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GLOBAL ENERGY SYSTEM BASED ON 100% RENEWABLE ENERGY – POWER SECTOR

Study by

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Global Energy System based on 100% Renewable Energy – Power Sector

Foreword

By signing the Paris Agreement, the world community has committed to limit the global warming to well below 2°C above pre-industrial levels. This is a very ambitious target. Therefore, the world community needs new and more aggressive climate protection strategies than in the past. According to the European Centre for Medium-Range Weather Forecasts (ECMWF) the global temperature increased to 1.3°C above the pre-industrial level in 2016. To achieve the Paris Agreement targets, we need a two-fold strategy: to reduce greenhouse gas emissions down to zero and to remove surplus carbon dioxide from the atmosphere. A key aspect of this strategy should be a transition to an emission-free global economy, based on 100% renewable energy.

For a transition to a 100% renewable energy system, all types of renewables and storage technologies need to be used. Solar and wind will make the largest contributions to electricity generation. During fluctuations in demand, hydropower, geothermal, bioenergy and tidal energy will help to make up for any shortfalls. Pumped hydro storage systems, batteries in all diverse forms, power-to-gas, power-to-heat, power-to-mobility and power-to-liquid as well as intelligent grid systems will help to compensate for fluctuations and ensure decentralized energy distribution.

Critics of the energy transition say that a global full-scale transition to renewable energy is impossible at least until the end of the century and that it would place too great a strain on the economy. But it is certain to take place much sooner. Under favorable political frameworks, the transition is possible even before 2050. The reasons for the accelerated energy transition are manifold: a search for real solutions to the challenges posed by climate change, air pollution, nuclear threats, poverty and refugee crises, but also technological and industrial breakthroughs in the field of renewable energy.

This study highlights the technical feasibility and the socio-economic viability of a transition of the global electricity system to 100% renewable energy sources. It is the first of its kind study, which analyses the transition on an hourly resolution for an entire reference year and simulates a global electricity system transition with an optimal mix of locally available renewable energy sources and technologies.

The results of the study show that a 100% renewable electricity system is an effective and urgently needed climate protection measure. A global zero emission power system is feasible and more cost-effective than the existing system based on nuclear and fossil fuel energy. It will reduce greenhouse gas emissions in the power sector to zero and lead to economic growth.

This report is the first part of a larger study, analysing the entire energy system, including electricity, heat, mobility, desalination and industrial energy demand. The Energy Watch Group in cooperation with Lappeenranta University of Technology will publish the findings of the entire study in 2018.

Hans-Josef Fell, President of Energy Watch Group

KEY FINDINGS

A global transition to 100% renewable electricity is feasible at every hour throughout the year and more cost effective than the existing system, which is largely based on fossil fuels and nuclear energy. Energy transition is no longer a question of technical feasibility or economic viability, but of political will.

- Existing renewable energy potential and technologies, including storage can generate sufficient and secure power to cover the entire global electricity demand by 2050[1]. The world population is expected to grow from 7.3 to 9.7 billion. The global electricity demand for the power sector is set to increase from 24,310 TWh in 2015 to around 48,800 TWh by 2050.

- Total levelised cost of electricity (LCOE) on a global average for 100% renewable electricity in 2050 is 52 €/MWh (including curtailment, storage and some grid costs), compared to 70 €/MWh in 2015.

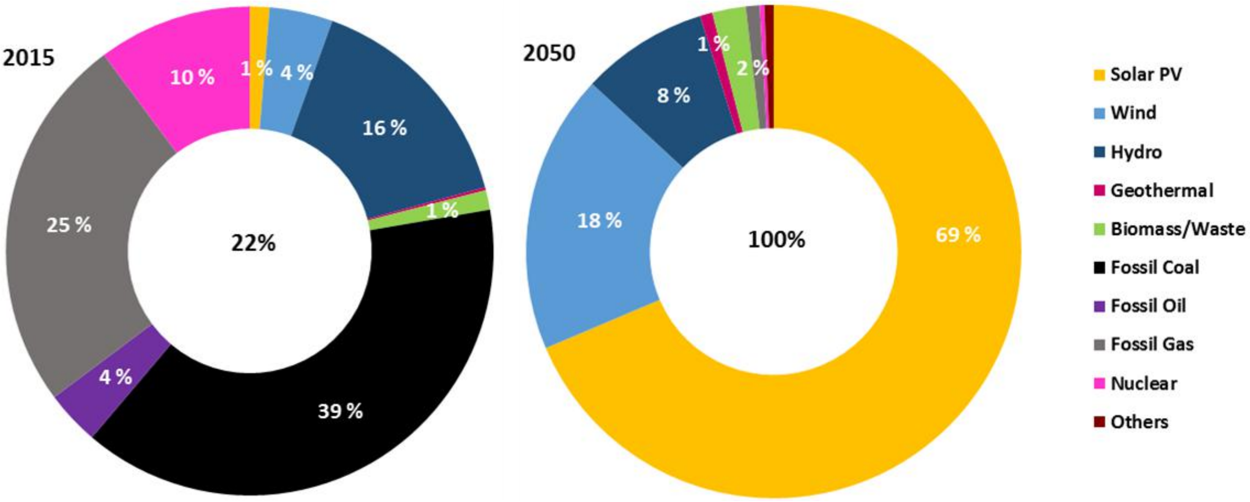
Solar PV and battery storage drive most of the 100% renewable electricity supply due to a significant decline in costs during the transition.

- Due to rapidly falling costs, solar PV and battery storage increasingly drive most of the electricity system, with solar PV reaching some 69%, wind energy 18%, hydropower 8% and bioenergy 2% of the total electricity mix in 2050 globally.

- Wind energy increases to 32% by 2030. Beyond 2030 solar PV becomes more competitive. Solar PV supply share increases from 37% in 2030 to about 69% in 2050.

- Batteries are the key supporting technology for solar PV. Storage output covers 31% of the total demand in 2050, 95% of which is covered by batteries alone. Battery storage provides mainly short-term (diurnal) storage, and renewable energy based gas provides seasonal storage.

Figure 1: Electricity generation from renewables in 2015 and 2050. In 2050, nuclear power still accounts for negligible 0.3% of the total electricity generation, due to the end of its assumed technical life, but could be phased out earlier



100% renewables bring GHG emissions in the electricity sector down to zero, drastically reduce total losses in power generation and create 36 million jobs by 2050

- Global greenhouse gas emissions significantly reduce from about 11 GtCO2eq in 2015 to zero emissions by 2050 or earlier, as the total LCOE of the power system declines.

- The global energy transition to a 100% renewable electricity system creates 36 million jobs by 2050 in comparison to 19 million jobs in the 2015 electricity system. Operation and maintenance jobs increase from 20% of the total direct energy jobs in 2015 to 48% of the total jobs in 2050 that implies more stable employment chances and economic growth globally.

- The total losses in a 100% renewable electricity system are around 26% of the total electricity demand, compared to the current system in which about 58% of the primary energy input is lost

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[1] *The simulations of the global power sector in this study were made until 2050. Yet, with favorable political frameworks, the transition to 100% renewable energy can be realized earlier than 2050.*

EXECUTIVE SUMMARY

The landmark Paris Agreement adopted in December 2015 has sent a historical signal: over 190 countries in the world have recognized the need for urgent climate action. If we are to keep the global temperature rise under 1.5°C, the transition to a 100% renewable global energy system, which is already underway in many communities, cities and countries, should be dramatically accelerated. As costs of solar, wind energy and battery storage keep falling, and emerging markets lead in investments in renewables, a global electricity system based on 100% renewables is no longer a long-term vision, but a tangible reality. The challenge is reaching a maximum synergy between various renewable energy resources and technologies across different regions of the world.

Modelling a Global Transition towards a 100% Renewable Power System

Lappeenranta University of Technology (LUT) on behalf of the Energy Watch Group has simulated a global transition to 100% renewable energy in the power sector by 2050. However, the transition can be realised earlier than 2050 under favourable political conditions. The first of its kind modelling, developed by LUT, computes the cost-optimal mix of technologies based on locally available renewable energy sources for the world structured in 145 regions and calculates the most cost-effective energy transition pathway for electricity supply on an hourly resolution for an entire reference year. The global energy transition scenario is carried out in 5-year time periods from 2015 until 2050. The results are aggregated into nine major regions of the world: Europe, Eurasia, MENA, Sub-Saharan Africa, SAARC, Northeast Asia, Southeast Asia, North America and South America.

a global transition to

100% RENEWABLE ELECTRICITY

is feasible at every hour throughout the year and is more cost-effective than the existing system

Transition to a 100% Renewable Power System

The study shows that a global transition to 100% renewable electricity is feasible at every hour throughout the year and is more cost-effective than the existing system, which is largely based on fossil fuels and nuclear energy.

Total levelised cost of electricity (LCOE) on a global average for 100% renewable electricity in 2050 is 52 €/MWh (including curtailment, storage and some grid costs), compared to the total LCOE of 70 €/MWh in 2015.

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The share of renewable energy sources in the global electricity supply mix increases from 22% in 2015 to 100% in 2050, with solar PV and wind emerging as the most prominent energy sources. At the same time, the shares of fossil fuels and nuclear energy in power generation continually decrease. By 2050, fossil fuel and nuclear energy are phased-out, as their generation costs become increasingly uncompetitive.

Due to rapidly falling costs, solar PV and battery storage increasingly drive most of the electricity system. Wind energy increases to 32% by 2030 and beyond 2030 solar PV becomes even more competitive. The solar PV share increases from 37% in 2030 to 69% in 2050. Solar PV emerges as the least cost energy source through the transition in almost all regions of the world. In 2050, solar PV reaches 69%, wind energy 18%, hydropower 8% and bioenergy 2% of the total electricity mix globally (see Figure ES-1).

In MENA, Sub-Saharan Africa, SAARC, Northeast Asia and Southeast Asia, mainly solar PV and batteries drive the power system in 2050. Meanwhile, Eurasia, Europe and North America rely substantially on wind energy to power their systems, mainly due to strong seasonal variations. South America benefits from rich resources leading to electricity generated largely from a combination of wind, solar PV and hydropower.

The various power generation sources and storage technologies considered in the energy transition with their corresponding installed capacities in different regions around the world in the years 2015, 2030 and 2050 are indicated in Table ES-1. In 2050, there are still coal power plant capacities in cold reserve (also strategic reserve), but they do not generate any electricity. Gas turbines only use renewable energy based fuels. Most of the nuclear power plants are phased out by 2050 but still contribute a negligible share of 0.3% to the total electricity generation, due to the end of their assumed technical life, but they could be phased-out earlier. This share could be compensated by generation and storage of other renewable energy capacities for no relevant extra cost and utilisation of curtailed electricity. In 2050, renewable electricity generation covers 119% of final electricity demand, which accounts for balancing losses due to grids, storage and curtailment.

Figure ES-1: Share of electricity generation from renewable sources in 2015 and 2050. Gas capacities in 2050 only use renewable based gas. In 2050, nuclear power still accounts for a negligible 0.3% of the total electricity generation, due to the end of its assumed technical life, but could be phased out earlier.

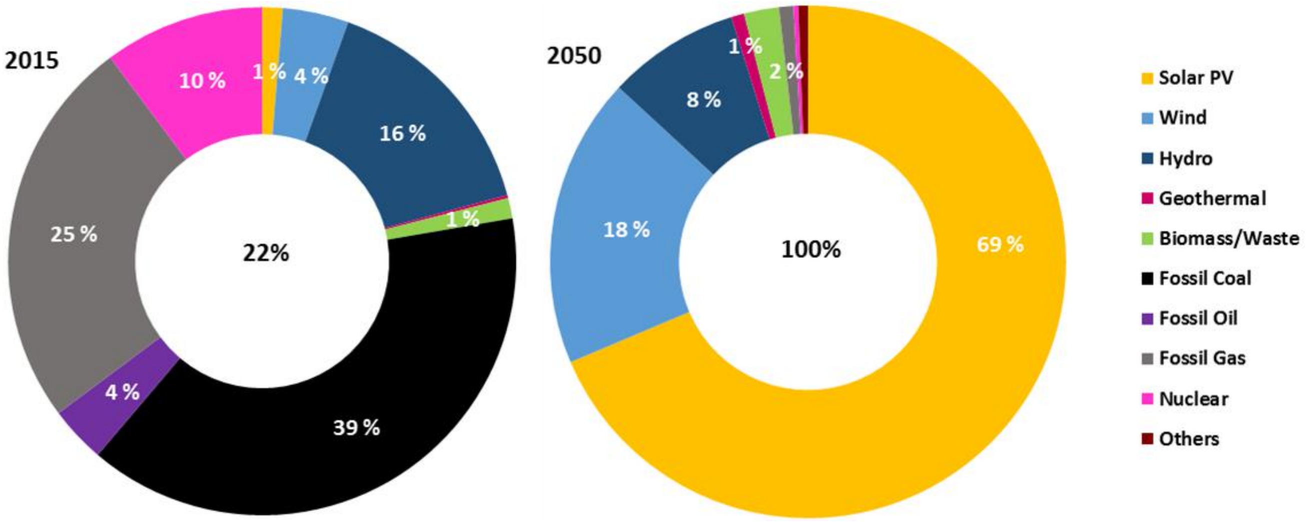

Table ES-1: Installed capacities of power and storage technologies across the major regions for the global energy transition in the representative years 2015, 2030 and 2050. Abbreviations: MENA – Middle East and North Africa, SSA – Sub-Saharan Africa, SAARC – South Asian Association for Regional Cooperation, NE-Asia – Northeast Asia, SE-Asia – Southeast Asia, N-Am – North America, S-Am – South America.

2015

Technology	Unit	Europe	Eurasia	MENA	SSA	SAARC	NE-Asia	SE-Asia	N-Am	S-Am	Global
PV utility-scale	GW	49	0	1	1	6	52	2	2	16	131
PV rooftop	GW	54	0	0	0	0	28	5	0	12	100
Wind	GW	135	0	2	1	24	118	5	78	8	372
Hydropower	GW	192	73	19	19	54	294	53	174	151	1028
Bioenergy	GW	56	0	0	0	7	13	8	23	13	120
Geothermal	GW	2	0	0	0	0	1	4	5	1	13
Gas Turbine	GW	274	156	239	25	63	251	108	606	67	1789
Coal PP	GW	234	67	7	43	163	942	80	348	10	1896
Nuclear PP	GW	138	24	1	2	6	80	0	114	3	368
Other generation	GW	58	9	78	10	16	103	17	68	27	386
Battery	GWh	0	2	0	0	0	0	0	0	0	2
Gas	GWh	0	0	0	0	0	0	0	0	0	0
Pumped Hydro	GWh	48	4	1	2	4	56	4	16	0	135
Other storage	GWh	0	0	0	0	0	0	0	0	0	0

2030

Technology	Unit	Europe	Eurasia	MENA	SSA	SAARC	NE-Asia	SE-Asia	N-Am	S-Am	Global
PV utility-scale	GW	281	94	377	180	717	1241	501	562	172	4124
PV rooftop	GW	590	13	52	48	273	880	221	634	145	2856
Wind	GW	487	208	240	71	172	1209	71	789	45	3293
Hydropower	GW	214	84	22	33	69	391	67	198	164	1242
Bioenergy	GW	254	12	10	4	61	77	51	67	63	598
Geothermal	GW	5	10	5	2	5	4	14	20	0	67
Gas Turbine	GW	318	201	468	96	170	354	171	876	81	2733
Coal PP	GW	72	12	5	26	142	902	60	66	8	1293
Nuclear PP	GW	58	10	1	0	6	63	0	43	1	182
Other generation	GW	6	1	25	7	5	21	7	8	15	94
Battery	GWh	1088	27	658	426	1930	2467	1234	1690	413	9934
Gas	GWh	68267	4694	977	466	2224	8194	4004	9899	3338	102062
Pumped Hydro	GWh	88	4	2	3	44	98	8	17	0	264
Other storage	GWh	47	1	68	22	20	1210	52	232	38	1691

2050

Technology	Unit	Europe	Eurasia	MENA	SSA	SAARC	NE-Asia	SE-Asia	N-Am	S-Am	Global
PV utility-scale	GW	688	218	1021	926	2593	5046	1733	1245	452	13921
PV rooftop	GW	1268	134	386	373	1137	2371	685	1302	383	8038
Wind	GW	560	267	237	78	200	921	80	766	44	3154
Hydropower	GW	224	91	22	40	70	394	69	202	169	1282
Bioenergy	GW	293	14	12	8	64	85	63	72	52	664
Geothermal	GW	6	12	6	2	5	5	14	18	0	67
Gas Turbine	GW	225	177	338	104	148	383	121	539	42	2077
Coal PP	GW	20	4	1	5	96	568	32	23	5	754
Nuclear PP	GW	2	2	1	0	3	18	0	0	0	26
Other generation	GW	6	0	52	4	12	5	14	3	1	98
Battery	GWh	3569	463	3593	3238	9191	15707	5288	5218	1590	47858
Gas	GWh	217330	49338	92575	54013	90806	185428	80533	222194	9681	1001898
Pumped Hydro	GWh	88	4	2	3	44	98	8	17	0	265
Other storage	GWh	466	69	729	263	498	589	829	248	53	3745

