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GLOBAL ENERGY SYSTEM BASED ON 100% RENEWABLE ENERGY

Power, Heat, Transport and Desalination Sectors

Study by

LUT University

P.O.Box 20
FI-53851 Lappeenranta
Finland
Tel.: +358 408171944
Email: manish.thulasi.ram@lut.fi

ENERGYWATCHGROUP

Albrechtstr. 22
10117 Berlin
Germany
Tel.: +49 30 609 898 810
Email: office@energywatchgroup.org

Authors

LUT Manish Ram, Dmitrii Bogdanov, Arman Aghahosseini, Ashish Gulagi, Solomon A. Oyewo, Michael Child, Upeksha Caldera, Kristina Sadovskaia, Javier Farfan, Larissa S.N.S. Barbosa, Mahdi Fasihi, Siavash Khalili, Christian Breyer

EWG Hans-Josef Fell, Thure Traber, Felix De Caluwe, Georg Gruber, Bernhard Dalheimer

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Thanks to all those involved, and congratulations for achieving these new scientific insights. Together, we have now built the foundation for the necessary transition towards a global energy system based on 100% renewables.

To Greta Thunberg and to the whole #FridaysForFuture movement,
for your relentless courage for the preservation of our planet,
and a better future for us all.

Foreword

The ongoing Fridays For Future movement initiated by young climate activist Greta Thunberg shall serve as a wake-up call for all of us to collectively do our best to hand over our planet to the next generation in the best condition possible. We need to radically change the status quo in which we have put our planet and our children; threatened by the challenges of climate change, air pollution, nuclear threats, conflicts over resources, poverty and refugee crises. With the scientific findings and elaborated set of policy measures of this study, we have developed a roadmap to achieve what our young generation calls for with great dedication and courage.

This research, jointly undertaken by Finland's LUT University and the Energy Watch Group, does not only add one more study about climate-benign future energy systems, but rigorously opens up a new perspective towards a shift to 100% renewable energy within the next two to three decades. It features a cost-efficient vision of a deep electrification of the heat and transport sectors around the globe based on a detailed assessment of spatially highly resolved renewable energy potentials that are domestically available in hourly resolution of a full year. The outlined global transition pathway stands out as the first to present a 1.5°C scenario that is technology-rich, multi-sectoral, multi-regional and cost-optimal. Notably, it achieves a cost decline without the reliance on high-risk technologies such as nuclear power and carbon capture and sequestration (CCS). A full energy transition to 100% renewable energy is not only feasible, but also cheaper than the current global energy system.

The study was set up with the belief that rapid and effective climate protection is the only way to save a planet worth living on for generations to come. From the start of the project, the team was also fully conscious about the anachronism of saving parts of the old, centralised conventional energy system based on fossil and nuclear fuels. Instead, this project was set up to show how techno-economic facts open the door for a much faster and more rigorous shift to renewable energy sources in order to trigger an even more dynamic technology development worldwide, and in addition a chance for all world regions to gain energy independence and benefit from the associated prospects of peace and conflict resolution.

The global report marks the finalisation of an intensive, ground-breaking and very rewarding project, that was executed over a span of more than four and a half years and included several milestones such as the publication of the power sector study in 2017 and the presentation of the regional European chapter at COP24 in Katowice last December.

We need to change the conversation: A transition to a global 100% renewable energy system is no longer a matter of technical feasibility or economic viability, but one of political will. Not only do we need ambitious targets, but also stable, long-term, and reliable policy frameworks, adapted to regional conditions and environments. We call on the global community to urgently pursue a forward-looking pathway towards net zero GHG emissions by launching a rapid change of the way we use natural resources and provide electricity, heat and transport.

Hans-Josef Fell

A 100% Renewable Energy System is Cheaper than the Current Global Energy Supply

Zero GHG Emissions from Power, Heat, Transport and Desalination Sectors is possible before 2050

KEY FINDINGS

A global transition to 100% renewable energy across all sectors – power, heat, transport and desalination before 2050 is feasible[1]. Existing renewable energy potential and technologies, including storage, is capable of generating a secure energy supply at every hour throughout the year. The sustainable energy system is more efficient and cost effective than the existing system, which is based primarily on fossil fuels and nuclear. A global renewable transition is the only sustainable option for the energy sector, and is compatible with the internationally adopted Paris Agreement. The energy transition is not a question of technical feasibility or economic viability, but one of political will.

The state-of-the-art scientific modelling of the "Global Energy System based on 100% Renewable Energy – Power, Heat, Transport and Desalination Sectors" study simulates a transition to 100% renewable energy of the entire world, structured in nine major regions and 145 sub-regions on an hourly resolution of 5-year time periods from 2015 until 2050. The modelling computes the cost-optimal mix of technologies, based on locally available renewable energy sources.

By 2050, the world's population is expected to grow from 7.2 billion in 2015 to 9.7 billion. Final energy demand is expected to grow by about 1.8% annually, driven by energy services for higher level of living standard, and is accompanied by massive energy efficiency gains.

Electrification and decentralisation lead to more efficiency

Electrification across all energy sectors is inevitable (see Figure KF-1) and is more resource efficient than the current system. Electricity generation in 2050 will exceed four to five times that of 2015, primarily due to high electrification rates of the transport and heat sectors. Final energy fuel consumption is reduced by more than 2/3 (68%) from 2015 numbers, as fossil fuels are phased out completely and remaining fuels are either electricity-based or biofuels. Electricity will constitute for more than 90% of the primary energy demand in 2050. This electrification results in massive energy efficiency gains when compared to a low electrification trajectory (see KF-1). Almost all of the renewable energy supply will come from local and regional generation.

