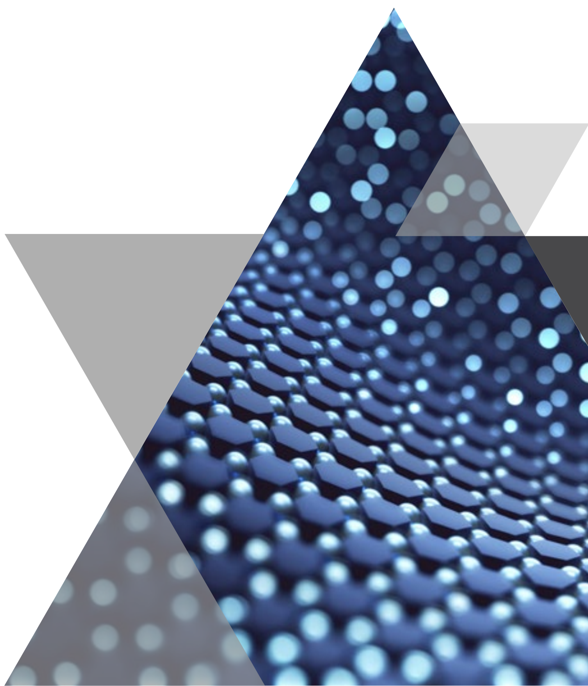
The energy transition, and especially the green and smart electrification, means a shift from a fuel-intensive to a material-intensive energy world. The drawback of the transition is that the current production of many energy transition minerals is more geographically concentrated than that of oil or natural gas. Scenarios to mitigate climate change require a rapid transition, leading to a situation where the required level of supply growth for most minerals is well above the levels seen in the past decade.

It is notable that demand is not only connected to critical raw materials. Increased demand will also concern structural materials, because massive support structures will be needed, for example, in offshore wind energy production, leading to a huge increase in the use of zinc for corrosion protection.

Critical raw materials, rare earths and copper demanded in electric machines

In electrical machines (generators, motors, power electronics) the question is not only the increased volumes, but also the enhancement of power densities and the mitigation of losses during operation. Together with the rare earth elements (REE), which are essential in permanent magnets, the huge increase in the demand of copper is creating the need and basis for developing novel materials and manufacturing solutions.

In the process industry, the heating of processes with fossil fuels is one of the most significant sources of CO_2 emissions.



Thus, the electrification of thermal processes and the development of new electrically-driven processes is progressing at an increasing pace. This change requires novel high-temperature materials and manufacturing technologies for electrically heated materials, high performance catalytic materials for novel processes, and materials withstanding future energy carriers, such as hydrogen and ammonia.

Alternative material solutions from VTT

To tackle these challenges, VTT is developing new alternative material solutions to secure the supply of raw materials and simultaneously guarantee that materials meet the demands of novel applications and manufacturing technologies.

How to move forward

1–3 years
Materials supporting the electrification of processes. Demonstration of an electrically heated reactor for the conversion of H_2 and CO_2 to synthetic fuels.

1–3 years
Lighter electrical machines. The development of soft magnetic materials and manufacturing technologies enabling freedom of design, leading to a 30% mass reduction of e-motors.

3–5 years
Future electrical machines. Novel REE-free permanent magnet composition and alternative design for Cu coils.

3–5 years
Materials for P2X. Novel catalysts without platinum group metals.