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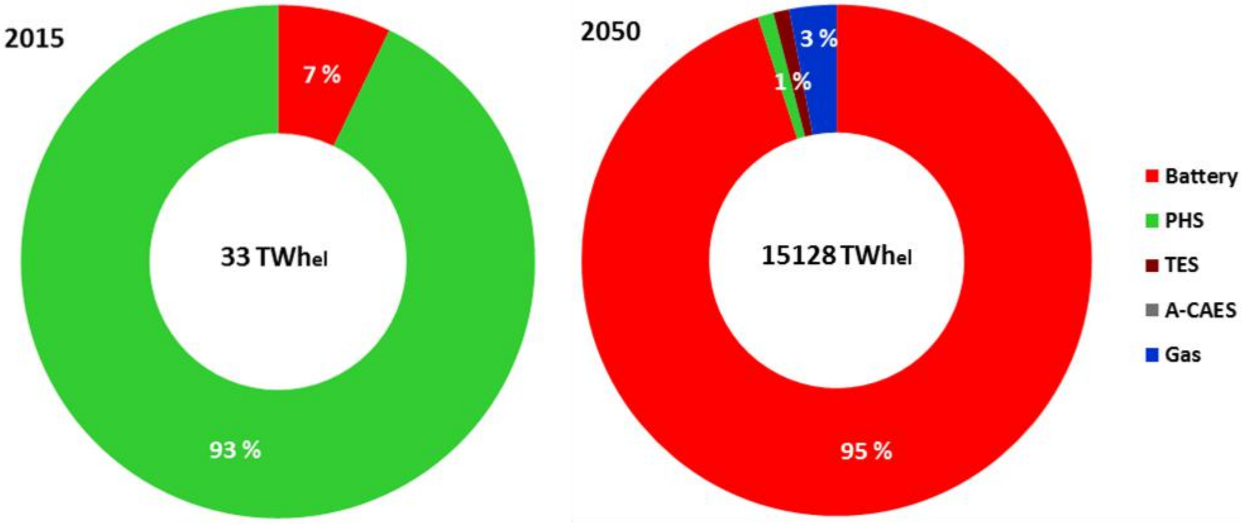
STORAGE

Storage technologies play a critical role in enabling a secure global power supply fully based on renewable energy. The results show that storage technologies increase from a mere 33 TWhel in 2015 to a substantial 15 128 TWhel in 2050. Batteries emerge as the critical storage technology in the global power mix, providing a major share of the output (almost 95%) by 2050 (see Figure ES-2).

The results indicate that with the arrival of cost-efficient storage, and as battery costs continue to decline dramatically, renewable power deployment will be further complemented.

Further price compression is expected as battery electric vehicles become more widespread and battery production ramps up.

Figure ES-2: Share of storage technologies in the overall output in 2015 and 2050. Gas storage in 2050 is based entirely on renewable resources.



Costs and investments

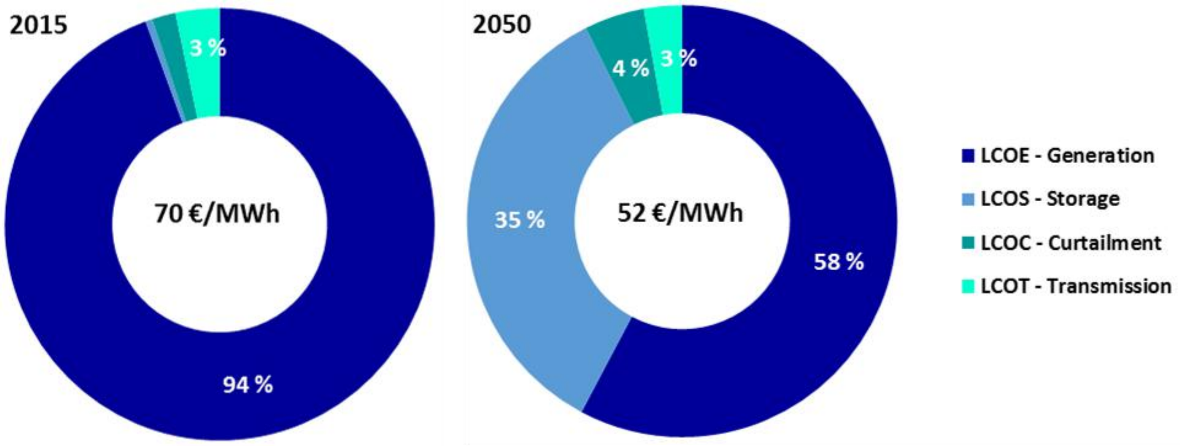
As increasing shares of power capacity are added globally, renewable energy sources on a levelised cost of electricity basis (LCOE) become the least cost power generation source. The global average energy system LCOE gradually declines from 70 €/MWh in 2015 to 52 €/MWh in 2050, with solar PV emerging as the least expensive source of power generation (see Figure ES-3).

Figure ES-3 displays different shares of generation, storage, curtailment and transmission in the total LCOE, and indicates a decrease in the share of generation costs. This implies that power generation costs will be extremely low in a 100% renewable electricity system.

Costs of **100%**
renewable energy
IN 2050 **52 €/MWH**
vs.
70 €/MWH
IN 2015

The results further imply an average annual investment requirement of 608 b€ globally during the energy transition period from 2015 to 2050, with higher investment requirements of 699 b€ per annum during 2020 to 2035 and then onwards less and stable investment needs of 488 b€ per annum from 2035 to 2050.

Figure ES-3: Total LCOE of global power supply in 2015 and 2050.

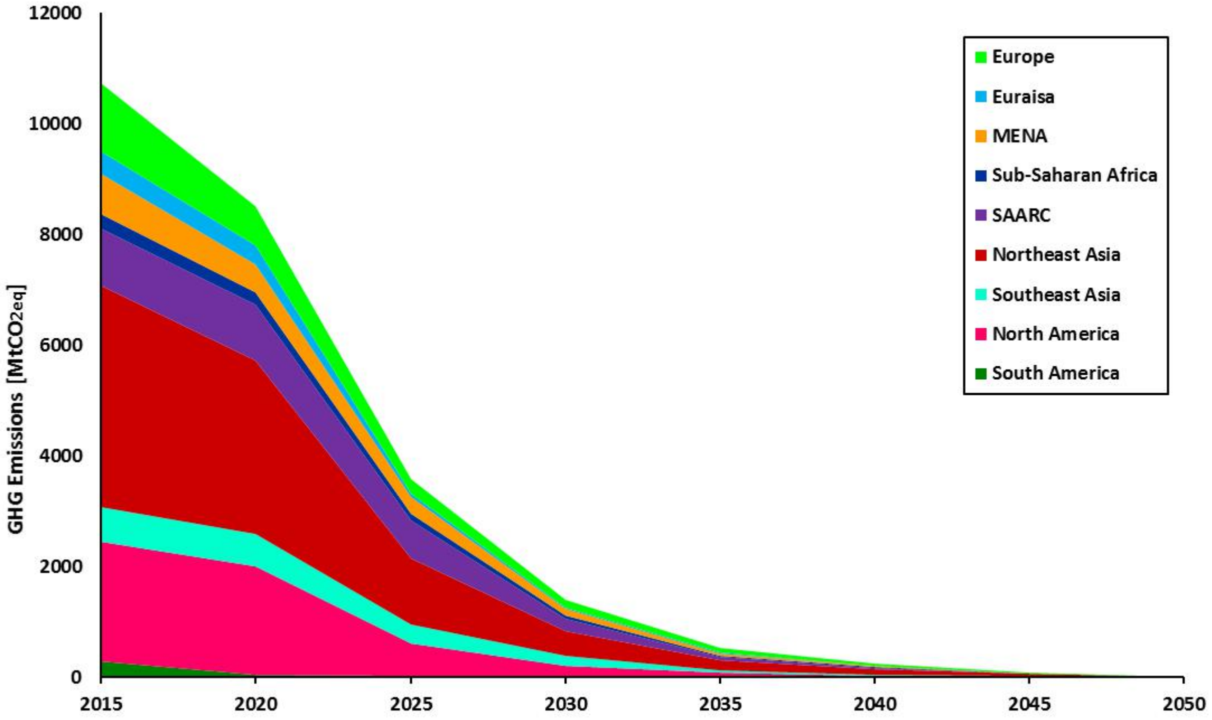


Socio-economic benefits

Development of renewable energy has emerged as a true multi-beneficial phenomenon, which enables climate change mitigation, drives economic growth, creates local value based on technology development, production, installation and maintenance, helps to increase energy access in a timely manner, and to reduce resource conflicts in water-stressed regions of the world.[14]

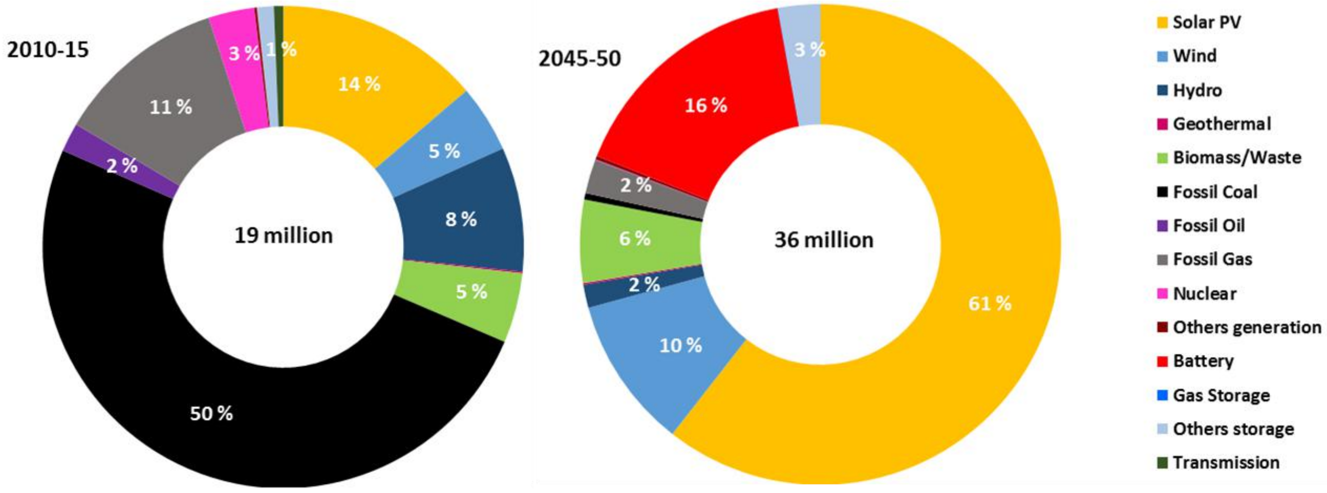
The results of the study indicate that greenhouse gas emissions in the global power sector can be reduced from about 11 GtCO2eq in 2015 to zero by 2050, with deep decarbonisation already by 2030 for many regions of the world (see Figure ES-4).

Figure ES-4: Decline in greenhouse gas (GHG) emissions during the energy transition from 2015 to 2050 from the power sector in different regions around the world.



A global transition towards a 100% renewable electricity system will create over 36 million direct jobs in the power sector by 2050 – an increase from 19 million jobs added in 2015 (see Figure ES-5). Solar PV and storage technologies led by batteries are expected to be the prime job creators in the next decades and beyond. Renewable energy technologies can generate additionally 2 to 3 indirect jobs for every direct job generated by the sector, eventually creating stable growing economies across the world.

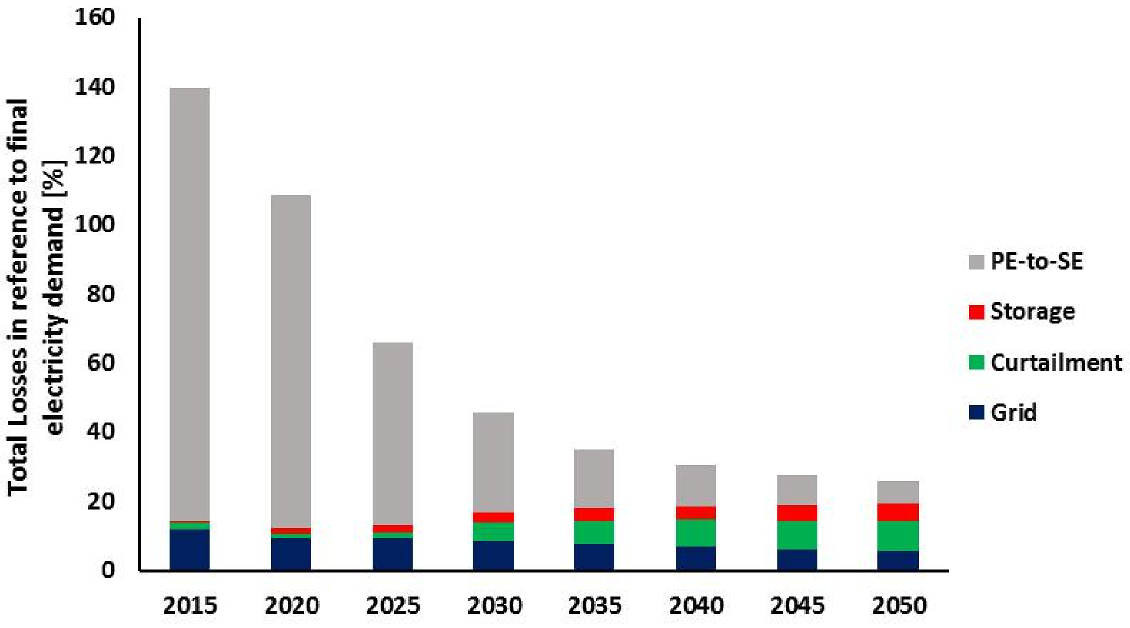
Figure ES-5: Jobs created globally during the energy transition from 2015 to 2050. Gas capacities in 2050 only use renewable based gas.



The results further highlight that a 100% renewable electricity system can increase the robustness of the system while decreasing overall energy system losses (see Figure ES-6). The total losses in a 100% renewable electricity system in 2050 are just around 21.6% of the total generation, compared to the current system with 58% of primary energy input lost. The overall energy system losses referenced to the final electricity demand decrease from 139% in 2015 to 26% in 2050, indicating far more efficient power systems globally. The huge losses of primary energy to secondary energy conversion of present thermal power plants (nuclear, coal, gas, oil, biomass) drastically reduce by 88%, mainly due to the phase out of thermal power plants.

Curtailment and storage losses increase to 8.5% and 4.8% of the final electricity demand, respectively. The shares of curtailment increase after 2030, mainly due to very low costs of renewable electricity, and this enables curtailment as a cheap flexibility option. Transmission and distribution grid losses decrease due to advanced grid management in presently emerging and developing countries.

Figure ES-6: Total losses (primary to secondary energy conversion, storage, curtailment and grid) of the global power system in reference to final electricity demand during the energy transition from 2015 to 2050.



POLICY RECOMMENDATIONS

The study results show that a global energy transition to 100% renewable electricity is no longer a question of technical feasibility or economic viability, but of political will. The global community can significantly accelerate this transition by implementing favourable political measures and frameworks.

The first decisive prerequisite for a transition to renewable energy is public support. The second prerequisite is a clear legislative framework promoting the fast and steady growth of renewables on the one hand and the phasing out all subsidies to fossil fuel and nuclear energy generation on the other hand.

To ensure a smooth, fast and cost-effective transition to 100% renewable energy, governments need to adopt national legislative acts, which ensure the sufficient flow of private investment in renewable energy and storage technologies. The following political measures and instruments are key:

- **Instruments, enabling direct private investments in renewable energy and other zero-emission technologies.**

  The German Renewable Energy Sources Act (EEG) with a fixed feed-in-tariff is one of the best-known and proven successful policy frameworks. We also need to implement new, innovative political measures encouraging investment in renewable energy, storage and network integration simultaneously. A reformed version of the EEG -a hybrid renewable power plant remuneration – enables just that. Tendering procedures should only apply for capacities above 40MW, as they otherwise limit investors to large companies and exclude investment from decentralized actors, such as cooperatives.