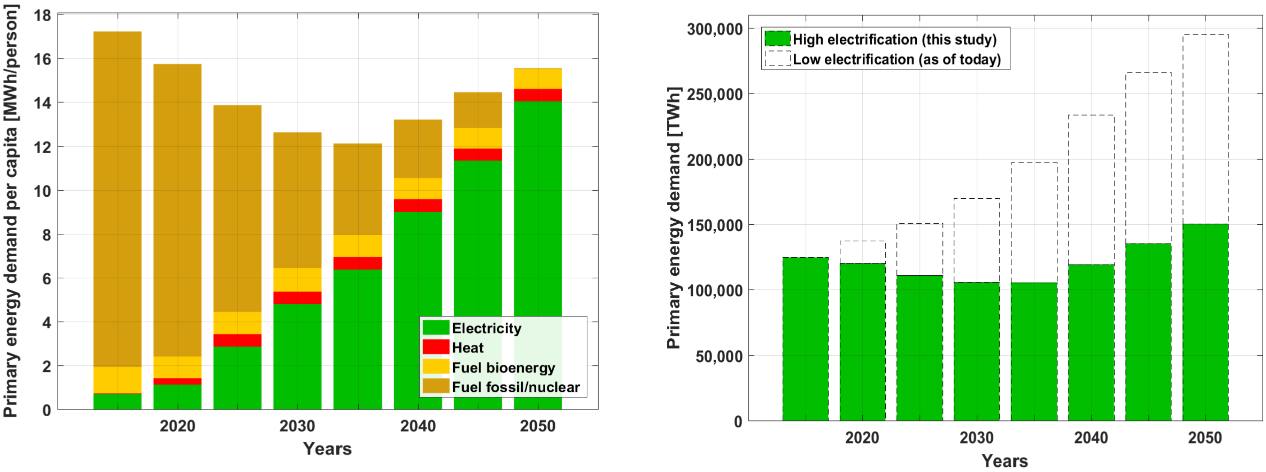


Figure KF-1: Primary energy demand per capita (left) and primary energy demand with high electrification and low electrification (right) through the transition.

[1] Energy transition simulations in this study are until 2050. However, with favourable political frameworks, the transition to 100% renewable energy can be realised well before 2050.

Solar PV and wind energy lead the transition

Primary energy supply in the 100% renewable energy system will be covered by a mix of sources, with solar PV generating 69%, followed by wind energy (18%), biomass and waste (6%), hydro (3%) and geothermal energy (2%) by 2050 (see Figure KF-2). Wind energy and solar PV make up 96% of total electricity, and approximately 88% of the total energy supply, which will have a synergetic balancing effect.

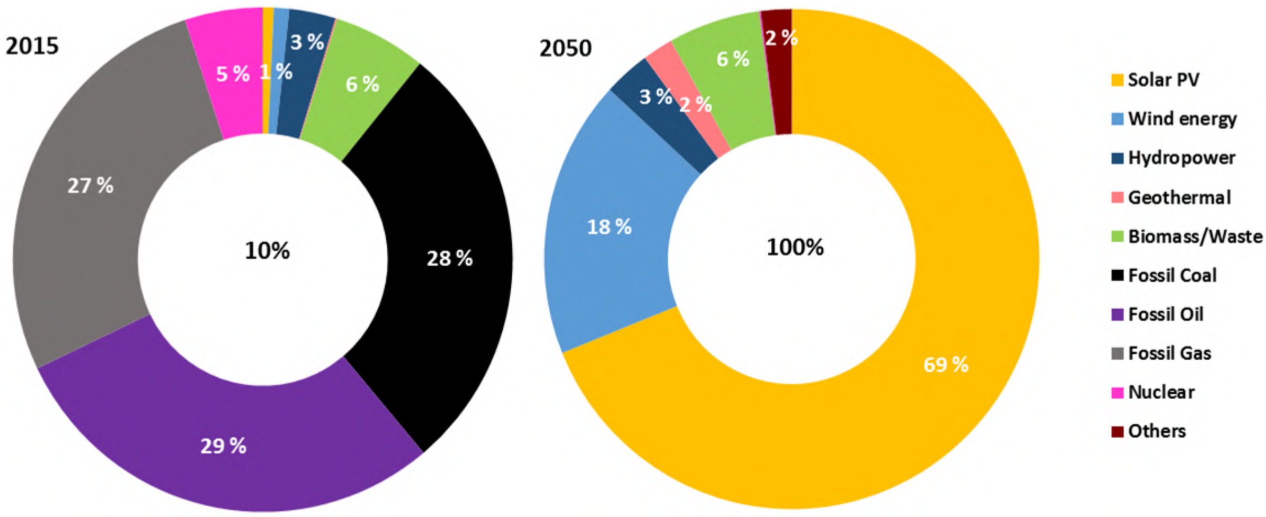


Figure KF-2: Shares of primary energy supply in 2015 and 2050.

100% renewable energy is cheaper than the current energy system.

- The levelised cost of energy for a fully sustainable global energy system will be slightly cheaper than for the current system, reducing from approximately 54 €/MWh in 2015 to 53 €/MWh by 2050 (see Figure KF-3). When taking into account negative externalities of the current system, which have been cited in numerous other contemporary studies, the 100% renewable global energy system is a substantially cheaper option.
- A 100% renewable energy system provides a win-win for the global community at large; with both economical and environmental benefits.
- Major regions can realise a substantial cost reduction including Middle East and North Africa (-31%), North America (-22%), South America (-34%), and Europe (-15%), while achieving zero emissions by 2050. The levelised cost of electricity decreases substantially from around 78 €/MWh in 2015 to around 53 €/MWh by 2050, while the levelised cost of heat increases from around 39 €/MWh in 2015 to around 49 €/MWh by 2050.
- It can be concluded from the results that the transition eliminates international energy dependencies and helps to solve energy-related conflicts.
- A trend develops where the levelised cost of energy becomes increasingly dominated by capital costs, as fuel costs lose importance through the transition period.
- Investments in the energy sector increase through the transition and are spread across a variety of technologies with major investments in solar PV, wind energy, batteries, heat pumps, and synthetic fuel conversion (see Figure KF-3).

The total annual transport energy costs decrease through the transition period from around 2.09 trillion euros in 2015 to about 1.9 trillion euros by 2050. Final transport passenger costs decline for road transport, whereas there is a marginal increase in costs for marine and aviation transport. Final transport freight costs decline in case of road, remain stable for rail and marine and increase slightly for aviation.