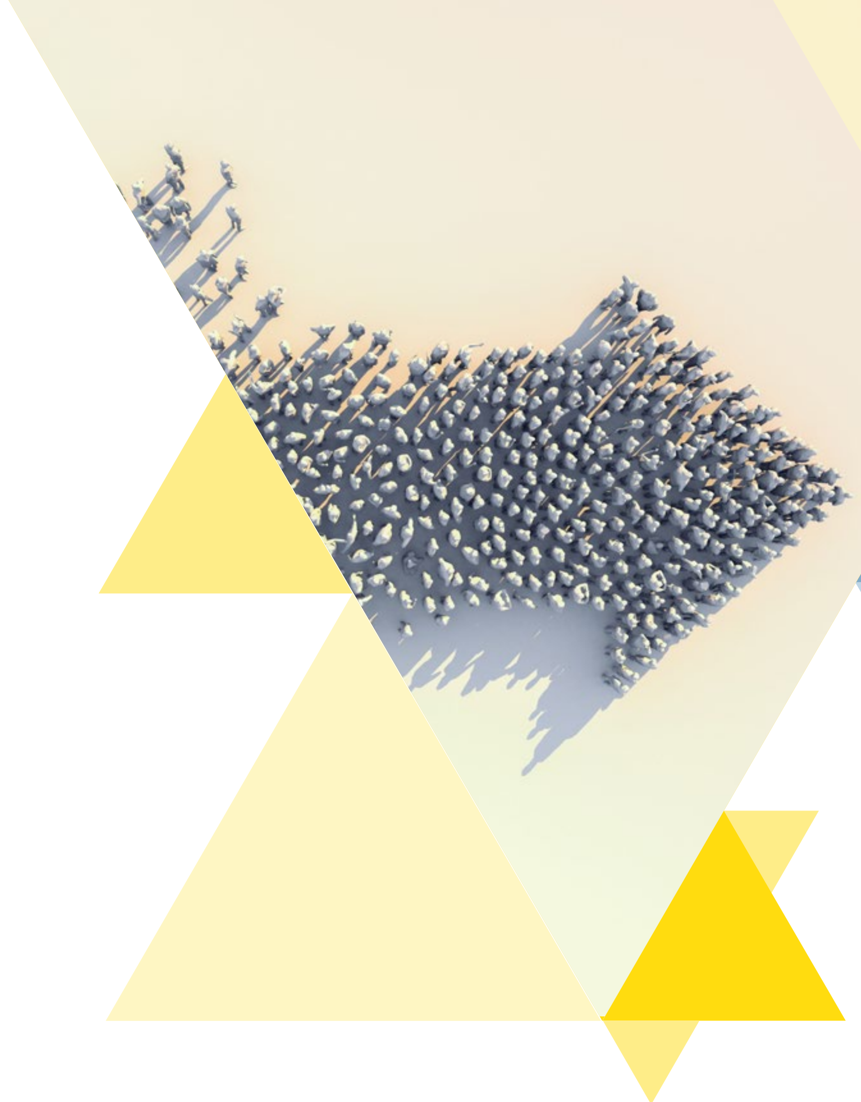
BOTTLENECK #5

Today's decisions will impact future generations

Today’s decisions will impact future generations

Path dependency is a phenomenon where history matters; what has occurred in the past persists because of resistance to change. Visions already exist of how a fully sustainable future would look like and function. However, we still have a lot of existing infrastructure that is not envisioned to play a role in that future. And on top of that, the pace of transition is faster than it would be based on the natural lifecycle of assets in general. This poses two challenges that create resistance to change.

Firstly, we need to find solutions that will function in the sustainable society of the future, but would also be viable today. Secondly, significant investments are tied to our existing infrastructure. The infrastructure would need to be depreciated significantly faster than originally planned. It would also take an enormous amount of resources, materials and energy to transform everything that exists into a completely new system and infrastructure. This challenges the transition economically and environmentally. We also do not know for certain which solutions will eventually be viable in the future system – we will only learn that during the transition.



SOLUTION #1

Evidence-based decision making

Due to the systemic nature of the challenges of the energy transition, it is impossible to find solutions through individual product or service innovations only. Instead, large-scale changes are required. The following three perspectives have been emphasized to solve system-level challenges:

1) The innovations needed are multiple in nature: technological and service-based novelties are interlinked with social and systemic innovations.

2) Collaboration between multiple actors representing different sectors of society is required: the synergies between public, private, and third sector organizations are essential.

3) Developing and disseminating innovations at the systemic level requires an understanding of the whole socio-technical system, including the dynamic interplay between its parts: companies, policymakers and citizens.

Sectoral policymaking has become challenging

The decisions made in one policy sector affect others and form complex dynamics. Therefore, traditional sectoral policymaking has, in many cases, become challenging and inefficient. Similarly, decision-making cannot be limited to a specific administrative silo or to a sector-specific issue, as the energy transition interlinks various fields of policy-making across sectors, necessitating, for instance, a fully renewed understanding of the goals, the actors and their roles and the logic of innovation.

Impact leadership combines vision building and foresight, systemic and comprehensive approaches to impact, and the systematic use of data and modelling for better decisions and proactive policies.

VTT's impact leadership method offers an evidence-based approach

At VTT, we have developed impact leadership as a method for building sophisticated and evidence-based approaches to decision-making to ensure sustainable and future-proof decisions. Impact leadership combines vision building and foresight, systemic and comprehensive approaches to impact, and the systematic use of data and modelling for better decisions and proactive policies. Through impact leadership, we can provide tools that help decision-makers confront various societal transformations and phenomena supported by good quality data, strong cooperation between stakeholders, and a comprehensive understanding of the potential impact of different scenarios.

