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HETR

Helmholtz Energy Transition Roadmap

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About this Roadmap

The Helmholtz Senate has commissioned the Helmholtz Research Field Energy with the task of developing a science and technology driven roadmap for energy research. The prime objective of this Helmholtz Energy Transition Roadmap (HETR) is to offer strategic guidance to the Helmholtz Research Field Energy, especially during the planning process for the forthcoming funding period, known as the POF-V-process. It also aims to provide orientation to external stakeholders in science, industry and politics.

While the project is spearheaded by the Helmholtz Vice-President Energy, the content framework for the roadmap has been created by a small group of leading authors, under the advisory of a core team. These authors received significant support from roughly 100 scientists from the Research Field Energy, who contributed their specific expertise. These scientists, organized into several interdisciplinary Expert Groups, span the full range of research in materials, technologies, systems and society within the ESD, MTET and FUSION programs. To align our research objectives and challenges, these Expert Groups participated in multiple feedback loops contributing to the roadmap's development.

The HETR fundamentally relies on energy scenarios (see figure below), encompassing both proprietary Helmholtz Energy scenarios, developed in the ESD program, as well as published national and international scenarios. We focused exclusively on net-zero scenarios that achieve a transition to climate neutrality by 2045 (D) and 2050 (EU) respectively. These scenarios underpin the Transition Narrative of Helmholtz Energy, which paints a picture of a future where the energy system is secure, environmentally conscious, economically viable, and socially accepted, with sustainable resource flows, not just in Germany and Europe, but across the globe. Based on these scenarios, we have identified two main sets of challenges:

1. The Transition Challenges, which outline the overarching hurdles encountered along possible energy system transformation paths.

2. The Research and Innovation (R&I) Challenges, which propose potential solutions to the Transition Challenges and concurrently demonstrate the necessary contributions of research and development in implementing these solutions.

In essence, the roadmap provides valuable insights into how energy research can facilitate the successful transformation of the energy system in the short, medium, and long term across all disciplines. It offers a comprehensive understanding of the challenges associated with energy transition and energy research. Helmholtz Energy addresses these challenges both through research aimed at the immediate transfer to application and through basic research aimed at fundamental understanding and long-term options for the future. In this sense, the HETR demonstrates a multitude of technologies, materials and methodologies that will or could be instrumental in addressing these challenges.

The HETR is now at a stage where Helmholtz Energy employs it for strategic planning in the course of the POF-V-process. In this process, the core topics and focus areas of Helmholtz Energy will be discussed, determined and prioritized to achieve maximum impact.

A preliminary version of the HETR was shared and discussed with stakeholders from science, industry, and politics in order to incorporate perspectives beyond the Helmholtz Energy research community. This updated version incorporates the constructive feedback we received.

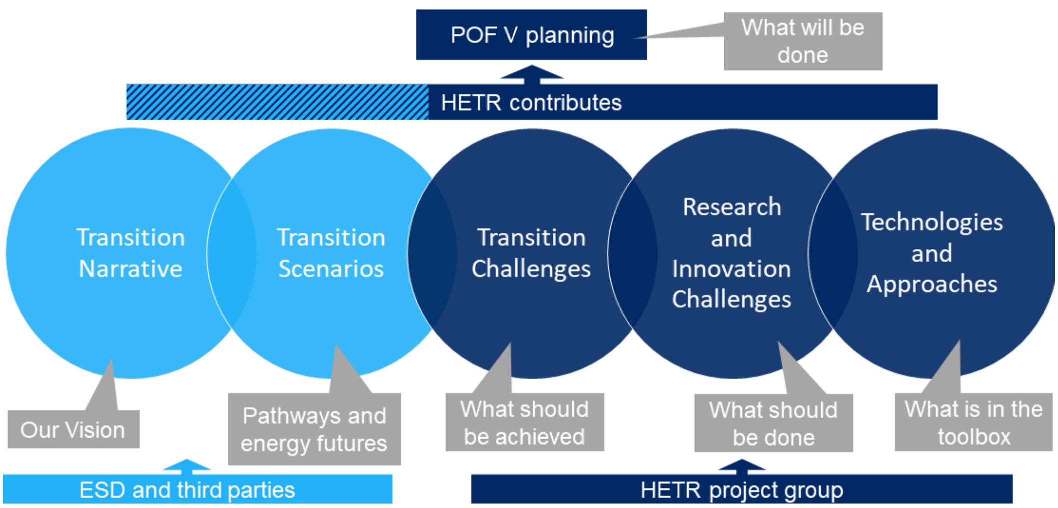

Table of Contents

Introduction

Climate change as a global challenge demands for international cooperation and for a global transformation strategy, which considers the different country-specific conditions and capabilities.

As a contribution to achieving the climate protection targets from the Paris Agreement, in the year 2021 Germany as well as the European Union (EU) agreed on the goal of climate neutrality by 2045 (Germany) and 2050 (EU), respectively, and passed corresponding legislation.

Climate neutrality requires a rapid and fundamental transformation of all sectors of the economy. The basic objective of the transformation is to improve the long-run living conditions of people. This requires recognizing societal demands, which range from fair and secure income to healthy living conditions and environment allowing for a decent life.

Therefore, sustainability goals beyond climate neutrality must be considered while transforming the energy system to net zero: (1) ecosystems must be protected, conserved and restored, (2) sustainable resource flows must be established, (3) economic efficiency must be ensured and (4) the transition must be embedded into societal demands.

Prerequisite for most solutions to achieve a sustainable climate-neutral economy is adequate availability of renewable energy and closing resource cycles in a circular economy. Thus, the energy transition is the most important building block for climate neutrality and one of the central social challenges of our time. The energy sector is crosslinked with the transportation, residential, commercial, industrial and agricultural sectors.

To counteract climate change, we must deploy technologies and processes to generate, store, use, and distribute energy in ways that are safe, reliable, affordable, resilient, and sustainable. Some of these technologies have yet to be developed to market maturity and require scientific and technological innovations that quickly move from the laboratories into practice.

However, a successful transformation of the energy system not only depends on technological solutions, but on their adequate implementation considering interactions between different sectors and policy fields, markets, and especially with society. For example, climate policy affects industrial and economic policy through legislation but also depends on it to develop and implement climate technologies, and to establish a circular economy. Transport policy interacts with climate policy but also with health policy, e.g., when considering active mobility and air quality. Linking climate policy with social policy will be essential to ensure citizens' acceptance for the transformation of the energy system.

As a roadmap for energy research, the Helmholtz Energy Transition Roadmap (HETR) is intended to act as an orientation aid for strategic research in Helmholtz Energy and beyond. Due to progressive technological, economic, societal, and political developments, which are hardly predictable in the long term, different futures of the energy system and correspondingly different transformation paths are possible.

For this roadmap, we have drawn on transformation paths that share a common goal, namely a secure, reliable, climate-neutral, environmentally friendly, economic and socially acceptable energy system of the future. This gives rise to overarching challenges that we call Transition Challenges in this roadmap. Transition Challenges are fundamentally multidisciplinary and cross-sectoral in character and contain technical as well as political, economic, environmental, and social components. They do not yet aim to describe solutions and are thus open to different technological and non-technological paths.

Depending on the choice of technologies and transformation paths, specific challenges arise for research and development. In this roadmap, we call them Research and Innovation Challenges. These address not only the techno-economic, but also environmental, and socio-economic including legal, spheres, with a view to the requirements of the energy system of the future. HETR aims to map these Research and Innovation Challenges for energy research.

The energy transformation takes place in a dynamic framework. It affects and is affected by economy, society and environment, with all these systems behaving and interacting dynamically. This means there is a need for continuous critical examination of the measures and policies introduced and their adjustment as required to reflect the dynamic development of the overall system during the transformation process. Against this background and the parallel ongoing development, technology paths will become more concrete and be subject to change. Accordingly, the HETR will also be updated in the future and adapted where needed.