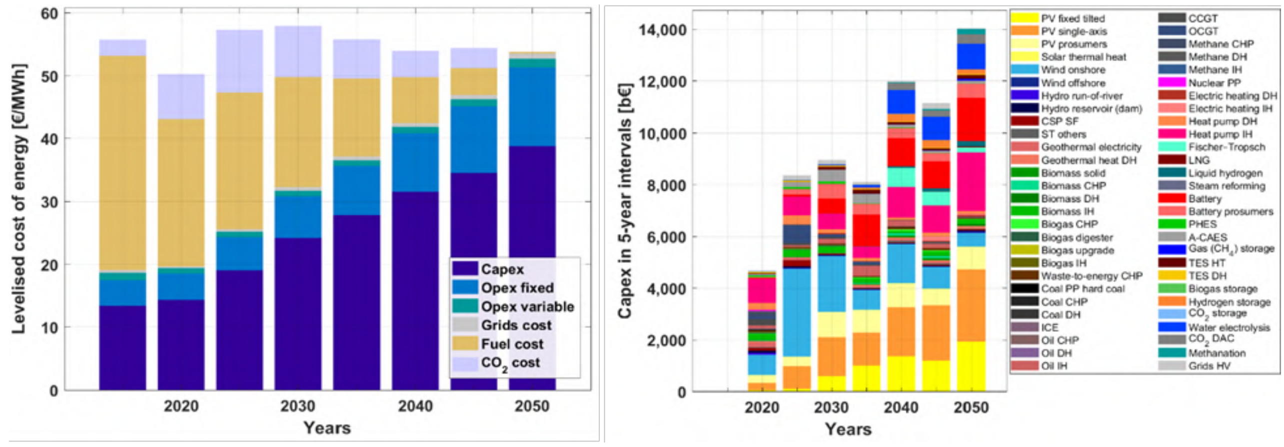


Figure KF-3: Levelised cost of energy (left) and investments in five-year intervals (right) during energy transition from 2015 to 2050.

Global energy-related greenhouse gas emissions can be reduced to zero by 2050, or sooner, across all energy sectors

- Annual global greenhouse gas (GHG) emissions in the energy sector decline steadily through the transition from approximately 30 $GtCO_{2eq}$ in 2015 to zero by 2050 (see Figure KF-4). The remaining cumulative greenhouse gas emissions are approximately 422 Gt_{CO2eq} from 2018 to 2050. Energy-related GHG emissions account for more than 60% of total global GHG emissions in 2015.
- In contrast to popular claims, a deep decarbonisation of the power and heat sectors is possible by 2030. The transport sector will lag behind, with a massive decline of greenhouse gas emissions from 2030 to 2050 (see Figure KF-4).

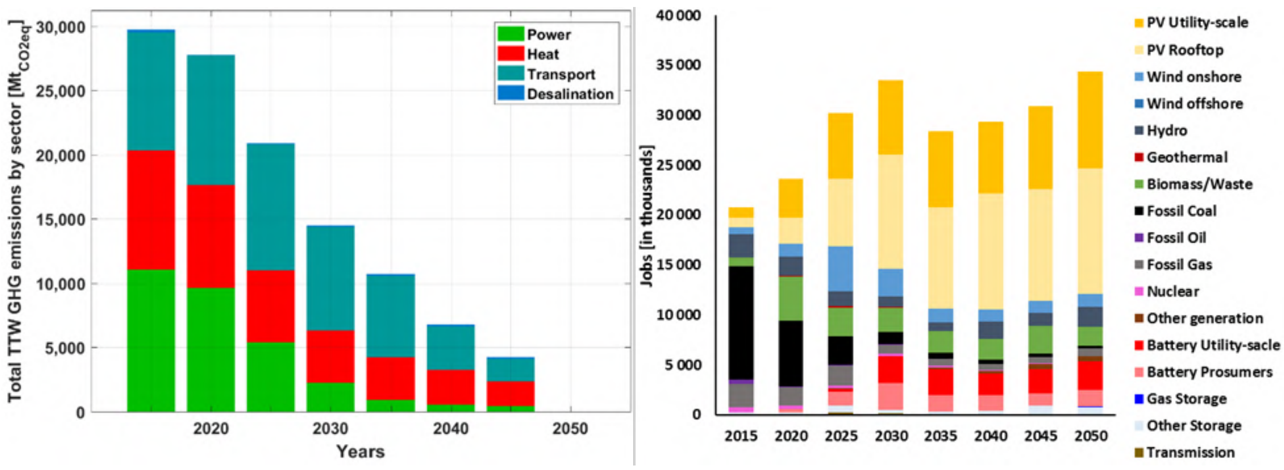


Figure KF-4: Total GHG emissions (left) and jobs in the power sector (right) during the energy transition from 2015 to 2050 worldwide.

A 100% global renewable energy system will support millions of local jobs in the power sector

- In 2015, the global power sector employed approximately 20 million people, with more than 70% in the fossil fuel sector (see Figure KF-4).
- A 100% renewable power system will employ 35 million people and solar PV emerges as the major job creating industry, employing more than 22 million by 2050, followed by battery, biomass, hydro and wind industries.
- The approximate 9 million jobs in the global coal industry of 2015 will be reduced to nearly zero by 2050 and will be overcompensated by more than 15 million new jobs in the renewable energy sector.

Global renewable energy generation and storage capacities will improve efficiencies and create energy independence

- Approximately 96% of renewable electricity generation will come from solar and wind energy by 2050, and with a significant amount of local generation, the system will be more efficient.
- Energy storage will meet nearly 23% of electricity demand and approximately 26% of heat demand. Batteries will emerge as the most relevant electricity storage technology and thermal energy storage emerges as the most relevant heat storage technology by 2050.

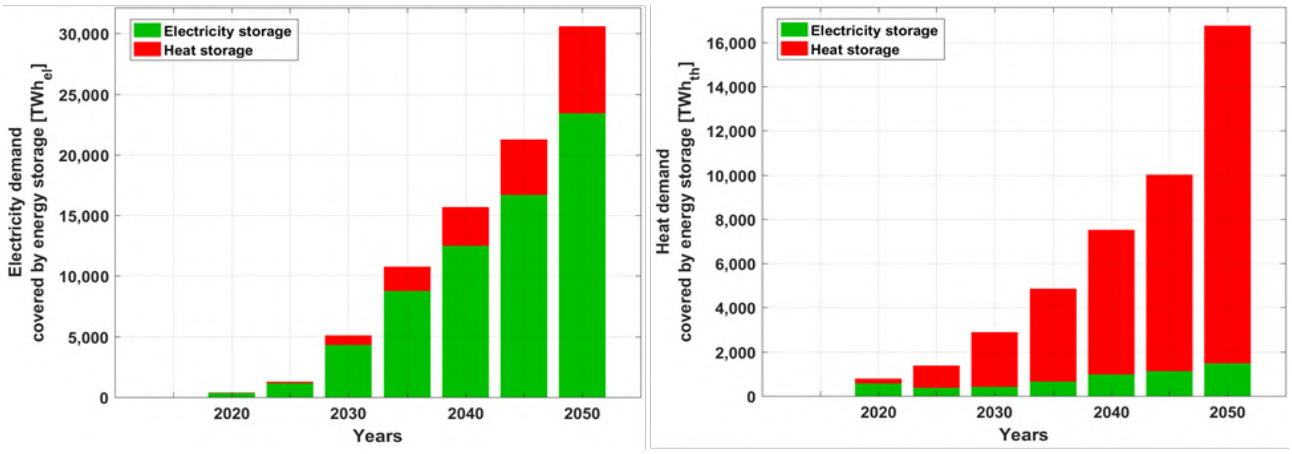


Figure KF-5: Electricity demand covered by energy storage (left) and heat demand covered by energy storage (right) during the transition from 2015 to 2050 worldwide.