How to move forward

Now

Provide understanding of the changes in the operational environment that affect the energy transition and create a common vision for sustainable energy future.

1–3 years

Offering guidelines for the transition by setting long-term impact targets in a balanced way, by emphasizing economic, environmental, societal and cultural impacts. Identifying concrete impact indicators and data to facilitate evidence-based decisions that enable the transition.

1–3 years

Identifying opportunities for renewal and co-creating new solutions to enable the energy transition. Creating collaborative models to design new technologies and services and to develop platforms for co-creation, testbeds and living labs to ensure scalability.

3–5 years

Provide data for the creation of actionable information and to support better decision-making. Taking into use and developing data to monitor whether we are moving to the right direction and to verify the value and multi-criteria impacts of solutions and decisions.

3–5 years

Driving and leading the transition with future-oriented and data-based tools. Expanding options for strategic decision-making. Identifying key actions in decision-making for renewal and development.

SOLUTION #2

Hydrogen - the no-regret option

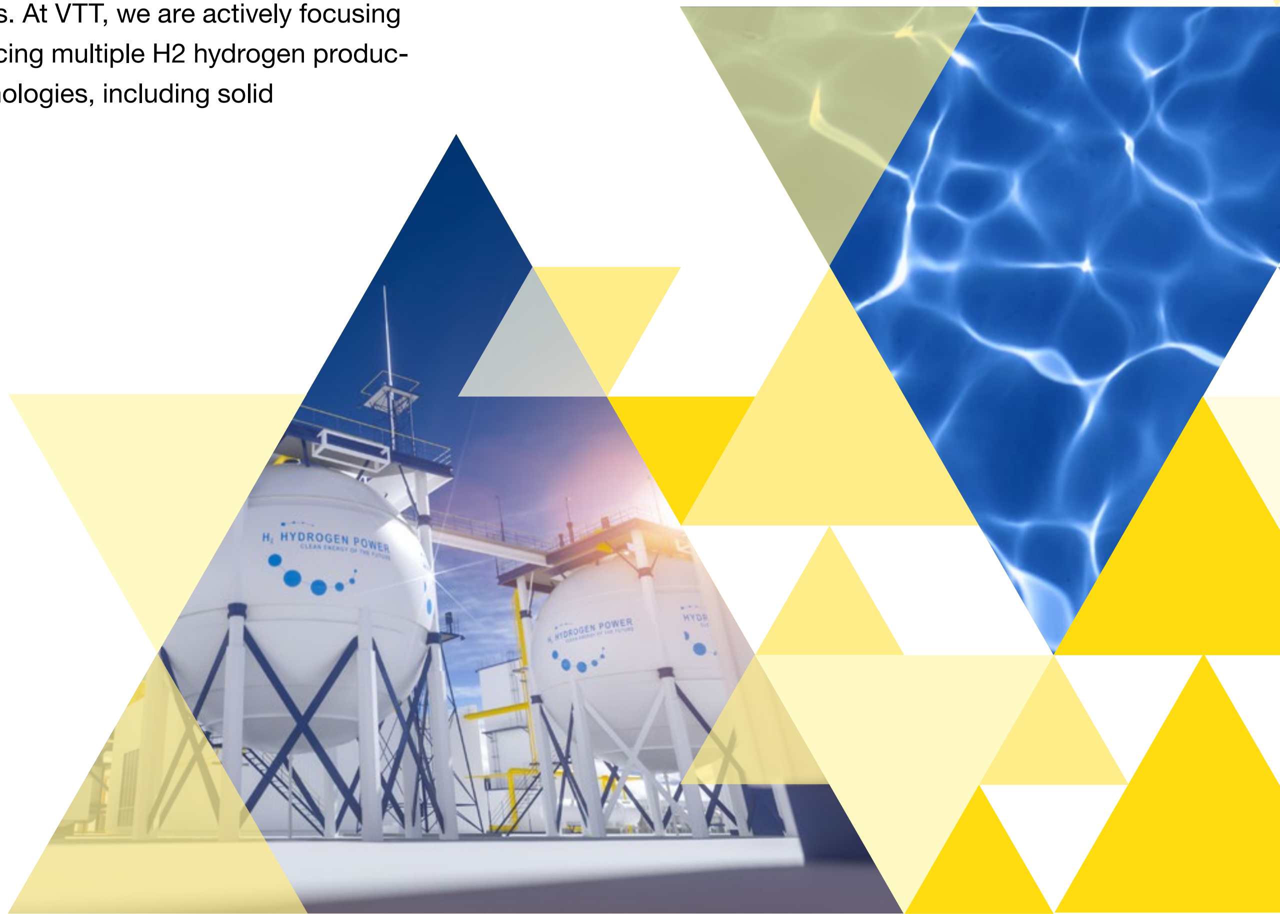
Unleashing the power of hydrogen for the decarbonized energy system