Energy Transition Scenarios

Energy transition scenarios are scenarios describing plausible transition pathways of the energy system. They help to identify the solution space for the transformation of the energy system by exploring different transformation paths and allow to derive transition and research challenges:

In the political and scientific discussion about energy futures and pathways to reach them, so called back casting scenarios are mostly used. Back casting scenarios are normative scenarios, in which the design of a target system or a target state in the future are defined exogenously. They allow to elaborate several paths to reach the target state and explicitly address deviations of the current path. These normative scenarios investigate what needs to be done to reach the emission-reduction goals. In this sense, they point out the margins of the solution space, to make the differences between if-options (e.g., strong focus on hydrogen as energy carrier versus strong focus on direct electrification) transparent for decision makers. Comparing different scenarios and transformations paths allows to derive no-regret options[8] for actions.

In contrast to normative scenarios, explorative scenarios are used to investigate what happens in the future, if condition A, B, or C changes by x and thus allow to elaborate multiple target states. They are often used to develop reference scenarios e.g., what happens, if expansion of renewable energies proceeds at current pace and thus will miss political targets - other than normative scenarios, which investigate what needs to be done to reach a certain target state t in year y.

While the primary goal of Germany's transition to climate neutrality by 2045 is straightforward, the integration of socio-economic-technical aspects makes the process remarkably complex. This complex transition requires recognition of the dynamic interrelationships between different technological, social, economic, and environmental spheres, both at regional and global levels. Energy transition scenarios can clarify the complex nature of these transition processes, potentially facilitating the creation of comprehensive, holistic solutions.

The current view on the appropriate transition process of the German energy system is as follows: By expanding renewable energies and importing sustainable energy sources from reliable partners, Germany will reduce its emissions to net zero and at the same time become independent of fossil fuel imports. Green hydrogen and other climate-neutral chemical energy carriers will be established in our product and value chains. For a successful transformation of the energy system, it is also essential to strategically consider both efficiency and sufficiency together. Experience has shown that in many cases an increase in efficiency has been overcompensated and led to an absolute increase in resource use.

To deal with fluctuating energy sources such as electricity from wind and photovoltaics (PV), and with seasonal variations in energy supply and demand, new storage capacity must be developed through sector coupling, new storage capacity must be built, and existing storage capacity must be integrated. These are needed to stabilize the frequency of the power grid and to balance the daily as well as seasonal variations in energy supply and demand. A variety of storage technologies based on storage principles ranging from chemical, electrochemical, electromagnetic, thermal and mechanical to electric allow to cover storage capacities reaching from one watt-hour to several terra-watt-hours and discharge times from milliseconds to weeks and months. Storage capacities are also relevant to increase energy security and sovereignty in case of political disruptions.

The German energy transition is closely linked to that of other European countries originally through the Articles 114 and 194 of the Treaty on the Functioning of the European Union and most recently via the EU Green Deal, its goals, initiatives and related legislation and regulation (e.g., the Fit for 55 package and REPowerEU), but also through European wide trade of electricity and other energy sources such as green hydrogen or other climate-neutral synthetic fuels.

Globally, an increasing number of countries adopt net zero greenhouse gas strategies, signifying a major shift in global climate discourse, with similar trends observed across various government levels and the private sector. Renewable energy resources can be harnessed by all nations for increased energy security and independence, aiding in the global energy system transformation towards a more resilient, just, and inclusive world if supported by appropriate policies.

Progress in renewable energy deployment has been significant but uneven, with Europe, the Unites States of America, and China leading in new capacity, while Africa, which has immense renewable potential and energy needs, only accounted for 1% of new capacity in 2020[9]. Globally, the uneven deployment also affects the distribution of jobs and industries worldwide.

The energy transition involves deep structural changes that will impact economies and societies. A holistic policy framework can ensure a timely and just transition, accounting for the varying starting points, socio-economic priorities, and resources of different regions and countries. However, misalignments in finance, labor markets, power systems, and the energy sector can pose challenges and slow down the energy transition if not well managed.

[8]Options for actions that make sense according to all scenarios, e.g. an expansion of renewable energies and a higher share of direct electrification

[9]IRENA (2021), World Energy Transitions Outlook: 1.5°C Pathway, International Renewable Energy Agency.

Transition Challenges

The Transition Challenges are inferred from energy scenarios and the discussion of their results. They are multidisciplinary and cross-sectoral in character and contain technical as well as political, economic, environmental, and social components. They are not intended to already target specific solution paths and are thus open to technology and solutions within the framework set by the energy scenarios.

Enhance involvement of societal needs and concerns

The transition to climate neutrality directly impacts many aspects of people's lives, such as mobility, heating and cooling homes, and building renovations and the construction of renewable energy facilities. Ensuring the success of this transformation requires broad social acceptance and active societal participation. Addressing social concerns and fears, and making the effects of climate policies transparent and fair, are crucial for achieving social acceptance[10].

Effective communication of climate policy is crucial for successful implementation. While broader regional concerns and misinformation can hinder climate measures, local initiatives demonstrate how community involvement and support can lead directly to success. Examples of successful projects in various municipalities illustrate that social acceptance is achievable today.

Establish a secure and sustainable energy and raw materials supply

The transition to a sustainable supply of energy and materials requires environment friendly sources which are equally affordable, secure, and accepted by society. A climate-neutral economy based on closed material cycles is top priority of this transition. Renewable energy systems require large amounts of non-energy raw materials and need renewable and climate-neutral sources for them. Thus, imports of potentially critical raw materials, plant components and plants become increasingly important for the energy transition. Secure supply principles include recycling of materials, utilizing domestic potentials, deploying innovative solutions, diversifying supply chains, reducing per capita consumption, and creating resilient infrastructures.

The European energy crisis highlighted the need to diversify import risk combined with strategies to reduce the environmental footprint and consumption, such as increasing energy and material efficiency, and investing in recycling technologies to close the material and carbon cycles (e.g., plastic waste recycling and Carbon Capture and Utilization (CCU)). Since a circular economy will still require primary raw materials, diversifying imports is crucial. The global energy transition will change trade of chemical energy carriers, with countries' resources shifting from fossil fuels to renewable sources. Establishing new and diversified supply chains will be vital for countries like Germany, which need to invest in infrastructure and forge new partnerships. Even though Germany’s dependence on energy imports will decrease because of the energy transition [11], it will remain an energy importing country.

Per capita energy consumption must be reduced, especially in industrialized nations. Technical solutions alone won't suffice; changes in consumption and mobility patterns are necessary[12]. Improving energy efficiency and reducing overall consumption are key, as is ensuring electrification efforts based on renewable energy. Hard-to-electrify processes need to be defossilized. Addressing challenges in power grid resilience and renewable energy infrastructure including energy storage will be critical tasks in the coming years.

Expand electrification

Advanced electrification of industry, transport, and buildings is seen crucial to achieve the sector-specific climate policy targets. Expanding renewable power generation, particularly solar and wind is crucial. Creating a suitable regulatory framework is a political and societal challenge, with acceptance issues among the population.

Scenarios estimate Germany's electricity demand will reach between 800 and 1050 TWh by 2045-2050, with most domestic generation coming from wind and photovoltaics[13][14][15]. By 2030, the largest greenhouse gas reduction comes from replacing lignite and hard coal for electricity and heat generation. Between 2030 and 2045, the focus will shift to substituting natural gas with hydrogen.

European and global greenhouse gas-neutral electricity generation will heavily rely on renewable

[10]Wissenschaftsplattform Klimaschutz (2022): Auf dem Weg zur Klimaneutralität: Umsetzung des European Green Deal und Reform der Klimapolitik in Deutschland. Jahresgutachten 2021 der Wissenschaftsplattform Klimaschutz. Berlin

[11]Luderer et al. (Hrsg.) Kopernikus-Projekt Ariadne. Deutschland auf dem Weg zur Klimaneutralität 2045. Szenarien und Pfade im Modellvergleich. DOI: 10.48485/pik.2021.006

[12]IRENA (2021), World Energy Transitions Outlook: 1.5°C Pathway, International Renewable Energy Agency.