Under favorable political frameworks, transition to **GLOBAL 100% RENEWABLE ELECTRICITY** can succeed **BEFORE 2050**

- **Phasing-out all state subsidies to fossil fuel and nuclear energy generation.**
- **Tax exemptions for investments in renewable energy.**
- **Replacement of the emission trading system with carbon and radioactivity taxes.**
- **Promoting research and education in the sphere of renewable energy and zero-emission technologies.**

Key Findings

Executive Summary

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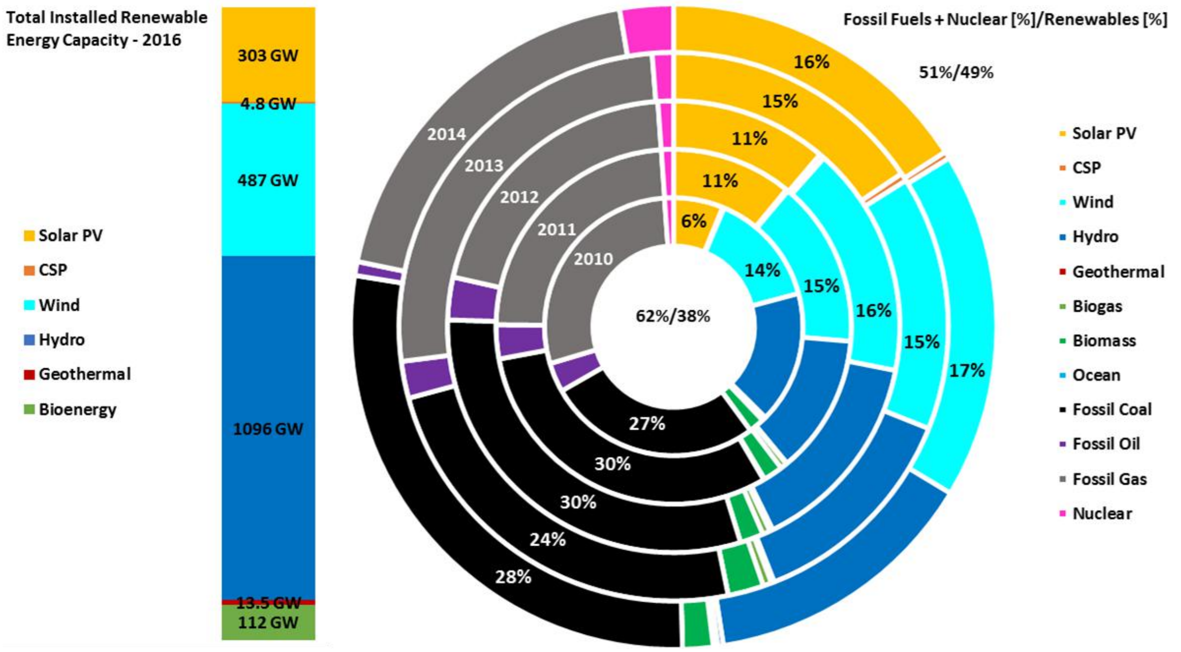
1. OVERVIEW OF THE GLOBAL ENERGY LANDSCAPE

The United Nations adopted two historically significant agreements in 2015: the Paris Climate Agreement[1] and the 2030 Agenda for Sustainable Development[2]. Governments agreed to a long-term target of keeping the increase in global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit temperature increase to 1.5 °C[1, 3]. The agreement calls for global greenhouse gas (GHG) emissions to peak as soon as possible, recognizing that this will take longer for developing countries, and for rapid emission reductions thereafter. On the other hand, the United Nations has for the first time included energy in its new Sustainable Development Goals (SDG 7 - Ensure access to affordable, reliable, sustainable and modern energy for all), calling for a significant acceleration of renewable energy deployment. As two-thirds of global GHG emissions stem from energy production and consumption, which puts the energy sector at the core of efforts to combat global climate change, the successful outcome of the historic Paris Agreement will depend on a rapid transition of the global energy system, led by the power sector.[4]

Global renewable power capacity including hydro has doubled since 2007, from around 1000 GW to about 2017 GW by the end of 2016, as indicated in Figure 1 (left).[5, 6] The addition of renewable power capacity in the year 2016, nearly 140 GW, was equivalent to 55% of all generating capacity added globally, the highest proportion in any year until now.[7] Renewable power capacity has been gradually increasing over the last few years,[8] from 38% in 2010 to 49% in 2014 as shown in Figure 1 (right).[9] The proportion of global electricity coming from renewable sources including hydropower has risen from around 25.3% in 2015 to 27.7% in 2016, and has prevented around 1.7 GtCO2eq of GHG emissions, which substantiates the decoupling of economic growth from fossil fuels.[7]

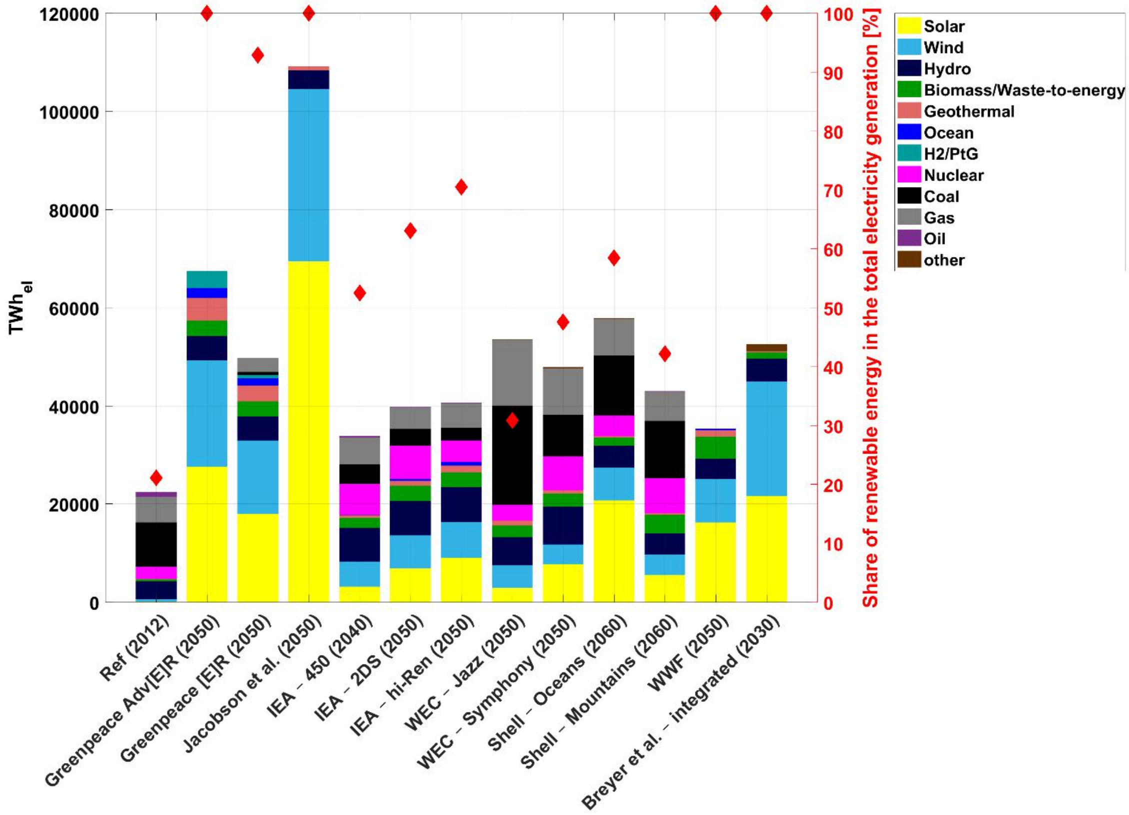
Figure 1: Total installed renewable energy capacity in 2016 globally (left) [6] and shares of annual power generation technologies installed globally from 2010 to 2014 (right). [9]



In this context, many global energy scenarios have tried to project the future transition of energy systems based on a wide ranging set of assumptions, methodologies and targets from a national as well as global perspective.[10] Some such as the IEA and Royal Dutch Shell, due to their close ties with the fossil fuel industry, inadvertently indicate limited growth of renewable energy in their respective scenarios. On the contrary, scenarios from organisations such as Greenpeace and WWF[11] focus on renewable energy growth with the aim of achie-ving a sustainable energy system for the world, using a mix of experts from renewable energy industries and academia. Researchers and scientists across the world also work on energy scenarios with diverse goals for either an overnight scenario or scenarios played out over several years.[12, 13, 14] A comparison of various global energy scenarios based on electricity generation by resource and the corresponding percentage shares of renewable energy contribution to total electricity generation is shown in Figure 2.

Due to significant variation in assumptions and targets, transparency is one of the most important elements for formulating global energy system scenarios. For instance, unrealistic assumptions have been considered for the costs of solar photovoltaics (PV), which lead to unrealistically high costs of PV in the future that is comparable to current costs in certain countries.[16] Therefore, the final cost of the electricity system with higher shares of renewables would be much more significant in comparison to other energy system analyses that consider realistic cost assumptions.

Figure 2: Electricity generation from different sources and share of renewable electricity in total generation across the various energy scenarios considered.[15] The reference scenario for the year 2012 is based on Teske et al.[11] For WWF and Shell scenarios the values are for final consumption; for WWS electricity generation is estimated from supplementary materials;[12] and for the rest the values indicate electricity generation.



In fact, the lower cost assumptions for non-renewable options can lead to considerable amounts of fossil fuel or nuclear shares in the future energy system analyses. Furthermore, most of the global energy scenarios fail to acknowledge the role of storage technologies in future power systems.[10] Battery storage technologies that are currently experiencing similar trends to solar PV in terms of growth and cost reduction cannot be ignored any longer. Moreover, the increasing adoption of variable renewable energy and the opportunity for new flexible power systems to be designed based on high shares of renewable generation eliminate the dependence on costly and less flexible traditional baseload generation.[6]

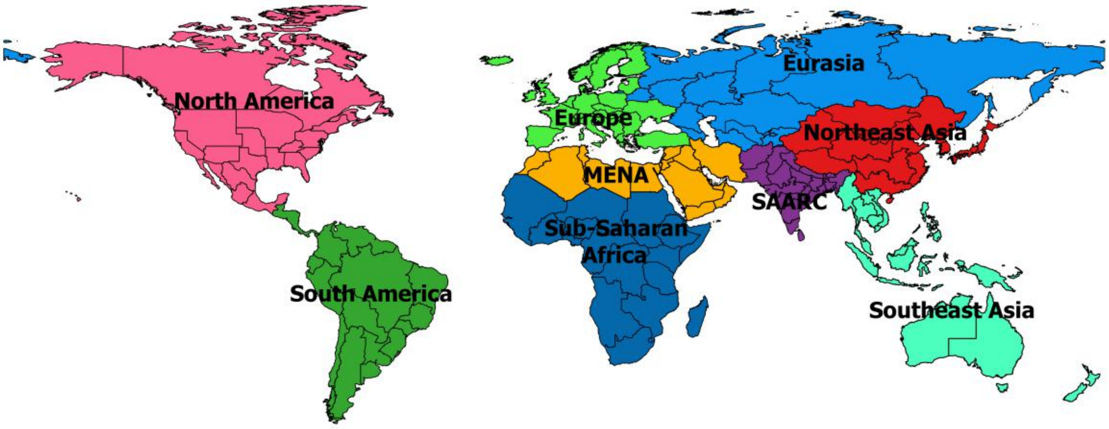
In as early as 2003, the German Advisory Council on Global Change (WBGU)[17] had presented a forward looking study of the very first energy transition on a global scale towards high shares of renewable energy during the 21st century. The study lays out a pathway to phase out non-sustainable technologies, such as nuclear energy and fossil fuel based energy conversion, while integrating sustainable renewable energy options to satisfy an increasing energy demand of the future global society. Recent research also indicate that achieving 100% renewable energy is possible, and most likely around the mid of this century.[11, 12, 18] Recent trends indicate that energy systems in this century will increasingly be based on electricity, mainly due to high technical efficiency, comparably lower cost and the availability of prospective power-to-X technologies. These power-to-X technologies include power-to-heat (electric heat pumps),[19, 20] power-to-water (reverse osmosis desalination[21]), power-to-hydrocarbons (hydrogen,[22, 23] methanation,[23, 24, 25, 26] synthetic fuels,[26, 27, 28] synthetic chemical feedstock[29, 30, 31, 32]) and a directly or indirectly electrified transport sector (battery electric vehicles,[33, 34] marine,[35, 36] aviation).[27] In consideration of these recent trends, decision-makers across the world increasingly require energy transition analyses with high spatial and temporal resolutions.

In this context, Lappeenranta University of Technology (LUT) and the Energy Watch Group (EWG) initiated this research to present an energy transition pathway encompassing all countries globally, which is required for a comprehensive societal discourse on national government levels as well as for international institutions and companies. Research results for a 100% RE system with hourly resolution for an entire year and 145 regions of the world have been previously made available by Breyer et al.[37, 38] This research presents for the first time a global energy transition towards 100% RE by 2050 in full hourly resolution, and for 145 regions in 5-year time periods. It further demonstrates that 100% RE can contribute to the utmost relevant societal requirement of achieving a zero-emission power sector by 2050 globally. This report presents an overview of the methodology, followed by the results for the energy transition with respect to installed capacities and electricity generation globally, as well as in major regions. In addition, the cost perspectives of the energy transition globally as well as in major regions are presented and the socio-economic benefits, such as job creation prospects, efficiency gains and GHG emission reduction potential of a 100% renewable electricity system are showcased. The report concludes with the policy perspectives of enabling a 100% RE power system globally.

2. TRANSITIONING TO A FULLY RENEWABLE POWERED ENERGY SYSTEM: METHODOLOGY AND INFLUENCING FACTORS

The transition to a fully renewable powered energy system has been carried out for the whole world, which is categorised into nine major regions as shown in the Figure 3.

Figure 3: The global map with the nine major regions constituted by the corresponding sub-regions.



The corresponding countries in the nine major regions are enlisted in Table 1; some of these countries are further divided into sub-regions, while some countries are integrated into a single region. Therefore, resulting in an overall 145 sub-regions globally.

Table 1: The nine major regions and the corresponding countries imparted into the LUT Energy System Transition model.

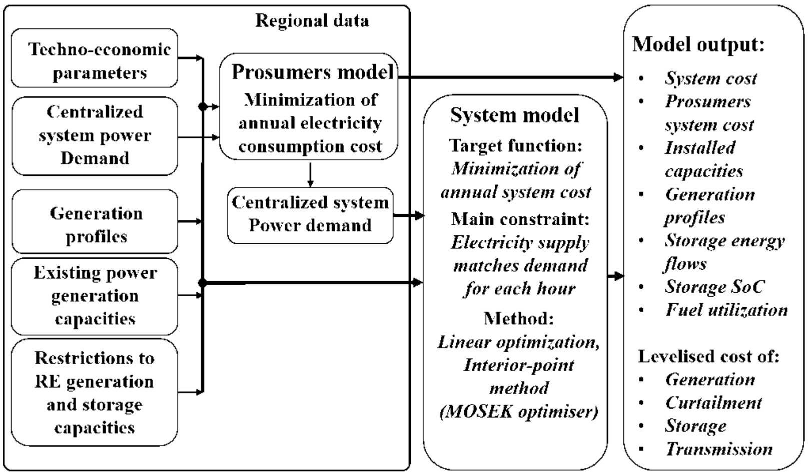
Major Regions	Countries
Europe	Norway, Denmark, Sweden, Finland, Iceland, Estonia, Latvia, Lithuania, Poland, Portugal, Spain, Gibraltar, France, Monaco, Andorra, Belgium, Netherlands, Luxembourg, Ireland, United Kingdom, Isle of Man, Guernsey, Jersey, Germany, Czech Republic, Slovakia, Austria, Hungary, Slovenia, Croatia, Romania, Bulgaria, Greece, Bosnia and Herzegovina, Serbia, Montenegro, Macedonia, Albania, Italy, San Marino, Vatican, Switzerland, Liechtenstein, Turkey, Cyprus, Ukraine, Moldova
Euraisa	Russia, Belarus, Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Uzbekistan, Turkmenistan
MENA	Algeria, Bahrain, Qatar, Egypt, Iran, Iraq, Israel, Jordan, West Bank and Gaza Strip as State of Palestine, Kuwait, Lebanon, Libya, Morocco, Oman, Saudi Arabia, Tunisia, United Arab Emirates, Yemen, Syria
Sub-Saharan Africa	Gambia, Cape Verde Islands, Guinea, Guinea Bissau, Liberia, Mali, Mauritania, Senegal, Sierra Leone, Benin, Burkina Faso, Cote d' Ivoire, Ghana, Togo, Chad, Niger, Nigeria, Sudan, Eritrea, Ethiopia, Somalia, Djibouti, Kenya, Uganda, Tanzania, Rwanda, Burundi, Cameroon, Central Africa Republic, Equatorial Guinea, Gabon, São Tomé and Príncipe, Congo Brazzaville, Congo, Angola, Botswana, Namibia, South Africa, Lesotho, Malawi, Mozambique, Swaziland, Zambia, Zimbabwe, Comoros Islands, Madagascar, Mayotte, Seychelles, Mauritius
SAARC	Afghanistan, Pakistan, India, Nepal, Bhutan, Bangladesh, Sri Lanka
Northeast Asia	China, Japan, Republic of Korea, Democratic People's Republic of Korea, Mongolia
Southeast Asia	Myanmar, Malaysia, Brunei, Singapore, Indonesia, Thailand, Laos, Vietnam, Cambodia, Philippines, Australia, New Zealand
North America	Canada, United States of America, Mexico
South America	Panama, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala, Belize, Colombia, Venezuela, Guyana, French Guiana, Suriname, Ecuador, Peru, Bolivia, Paraguay, Brazil, Argentina, Uruguay, Chile
Europe	Norway, Denmark, Sweden, Finland, Iceland, Estonia, Latvia, Lithuania, Poland, Portugal, Spain, Gibraltar, France, Monaco, Andorra, Belgium, Netherlands, Luxembourg, Ireland, United Kingdom, Isle of Man, Guernsey, Jersey, Germany, Czech Republic, Slovakia, Austria, Hungary, Slovenia, Croatia, Romania, Bulgaria, Greece, Bosnia and Herzegovina, Serbia, Montenegro, Macedonia, Albania, Italy, San Marino, Vatican, Switzerland, Liechtenstein, Turkey, Cyprus, Ukraine, Moldova

2.1 LUT ENERGY SYSTEM TRANSITION MODEL

The LUT Energy System Transition modelling tool[39, 40] simulates an energy system under given conditions and this simulation is applied for 5-year time periods from the years 2015 to 2050. For each period, the model defines a cost optimal energy system structure and operation mode for the given set of constraints that are power demand, available generation and storage technologies, financial and technical assumptions, and limits on installed capacity for all applied technologies. The model is based on linear optimisation and performed on an hourly resolution for entire years (further details on the working of the model along with the respective mathematical representation of the target functions can be found in the methodology section of the appendix). The model ensures high precision computation and reliable results. The costs of the entire system are calculated as a sum of the annualised capital expenditures including the cost of capital, operational expenditures (including ramping costs), fuel costs and the cost of GHG emissions for all available technologies.