Sustainable biofuels and natural carbon sinks will offset emissions

- Biofuels will be produced only in a sustainable way on degraded lands. Globally, around 6.7 million km^2 of degraded arid lands are available, on which 263 million tons of sustainable Jatropha plant oil could be harvested up to 2050. The potential to offset emissions range from 1 to 15 $tCO_2/(ha{\cdot}a)$. Up to 10 gigatons of annual natural carbon sinks might be created on jatropha basis on degraded land.

Desalination

- By 2050, water desalination will be nearly 40 times the amount of 2015. This will require substantial desalination capacities and some water storage. Desalination will account for approximately 4% of total primary energy demand in 2050, which can be fully met with renewables.
- Eurasia, the Middle East and North Africa, SAARC with India, Northeast Asia and North America will demand 91% of the global energy used for desalination. Europe, Southeast Asia, Sub-Saharan Africa, and South America share just 9%.

Regional differences in electricity supply

- The energy transition will have some key regional renewable energy generation differences (see Figure KF-6). Almost all Sun Belt countries will use solar PV as their primary source of electricity.
- South Asia (SAARC)[2] has a world record share of 95% solar PV electricity generation by 2050 in its cost-effective generation mix.
- In Eurasia, onshore wind dominates electricity generation, with the highest shares worldwide. Onshore wind ranges from 61% in 2025 to 47% in 2050, with solar PV generation only gradually increasing towards 2050.
- Few regions have a diversified mix of renewables with solar PV, wind energy, and hydropower in their energy supply, such as: the Nordic region, Western Eurasia, Central China, Chile, and New Zealand.).
- By 2025, North America is set to have approximately 25% of the global wind energy provision. Towards 2050, the costs of electricity provision in North America can be reduced by more than a third. The transition will be accompanied by an increase in jobs from around 1.8 million to about 2.7 million by 2050.
- The diverse range of energy systems is induced by locally available resources, which enhances energy security around the world; this could lead to a more peaceful and prosperous global community.

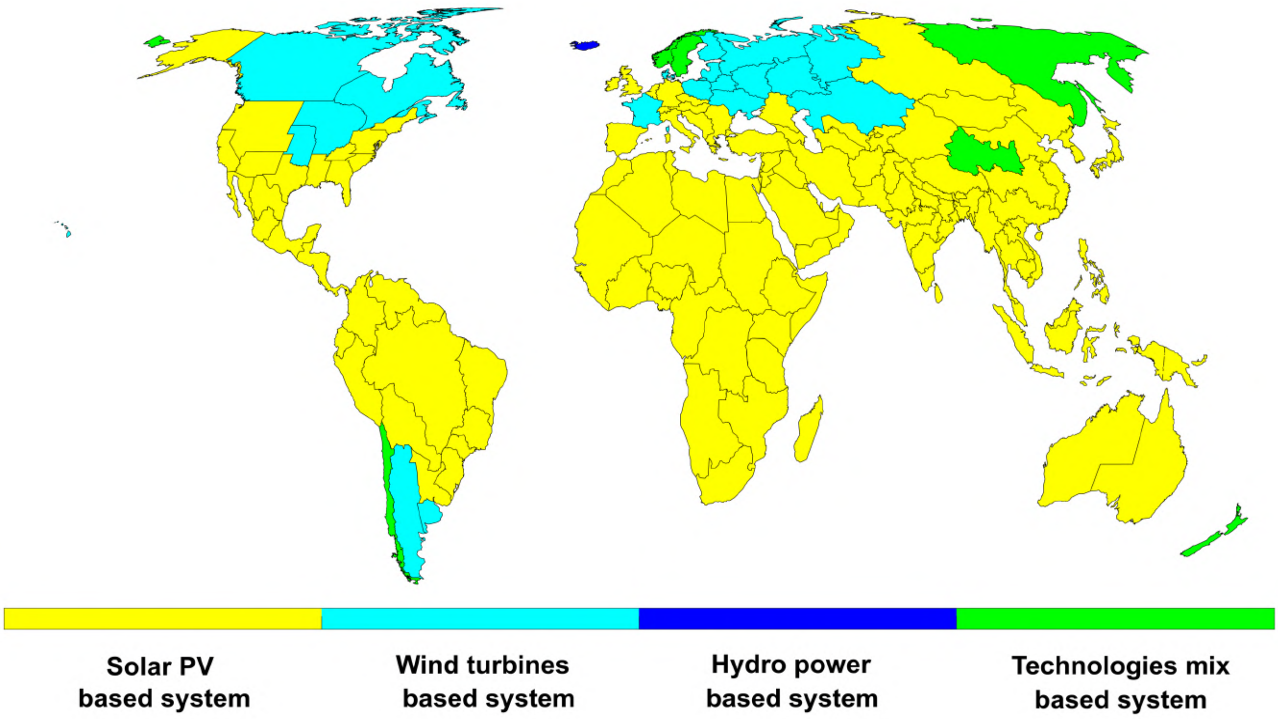


Figure KF-6: Main types of 100% renewable electricity systems.

[2] Countries of the South Asian Association for Regional Cooperation

Policy Recommendations

To ensure a smooth, fast, and cost-effective transition to 100% renewable energy across all sectors, governments need to adopt national legislative acts that will ensure the swift uptake in the development of renewable energy, storage technologies, sector coupling, and smart energy systems. Frameworks should include favourable investment conditions for all actors, including businesses and communities. The following key political support measures will accelerate the energy transition:

- Policies and instruments focused on sector coupling and enabling direct private investment in renewable energy and other zero emission technologies.
- Feed-in Tariff laws should be adopted to enable investments (under 40 MW) from decentralised actors, such as small and medium enterprises, cooperatives, communities, farmers and citizens. Tendering procedures for large scale investors should only be applied for utility-scale capacities above 40 MW.
- A responsible phase-out of all state subsidies to fossil fuel and nuclear energy generation is necessary.
- Introduction of carbon, methane and radioactivity taxes.
- Incentives created to spur the growth of renewable energy technologies; such as tax exemptions, direct subsidies, and legal privileges.
- Policies and frameworks that promote research, education and information sharing on renewable energy and zero emission technologies.