[13]Deutsche Energie-Agentur GmbH (Hrsg.) (2021), dena-Leitstudie Aufbruch Klimaneutralität

[14]Prognos, Öko-Institut, Wuppertal-Institut (2021), Klimaneutrales Deutschland 2045.

[15]BMWK Langfristszenarien (2021), Modul Energieangebot.

energy, with a high share of wind and solar[16][17][18]. A major challenge in electrification is balancing the intermittent power supply from wind and solar, which poses challenges for grid integration and stability, energy storage, and supply and flexibility of demand. Resilience, robustness, and cybersecurity must also be maintained. Another major challenge is the social acceptance of the transition to a renewable power system.

Fusion as a power source is considered a perspective for resilient and sustainable power generation in the second half of the century. The development of fusion as an electricity generation technology up to the construction of a power plant, however, still requires intensive research regarding technology development and techno-economic and societal system integration.

Generate heat for buildings and industrial processes

About 40% of Germany's energy demand is used for heat, with only 20% coming from renewables[19]. To reduce CO_2 emissions in the building sector, two challenges must be addressed: increasing the refurbishment rate of buildings and replacing fossil fuel-based heating systems with renewable energy. A mix of technologies should be used, considering regional and building-specific factors. Thermal storage can help decouple fluctuating input and demand, enabling sector coupling between electricity and heating.

Industrial heat demand is even more challenging to defossilize, as it requires higher power levels and temperatures. A reliable heat supply throughout the year will require a technology mix and integrated thermal storage devices with additional benefits from coupling power, heat, and fuel sectors using renewable energy.

Build a hydrogen economy

Hydrogen contributes to five central applications in a renewable energy system: a) feedstock for the chemical industry and synthetic fuel production, b) reducing agent in iron production, c) storage medium for renewable energies, d) greenhouse gas-neutral fuel, and e) long-distance energy transport option.

Hydrogen will be essential to defossilize the industry sector, particularly the chemical and steel industries, and as a fuel for flexible gas power plants. Although the degree, by which hydrogen will be used in the transport and building sectors, is still under discussion, the annual demand for hydrogen could be as high as 92-129 TWh (incl. grey hydrogen) in 2030 and 964-1364 TWh between 2040 and 2050[20]. Hydrogen is also a viable option for long-term and seasonal storage. However, hydrogen storage and transport are challenging tasks due to its low volumetric energy density and high mobility.

Green hydrogen production is currently minimal compared to natural gas, and large investments are needed for its expansion. The European roadmap aims for 10 GW production by 2025 and 40 GW electrolyzer capacity by 2030 [21]. International coordination, legislation, and standards are essential for the market ramp-up of a global hydrogen economy. Other types of CO_2-reduced hydrogen (e.g. in combination with carbon capture and storage (CCS)) may help speeding up the required fast transition to a hydrogen economy.

Remove CO_2 from process emissions and from the atmosphere

Current energy scenarios indicate that climate targets won't be achieved anymore without targeted removal of CO_2 from the atmosphere (Carbon Dioxide Removal, CDR). CDR is necessary to compensate residual emissions from agriculture or specific industrial processes that can't be avoided or are hard-to-abate in the long-term (IPCC 2022[22]) and to compensate for a potential temporary overshoot of the carbon budget (WBGU 2021[23]).

National and international energy scenarios assume that a CO_2 infrastructure for capture and permanent storage will be established by mid-century. However, no large-scale infrastructure currently exists to enable high feed-in rates of large volumes. Developing this infrastructure requires long lead times, potential business models, financing, and addressing societal concerns.

Geological storage sites for CO_2 are limited, with the largest storage potential in Europe being offshore in the North Sea and on the Norwegian shelf. In

[16]IRENA (2021), World Energy Transitions Outlook: 1.5°C Pathway, International Renewable Energy Agency.
[17] European Commission (2021), EU reference scenario 2020 : energy, transport and GHG emissions : trends to 2050, https://data.europa.eu/doi/10.2833/35750
[18] IEA (2021), Net Zero by 2050, https://www.iea.org/reports/net-zero-by-2050
[19]Prognos, Öko-Institut, Wuppertal-Institut (2021), Klimaneutrales Deutschland 2045.
[20] Nationaler Wasserstoffrat (2023), Grundlagenpapier Treibhausgaseinsparungen und der damit verbundene Wasserstoffbedarf in Deutschland.
[21]Expert groups of the agenda process (2022), SRIA, Agenda process for the European research and innovation initiative on green hydrogen.
[22]IPCC (2022), Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/9781009157926.001
[23]WBGU – Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (2021), Über Klimaneutralität hinausdenken. Politikpapier 12.

Germany, the combined onshore and offshore storage potential is about 12 Gt of CO_2, while around 200 Gt of CO_2 could be stored in European locations[24].

Provide basic materials for the chemical industry

In 2022, about 86% of organic feedstocks for the chemical and pharmaceutical industry come from fossil sources, primarily crude oil and natural gas. Naphtha accounts for around 72% of the raw materials, with over 14 million metric tons needed annually in Germany. Natural gas constitutes about 14% of the feedstock, with 80% of the hydrogen produced from natural gas going into ammonia production[25].

The transition to a sustainable supply will require alternative sources of hydrogen and carbon. Establishing a circular carbon economy through recycling of plastics and sustainable biomass can partially provide carbon sources for industry. However, since their potential is limited, synthetic feedstocks will eventually have to balance the demand. These feedstocks will rely on green hydrogen, likely from electrolysis, and synthesis processes as well as on carbon from processes like direct air capture, which all require substantial electricity, increasing the chemical industry's long-term power demand[26].

Defossilize transportation

Since 1990, the transport sector has struggled to reduce greenhouse gas emissions. Efficiency improvements and biofuels have been offset by increasing traffic volumes and vehicle weights. Globally, the sector is the second-highest CO_2 emitter[27]. And it has the lowest share of renewable energy in Germany[28].

The challenges for road, aviation, shipping, and rail transport are diverse, with energy sources depending heavily on available drive concepts. Each transport mode has specific powertrain requirements regarding power, weight, size, range, and infrastructure.

For road transport, two main CO_2-neutral powertrain options exist: electric drives (battery electric vehicle or fuel cell electric vehicle) or combustion of CO_2-neutral fuels in internal combustion engines or turbines. Combinations are also possible, with various energy carriers and storage media.

For long-distance aviation and shipping, which cannot be directly electrified, renewable fuels such as CO_2-neutral kerosene, hydrogen or hydrogen carriers are being considered. The adoption of these energy sources depends on factors such as availability of energy, raw materials, carriers, and storage media, economic key indicators, technological maturity of drive concepts, existing infrastructure and requirements for new infrastructure, and technological requirements specific to each transport mode.

In addition to technological options, an overall reduction in mileage, a speed limit, and a shift in the modal split namely from motorized private transport to active mobility, public transport, and rail would not only contribute to greenhouse-gas reductions in the transportation sector, but would also (1) have positive health effects, leading to increased well-being and to cost reductions in the health care system, and (2) reduce land consumption.

Adapt the energy market design

Achieving a climate-neutral system requires deploying renewables and designing policies that support them. As the market becomes saturated with renewable energy, priorities may shift towards market efficiency, socio-political acceptance, and community support. Technology-specific market designs will likely persist, with emphasis on efficiency, security, environmental sustainability, and social acceptance.

An effective market design should address challenges like fragmented energy policy, regulations and initiatives on different scales (EU, federal, state, local), grid operation and management, digital technology integration, and financing coupled energy markets[29]. This requires addressing complex interdependencies, market-driven integration of distributed systems, adhering to privacy and security standards, and incentivizing investments that align with efficiency, security, sustainability, and acceptance. Market designs should consider both European and national demands, with the question of suitable design becoming relevant by the early 2030s.