The energy system transition analyses also consists of distributed self-generation and consumption of residential, commercial and industrial PV prosumers, which are simulated with a different model describing the PV prosumer and battery capacity development. PV prosumers have the option to install their own rooftop PV systems with or without lithium-ion batteries, and draw power from the grid in order to fulfil their demand[41, 42] while also having the option to feed-in to the grid their surplus electricity. The target function for PV prosumers is the minimisation of the cost of consumed electricity, calculated as a sum of self-generation, annual costs and the cost of electricity consumed from the grid, minus the cost of electricity sold to the grid. The share of consumers opting to install their own generation and storage is projected to gradually increase from 3% in 2015[43, 44] to 20% by 2050 . The share of PV prosumers increases in accordance with the logistic function, in steps of 3, 9, 15, 18 and 20%. For a given year, if self-consumption of electricity becomes economically feasible, then the share of prosumers for the following year increases, otherwise the share of potential prosumers remains the same. For some countries, such as Germany and Italy, the starting share of PV prosumers is 9% in 2015. The flow diagram of the LUT Energy System model including input and output data is presented in Figure 4. The technical and financial assumptions section of the appendix (Tables 2.2 to 2.5) provides the full set of technical as well as financial assumptions utilised in the modelling of the energy transition.

Figure 4: Key inputs and outputs of the LUT Energy System model.[40]



Two crucial constraints are factored into the model in order to establish a sound basis for the energy system transition modelling, these are:

1. New nuclear, coal and oil-based power plants are prohibited from being installed post-2015, mainly due to their inability to fulfill the high sustainability criteria set in the model.

2. The incremental increase in the share of installed capacities of renewable energy technologies is not permitted to exceed 4% per annum in congruence with empirical data.[9] Additionally, this increase in share is further limited to 3% between 2015 and 2020.

The applied strong sustainability requirements do not allow new investments in nuclear power plants, as mentioned, but the utilisation of the existing capacity continues until the end of individual technical lifetimes to facilitate a gradual phase out. This leads to 0.3% of nuclear generation in 2050, which is obviously negligible, but as a consequence of the applied rule. The total system cost will not be affected, even if this tiny generation share was to be substituted by renewable energy and respective storage capacities. Coal-fired power plants are also not permitted to receive new allocations. However, the existing capacities have to be amortised until the end of their technical lifetimes. Their utilisation is cost optimised so that, in later periods of some countries, full load hours decline to zero. Even though, the capacities do not produce electricity any longer, they have to be amortised due to political reasons, a procedure which is known as cold reserve (also called security reserve).[45] Gas turbines are permitted to be installed beyond 2015 due to lower carbon emissions and the possibility to accommodate synthetic natural gas (SNG) or bio-methane into the system.[25] Gas-fired power plants are more flexible, not only in their ramping rates, but also in the origin of the methane firing, as fossil gas is gradually phased out and incrementally substituted with bio-methane and synthetic gas via power-to-gas technologies.

2.2 RENEWABLE ELECTRICITY GENERATION TECHNOLOGIES AND RESOURCES

The model has integrated all crucial aspects of power systems: power generation, storage and transmission. The technologies introduced to the model are classified into the following categories:

- Technologies for electricity generation: RE, fossil and nuclear technologies
- Energy storage technologies
- Electricity transmission technologies

Figure 5 displays the schematic representation of the LUT Energy System model and all the power sector technologies considered for simulating the global energy transition.[46]

Table 2 enlists all the power sector technologies and their brief descriptions. RE technologies are solar PV (optimally fixed-tilted, single-axis north-south tracking and rooftop PV), concentrating solar thermal power (CSP), wind turbines (onshore and offshore), hydropower (run-of-river and dam), geothermal and bioenergy (solid biomass, biogas and waste-to-energy power plants). Fossil fuel based generation technologies considered are coal-fired power plants, oil-based internal combustion engines (ICE), open cycle gas turbines (OCGT) and combined cycle gas turbines (CCGT).

Figure 5: The schematic representation of the LUT Energy System model for the power sector representing the various RE sources for power generation, transmission options, storage technologies and power demand sectors.

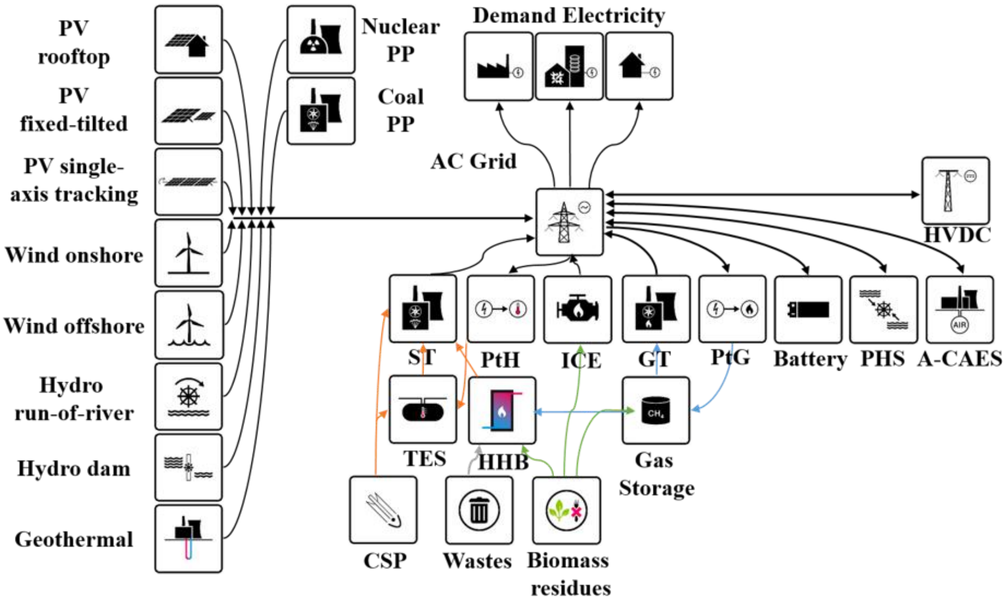


Table 2: List of power generation, storage and transmission technologies considered in the LUT energy system model and their brief descriptions.[46]

Technologies	Description
	Power Generation
PV ground mounted fixed tilt	These are large-scale installations of solar PV systems on land.
PV single-axis tracking	These are large-scale installations of solar PV systems with tracking systems, which allow tracking the movement of the sun along a single-axis.
PV rooftop	These are installations of solar PV systems on roofs of residential, commercial or industrial buildings and sometimes on the premises.
Wind onshore	Wind turbines built on land, usually in wind resource rich areas.
Wind offshore	Wind turbines built in areas off the coast located in seas and oceans, with high wind speeds.
Hydro Dam	Power plants that generate electricity with high-pressure turbines from water stored in reservoirs.
Hydro RoR	Power plants that capture the kinetic energy in rivers or streams and convert it to electricity.
Biomass	Power plants that generate electricity utilising organic matter as their fuel source.
Biogas	Power plants that utilise gas (usually methane) from anaerobic digestion of organic material to produce electricity.
Waste-to-energy	Power plants utilising waste materials such as non-degradable municipal solid waste and used wood to produce electricity.
Geothermal	Power plants utilising the thermal gradient of the various layers underground to produce electricity, usually in areas with high geothermal gradients.
CSP	Solar power plants utilising thermal energy from the sun to produce electricity, usually located in solar resource rich areas.
CCGT	Power plant utilising the combined cycle gas turbine (having both steam and gas turbines) and gas (methane: fossil, bio-methane, SNG) as fuel source to generate electricity.
OCGT	Power plant utilising the open cycle gas turbine (having just a gas turbine) and gas (methane: fossil, bio-methane, SNG) as fuel source to generate electricity.
Internal Combustion Engine	Power plants utilising internal combustion engines to generate electricity utilising petrol fractions as fuel.
Coal PP (Hard Coal)	Power plants that generate electricity utilising coal as their fuel source.
Nuclear PP	Power plants that generate electricity through nuclear reactions (fission) and utilising uranium as their fuel source.

	Storage
Battery	Lithium-ion batteries that store power, charge and discharge whenever required.
Power-to-Gas	Synthetic methane (SNG) production using methanation reaction from Hydrogen (produced with electrolysers) and Carbon dioxide (produced with direct air capture (DAC) units).
Gas Storage	Storing energy in the form of gas (synthetic methane - SNG) in high-pressure underground inventories. SNG is produced by Power-to-Gas conversion and later converted to electricity by gas turbines.
Pumped Hydro Storage	Storing energy by pumping water into reservoirs (generally located at a higher elevation) to produce electricity via turbines whenever required.
Adiabatic Compressed Air Energy Storage	Energy is stored by compressing air with turbomachinery and storing it in underground caverns for usage whenever required.
Thermal energy storage	Energy is stored as thermal energy via heating of energy carriers, which is thermal potential that can be used for electricity generation.
Power-to-Heat	Heating of energy carriers via electric heaters.
Hot Heat Burner	Heating of energy carriers via boilers utilising fuel.
Steam Turbine	Steam turbines used to convert thermal potential of energy carriers from thermal storage to produce electrical energy.
	Transmission
HVAC	High voltage alternating current grid lines, which are currently in use across electrical networks.
HVDC with Converters	High voltage direct current grid lines are a more efficient way of transmitting electricity over longer distances.

Storage technologies are further classified into the following categories:

- Short-term: Li-ion batteries and pumped hydro storage (PHS)
- Medium-term: adiabatic compressed air energy storage (A-CAES) and thermal energy storage (TES)
- Long-term: gas storage including power-to-gas technology, which allows production of synthetic methane for the energy system.

The energy transition simulation takes into account the existing power grid, its development and impact on overall electricity transmission and distribution losses[47]. All regions within a country can be interconnected with high voltage direct current (HVDC) or high voltage alternating current (HVAC) power lines, therefore increasing local flexibility while reducing overall national system costs. Concentrating photovoltaics (CPV) are not included in this research, mainly due to its negligible market share, poor mid-term expectation of market penetration and ongoing rapid technological as well as economic progress of the benchmarking non-concentrating PV technology.

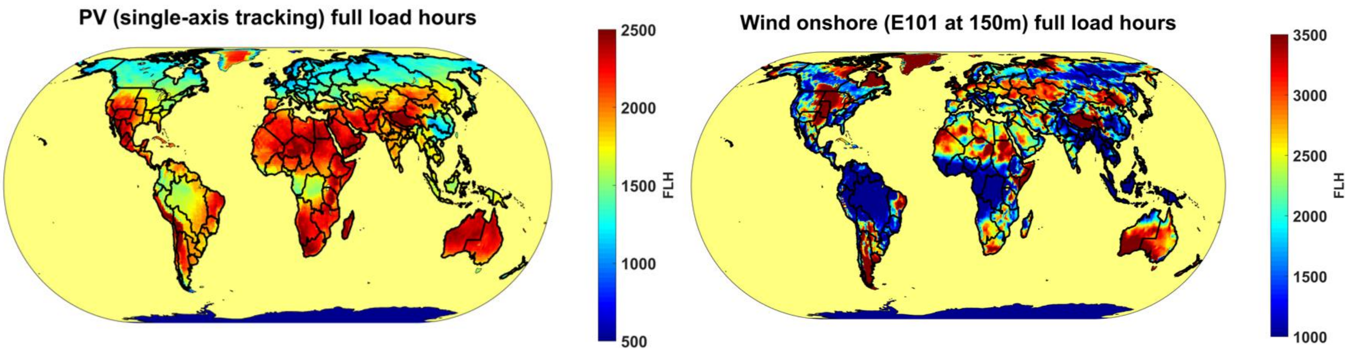
2.3 FINANCIAL AND TECHNICAL ASSUMPTIONS

The financial and technical assumptions are mostly taken from various sources (Pleßmann et al.[48], European Commission,[49] ETIP-PV,[50] Vartiainen et al.[51], Fraunhofer ISE 2015,[52] Neij 2008,[53] Haysom et al.[54], Kutscher et al.[55], Sigfusson and Uihlein,[56] Agora Energiewende,[57] Breyer et al.[58], IEA,[59] McDonald and Schrattenholzer,[60] Urban et al.[61] and Hoffmann[62]); all the financial and technical assumptions with the corresponding references to data sources for all energy system components can be found in the technical and financial assumptions section of the appendix (Table 2.2 to 2.5). Assumptions are considered for 5-year time periods from the year 2015 to 2050. The weighted average cost of capital (WACC) is set to 7%, but in the case of residential solar PV prosumers, WACC is set to 4% due to lower financial return requirements. Electricity prices for residential, commercial and industrial consumers were derived according to Gerlach et al.[63], and extended to 2050 based on the methodology of Breyer and Gerlach.[64] Excess electricity generated by PV prosumers is limited to 100% of their own demand, the surplus is fed into the national grid, and is assumed to be incentivised for a transfer price of 0.02 €/kWh. The model ensures that prosumers satisfy their own demand for electricity before feeding it to the grid. The costs for biomass are calculated using data from the IEA[65] and Intergovernmental Panel on Climate Change (IPCC).[66] Solid wastes gate fees for 2015 vary from 50 €/ton in developing countries to 100 €/ton in Western Europe, North America and other developed countries; gate fees were assumed to gradually increase globally and by 2050 reach 100 €/ton in most of the countries.

2.4 RESOURCE POTENTIAL FOR RENEWABLE ENERGY TECHNOLOGIES

The generation profiles for optimally fixed-tilted PV, solar CSP and wind energy are calculated according to Bogdanov and Breyer[40] and for single-axis tracking PV according to Afanasyeva et al.[67] The hydropower feed-in profiles are computed based on daily resolved water flow data for the year 2005[68]. The potentials for biomass and waste resources were obtained from Bunzel 2009[69] and further classified into categories of solid wastes, solid residues and biogas. Geothermal energy potential is estimated according to the method described in Gulagi.[70] The global distribution of full load hours (annual generation) of solar PV (single-axis tracking) and wind onshore (at 150 m hub-height), which are the two most vital sources of electri-city in the energy transition are shown in Figure 6. It can be observed that countries in the Sun Belt region (between the tropic of Cancer and tropic of Capricorn) have great potential for solar all year round, while regions in the northern and southern temperate zones have exceptional wind potential.

Figure 6: Global mapping of annual full load hours for solar PV with single-axis tracking (left) and onshore wind at 150 m hub-height (right).



2.5 DEVELOPMENT OF ELECTRICITY DEMAND

Electricity demand of the global power sector is estimated to increase from 23,141 TWh in 2015 to about 48,800 TWh in the year 2050, which represents a global average compound annual growth rate of 2.2% in the energy transition period, and is comparable to the assumption of 1.9% by the IEA.[71] This marginally higher rate reflects the consideration of some local data. The increasing demand for electrification of other sectors such as heat, mobility and industry is beyond the scope of this study. The world population is expected to grow from nearly 7.3 billion people in 2015 to around 9.7 billion people, while the global average per capita electricity demand rises from 3.2 MWh in 2015 to 5.0 MWh in 2050 as highlighted in Figure 7.