Executive Summary

Climate change is impacting every continent on Earth at increasing intervals. The detrimental impacts of climate change are projected to get much worse at a temperature rise of 2°C above pre-industrial levels. Limiting global warming to 1.5°C by mid-century could reduce the exposure to both climate-related risks and the corresponding susceptibility to economic burdens. Rapid and fundamental change is required across all carbon emitting sectors of the global economy, most particularly in the energy sector, which is the primary contributor to greenhouse gas (GHG) emissions. There is an urgent need for the global community to collectively pursue a pathway towards net zero GHG emissions by launching a rapid transition of the energy sector. There are still many countries and regions that have yet to initiate plans which will align their short-term actions and long-term energy goals with the degree of ambition that is required to realise the objectives of the Paris Agreement.

This research study undertaken by Finland's LUT University (LUT) and the Energy Watch Group (EWG) presents a first of its kind technology-rich, multi-sectoral, multi-regional and cost-optimal global energy transition pathway. Led by Dr. Christian Breyer, a group of 14 of the world's leading energy transition scientists conducted the study over a period of four and a half years. Using LUT's state-of-the-art energy transition modelling simulation, full hourly geo-spatial resolutions were used to compute the cost-optimal mix of technologies based on local available renewable energy sources. The research conducted in this study provides cost optimised simulations of energy systems for 145 global regions, the study has been aggregated into nine major world regions. The study is a techno-economic blueprint demonstrating the least-cost and feasible energy mix with the transitioning of the global power, heat, transport and desalination sectors to net zero GHG emissions by 2050.

The study showcases that a global 100% renewable energy system can be achieved with zero GHG emissions before 2050 and more cost-effectively than the current fossil fuel and nuclear-based energy system. Solar photovoltaics (PV) and wind energy emerge as the new workhorses of the future global energy system. Solar PV emerges as the most prominent electricity supply source accounting for approximately 69% of the total energy supply by 2050, complemented by wind energy at 18%, hydropower at 3% and bioenergy at 6%. This translates to a total installed capacity of approximately 63,400 gigawatts of solar PV and 8,000 gigawatts of wind energy across the world by 2050. PV prosumers will drive a more decentralised energy transition across the different regions of the world, contributing to approximately 19% of electricity generation. Low-cost renewable energy supply enables electrification across the power, heat, transport and desalination sectors. A 100% renewable energy system is more efficient and cost competitive than the current fossil fuel and nuclear power based system.

Energy Demand

A fundamental shift in the energy sector is shaping the energy transition, which is currently predominantly based on fossil fuels. As indicated in Figure ES-1, electrification across the energy sector, comprising of power, heat, transport and desalination results in a primary energy share of 90% renewable electricity by 2050 and zero fossil fuels. This is a complete shift from the primary energy supply of the 2015 energy system, which depended primarily on fossil fuels (89%) and just 4% electricity from renewables.

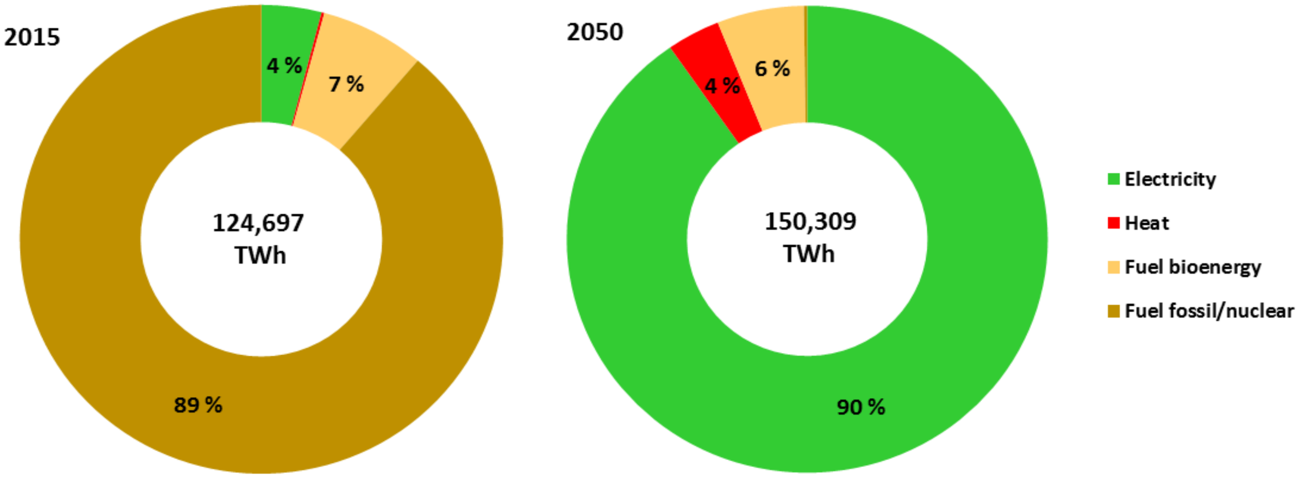
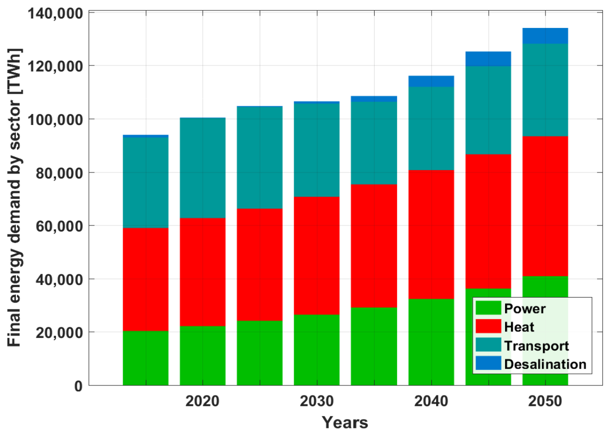


Figure ES-1: Shares of main fuels in the total primary energy demand globally, in 2015 and 2050.