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[25] VCI (2022), https://www.vci.de/ergaenzende-downloads/22-05-04-oel-ist-die-basis-fuer-die-chemieproduktion.pdf
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[28] Umweltbundesamt (2021), Erneuerbare Energie im Verkehr.
[29] Bichler, M. et al. (2021), Electricity Spot Market Design 2030-2050, https://doi.org/10.24406/fit-n-621457

Research and Innovation Challenges

Different technology paths pose different challenges on research and development. Here we map these as “Research and Innovation Challenges” – challenges that are often tackled by Helmholtz Energy research but may also extend beyond its (current) scope. These challenges were revised and amended by a large number of Helmholtz Energy scientists, organized in the HETR Expert Groups.

They address not only techno-economic aspects but also environmental, legal, and socio-economic factors, considering the needs of the future energy system. The goal of HETR is to outline and explore these Research and Innovation Challenges for a comprehensive understanding of energy research requirements, fostering a holistic approach to addressing the complexities of the energy sector.

System and Society

Understanding the energy transition as the change of a socio-technical system

Energy transition requires understanding the complex interrelationships between technology, environment, markets, institutions, and social behavior in a dynamic system. Socio-technical energy scenarios and sustainability assessments can guide policy decisions at various scales. Challenges include identifying drivers and impediments, improving assessment methods, and addressing energy justice and poverty.

Resilience is vital, focusing on socio-economic-ecological aspects and measuring the vulnerability of the economy, society and the environment. Transforming the energy system requires long-term governance and balancing current interests with future demands at international, national, and regional levels.

Research Objectives

- Identify drivers and impediments of social behavior and technological progress.
- Investigate individual decision-making related to energy consumption and sustainable behaviors and explore strategies to encourage sustainable choices and reduction of energy consumption.
- Examine the influence of social norms on individual behavior and assess policy interventions to shift norms towards sustainability.
- Improve multi-criteria decision analysis (MCDA) methods and use findings for societal discussions on policy targets and sustainable pathways.
- Operationalize and include inter- and intragenerational energy justice in sustainability assessments.
- Examine factors affecting energy poverty.
- Define and measure socio-economic-ecological resilience in energy systems.
- Assess effects of disruptive events in the energy sector on societal wealth and the environment.
- Study energy transition's impact on societal wellbeing and potential negative consequences in low-income countries.
- Identify policies supporting favorable socio-technical pathways.
- Engage with individuals resistant to energy transitions.
- Develop concepts against energy poverty.

Understanding and adapting to the impacts of climate change on the energy system

Climate change influences the energy system through occurrences of extreme weather events and shifts in average weather patterns, potentially leading to issues like water scarcity. Such conditions can inflict damage on infrastructure and cause disruptions to supply chains. It changes energy demand due to shifting air conditioning and heating needs and alters energy supply from hydropower, wind, solar, and thermal plants. This will or should induce regulatory changes like greenhouse gas emission reduction policies and raw -material acts. Adaptation strategies involve designing resilient energy systems with robust materials, backup systems, and measures prepared for extreme weather conditions. Continuously monitoring and assessing climate change impacts are prerequisite to adjust energy systems accordingly.

Research Objectives

- Assess climate change impact on energy systems.
- Identify strategies for adaptation and incorporate findings into energy scenarios.
- Create technical solutions to protect affected equipment.

Minimizing the impact of renewable energy technologies on the environment

Like any use of technology, the energy transition carries the risk of environmental impacts. Harnessing society's willingness to participate in the energy transition requires technical solutions to minimize environmental and quality of life impacts. A key research tool is life cycle assessment (LCA), the results of which should be applied in the evaluation of energy scenarios and in the development and design of advanced technologies and materials for closing material cycles.

Research Objectives

- Include "closed" carbon loops and battery technologies in sector-coupled models and system optimization.
- Enhance storage and conversion technologies: ensure recyclability, increased lifetime, and material efficiency.

- Develop technologies with fewer critical materials and ensure sustainable production, use, and recycling.
- Evaluate resource intensity and criticality aspects and integrate them in energy system models.
- Assess environmental impacts and greenhouse effect for synthetic fuels and Power-to-X (PtX)-products.

Increase acceptability of renewable energy technologies

Social acceptance for the use of renewable energy technologies is one of the key challenges but also opportunities for the transformation of the energy system. Reservations in society and business often exist when stakeholders fear economic disadvantages or harmful effects on the environment or their immediate neighborhood. At the same time, there is a great willingness in society to participate in the energy transition.

Reservations can basically be countered in four ways:

1. Identifying and implementing strategies to involve stakeholders in the development and deployment of new technologies.

2. Regulatory measures that contribute to a socially just energy transition and prevent energy poverty,

3. Technical solutions that minimize environmental impacts and effects on the quality of life of residents, and

4. Enabling active civic agency for the transformation

Research Objectives

- Improve strategies to include community engagements in renewable energy projects.
- Understand the interrelationship between factors affecting acceptability.
- Address land use conflicts and green-on-green issues for wind and photovoltaic systems.
- Improve science communication channels with the public.
- Address stakeholder concerns.
- Develop concepts against energy poverty.
- Improve methods to assess and use them to assess government policies regarding energy justice.

Develop comprehensively assessed energy scenarios as bases for decision-makers

Understanding interactions of technologies and infrastructures in the energy transition is crucial. Efforts should focus on representing emerging technologies in energy system models and assessing their economic, environmental, and social effects. Given the dynamic context, energy system models should provide timely insights on impacts and adjustments of transformation paths.

Research Objectives

- Develop sector-integrated energy system models with broad techno-economic calibration.
- Close the granularity gap in models geographically and technologically.
- Provide consistent future scenarios for climate-neutral sectors.
- Optimize production, transport, and import interactions for power, hydrogen, and synfuels.
- Develop market designs and business models for sector-integrated energy systems and value demand flexibilities.
- Focus on climate change adaptation and consequences, including beyond 2045.
- Incorporate life cycle assessment, resilience, user behavior, and acceptance into models.
- Address safety of fuel and energy storage solutions.
- Adapt models for quick policy advice.
- Consider legal regulations in concepts and models for viable business cases.
- Rework regulatory aspects for emerging technologies like hydrogen, synfuels, and storage.
- Create and evaluate target failure scenarios
- Anticipate and model disruptive events, developments and technologies

Electricity Supply

Maximize the exploitation of potentials for renewable power generation

The expansion of renewable energy in densely populated countries, such as Germany, is a challenge that requires a supportive legal framework, efficient land use, social acceptance, and synergies. Key approaches involve improving energy conversion and land-use efficiency in integrated systems, accessing currently unusable areas, and developing dual-use technologies and regulations. Optimizing design, operation, and repowering of existing systems, employing energy storage for excess energy management, and enhancing power generation and distribution efficiency are also important. Involving local communities and stakeholders in renewable energy projects is essential for success.

Research Objectives

- Assess techno-economic, socio-ecological impacts, and societal challenges of renewable power generation in regional settings.
- Enable community participation in land use and renewable energy decisions.
- Minimize the impact on the local environment.
- Develop and optimize materials, technologies and control systems for increased efficiency.

- Develop technologies to tap new (dual-use) areas (e.g., building integrated photovoltaics (PV, agri-PV, floating PV, canal-top PV).
- PV challenges: performance enhancement, integration, socio-economic and ecological aspects, roof and facade potential, agricultural impact assessment, recycling, life cycle and sustainability assessment.
- Wind challenges: site assessment, predictive capability, holistic design, noise reduction, wind park optimization, intelligent turbines, recycling, life cycle and sustainability assessment.
- Develop adaptable energy storage systems for various scales and response times.

Reducing levelized cost of electricity (LCOE)

The levelized cost of electricity (LCOE) is a measure of the overall cost of generating electricity and should be kept as low as possible. Reducing the LCOE can be achieved by enhancing technology efficiency without a proportional increase in cost, scaling up renewable generation and storage for economies of scale, optimizing production processes, reducing or replacing costly materials, storing excess renewable energy for dispatchability, increasing distributed energy supply, and creating a well-designed electricity market for renewable integration and cost reduction.