The assumptions for the electricity growth rate from 2015 to 2050 for the various regions can be found in the technical and financial assumptions section of the appendix (Table 2.1).

Figure 7: Development of average electricity consumption per capita globally and in OECD countries, growth in population from 2015 to 2050 (left) and the global synthetic load profile in 2050 (right).[72]

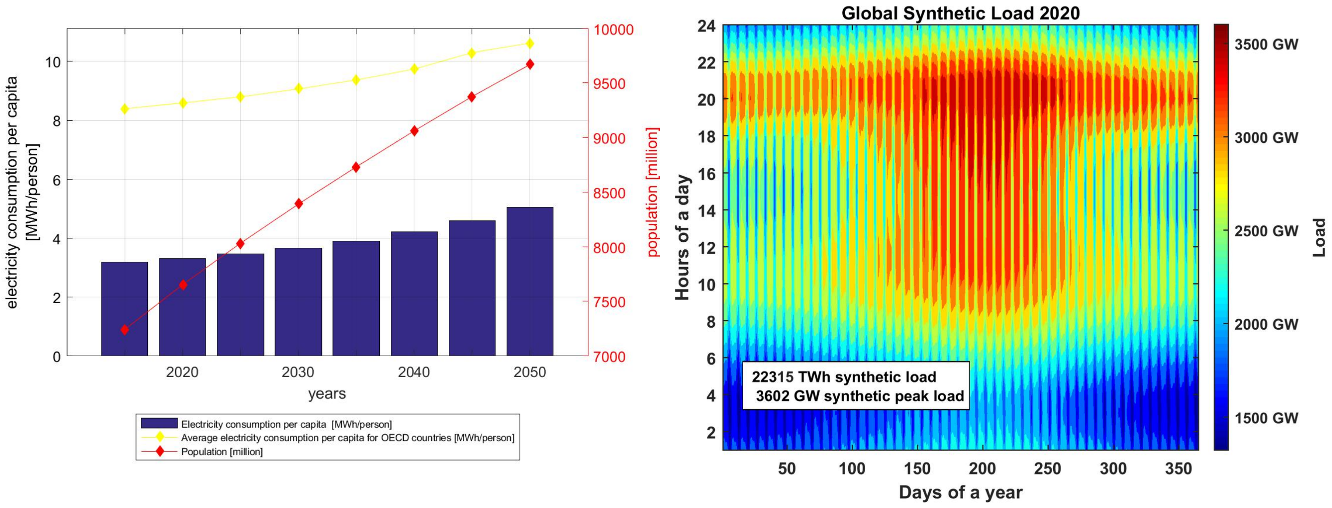
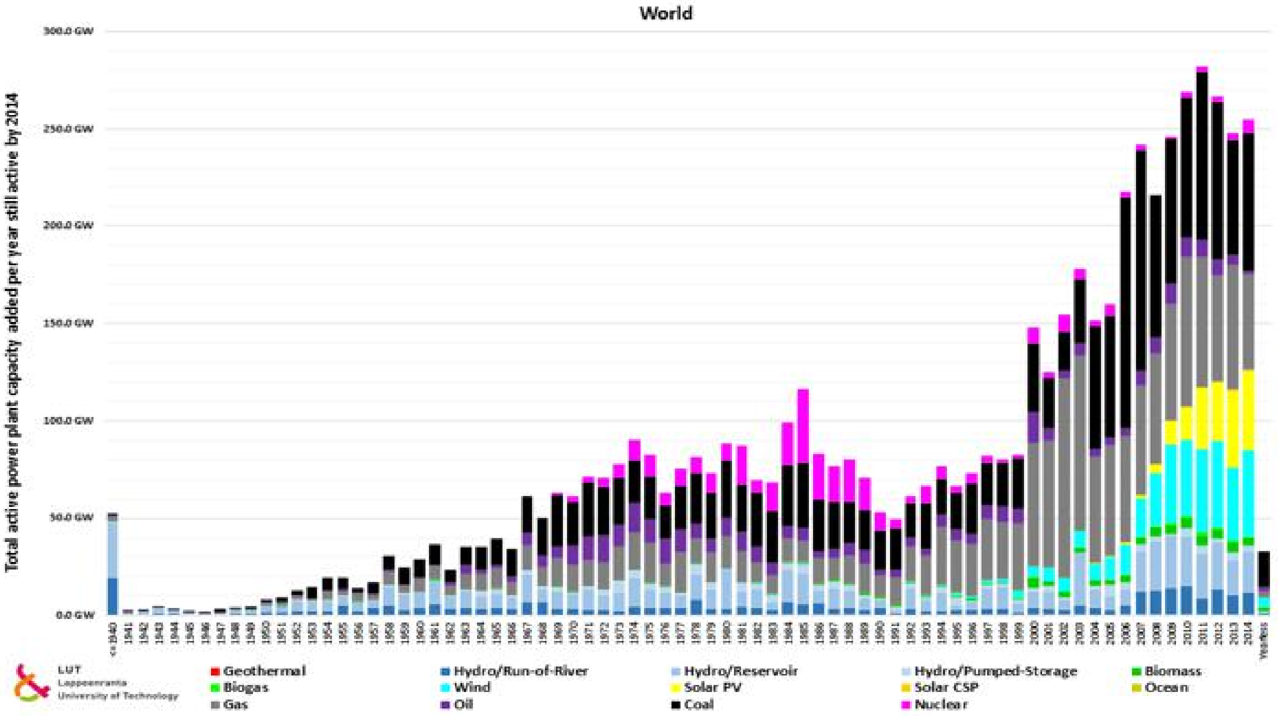


Figure 8: Historical power plant infrastructure development with annual installed capacities.[9]



The synthetic electricity demand profiles from 2015 until 2050 are generated based on the methodology from Toktarova et al.[72]. Figure 7 shows the global synthetic load profile for the year 2020 with a synthetic peak load of 3602 GW. For the modelling of countries and regions, their corresponding load profiles are used.

The global power plant capacity is structured according to the major technologies and their corresponding country of location along with the year of commissioning in an annual resolution[9], as is displayed in Figure 8. This facilitates proper accounting of power plant capacities that need to be phased out after reaching their end of technical lifetime. This is applied to all of the 145 regions globally, in order to improve the accuracy of determining power capacity requirements during the transition period.

As the raison d'être for the global energy transition is the reduction of GHG emissions and achieving the goals set by the Paris Agreement, costs for CO2 emissions during the transition period (refer to Table 2.4 in the methodology section of the appendix) are considered while modelling the energy transition scenario. This results in different emission reduction pathways corresponding to the various countries and regions across the world.

2.6 METHODOLOGY FOR ESTIMATING JOB PROSPECTS OF THE GLOBAL ENERGY TRANSITION

The jobs created during the global energy transition from 2015 to 2050 are estimated utilising the employment factor approach, adopted from Rutovitz et al.[73]. The employment factor method was utilised amongst the other methods[74], due to its simplicity and effectiveness to estimate direct employment associated with energy generation, storage and transmission. In this context, direct employment includes jobs in manufacturing, construction and installation, operations and maintenance, fuel supply and transmission associated with electricity gene-ration.

The Figure 9 gives an overview of the methodology adopted to estimate the overall direct jobs created by the global energy transition.

Employment Factors are the number of jobs per unit of capacity, separated into manufacturing, construction and installation, operation and maintenance, and per unit of primary energy of fuel supply. In the case of transmission, jobs per annual investments are considered. Employment Factors[73] were mainly adopted from Rutovitz et al., along with some modifications and a few other sources. The employment factors for the various power generation and storage technologies, along with transmission can be referred to in the methodology section of the appendix (Table 2.6).

Decline Factors are used to account for the maturity of all the technologies considered and potential reduction in employment creation as production capacities increase. These are correlated with the reduction in capital costs (CAPEX) of the various generation and storage technologies during the transition period of 2015 to 2050, in the case of manufacturing, and construction and installation jobs. While, in the case of operation and maintenance jobs the Decline Factor is correlated with the decline in operational costs (OPEX) of the respective generation and storage technologies though the transition period (CAPEX and OPEX costs can be referred to in the appendix, Table 2.1).

Figure 9: Methodology for the estimation of job creation during the energy transition adopted from Rutovitz et al. [73] *Wherein, EF stands for Employment Factor. The calculations are applied to all technologies.*

Manufacturing Jobs = ***Installed Capacity per year (MW/year)*** * ***Manufacturing EF (job-years/MW)*** * ***Decline Factors based on Capex*** * ***Global employment multiplier***

Construction and Installation Jobs = ***Installed Capacity per year (MW/year)*** * ***Construction and Installation EF (job-years/MW)*** * ***Decline Factor based on Capex*** * ***Global employment multiplier***

Operation and Maintenance Jobs = ***Cumulative Capacity (MW)*** * ***Operation and Maintenance EF (jobs/MW)*** * ***Decline Factor based on Opex*** * ***Global employment multiplier***

Fuel Jobs = ***Primary energy demand (PJ)*** * ***Fuel EF (Jobs/PJ)*** * ***Global employment multiplier***

Transmission Jobs = ***Investments per year (b€)*** * ***Transmission EF (jobs/b€)*** * ***Global employment multiplier***

Total Jobs = ***Manufacturing Jobs*** + ***Construction and Installation Jobs*** + ***Operation and Maintenance Jobs*** + ***Fuel Jobs*** + ***Transmission Jobs***

The global employment multiplier is a factor for the differential labour-intensive economic activity in the different regions across the world. As the employment factors considered are mainly from OECD countries, the global em-ployment multiplier accounts for the additional employment that will be generated in non-OECD countries. The methodology from Ruto-vitz et al.,[73] along with labour productivity data from the International Labour Organization (ILO),[75] was used to determine the global em-ployment multiplier.

3. THE GLOBAL ENERGY TRANSITION: RESULTS FOR THE POWER SECTOR

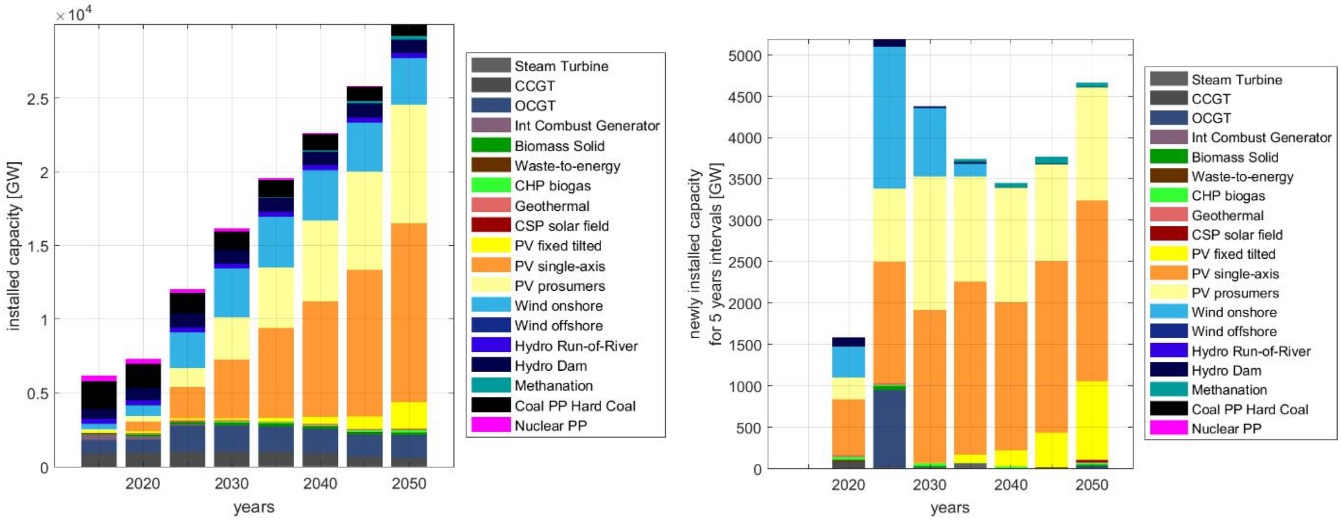
The results of the global energy transition are presented in a globally aggregated power scenario, followed by independent power scenarios of the nine major regions. Links to the results of all countries and sub-regions are provided in the appendix (Table 4.1).

3.1 GLOBAL

The development of the power sector is characterised by a dynamically growing electricity demand driven by developing and emerging countries and an increasing share of renewable electricity in the overall supply mix. The results show a growing RE trend that will compensate for the phasing out of nuclear power production as well as for the continually reducing number of fossil fuel based power plants. As per the results, the installed capacity of renewables will reach about 14,000 GW in 2030 and more than 28,000 GW by 2050.

A 100% electricity supply from renewable energy resources leads to around 23,600 GW of installed generation capacities of solar PV, wind and hydropower by 2050 as shown in Figure 10. A significant amount of wind and solar PV, roughly around 4000 GW, is installed from 2020 to 2025 and 4300 GW is installed from 2025 to 2030. Solar PV drives the major share of installed capacities between 2035 and 2050, as it delivers the least cost source of electricity as shown in Figure 10.

Figure 10: Global – Cumulative installed capacities of various power generation technologies from 2015 to 2050 (left) and new installed capacities of various power generation technologies for every 5-year interval from 2015 to 2050 (right).



The global electricity generation of 23,141 TWh in the year 2015 is composed of 40.2% coal, 21.3% fossil gas, 4.3% oil, 10.5% nuclear energy, 16.6% hydropower, 3.7% wind energy, 1.2% solar PV, 2.0% bioenergy and 0.4% others (mainly geothermal and CSP).[71, 6] The evolution towards 100% RE is visualised in Figure 11 and tabulated in Table 3. The share of renewable electricity in the overall mix will reach 99.65% of the electricity generated worldwide in 2050. Renewable power generation technologies – mainly solar PV and wind – will contribute nearly 87% to the total electricity generation by 2050 as shown in Figure 11. The share of renewable electricity production will already be around 40% in 2020 and reach 85% by 2030.

Figure 11: Global – Net electricity generation by various power sources from 2015 to 2050 (left) and relative shares of electricity generation by various power sources from 2015 to 2050 (right).

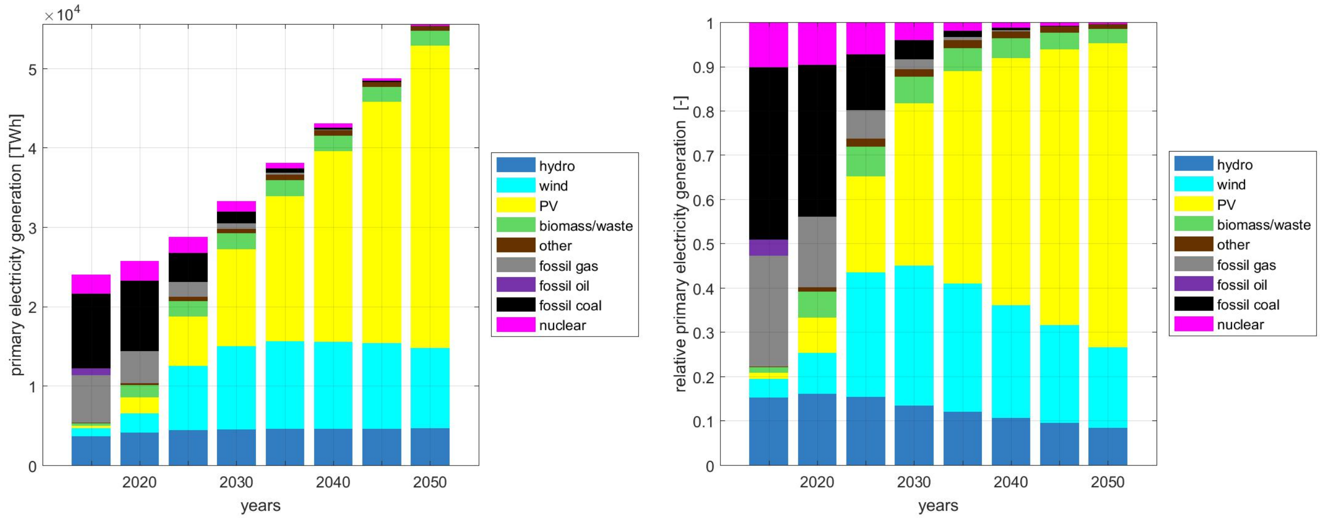
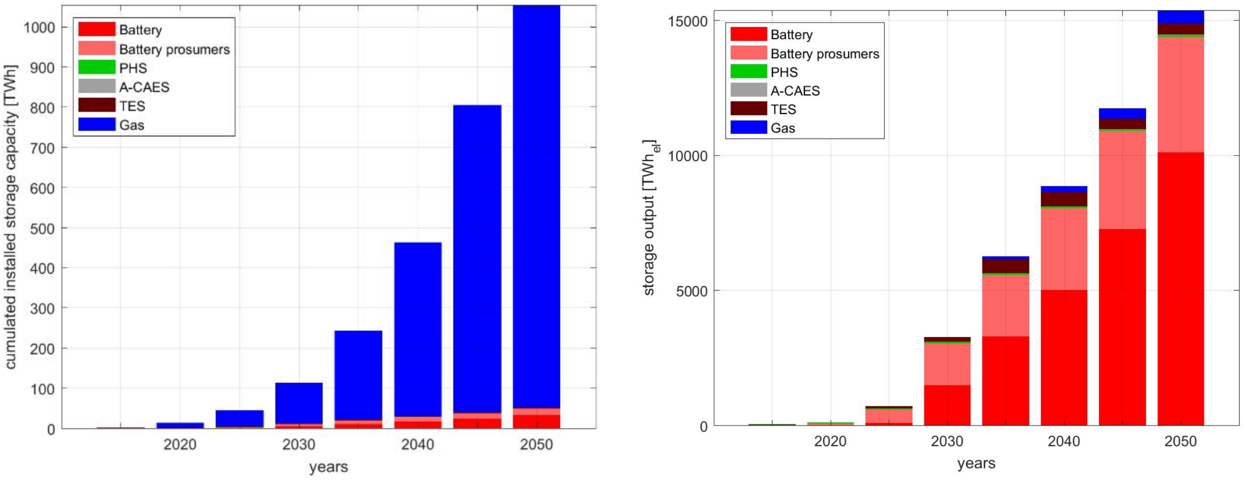


Figure 12: Global – Cumulative installed capacities of various storage technologies from 2015 to 2050 (left) and net output by various storage technologies from 2015 to 2050 (right). Gas storage output (right) includes only stored SNG. The output of stored bio-methane is not classified as part of gas storage output even though it contributes significantly to the need of gas storage capacity (left). Bio-methane represents 51% of gas consumed globally, and is instead accounted as bioenergy generation.