A global cumulative average annual growth rate of approximately 1.8% in final energy demand triggers the transition (see Figure ES-2). This is driven by a growth in demand for energy-related services including power and heat, desalinated water and transportation, and additionally, by more energy efficient conversion and demand side technologies. The comprehensive electrification massively increases overall energy efficiency, which implies an even higher growth rate in provided energy services. The primary energy demand decreases from roughly 125,000 TWh in 2015 to nearly 105,000 TWh by 2035 and increases to over 150,000 TWh by 2050. By comparison, current practices and low electrification would result in a primary energy demand of nearly 300,000 TWh by 2050 (see Figure ES-2). This massive gain in energy efficiency is primarily due to the high level of electrification of around 90% of primary energy demand, and will save nearly 150,000 TWh compared to the continuation of current practices with low shares of electrification.



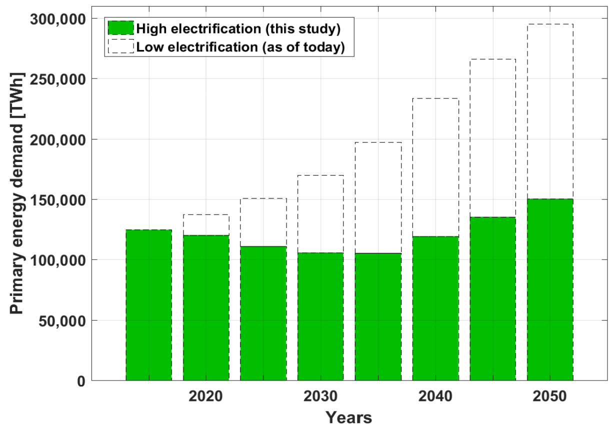


Figure ES-2: Sectoral final energy demand through the transition (left) and primary energy demand with high electrification and low electrification through the transition (right).

Primary Energy Supply

As the primary energy supply increasingly shifts toward electricity, correspondingly, the share of renewable energy increases from around 10% in 2015 to 100% by 2050. Solar PV and wind energy emerge as the most prominent electricity supply sources with approximately 76% and 20%, respectively, of the total primary electricity supply by 2050 across the power, heat, transport and desalination sectors (see Figure ES-3). Solar PV is comprised of prosumer rooftop PV, fixed-tilted and single-axis tracking PV power plants. Additionally, hydropower contributes to around 3%, biomass 6%, and geothermal energy 2% and a further 2% by other renewables contribute to the lowest cost energy mix in 2050.

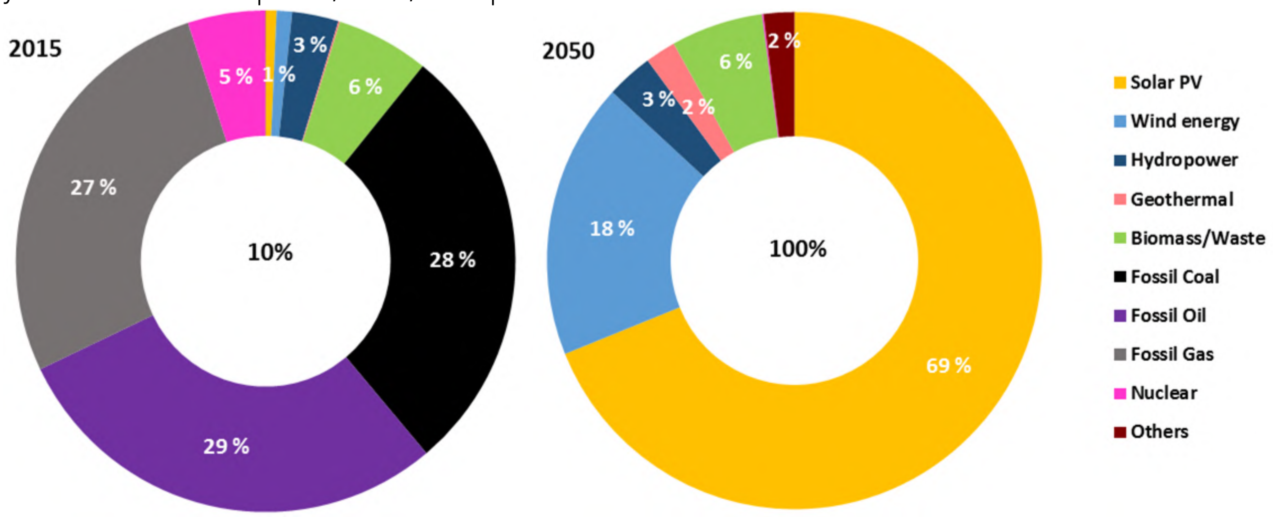


Figure ES-3: Shares of primary energy supply in 2015 and 2050.

Heat Supply

The heat supply shifts from being dominated by 85% fossil fuels in 2015, towards 100% renewable energy sourcing in 2050. Heat pumps play a significant role accounting for an approximate 44% share, followed by direct electric heating at 26%, and biomass-based heat accounting for 12% of the mix (see Figure ES-4). Additionally, renewables-based gas provides around 12% of heat supply in 2050. Gas as a fuel shifts from extracted fossil fuels towards synthetically produced gas by renewable electricity along with biomethane throughout the transition.

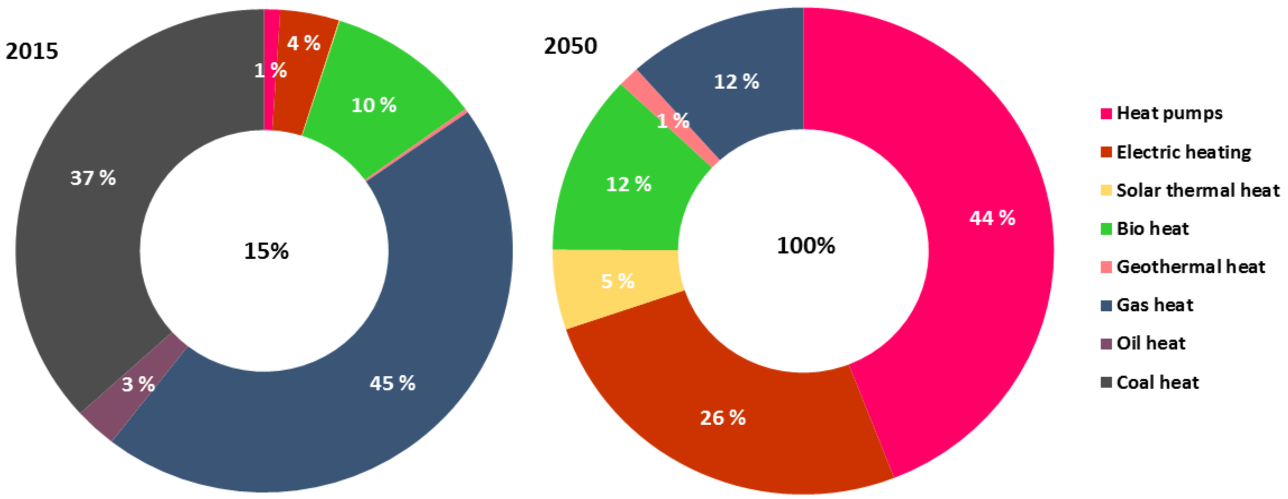


Figure ES-4: Shares of heat supply in 2015 and 2050.