Research Objectives

- Explore low-cost advanced materials for improved properties and durability.
- Develop and optimize materials and technologies for efficiency, durability, and lifetime.
- Create smart control systems and reduce maintenance costs.
- Optimize production processes and enable high-temperature heat transfer media.
- Photovoltaic challenges: enhance performance, cost reduction, lifetime, reliability, integration, and market incentives.
- Gas turbine challenges: develop high-temperature materials, adjust technology for costs, load, fuel flexibility, and retrofit for renewable fuels.
- Concentrated solar power (CSP) challenges: develop plants for heat, power, chemical fuels, improve efficiency, and innovate with supercritical carbon dioxide (sCO_2) Brayton cycle.
- Wind challenges: integrate structural health monitoring, improve component evaluation on plant and system levels.
- Research fusion technology for power generation and power plant construction.
- Increase cost-effectiveness through recycling and retrofitting material-saving solutions.

Explore solutions for an advanced, sector-coupled energy grid design

Advanced sector-coupled energy grids, including electricity and gas, require a multi-dimensional approach addressing integration, efficiency, flexibility, stability, reliability, robustness, and economic considerations. Technical and IT solutions must be tested in grid networks before real-world use. Ensuring that solutions can be socially accepted, align with regulatory frameworks or developing proposals to adapt regulations is also crucial.

Research Objectives

- Develop co-simulation environments for sector-coupled systems and large-scale/real-time simulations of interconnected power grids.
- Create automated forecasting algorithms for grid stabilization and advanced control strategies in real-time simulations.
- Assess the impact of new technologies and evaluate resilient, sustainable energy grid designs.
- Implement pilot projects and demonstration programs for sector-coupled systems.
- Assess techno-economic, socio-ecological impacts, and societal challenges.
- Conduct life cycle assessments, propose regulatory adjustments, and perform techno-economic modeling of energy grid designs.
- Address global perspectives of hydrogen-import dependency using global models.
- Develop robust, non-manual solutions for complex, multi-criteria technology integration in sector-coupled energy systems.

Make electricity transmission and distribution more efficient

Regions with abundant renewable energy may be far from consumers, requiring efficient long-distance electricity transmission. The same holds true for energy-intensive industries.

Technical approaches include smart grid, sector coupling, and demand response technologies to monitor and manage electricity demand across sectors, high voltage direct current (HVDC) transmission for efficient long-distance electricity transmission, high-temperature superconducting (HTS) transmission with zero resistance and power loss possibly combined with a liquefied hydrogen transport infrastructure, and flexible alternating current transmission systems (FACTS) to improve existing alternating current (AC) transmission lines' efficiency, flexibility, and stability.

Research Objectives

- Maximizing grid transportation capacity and battery capacities for optimal renewable energy harvesting.

- Ensuring power grid stability without classic inertia in a converter-based grid.
- Translating globally efficient measures, such as grid expansion, into local incentives.
- Addressing smart grid, sector coupling, and demand response challenges, including real-time data management, interoperability, cybersecurity, and control algorithms.
- Overcoming HVDC challenges, such as developing efficient converter technologies, advanced protection mechanisms, and grid integration strategies.
- Tackling HTS challenges, such as system designs, cost reduction, advanced materials, and standards development.
- Addressing FACTS challenges, including modeling, control strategies, optimization algorithms, integration of intermittent power sources, and technology standardization.

Develop flexibility options for power grid and power generation

Flexibility options in renewable energy systems address intermittency of power production, uncertainty, and grid stability through a range of strategies. These include energy storage, diversified energy sources, demand response programs, cross-sector coupling, microgrids, peaker plants, combined heat and power (CHP) systems, smart grid technology, virtual power plants, and local urban energy solutions with various storage facilities.

Research Objectives

- Create integrated local power production with backup plants and storage.
- Design decentralized power plants and high-temperature heat storage.
- Enhance battery, Power-to-X and other storage capabilities.
- Develop heat pumps, predictive energy distribution, and carbon capture and storage (CCS) strategies.
- Utilize the mobility sector with fuel cell electric vehicle (FCEV) and battery electric vehicle (BEV).
- Develop flexible power management for urban areas.
- Integrate wastewater treatment plants into city power and heat supply.
- Model integrated infrastructure planning for electricity and hydrogen.
- Conduct life cycle assessments for energy storage and flexibility options.
- Motivate household participation in demand-side management.

Ensure reliability and resilience of the power grid

To ensure a reliable and resilient power grid, several measures need to be combined. These include energy storage systems for a consistent power supply, additional grid interconnections for balancing renewable energy variations, and microgrids for decentralized energy generation and storage. Smart grid technology for real-time monitoring and control, upgraded and maintained grid infrastructure, and incorporation of distributed energy resources are also essential. Furthermore, comprehensive crisis management plans and ensuring cybersecurity to protect against cyber-attacks contribute to a resilient power grid.

Research Objectives

- Develop strategies for protecting critical infrastructures.
- Develop microgrid solutions using advanced optimization approaches like quantum computing and artificial intelligence (AI).
- Create IT solutions for intelligent control and automation.
- Test components and control mechanisms in realistic simulations.
- Identify and classify vulnerabilities in critical infrastructures to develop protection strategies.
- Develop scenarios for disruptions, crisis management plans, and AI-based decision support frameworks.
- Assess automated cybersecurity management, balancing resiliency and costs.
- Adapt to changing risks, like disruptive technologies and geopolitical factors.
- Develop real-time resilience distribution management in smart grids.
- Identify frameworks for analyzing systemic risk and supporting decision-making for general resilience.

Develop solutions for electrification in the transport sector

The transportation sector will shift towards sustainable transportation, with direct electrification using batteries offering zero-emission propulsion. For long-range, high-performance applications like heavy-duty transport, shipping, and aviation, indirect electrification via fuel cells, or the combustion of bio/synthetic fuels are alternatives.

A suitable framework must be established for electrification, which includes improved battery technology for increased range and reduced cost, affordable fuel cell technology, adequate charging infrastructure for battery electric vehicles, and hydrogen fuel stations for fuel cell electric vehicles. Additionally, electric vehicle integration into the power grid for supply-demand balance and energy system efficiency, as well as regulations and standards ensuring safety and performance of electric and fuel cell vehicles, charging, and fueling infrastructure are crucial.

Research Objectives

- Enhance battery energy density and charging speed.
- Reduce battery production costs and (critical) materials demand.
- Improving the customer acceptability (e.g., by improved sustainability and recyclability, increased range, reduced costs, automated user-vehicle interfaces, smart charging strategies).
- Improve fuel cell performance and cost for heavy duty applications.
- Develop materials and devices for power electronics.
- Optimize battery-fuel cell connections.
- Conduct life cycle assessments and material criticality assessments.
- Develop regulations for consumer-provided vehicle-to-grid ancillary services.

Advance fusion technology for application in the energy system

Complementary to intermitting renewable energy technologies, fusion power could contribute significantly to a future energy supply 2045++, mitigating the climate change and satisfying the world's continuously and rapidly growing energy demand in a potentially environmentally responsible way.

Since fusion is challenging and complex, and a proof of feasibility for its application to a reliable energy generation still needs to be provided, a long-term strategic approach based on European and international cooperation is essential to develop it as a future technology option. At this, fusion has to show long-term fuel availability, and controlled operating characteristics to be qualified as an additional option that complements other greenhouse gas-neutral dispatchable electricity technologies in a diversified and climate-neutral energy system. Perspectively, fusion power could be an appropriate energy supply technology especially for areas with high population density and industrial centers due to its high energy density and low land-use. Its baseload capacity and relatively high temperature levels could enable fusion as a reliable supply for Power-to-X.