Storage technologies play a vital role in enabling the transition towards a fully renewables powered energy system. As shown in Figure 12, a significant share of gas storage is installed, which provides vital seasonal storage. However, batteries are even more critical as they provide the maximum output combining with solar PV both in the form of prosumers as well as large-scale battery storage. Other sources that have a minor share in the total output are PHS, TES and A-CAES.

The overall storage output covers 31% of the total electricity demand in 2050, of which 95% is delivered by batteries. The installed capacities are dominated by gas storage, whereas the overall output is dominated by battery storage. This is explained by the short-term and long-term storage characteristics of the respective technologies. Short-term battery storage has a lower energy-to-power ratio – such that the storage can be charged and discharged faster. Additionally, the difference in annual full charge cycles, which are around 300 for batteries and just 1-2 for gas storage result in very high shares of battery output in comparison to gas storage. It should also be kept in mind that gas storage is also used for bio-methane, which represents 51% of all gas consumed globally and contributes significantly to the need of gas storage capacity. However, only SNG is classified as gas storage output, while bio-methane is accounted as bioenergy generation. The technology-wise installed capacities and total output through the transition period of 2015 to 2050 are indicated in Table 3.

Solar PV and wind energy evolve to become the backbone of the global electricity supply system in the first half of the 21st century, growing from a supply share of just 4.9% in 2015 to 87% in 2050. The contribution of CSP is found to be negligible, mainly due to the extremely high cost competiveness achieved by solar PV that is additionally well complemented by low-cost batteries. The share of wind energy increases significantly until 2030, achieving around a 32% supply share of global electricity generation. The high cost competiveness of PV-battery systems limits further contribution from wind energy in the period 2035 to 2040 and even forces a decline in terms of absolute electricity generation until 2050. This is due to existing capacities not being repowered any longer, mainly in solar resource rich regions with moderate seasonality. Consequently, the relative electricity generation share of wind energy declines to 18% in the year 2050. The growth of hydropower from 3890 to 4640 TWh is relatively low, as the overall resource constraint is taken into account[76] as well as the comparably higher costs of new large-scale hydropower,[77] the respective risks of cost overruns,[78] and the larger risk of violating societal and ecological sustainability criteria of large-scale hydropower projects.[79, 80] The generation of electricity from bio-based products increases from 322 to 1804 TWh, and is not only limited by the availability of residual and waste energy resources, but by the comparably higher costs. Geothermal power generation grows from 35 to 470 TWh and is impeded by limited resource availability and comparably higher costs.

Table 3: Global – Installed cumulative capacities and net electricity generation by various power sources; installed capacities and net output of various storage sources during the energy transition from 2015 to 2050 at 5-year intervals.

Technology	2015	2020	2025	2030	2035	2040	2045	2050
Power Generation	**Installed Capacity [GW]**							
PV utility-scale	131	803	2269	4124	6312	8297	10790	13921
PV rooftop	100	365	1245	2856	4127	5508	6675	8038
Wind	372	747	2462	3293	3447	3395	3329	3154
Hydropower	1028	1137	1224	1242	1260	1267	1271	1282
Bioenergy	120	376	440	479	489	505	511	554
Geothermal	13	39	64	67	69	69	67	67
Gas Turbine	1789	1828	2763	2733	2635	2463	2136	2077
Coal PP	1896	1665	1435	1293	1181	1083	955	754
Nuclear PP	368	331	277	182	96	69	49	26
Other generation	386	243	103	94	111	87	65	98
Power Generation	**Generation [TWh]**							
PV utility-scale	187	1561	4466	8053	12234	15928	20529	26217
PV rooftop	131	513	1788	4173	6051	8111	9867	11912
Wind	1002	2373	8091	10514	11072	10993	10816	10156
Hydropower	3679	4132	4427	4489	4555	4584	4604	4638
Bioenergy	322	1493	1948	1994	1984	1913	1845	1804
Geothermal	34	259	466	478	476	475	471	470
Gas Turbine (fossil gas)	5996	4082	1852	748	229	87	32	0
Coal PP	9358	8830	3658	1422	556	256	83	0
Nuclear PP	2451	2466	2062	1355	718	513	364	194
Other generation	871	8	34	71	223	231	171	180
Storage	**Installed Capacity [GWh]**							
Battery	2	217	1967	9934	18440	26756	36348	47858
Gas	0	11931	39931	102062	220581	432784	765826	1001898
Pumped Hydro	135	144	225	264	265	265	265	265
Other storage	0	1320	1411	1691	3627	3771	2757	3745
Storage	**Output [TWh_{el}]**							
Battery	2	64	571	3021	5571	8040	10893	14392
Gas	0	964	1013	1086	1264	1472	1722	1897
Pumped Hydro	27	31	55	63	57	58	54	53
Other storage	0	15	82	171	528	536	398	432

3.2 EUROPE

Europe is one of the major economic centers of the world with an 18% share of global GDP[81] and amongst the biggest energy consumption centers across the world, with total electricity consumption of around 4000 TWh in 2015,[71] which is estimated to rise to 5400 TWh by 2050.[72] Europe, led by countries such as Denmark, Spain, Germany and Italy, among others, has been at the forefront of the global energy transition with 37% of installed power capacity and nearly 30% of electricity generation coming from renewables.[6] The results indicate a smooth transition to a 100% renewable powered energy system for the European region with net installed capacity of renewables reaching 2200 GW in 2030 and close to 3000 GW by 2050 as shown in Figure 12. A significant amount of wind and solar PV, roughly around 250 GW, is installed from 2020 to 2025 and 530 GW from 2025 to 2030. Solar PV drives the major share of installed capacities between 2040 and 2050, as it delivers the least cost source of electricity as shown in Figure 13.

Links to the results of all countries and regions within Europe are provided in the appendix (Table 4.1).

The total electricity generation of Europe is 4003 TWh in the year 2015, which is comprised of 28.6% coal, 15.7% fossil gas, 1.6% oil, 24.4% nuclear energy, 13.8% hydropower, 8.8% wind energy, 3.1% solar PV, 3.8% bioenergy and 0.3% others (mainly geothermal and CSP).[6, 71] The evolution towards 100% renewable electricity generation is visualised in Figure 14 and tabulated in Table 4. The share of renewable electricity in the overall mix will reach 99.8% of the total electricity generated across Europe in 2050. Renewable power generation technologies – mainly solar PV and wind – will contribute nearly 75% to the total electricity generation by 2050 as shown in Figure 14. The share of renewable electricity production will already be around 50% in 2020 and reach over 85% by 2030.

Figure 13: Europe – Cumulative installed capacities of various power generation technologies from 2015 to 2050 (left) and new installed capacities of various power generation technologies for every 5-year interval from 2015 to 2050 (right).

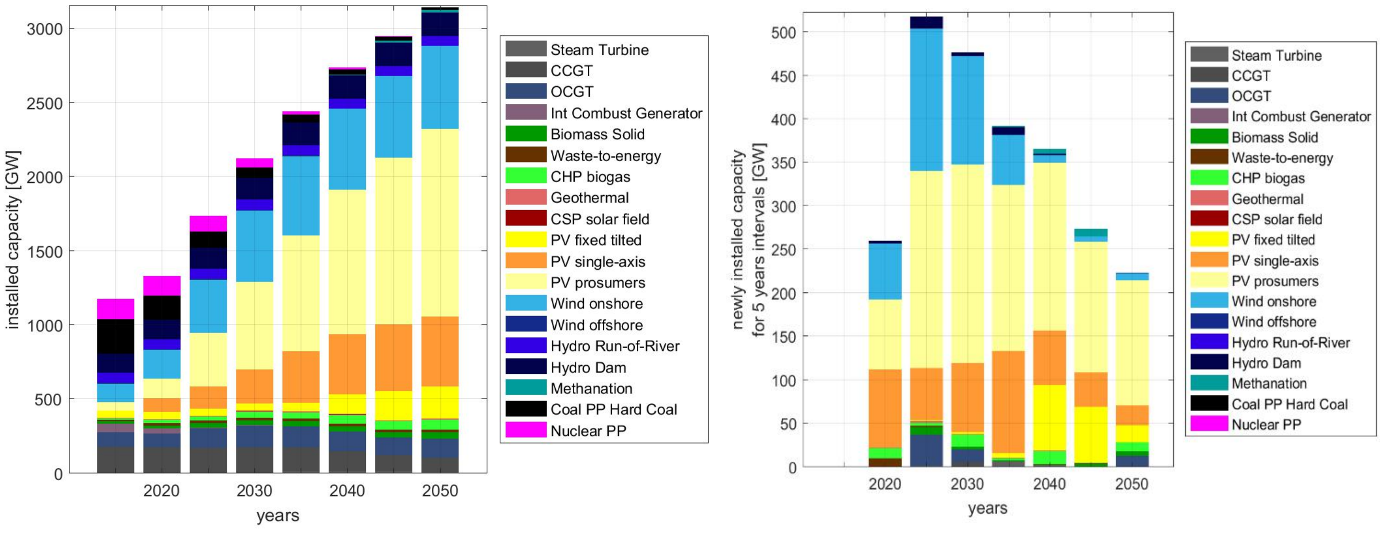
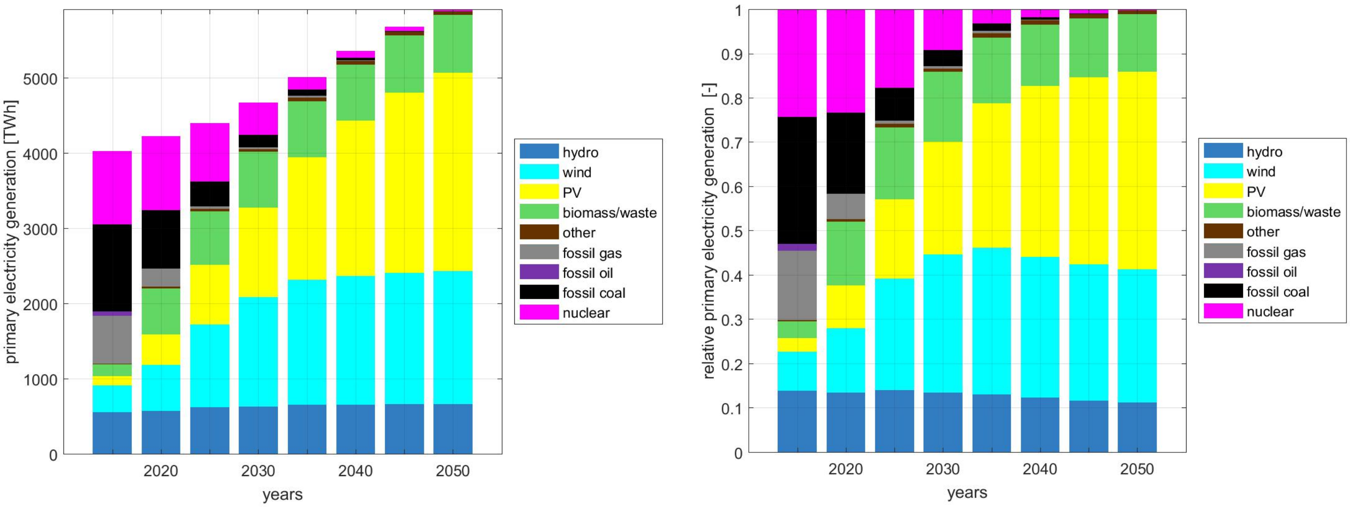
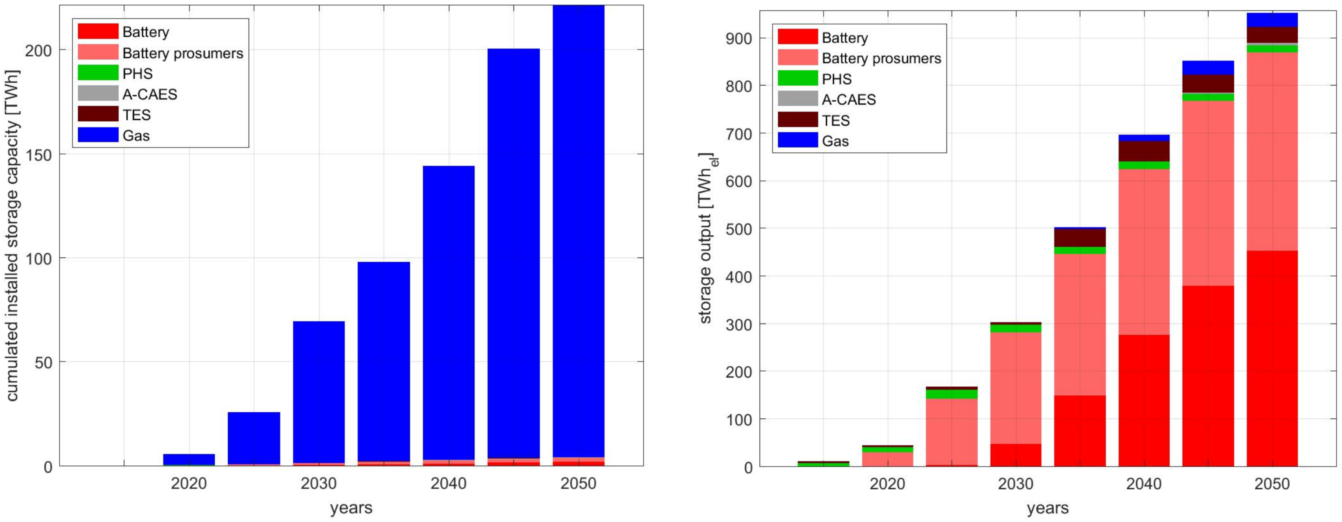


Figure 14: Europe – Net electricity generation by various power sources from 2015 to 2050 (left) and relative shares of electricity generation by various power sources from 2015 to 2050 (right).



Storage technologies play a vital role in enabling the transition towards a fully renewable powered energy system for Europe. As shown in Figure 15, a significant share of gas storage is installed, which provides vital seasonal storage especially during the cold winters. However, batteries are even more critical as they provide the maximum output, combining with solar PV in the form of prosumers, which are higher in share for Europe due to a larger number of decentralised and rooftop solar PV installations, as well as in large-scale battery storage. Other sources that have a minor share in the total output are PHS, TES and A-CAES.

Figure 15: Europe – Cumulative installed capacities of various storage technologies from 2015 to 2050 (left) and net output by various storage technologies from 2015 to 2050 (right). Gas storage output (right) includes only stored SNG. The output of stored bio-methane is not classified as part of gas storage output even though it contributes significantly to the need of gas storage capacity (left). Bio-methane represents 90% of gas consumed in Europe, and is instead accounted as bioenergy generation.