Energy Storage

Energy storage plays a critical role in the transition of the global energy system toward 100% renewables. A combination of both electricity and heat storage technologies cover the energy demand throughout the transition period (see Figure ES-5). Energy storage covers about 23% of the electricity demand and about 26% of heat demand in 2050.

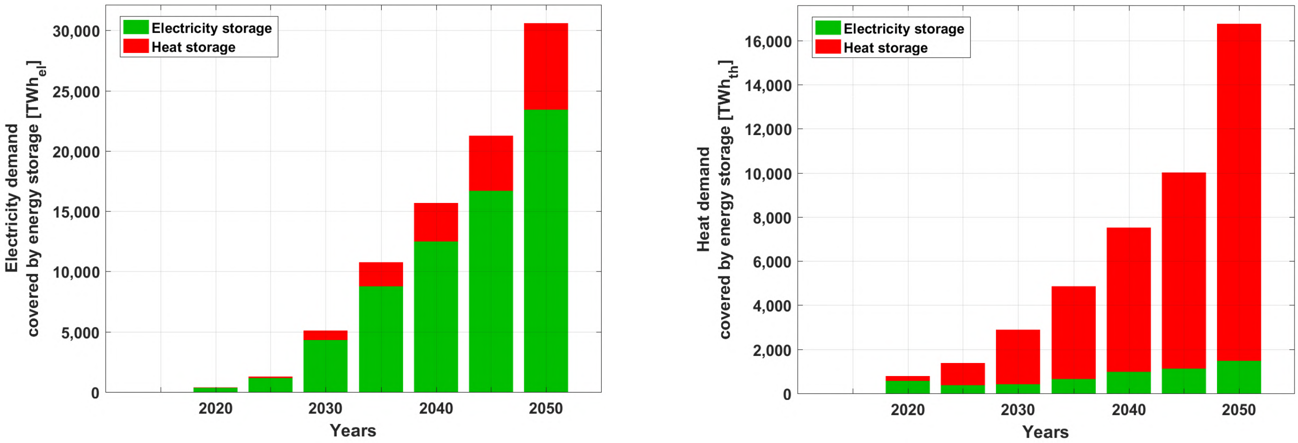


Figure ES-5: Energy Storage through the transition from 2015 to 2050 for electricity demand (left) and heat demand (right).

Synthetic Fuel Production

A critical aspect to enabling a 100% renewable energy system is the production of synthetic fuels. Fuel conversion technologies such as Fischer-Tropsch, water electrolysis, methanation, and others supply renewables-based fuels through the energy transition. Along with sustainably produced biofuels, such as jatropha plantations on degraded land, electrification, and renewables-based synthetic fuels, ensure a 100% renewable energy-based transport sector across the different regions of the world. The corresponding capacities of fuel production technologies are phased-in predominantly beyond 2035 (see Figure ES-6).

Heat management plays a vital role in efficiently producing synthetic fuels. Recovered heat can provide a high share of the energy needed for CO_2 direct air capture, which in turn provides carbon from the atmosphere for the production of synthetic fuels. Utilisation of recovered heat and excess heat are vital for a cost optimal energy transition in the transport sector. This occurs significantly beyond 2035 (see Figure ES-6).

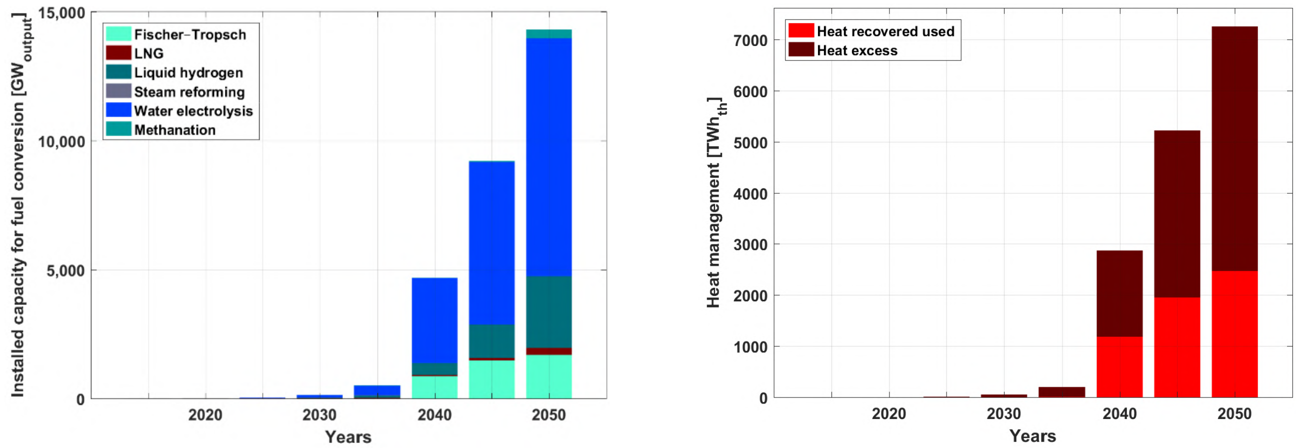
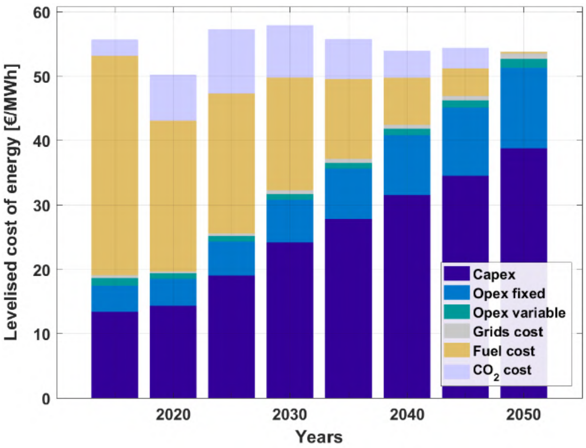


Figure ES-6: Installed capacities of fuel conversion technologies (left) and heat management (right) through the energy transition from 2015 to 2050.