Research Objectives

- Research plasma operational scenarios for fusion power plants
- Develop reliable and efficient fusion power plant technologies (power exhaust, fuel cycle, tritium breeding blanket, plasma heating, current drive systems, remote handling, superconductors)
- Research and optimize high-performance materials (neutron and temperature resistant, low activation, resilient) and high-temperature components
- Validate reliable diagnostic and instrumentation systems
- Develop balance of plant concepts for fusion power plants in a flexible power and heat grid
- Improve simulation tools and model approaches
- Identify strategies regarding safety and waste management
- Provide operation scenarios for fusion power plants in a diversified and climate-neutral energy system 2045++
- Explorative techno-economic evaluation of fusion integration into fully renewable systems (e.g., technology cost, transaction cost)
- Evaluate the socio-economic impacts of fusion power technology (e.g., value added chains, geopolitical and supply risks, acceptance)
- Evaluate the impacts of fusion power technology on sustainable development via methods as Life Cycle Sustainability Assessment
- Socio-technical energy system scenarios including fusion

Heat Supply for Buildings

Reducing the heating demand of buildings

Technologies and methods for increasing heating efficiency in new buildings, but also for the refurbishment of existing buildings, must be advanced and newly developed. Efficient refurbishment strategies for reducing heating demand, however, require knowledge of a building's design status. Advancing methods for evaluating existing buildings and disseminating this knowledge to the construction industry is crucial for cost-effective, holistic strategies that consider life cycle impacts.

Research Objectives

- Real-world labs to develop strategies for homeowner home refurbishment.
- Improve building analysis methods (scanning tools) to efficiently assess a building's design status and develop model-based refurbishment strategies that consider life-cycle and sustainability effectiveness of interventions.
- Advanced databases that provide information of building infrastructure, its status, and current heat demand as a basis for future heating grids.
- Tools for optimizing energy infrastructure in city quarters and evaluating technical building equipment's role in grid support.
- Heat storage systems for integration in building envelopes for seasonal storage.
- Adaptive facades with adjustable thermal insulation.
- Develop strategies to raise awareness and educate the population on energy-saving heating.

Replacing fossil fuel-based heating systems by renewable energy

Renewable energy sources can replace fossil fuels, but challenges arise from high winter demand and simultaneous low solar input. Solutions include efficient heating systems, seasonal energy storage, sector coupling, low-temperature heat sources, and using sustainable biomass and geothermal energy. The choice depends on location, resources, and infrastructure. Policy regulations, incentives, and education are essential to support architects and service companies in developing effective refurbishment and city quarter energy strategies.

Research Objectives

- Real-world labs to develop strategies for homeowner home refurbishment.
- Heat grid solutions for neighborhoods and districts, including seasonal storage.
- Integrate Power-to-heat links into heat grids for seasonal storage and for power grid support.
- Identify and assess potential heat grid locations.
- Linking heat supply in winter with cooling supply in summer over seasonal storage.
- Develop solutions for second use of gas infrastructure.
- Improving efficiency, power level and system integration of heat technologies (e.g., (High-Temperature-) heat pumps, direct electric heating, hydrogen combustion, biomass or biogas, combined heat and power including fuel cell systems, geothermal systems, advanced solar thermal, waste heat recovery).
- Developing alternative seasonal heat storage concepts for individual buildings and heating grids (thermochemical, latent, geothermal).
- Reducing the temperature of heat grids.

Industrial and Process Heat

Technology development for renewable process heat production

Tailored energy solutions and a mix of renewable technologies are crucial for industrial sector defossilization. Advancements in technical systems, adaptable production routes, and waste heat recovery can improve efficiency, reduce costs, and lower environmental footprints. To ensure a sustainable transition, policy regulations, incentives, and education efforts must support these developments.

Research Objectives

- Develop solutions for process heat generation and storage.
  - Heat storage technology for diverse fluids and temperatures.
  - Technologies including direct electric heating, solar collectors, high-temperature heat pumps, geothermal energy and biogas/hydrogen-based combined heat and power (CHP).
  - Hybrid integration and storage applications.
  - Waste heat recovery and integration for industrial energy savings.
  - CHP power development with carbon capture, storage (CCS), and exhaust gas recirculation for transition (fuel oil/natural gas to hydrogen).
- Consider recycling in all technology & product developments.

System level optimization of renewable heating supply systems

As heat sector diversity and sector coupling increase, assessing technologies and interactions becomes more complex. Advanced modeling tools are essential for selecting and designing renewable energy systems that combine heat pumps, solar power, electric heating, geothermal, heat storage, and green-fueled combined heat and power (CHP). These tools also help optimize operations strategy, including demand-side management, evaluate resilience and environmental footprint, and interact with comprehensive, cross-sector energy system models.

Research Objectives

- Develop modeling tools for optimizing complex industrial energy systems, including:
  - Multi-fidelity models for process simulations
  - Design and operation tools for hybrid renewable supply technologies.
  - Operations strategy, resilience, and demand-side management.
  - Environmental and social impact assessment methods.
  - Interface with existing energy system models (for sector coupling).
- Focus on policy-making, regulation adaptation, governance, and their impact on sector-coupled energy systems.

Hydrogen and Synthesis Gas

Enable economic mass production of green hydrogen

Green hydrogen production is vital for the transformation of the energy system and has various applications, such as fuel cells, industrial processes, and synthetic fuel production. Currently, electrolysis is the most viable method, with research focused on efficiency, reducing Capital Expenses (CapEx) and Operational Expenditures (OpEx), and environmentally friendly materials.

Alternative hydrogen production methods under research include biomass gasification, methane pyrolysis, photo-electrochemical cells, plasma conversion technology, and thermochemical cycles. Cost-effective green hydrogen production depends on optimized system design, renewable energy potential, system lifetime, and full load hour maximization.

From a system perspective, additional factors include transport modes and costs, integrated infrastructure planning, a stable regulatory framework, political stability, diversified trading routes, cost competition, sustainability standards, low emissions, facility and infrastructure life cycles, qualified personnel, and public acceptance.

Research Objectives

- Develop sustainable, cost-effective catalysts.
- Improve catalyst and redox material stability.
- Create new materials for efficiency and cost reduction.
- Speed up design-build-test-learn cycle.
- Develop scale-bridging approaches in manufacturing.
- Increase long-term stability of materials.
- Optimize energy efficiency (e.g., by process coupling, reducing required process temperature).
- Improve process selectivity.
- Develop standard analysis techniques.
- Develop advanced components and cell designs.
- Innovate process designs.
- Create scalable (membrane) reactor and separation concepts, and devices.
- Develop high-temperature components and systems.
- Improve sealing for high-temperature devices.
- Understand (non-potable) water and CO_2 quality requirements.
- Develop operational strategies for renewable hydrogen production.
- Optimize manufacturing processes for scale-up.
- Analyze global hydrogen markets and potential production sites.
- Conduct macroeconomic and sustainability assessments.
- Ensure critical resource supply and study public perception.
- Standardize integration and develop oxygen utilization concepts.
- Model global energy systems with hydrogen infrastructure.
- Assess energy balance, production costs, and multiscale modeling.

Enable efficient storage and transport of hydrogen

In net zero scenarios, large-scale hydrogen production relies on efficient infrastructure connecting producers and consumers.

Research addresses economic and technical uncertainties by modeling and comparing transport and storage options, and overcoming technical challenges. Hydrogen transport and storage methods include compressed hydrogen, liquid hydrogen, chemical compounds, metal hydrides, underground salt caverns, and carbon-based materials. Each has its pros and cons depending on the application, existing infrastructure, and transport distance. Research ensures safety, develops new processes, and increases efficiency for optimal techno-economic solutions.