Hydrogen is a carbon-free energy carrier playing in the future a key role in a fully decarbonized energy system. It seamlessly integrates with existing infrastructure, including thermal energy production assets, hydrocarbon-dependent mobility, and bolstering the storage capacity of the power system. What sets hydrogen apart as a solution is its ability to adapt to current infrastructure while also serving as a no-regret option, perfectly aligning with the demands of the future.

Hydrogen is a carbon-free energy carrier.

More efficient hydrogen production with high-temperature technology

Clean hydrogen is produced from water through electrolysis. However, the transition towards widespread utilization faces a critical hurdle: the inadequate efficiency of hydrogen production, conversion, and utilization processes. At VTT, we are actively focusing on advancing multiple H2 hydrogen production technologies, including solid oxide technology and proton-exchange membrane systems. The Solid Oxide Electrolyzer (SOE) stands out as a high-temperature technology that holds tremendous potential for significantly boosting hydrogen production efficiency by tens of percentage points. This paves the way for superior systemic efficiency, facilitating the seamless deployment of hydrogen's benefits, particularly when integrated closely with the process industry.



VTT's rSOC, reversible solid oxide electrolyzer, is able to function as an electrolyzer producing H_2 from electricity, but the same process, when reversed, is also able to operate in fuel cell mode, producing electricity from hydrogen. This means the same investment can produce hydrogen in times of moderately priced electricity, but also increase its operation time and produce electricity and support the electricity system through long-term balancing when electricity is expensive.

How to move forward

1 year
Successful Proof-of-Concept of the Solid Oxide Electrolyzer system in the VTT Bioruukki Pilot Centre.

1–3 years
Commercial design and demonstration of the rSOC electrolyzer system based on VTT technology.

3–5 years
Upscaling of electrolyzer system manufacturing capacity to increase global CO_2 handprint by providing hydrogen production systems.

SOLUTION #3

Small modular nuclear reactors for local energy production

Much of the infrastructure of our society is built on the assumption of available on-demand energy; mostly in the form of thermal energy from combustion. Nuclear energy is a way to produce such energy with a high energy density and without direct CO_2 emissions. Traditionally, nuclear energy is produced in large power plants supplying electricity to the grid, however with the advent of small modular reactors (SMRs) this paradigm may change.

Small modular reactors can serve the society and industry in several ways

Three separate applications for SMRs are probable in the near future: larger SMRs will produce electricity at dedicated nuclear sites, while smaller SMRs will produce superheated steam and electricity locally for industry, and nuclear plants located close to urban areas may produce heat for district heating grids. All of these options both offer opportunities to produce clean energy in a novel way where it is needed, as well as face challenges in their implementation. Various SMR designs are under development, and the first construction projects have been initiated for some of them. There is a need to understand how nuclear energy could best be used in the local production of energy, and how to bridge the potential gaps in our know-how.

Various SMR designs are under development, also in Finland.

The needs and development processes differ from country to country

As situations and industries vary by country, the focus of SMR development also differs. In the case of Finland, the extensive infra-structure for district heating is something that is not seen in many other countries hosting SMR development. And as such, there are very few designs internationally targeting the low-temperature heat supply, in contrast to numerous advanced nuclear reactor designs aiming to provide superheated steam for industry. This is also an opportunity to create new industrial capabilities for the district heating reactors.

VTT is developing a nuclear facility suitable for the district heating grid

VTT has initiated a project to design a nuclear facility suitable for providing heat to a district heating grid. The design, LDR-50, would take advantage of the low-temperature target of district heating supply to simplify and lighten the nuclear reactor design.

How to move forward

1–2 years

Increasing the technical readiness level of designs and customer commitment – for VTT's LDR-50 design, the R&D work for maturing of the design along with commercialization activities.

3–4 years

Starting the first projects to use nuclear energy locally (either in district heating or an industrial application). Environmental impact assessment of the first LDR-50 project, as well as experimental validation of the key safety functions of the design.

5–10 years

Successful initiation and eventual completion of the first LDR-50 project.

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