The overall storage output covers 18% of the total electricity demand in 2050, of which 93% is delivered by batteries. It should also be kept in mind that gas storage is also used for bio-methane, which represents 90% of all gas consumed in the region and contributes significantly to the need of gas storage capacity. However, only SNG is classified as gas storage output, while bio-methane is accounted as bioenergy generation. The technology-wise installed capacities and total output through the transition period of 2015 to 2050 are indicated in Table 4.

Solar and wind energy evolve to become the backbone of the European electricity supply system until 2050, growing steadily from a supply share of 11.9% in 2015 to 74.6% in 2050. The contribution of CSP is found to be negligible, mainly due to the extremely high cost competiveness achieved by solar PV that is additionally well complemented by low-cost batteries. The share of wind energy increases significantly until 2030, achieving around 30% supply share of total electricity generation across Europe. Wind energy continues to contribute steadily, utilising the excellent potential available in Europe, while solar steadily increases in generation share to reach around 45% of the total in 2050. Wind energy remains in the European electricity system, mainly due to the strong seasonality and excellent wind conditions for the period between autumn and spring, which coincides with higher electricity demand. The hydropower electricity share declines from around 14% to just over 11%, as the overall resource constraint is taken into account, also most of the hydropower potential across Europe has already been realised. The generation of electricity from bio-based products increases from 151 to 773 TWh, and is not only limited by the availability of residual and waste energy resources but, also by the comparably higher costs. Geothermal power generation grows from 11 to 35 TWh and is impeded by limited resource availability and comparably higher costs.

Table 4: Europe – Installed capacities and net electricity generation by various power sources; installed capacities and net output of various storage sources during the energy transition from 2015 to 2050 at 5-year intervals.

Technology	2015	2020	2025	2030	2035	2040	2045	2050
Power Generation	Installed Capacity [GW]							
PV utility-scale	49	139	199	281	403	541	646	688
PV rooftop	54	135	362	590	781	974	1124	1268
Wind	135	200	363	487	543	546	552	560
Hydropower	192	195	209	214	222	224	224	224
Bioenergy	37	57	72	88	92	109	113	128
Geothermal	2	3	5	5	6	6	6	6
Gas Turbine	274	266	298	318	307	270	229	225
Coal PP	234	166	111	72	51	36	24	20
Nuclear PP	138	133	105	58	22	13	8	2
Other generation	58	35	10	6	10	10	7	6

Generation	**Power Generation [TWh]**							
PV utility-scale	60	232	340	461	666	871	1025	1088
PV rooftop	65	171	450	729	962	1195	1376	1546
Wind	355	619	1106	1454	1662	1711	1749	1773
Hydropower	556	567	617	631	654	656	658	659
Bioenergy	151	615	714	741	742	741	757	773
Geothermal	12	17	31	34	37	37	36	36
Gas Turbine (fossil gas)	632	243	33	23	26	10	0	0
Coal PP	1152	774	328	168	83	26	7	0
Nuclear PP	982	989	779	432	162	97	56	12
Other generation	65	2	2	3	16	19	16	15

Storage	**Installed Capacity [GWh]**							
Battery	0	111	548	1088	1763	2511	3128	3569
Gas	0	5362	24979	68267	95766	141174	196765	217330
Pumped Hydro	0	24	44	47	248	315	387	466
Other storage	0	23	32	33	234	290	269	268

Storage	**Output [TWh$_{el}$]**							
Battery	0	30	142	281	445	624	767	869
Gas	0	429	465	527	555	570	580	569
Pumped Hydro	48	49	88	88	88	88	88	88
Other storage	0	24	44	47	248	315	387	466

3.3 EURASIA

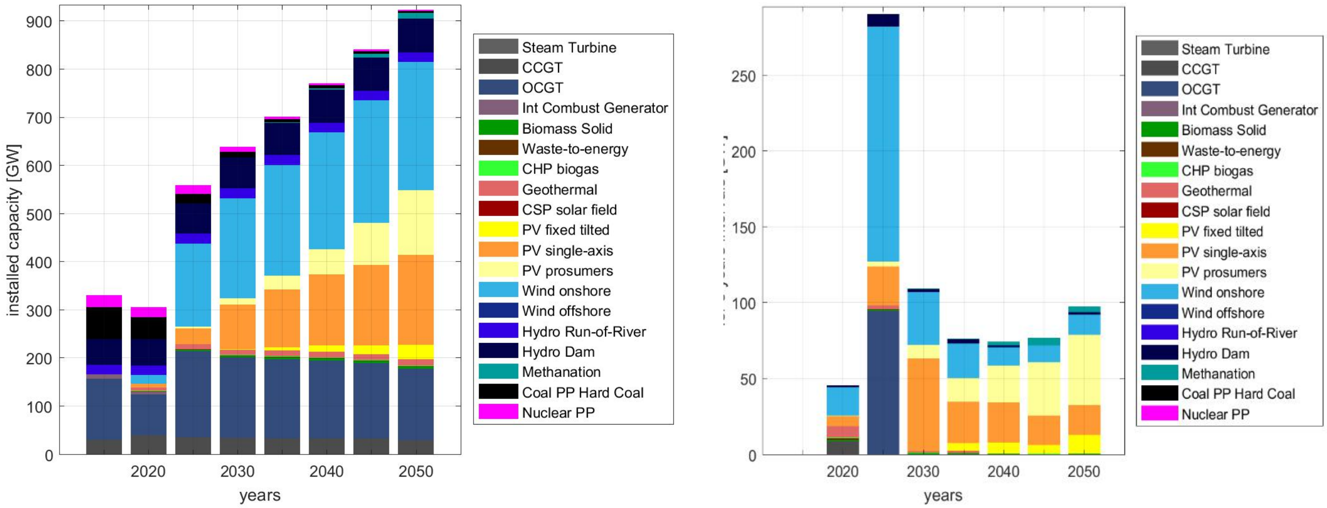
Countries in Eurasia are amongst the emerging economies of the world, with around a 6% share of global GDP[81] and an increasing appetite for energy, and with total electricity consumption of around 1080 TWh in 2015 that is estimated to grow to 1630 TWh by 2050.[72] Eurasia has an ageing power sector, with the majority of its power plant infrastructure built prior to 1990. This provides an opportunity for the region to leapfrog into the energy transition by switching to renewable power plant installations of the future.[9] The results indicate an incremental shift towards a 100% renewable powered energy system for Eurasia with net installed capacity of renewables reaching 230 GW in 2030 and close to 500 GW by 2050 as shown in Figure 15. A significant amount of wind and solar PV, roughly around 200 GW, is installed from 2020 to 2025 and 100 GW from 2025 to 2030. Wind energy drives the major share of installed capacities between 2025 and 2050, as it is the most abundant source of electricity as shown in Figure 16. Links to the results of all countries and regions in Eurasia are provided in the appendix (Table 4.1)

The total electricity generation in Eurasia is 1080 TWh in the year 2015, which is comprised of 19.4% coal, 41.2% fossil gas, 1% oil, 16.1% nuclear energy, 22.3% hydropower and 0.1% others (e.g. geothermal) with almost no wind, solar PV and bioenergy generation.[71, 6] The evolution towards 100% renewable electricity generation is visualised in Figure 17 and tabulated in Table 5. The share of renewable electricity in the overall mix will reach 99.2% of the total electricity generated across Eurasia in 2050. Renewable power generation technologies – mainly solar PV and wind – will contribute just over 74% to the total electricity generation by 2050 as shown in Figure 17. The share of renewable electricity production will already be around 36% in 2020 and reach over 80% by 2030.

Storage technologies play a vital role in enabling the transition towards a fully renewable powered energy system for Eurasia. As shown in Figure 18, a significant share of gas storage is installed, which provides vital seasonal storage especially during the harsh winters prevalent in these areas.

However, batteries are even more critical as they provide the maximum output, combining with solar PV both in the form of prosumers, as well as in large-scale battery storage. Other sources that have a minor share in the total output are PHS, TES and A-CAES.

Figure 16: Eurasia – Cumulative installed capacities of various power generation technologies from 2015 to 2050 (left) and new installed capacities of various power generation technologies for every 5-year interval from 2015 to 2050 (right).



The overall storage output covers over 9% of the total electricity demand in 2050, of which 82% is delivered by batteries. It should also be kept in mind that gas storage is also used for bio-methane, which represents 30% of all gas consumed in the region and contributes significantly to the need of gas storage capacity. However, only SNG is classified as gas storage output, while bio-methane is accounted as bioenergy generation. The technology-wise installed capacities and total output through the transition period of 2015 to 2050 are indicated in Table 5.

Figure 17: Eurasia – Net electricity generation by various power sources from 2015 to 2050 (left) and relative shares of electricity generation by various power sources from 2015 to 2050 (right).

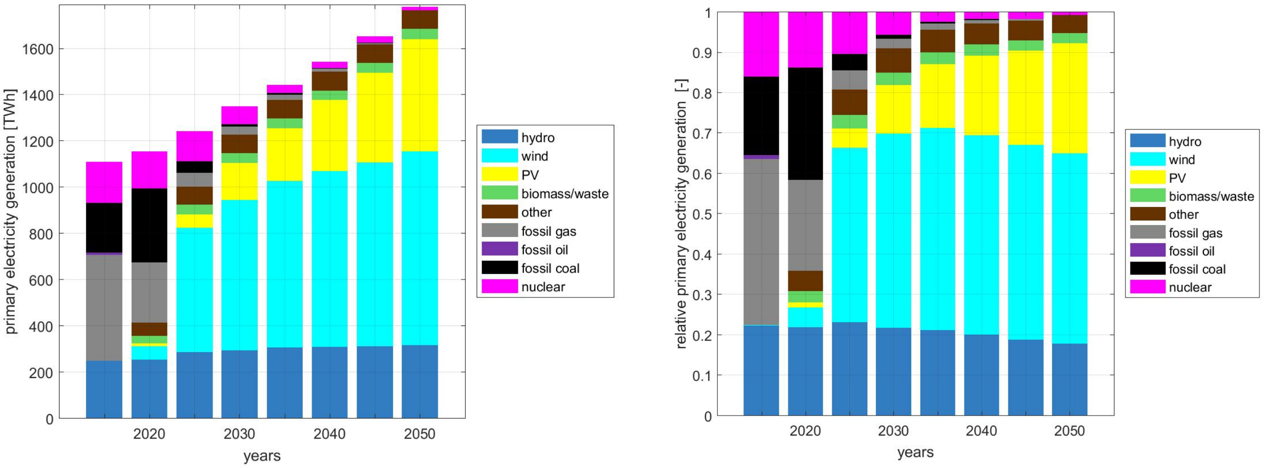
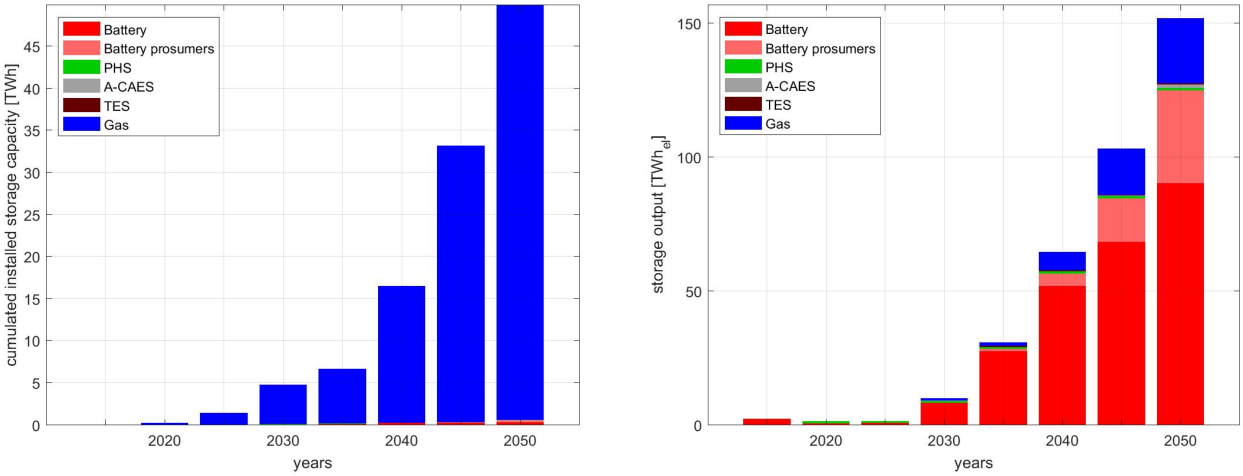


Figure 18: Eurasia – Cumulative installed capacities of various storage technologies from 2015 to 2050 (left) and net output by various storage technologies from 2015 to 2050 (right). Gas storage output (right) includes only stored SNG. The output of stored bio-methane is not classified as part of gas storage output even though it contributes significantly to the need of gas storage capacity (left). Bio-methane represents 30% of gas consumed in Eurasia, and is instead accounted as bioenergy generation.



Wind and solar energy evolve to become the backbone of the Eurasian electricity supply system until 2050, growing rapidly from almost no supply share in 2015 to 74.4% in 2050. The contribution of CSP is found to be negligible, mainly due to the extremely high cost competiveness achieved by solar PV that is additionally well complemented by low-cost batteries. The share of wind energy increases significantly until 2030, achieving around 48% supply share of total electricity generation across Eurasia. Wind energy continues to contribute steadily utilising the excellent potential available in Eurasia, while solar steadily increases in generation share to reach around 27% of the total in 2050. The dominance of wind energy in Eurasia is a consequence of the excellent wind resources, and supported by the presence of a well-developed power grid across Russia and some parts of central Asia. The large grid complements wind generation across the country and extended regions, allowing for power flow between regions with higher electricity demand and regions with higher electricity generation. The hydropower electricity share declines from around 22% to nearly 18%, as the overall resource constraint is taken into account, also most of the hydropower potential across Eurasia has already been realised. The generation of electricity from bio-based products
increases slightly to 43 TWh, and is not only limited by the availa-bility of residual and waste energy resources but, also by the comparably higher costs. Geo-thermal power generation grows from almost nothing
to 81 TWh and is impeded by limited resource availability and comparably higher costs.

Table 5: Eurasia – Installed capacities and net electricity generation by various power sources; installed capacities and net output of various storage sources during the energy transition from 2015 to 2050 at 5-year intervals.

Technology	2015	2020	2025	2030	2035	2040	2045	2050
Power Generation	Installed Capacity [GW]							
PV utility-scale	0	7	33	94	126	160	185	218
PV rooftop	0	0	4	13	28	52	87	134
Wind	0	18	173	208	231	243	254	267
Hydropower	73	74	83	84	88	89	89	91
Bioenergy	0	3	4	5	6	6	7	7
Geothermal	0	7	10	10	12	12	12	12
Gas Turbine	156	124	213	201	197	195	189	177
Coal PP	67	45	21	12	7	6	5	4
Nuclear PP	24	21	17	10	5	4	4	2
Other generation	9	5	1	1	0	0	0	0
Generation	Generation [TWh]							
PV utility-scale	0	13	54	147	195	245	284	330
PV rooftop	0	0	4	15	33	62	103	156
Wind	0	57	537	649	723	761	797	838

Hydropower	248	252	286	293	304	308	310	316
Bioenergy	0	32	42	32	43	42	43	43
Geothermal	0	59	79	80	81	81	80	81
Gas Turbine (fossil gas)	457	261	59	34	22	13	6	0
Coal PP	215	320	51	12	6	3	1	0
Nuclear PP	178	160	129	77	35	28	28	14
Other generation	11	0	0	0	0	0	0	0
Storage	**Installed Capacity [GWh]**							
Battery	2	2	2	27	96	192	296	463
Gas	0	203	1373	4694	6516	16283	32873	49338
Pumped Hydro	4	4	4	4	4	4	4	4
Other storage	0	0	1	1	5	5	6	69
Storage	**Output [TWh_{el}]**							
Battery	2	0	1	8	28	56	84	125
Gas	0	20	20	22	23	33	53	67
Pumped Hydro	0	1	1	1	1	1	1	1
Other storage	0	0	0	0	0	0	0	2

3.4 MIDDLE EAST AND NORTH AFRICA (MENA)

The Middle East and North African region is a mix of emerging economies as well as developed countries, with 7% share in global GDP.[81] It is one of the biggest energy production cen-ters across the world, but also has an increasing high share of demand,[82] with total electricity consumption of around 1360 TWh in 2015, which is estimated to rise to 3320 TWh by 2050.[82, 72] The substantial link between fossil fuels and socio-economic development make the region highly vulnerable to the impacts of climate change. As global temperatures continue to rise, it will have detrimental effects on the region, such as increasing the temperature above average and decreasing precipitation, which will lead to a rise in demand for water desalination and air conditioning, in a region that is amongst the most water-stressed across the world.[21] There are growing concerns that a threshold temperature could be exceeded, which would overstretch human adaptability and result in the region being uninhabitable for humans.[83] In this context, renewables have a major role in ensuring a sustainable energy supply for the region, and the results indicate an incremental transition to a 100% renewable powered energy system for the MENA region with net installed capacity of renewables reaching 650 GW in 2030 and close to 1700 GW by 2050 as shown in Figure 19. A significant amount of solar PV and wind, roughly around 350 GW, is installed from 2020 to 2025 and 300 GW from 2025 to 2030. Solar PV drives the major share of installed capacities between 2040 and 2050, as it delivers the least cost source of electricity as shown in Figure 19. Links to the results of all countries and regions in the MENA region are provided in the appendix (Table 4.1).