Research Objectives

- Understand future global hydrogen markets (economics, risks, geopolitical factors).
- Develop techno-economic models for small and medium-scale hydrogen production and storage.
- Model incentives and political goals (e.g., synfuels, inflation reduction act).
- Rework regulatory framework (e.g., hydrogen storage > 3000 kg).
- Retrofit existing gas infrastructure (leak tightness, corrosion).
- Explore synergies between liquid hydrogen and electrical engineering (e.g., pipelines and superconductors).
- Develop dynamic operating regimes for caverns and surface facilities.
- Assess hydrogen quality, purification, and leakage in underground storage.
- Model integrated infrastructure planning (electricity, gas, hydrogen, heat) from local to global scales.
- Perform Life Cycle Sustainability Assessment (LCSA) for sustainable technology development.

Advancing hydrogen-based energy conversion

Hydrogen is vital as an energy carrier in renewable systems, serving in electricity generation, heat production, and mobility. Fuel cells convert hydrogen to electricity, but high costs limit widespread adoption. Research aims to reduce costs, boost efficiency, and improve durability. Hydrogen combustion in gas turbines faces challenges like NOx emissions, material stress, and fewer operating hours. Reducing investment costs is crucial, with research and development (R&D) playing a significant role.

Research Objectives

- Enhance fuel cell performance: catalysts, membranes, electrodes, manufacturing processes, system integration.
- Reduce fuel cell costs: materials, manufacturing processes.
- Increase gas turbine load flexibility: improve response time to renewable energy fluctuations.
- Enable fuel-flexible gas turbines: hydrogen, syngas, biogas, liquid synfuels.
- Mitigate NO_x emissions: adapted catalysts, additional devices.

- Develop high-performance materials for high-temperature combustion: creep-resistant, corrosion-resistant.
- Model green hydrogen market ramp-up.
- Conduct life cycle sustainability assessment during development stages to ensure sustainability.

Developing sustainable processes to produce syngas

Replacing fossil hydrocarbons with synthetic, renewable products is essential for the energy transition. Hydrocarbons are crucial for the production of numerous consumer products, and some transport applications have no fuel alternative, like long-range aviation and cargo-shipping. Producing synthetic products from biomass is highly efficient but limited by the sustainable biomass potential.

Syngas, a mixture of hydrogen and carbon-monoxide, is essentially required to produce synthetic hydrocarbons, the base molecules for consumer products and technical units. Producing carbon-neutral syngas either (i) requires the use of green hydrogen along with a non-fossil or hard-to-abate carbon source, such as direct air capture or cement production, or (ii) involves the utilization of anthropogenic waste (e.g., plastics), biomass, or biogas. Both paths demand substantial renewable power input. Syngas production methods include biomass or waste gasification, CO_2 reduction reaction, solar/thermal conversion, thermochemical processes, high-temperature electrolysis, plasma conversion, photoelectrochemical reduction, and direct electroreduction. These processes are typically in high temperature and pressure and partly involve various catalysts or redox materials. R&D focuses on functional materials, process efficiency, and process design challenges.

Research Objectives

- Develop advanced, cost-effective catalysts.
- Improve redox materials for thermochemical splitting.
- Enhance reaction selectivity in biomass gasification, CO_2 reduction and synthesis pathways with direct CO_2 usage.
- Increase energy efficiency (catalysts, redox materials, waste heat recovery).
- Scale up processes, especially for CO_2 reduction and direct usage of CO_2 in fuel synthesis
- Integrate intensified reactors (membrane, micro, multiphase).
- Address plasma conversion challenges (gas separation, ammonia cycle).
- Manage biomass and waste gasification challenges:
  - Gasifier design for a wide range of feedstock specification
  - Pre-processing (mechanical, pyrolysis).
  - Slag flow behavior.
  - KI-based process control for flexible feedstock and dynamic operation.
  - Understand catalytic effects of components like alkali and explore mixing of feedstocks.
  - Reduce tar formation and improve removal.
  - Enhance syngas conditioning and impurity removal.

Synthetic Fuels and Chemicals

Enable mass supply of renewable base chemicals

Synthetic base chemicals from renewable feedstocks are crucial for defossilizing the chemical industry. Economic efficiency must be improved through regulatory measures and process efficiencies. Key prerequisites include sufficient renewable feedstocks, low-cost renewable energy, efficient large-scale production, untapped carbon sources, and a suitable regulatory framework.

The synthesis of large quantities of renewable base chemicals thus depends heavily on upscaling green hydrogen and sustainable syngas production processes, and the recycling of plastic waste. Maintaining established production routes and using renewable raw materials will aid transition. Examples of base chemicals needing renewable synthesis are bulk chemicals like ammonia, methanol, ethylene, propylene, and naphtha. Research and development aim to improve process efficiencies, selectivity, product yield, and cost reduction, while systems research evaluates techno-economic performance, system integration, and environmental impacts.

Research Objectives

- Increase production efficiency and process flexibility.
- Reduce costs and improve product yields.
- Develop alternative catalysts, membranes, reactors and synthesis routes.
- Scale up reactor technology and address lifetime issues.
- Integrate syngas production with producing units
- Improve mechanical and chemical recycling of plastic waste.
- Develop processes compatible with non-potable water and carbon capture utilization (CCU).
- Optimize overall Power-to-X process routes and increase technology readiness level (TRL) of non-market-ready technologies.
- Standardize system concepts.
- Develop process chains for energy reuse and close integration of generation/conversion processes.
- Assess environmental, macro-economic impacts and (critical) material demand, and identify promising value chains.

- Adapt techno-economic models and develop strategies for production sites and import routes.
- Derive future base chemicals demands and transition pathways to a renewably based economy.

Facilitate economic production of synfuels

Synfuels offer CO_2-neutral alternatives for hard-to-electrify transport sectors and heating applications. They can be used in existing infrastructure and blended with fossil fuels. Synfuels can be classified as biomass-to-liquid (BtL), power-to liquid (PtL or e-fuels) or sun-to-liquid (solar fuels). Research aims to improve process efficiency, selectivity, product yield, and lower costs while addressing system design, integration, environmental impacts, and social acceptance.

Research Objectives

- Boost efficiency and yields in production.
- Optimize Power-to-liquid/gas (PtL/PtG)-process trains and routes.
- Develop alternative catalysts, reactors, reactor-components and synthesis routes
- Scale reactor technology, address lifetime issues.
- Support flexible feed, yield, and multi-product facilities.
- Enhance fuel design and target properties.
- Assess technical fuel performance, optimize combustion systems.
- Co-optimize specifications, develop efficient Power-to-Liquid (PtL)-Fuels.
- Implement flexible PtL/PtG operations and evaluate synfuel sources.
- Innovate PtL/PtG concepts, prove plant feasibility.
- Adapt models for PtL/PtG, assess renewable fuel viability.
- Identify value chains, project technology transitions.
- Evaluate environmental impacts and social acceptance.
- Utilize non-potable water, assess critical material demand.
- Strategize production sites, import routes, and supply chain infrastructure.
- Recycle and convert plastics.
- Develop optimization tools, track synthetic fuel development.
- Implement smart sensors and digital fuel twins.

Circular Economy and Raw Materials

Develop and enhance methods for closing material cycles

A sustainable energy transition depends on a sustainable, secure and defossilized raw material supply and recycling. Closing material cycles is crucial for climate neutrality, carbon recovery, sustainability of the renewable energy system, domestic value generation and reducing import dependence, specifically for critical raw materials and subsequently for plants and plant components. Key challenges include defossilization, development of energy efficient and eco-friendly processes, increasing the recovery of many different raw materials including technology metals, building materials and carbon sources like plastics from waste streams, promoting a bioeconomy, and understanding how to incentivize suitable consumer behavior. Closing material cycles contributes to raw material security, climate neutrality, reduction of CO_2 emission export, industrial production, sustainable consumer behavior, and environmental protection.