Energy Costs and Investments

A shift to a 100% renewable energy sourced system results in a stable levelised cost of energy across the different regions of the world throughout the transition. The levelised cost of energy for a fully sustainable global energy system remains stable in the range of 50-57 €/MWh throughout the transition from 2015 to 2050 (see Figure ES-7). A trend develops where the levelised cost of energy shares become increasingly dominated by capital costs, as fuel costs lose significance through the transition period. There could be increased energy diversification and local self- reliance across the different regions of the world by 2050.

Investments in the energy sector increase through the transition and are well spread across a range of technologies with major investments for solar PV, wind energy, batteries, heat pumps, and synthetic fuel conversion (see Figure ES-7). Investments are also well distributed across the three major sectors of power, heat and transport through 2050.



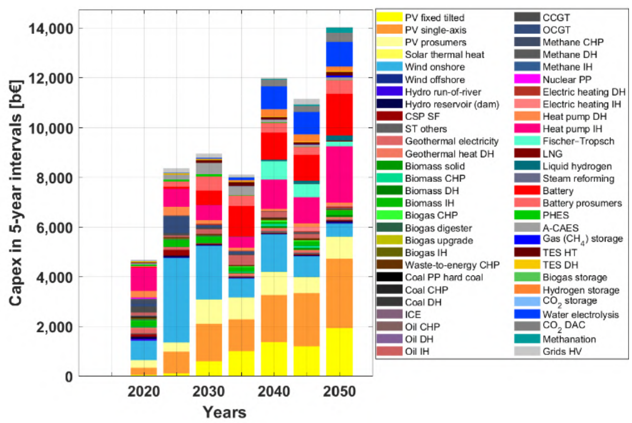
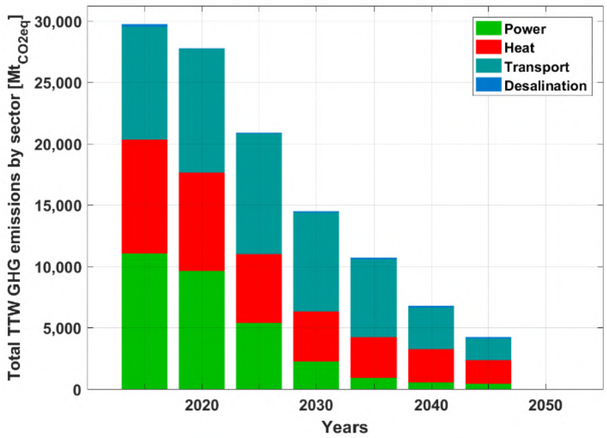


Figure ES-7: Levelised cost of energy (left) and investments in five-year intervals (right) through the energy transition from 2015 to 2050.

Emissions Reduction

The most important result of the global energy transition is that GHG emissions can be reduced from nearly 30,000 mega tonnes CO_2 equivalent ($MtCO_{2eq}$) in 2015 to zero by 2050 (see Figure ES-8). The remaining cumulative GHG emissions of around 422 gigatonnes CO_2 equivalent ($GtCO_{2eq}$) are in adherence to the ambitious goals of the Paris Agreement of limiting temperature rise to 1.5°C.



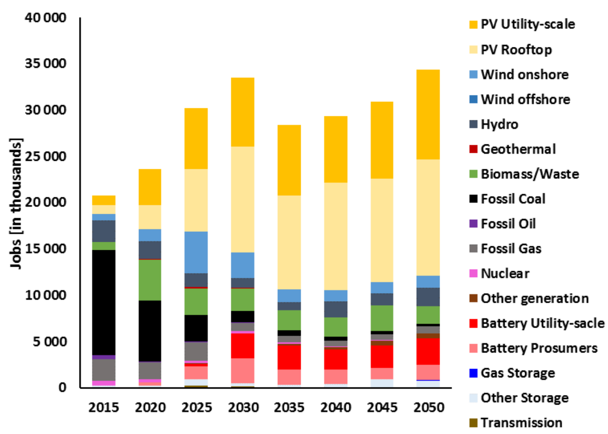


Figure ES-8: Sectoral GHG emissions (left) jobs created by different energy resources (right) through the energy transition from 2015 to 2050

Job Creation

Approximately 35 million direct energy jobs are created over the transition in the power sector across the different regions of the world (see Figure ES-8). Jobs shift from the fossil fuel sectors toward renewable energy and storage sectors, with solar PV and batteries providing the majority of energy jobs by 2050. Jobs lost in the fossil fuel sectors are more than compensated with an additional 15 million jobs being created by 2050.

Policy Recommendations

To achieve a 100% renewable energy system, ambitious targets must be set and supported by stable, long-term, and reliable policies. Policy frameworks will need to be locally adapted to regional conditions and environments on the basis of subsidiarity. The energy transition can be spurred by:

- Feed-in policies, such as tariffs, guarantee a minimum price per unit of electricity. They stimulate local and regional, private and public, small-and medium-scale investments.
- Tendering procedures that are recommended for utility-scale projects with capacities above 40 MW. For projects below 40 MW of capacity, feed-in tariffs should apply to encourage distributed generation.
- Tax exemptions, direct subsidies, and legal privileges for renewable energy technologies.
- Introduction of carbon, methane, and radioactivity taxes.
- Regulation, mandates, and infrastructure planning that encourage heightened efficiency in buildings, lighting, electric appliances, electronic devices, and other energy loads.
- Co-generation (particularly bioenergy and power-to-gas) with full heat recovery.
- Levelling the playing field of energy supply through the removal of subsidies and by pricing negative externalities.
- An essential scaling-up of both public and private funding.
- Consistency of financial support from local, national, and regional governments.
- Divestment, investment, and setting up of new and innovative financing schemes.
- Creating stakeholder engagement across sectors to inclusively identify and take advantage of opportunities and eliminate barriers throughout the energy transition.
- Cooperative funding and share-based models combined with open and accessible online tools to monitor public expenditures (e.g. participatory budgeting schemes).

→ Further sectoral and regional results of this global energy transition are presented in the report.

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