Research Objectives

- Develop recycling-friendly designs and recirculation systems for efficient resource recovery, considering sustainability impacts and setting incentives for sustainable design, usage, and collection.
- Develop and optimize energy-efficient recycling processes to improve sorting, waste treatment, and raw material recovery, focusing on efficient and sustainable disassembly, comminution, separation, and refinement technologies.
- Address recycling across various waste streams, including electronic waste, energy system components, building materials, industrial and consumer products, while ensuring functional recovery and avoiding downcycling.
- Develop efficient carbon-cycle process chains (i.e. pre-treatment: mechanical vs. pyrolysis / base chemicals via gasification vs. steam cracker).
- Evaluate carbon-cycle process chains under recognition of industrial structures in Germany.
- Develop sustainable biomass conversion technologies.
- Perform life cycle assessments of recycling- and bio-based products.
- Enhance the technical lifetime of technologies, reduce demand for critical raw materials, and develop strategies to prevent unwanted substances in waste streams, focusing on valuable resource recovery.
- Analyze potential supply bottlenecks regarding raw materials and plants & components and identify countermeasures.
- Provide integrated assessment methodologies for multicriteria decisions or multicriteria optimization of various sustainability aspects.
- Promote sustainable consumer behavior through regulations, incentives, and business models, while analyzing systemic circular economy aspects, managing geopolitical risks, and diversifying supply chains for critical raw materials.

Develop methods for sustainable and responsible mining

Recycling alone will not be able to meet the global demand for raw materials. Shifting focus to a more sustainable extraction of metals like cobalt, zinc, and lithium and other critical materials is therefore crucial for the global energy transition. Economical and environmentally friendly methods must be prioritized, aligning with the EU's Critical Raw Materials Act. This requires a holistic assessment of the impacts of the use of raw materials across the complete exploitation and recycling chain, including the energy system. Raw material extraction involves land use and environmental impacts, so public information and citizen participation are essential.

Research Objectives

- Develop and optimize environmentally-friendly processes for primary raw material extraction (e.g., extraction from geothermal fluids).
- Reduce waste and water usage through efficiency improvements and wastewater treatment.
- Develop post-mining strategies and use cases
- Recover valuables from fine-grained and complex material sources.
- Utilize complex, multi-element deposits with advanced mining technologies.
- Transfer knowledge from conventional raw material exploration and exploitation.
- Assess sustainability and environmental impacts of mining activities.
- Holistic impact assessment and evaluation of material use in transformation strategies.
- Examine ways to promote community participation in decision-making to address social acceptance challenges and "not in my backyard" mentalities.

Increase material and energy efficiency across industries

The potential for sustainable sourcing of energy and materials is inherently limited. Every instance of material consumption indirectly expends additional energy in upstream and downstream industries. Energy and materials efficiency thus is crucial in all energy intensive production processes. Research to improve energy and material efficiency is not just a part, but the very foundation of broader, energy-related investigations. Moreover, the relevance of this research extends beyond the boundaries of the energy system and raw materials industry, impacting every aspect of an economy.

Research Objectives

- Develop energy efficient processes for the chemical industry
- Energy efficient processes for the metal processing industry.
- Energy efficient processes for the glass, ceramics and stone processing.
- Energy efficient processes for water processing and waste water treatment.
- Establish methods for measuring and controlling efficiency across connected industrial sectors.
- Better understand the energy-raw material nexus and integrate it into the energy system models.

Carbon Management

Efficiently remove CO_2 from process emissions and the atmosphere

To meet Paris Agreement goals, compensate for residual emissions (e.g. from cement industry, agriculture), and for a potential temporary overshoot of the carbon budget, we must implement carbon dioxide removal (CDR) options to remove CO_2 from the atmosphere. Methods include afforestation and reforestation, soil carbon enrichment, ocean fertilization, carbon mineralization, enhanced weathering, bioenergy with carbon capture and storage (BECCS) and direct air capture with carbon capture and storage (DACCS).

Research Objectives

- Enhance efficiency and scalability to meet global emission reduction targets.
- Advance technological innovation and performance.
- Decrease costs for economically viable deployment and operation.
- Identify and mitigating potential negative environmental impacts.
- Develop accurate monitoring and verification techniques.
- Integrate technologies with existing energy systems and processes.
- Address social, political acceptance, and regulatory issues.
- Evaluate risks and impacts of large-scale deployment of carbon dioxide removal methods.
- Integrate carbon dioxide removal options into the prospective modeling of supply and demand.

Develop technologies for closing the carbon loop

Carbon compounds are and will continue to be indispensable components of a modern industrial society. At the end of their life cycle, carbon compounds are nowadays mostly incinerated. This is associated with the release of CO_2. The aim of research and development is to capture these emissions or other hard-to-abate process emissions and return them to the material cycle (carbon capture and utilization (CCU)) or to directly reuse these carbon compounds as materials.

Research Objectives

- Utilize bio-residues as alternative carbon sources.

- Develop innovative plastic waste recycling techniques.
- Explore concrete recycling methods.
- Perform life cycle assessment (LCA) of recycling technologies and pathways.
- Integrate oxyfuel combustion technologies to facilitate to close the carbon loop
- Integrate recycling options and circular material flows into energy system models.

Permanently store CO_2

Geological storage is a way to permanently remove CO_2 from the atmosphere. Geological storage of CO_2 involves injecting compressed CO_2 into deep underground rock formations where it will be trapped by the surrounding rock layers and prevented from entering the atmosphere. Key rock formations for CO_2 storage are depleted oil and gas reservoirs with existing infrastructure, saline aquifers, basalt formations forming solid carbonates. Geological underground storage in combination with CO_2 capture is known as carbon capture and storage (CCS) - a technology that has met with massive public concern in Germany and other parts of Europe. An alternative to CCS is mineral (e.g. olivine) carbonation using natural weathering processes.

Research Objectives

- Address public acceptance and creating policy frameworks.
- Identify suitable storage sites with optimal characteristics.
- Ensure CO_2 storage permanence.
- Develop advanced monitoring and verification techniques.
- Study long-term behavior of stored CO_2 for safety.
- Reduce costs for capturing, transporting, and injecting CO_2.
- Demonstrate efficiency and feasibility of mineral carbonation processes.
- Integrate technologies with existing energy systems and processes.
- Integrate CCS facilities and infrastructure in energy system models.
- Perform life cycle assessment (LCA) along the CCS process chain.
- Develop alternative storage processes

Evaluate risks and impacts of large-scale deployment of carbon dioxide removal (CDR) methods

Key steps in CDR method evaluation include identifying risks and impacts, assessing their likelihood and severity, identifying mitigation strategies, performing cost-benefit analysis, engaging stakeholders, and monitoring and evaluating the method's performance. This transparent, participatory, and accountable process should be conducted on a case-by-case basis, considering both technical and non-technical aspects.

Research Objectives

- Integrate CDR options into the prospective modeling of supply and demand.
- Prove relevance of CDR technologies to the broader scientific energy community.
- Expand the perspective beyond the 21st century to address the net CO_2 budget perspective.

About Helmholtz Energy

With research ranging from basic principles to applications, Helmholtz Energy, the Helmholtz Research Field Energy, creates the scientific basis for an independent, climate-neutral energy supply that is economically and socially sustainable.

In interdisciplinary programs more than 2,200 scientists (in 2023) are developing innovative solutions for the energy transition in Germany and for the sustainable transformation of energy supply worldwide. They are researching and developing innovative conversion, distribution, and storage technologies and creating solutions for a cross-sector energy system. Taking into account all relevant energy conversion chains and future-proof technological options, Helmholtz Energy develops systemic and holistic concepts for tomorrow's energy system.

In the funding period 2021-2027 five Helmholtz Centers and one associated partner are involved in Helmholtz Energy and combine their energy research activities:

Participating Helmholtz Centers

- German Aerospace Center (DLR)
- Forschungszentrum Jülich (FZJ)
- Helmholtz-Zentrum Berlin für Materialien und Energie (HZB)
- Helmholtz-Zentrum Dresden-Rossendorf (HZDR)
- Karlsruhe Institute of Technology (KIT)

Scientifically associated Center

- Max-Planck-Institute for Plasma Physics (IPP)

Website

- https://energy.helmholtz.de