The total electricity generation in the MENA region is 1360 TWh in the year 2015 and is composed of 3.4% coal, 68.5% fossil gas, 23.3% oil, 0.3% nuclear energy, 3.9% hydropower, 0.3% wind energy and 0.2% solar PV.[82] The evolution towards 100% RE is visualised in Figure 20 and tabulated in Table 6. The share of renewable electricity in the overall mix will reach 99.8% of the electricity generated in the MENA region in 2050. Renewable power generation technologies – mainly solar PV and wind – will contribute over 94% to the total electricity generation by 2050 as shown in Figure 20. The share of renewable electricity production will already be around 18% in 2020 and reach 84% by 2030. Meanwhile, other renewable energy technologies such as CSP, bioenergy and geothermal energy provide further flexibility and energy security to the power sector.

Figure 19: MENA – Cumulative installed capacities of various power generation technologies from 2015 to 2050 (left) and new installed capacities of various power generation technologies for every 5-year interval from 2015 to 2050 (right).

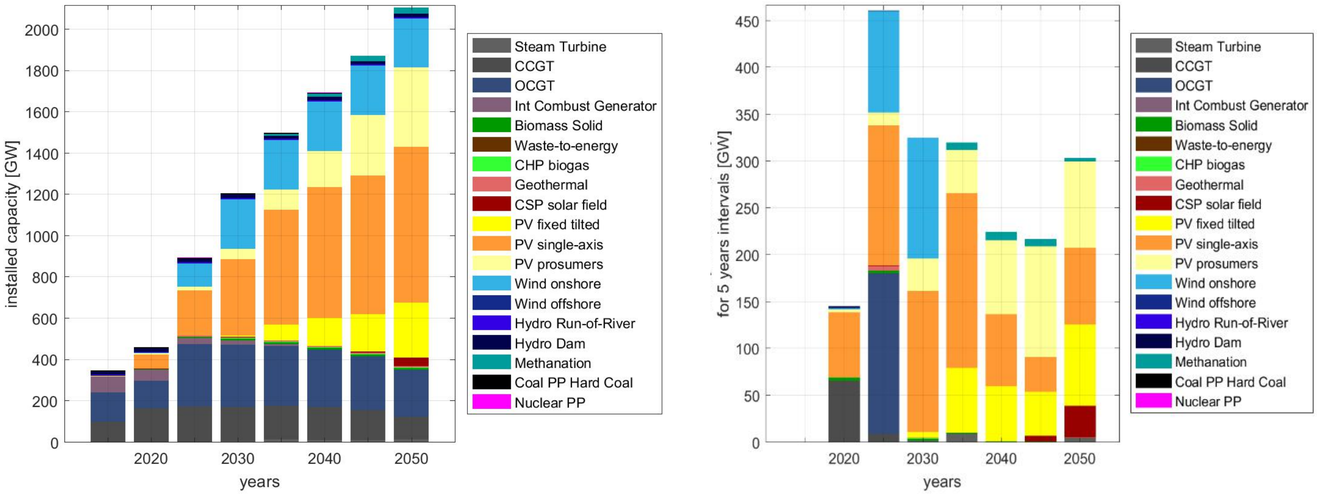


Figure 20: MENA – Net electricity generation by various power sources from 2015 to 2050 (left) and relative shares of electricity generation by various power sources from 2015 to 2050 (right).

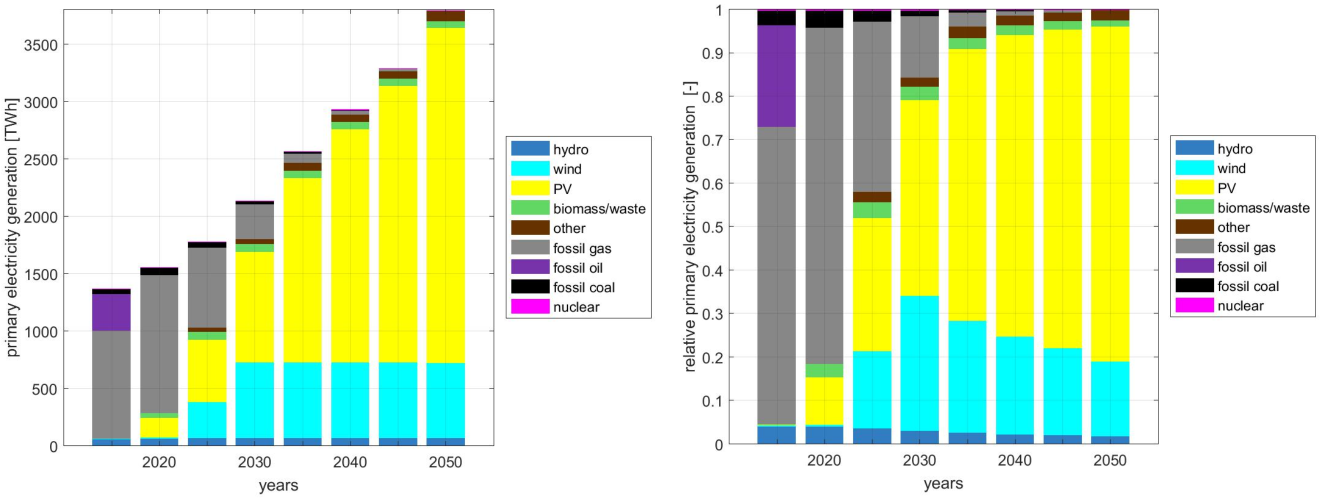
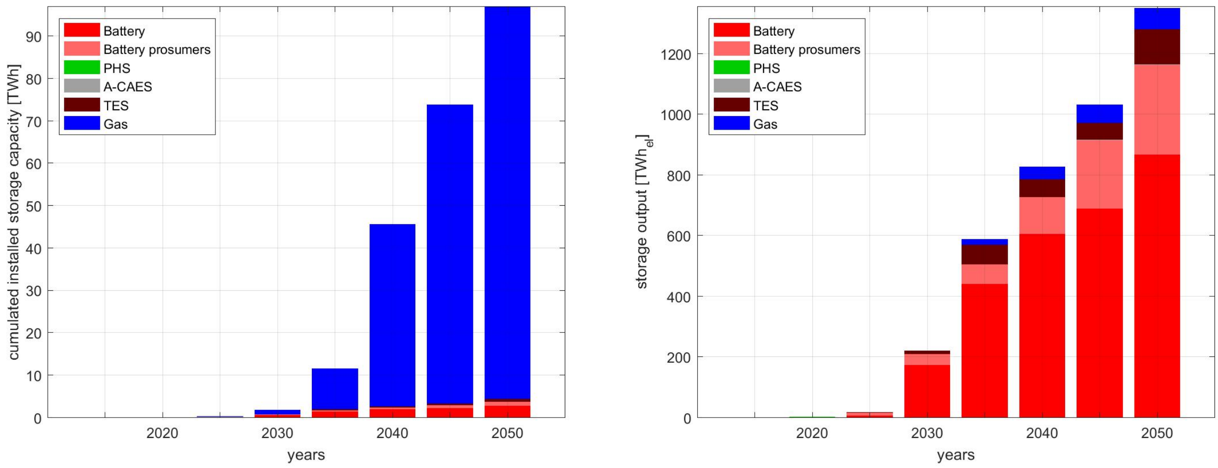


Figure 21: MENA – Cumulative installed capacities of various storage technologies from 2015 to 2050 (left) and net output by various storage technologies from 2015 to 2050 (right). Gas storage output (right) includes only stored SNG. The output of stored bio-methane is not classified as part of gas storage output even though it contributes significantly to the need of gas storage capacity (left). Bio-methane represents 15% of gas consumed in MENA, and is instead accounted as bioenergy generation.



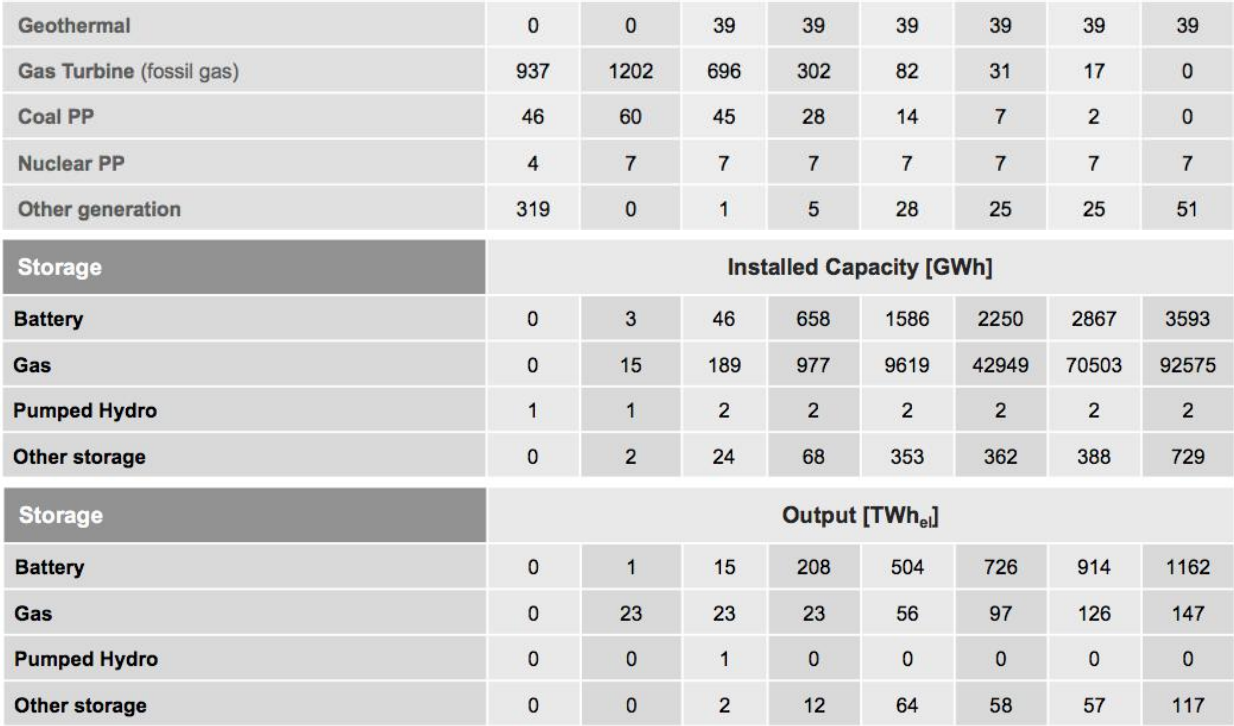
Storage technologies play a vital role in enabling the transition towards a fully renewable powered energy system. As shown in Figure 21, a significant share of gas storage is installed which provides vital seasonal storage. However, batteries are even more critical as they provide the maximum output, combining with solar PV both in the form of prosumers as well as in large-scale battery storage. Other sources that have a minor share in the total output are PHS, TES and A-CAES.

The overall storage output covers around 39% of the total electricity demand in 2050, of which 90% is delivered by batteries. It should also be kept in mind that gas storage is also used for bio-methane, which represents 15% of all gas consumed in the region and contributes significantly to the need of gas storage capacity. However, only SNG is classified as gas storage output, while bio-methane is accounted as bioenergy generation. The technology-wise installed capacities and total output through the transition period of 2015 to 2050 are indicated in Table 6.

Solar PV and wind energy evolve to become the backbone of the MENA region's electricity supply system until 2050, growing from a supply share of 0.5% in 2015 to 94.4% in 2050. The contribution of CSP is found to be negligible, with around 40 GW of installed capacity by 2050, mainly due to the extremely high cost competiveness achieved by solar PV that is additionally well complemented by low-cost batteries. The share of wind energy increases rapidly until 2030, achieving around a 31% supply share of total electricity generation of the MENA region. The very high cost competiveness of PV-battery systems limits further contribution from wind energy in the period from 2035 until 2040 and even forces a decline in terms of absolute electricity generation until 2050. This is largely due to existing capacities not being repowered any longer, mainly in solar resource rich regions with moderate seasonality. Consequently, the relative electricity generation share of wind energy declines to 17% in the year 2050. The marginal increase of hydropower from 53 to 63 TWh is relatively low, as the overall resource constraint is taken into account, also the comparably higher costs of new large-scale hydropower, the respective risks of cost overruns, and the larger risk of violating societal and ecological sustainability criteria of large-scale hydropower projects. The generation of electricity from bio-based products increases from almost nothing to 55 TWh, and is not only limited by the availability of residual and waste energy resources but, also by the comparably higher costs. Geothermal power generation grows from a very small amount to 39 TWh and is impeded by limited resource availability and comparably higher costs.

Table 6: MENA – Installed capacities and net electricity generation by various power sources; installed capacities and net output of various storage sources during the energy transition from 2015 to 2050 at 5-year intervals.

Technology	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Power Generation	**Installed Capacity [GW]**							
PV utility-scale	1	71	220	377	632	768	852	1021
PV rooftop	0	4	18	52	97	176	294	386
Wind	2	3	111	240	240	239	239	237
Hydropower	19	21	21	22	22	22	22	22
Bioenergy	0	4	7	10	11	11	12	12
Geothermal	0	0	5	5	5	5	5	6
Gas Turbine	239	295	474	468	456	438	405	338
Coal PP	7	7	7	5	5	3	2	1
Nuclear PP	1	1	1	1	1	1	1	1
Other generation	78	55	28	25	20	10	15	52
Generation	**Power Generation [TWh]**							
PV utility-scale	2	163	514	872	1432	1718	1888	2235
PV rooftop	1	6	31	91	173	314	525	689
Wind	4	7	315	662	661	660	658	654
Hydropower	53	60	62	63	63	63	63	63
Bioenergy	0	47	65	66	66	66	65	55



Geothermal	0	0	39	39	39	39	39	39
Gas Turbine (fossil gas)	937	1202	696	302	82	31	17	0
Coal PP	46	60	45	28	14	7	2	0
Nuclear PP	4	7	7	7	7	7	7	7
Other generation	319	0	1	5	28	25	25	51
Storage	**Installed Capacity [GWh]**							
Battery	0	3	46	658	1586	2250	2867	3593
Gas	0	15	189	977	9619	42949	70503	92575
Pumped Hydro	1	1	2	2	2	2	2	2
Other storage	0	2	24	68	353	362	388	729
Storage	**Output [TWh_{el}]**							
Battery	0	1	15	208	504	726	914	1162
Gas	0	23	23	23	56	97	126	147
Pumped Hydro	0	0	1	0	0	0	0	0
Other storage	0	0	2	12	64	58	57	117

3.5 SUB-SAHARAN AFRICA

Sub-Saharan Africa is a region with a large number of emerging economies, with just around a 3% share in global GDP[81] but has the potential to become one of the fastest growing regions in the world. With a rapidly growing population, unprecedented economic progress and need for reliable, modern energy access, which is expected to require at least double the energy supply by 2030 and might even triple for electricity.[84] The total electricity consumption is around 484 TWh in 2015, which is estimated to rise to 2747 TWh by 2050.[84] Africa's energy sector is vital to its development. Therefore, effective energy planning, optimal design, wise utilisation of all available renewable energy resources and maximum synergy between various regions (regional electricity networking due to dispersed energy resource) of Africa will positively impact the energy systems of the continent. The results indicate an incremental transition to a 100% renewable powered energy system for the Sub-Saharan Africa region, with net installed capacity of renewables reaching 300 GW in 2030 and close to 1400 GW by 2050 as shown in Figure 22. A significant amount of solar PV and wind, roughly around 120 GW, is installed from 2020 to 2025 and 150 GW from 2025 to 2030. Solar PV drives the major share of installed capacities between 2035 and 2050, as it delivers the cheapest source of electricity as shown in Figure 22. Links to the results of all countries and regions in Sub-Saharan Africa are provided in the appendix (Table 4.1).

The total electricity generation in the Sub-Saharan Africa region is 484 TWh in the year 2015 and is composed of 51.7% coal, 20.5% fossil gas, 6.1% oil, 2.2% nuclear energy, 18.4% hydropower, 0.5% wind energy, 0.5% solar PV and 0.1% others (mainly geothermal and CSP) 6. The evolution towards 100% RE is visualised in Figure 23 and tabulated in Table 7. The share of renewable electricity in the overall mix will reach 100% of the electricity generated in Sub-Saharan Africa by 2050. Renewable power generation technologies – mainly solar PV and wind – will contribute over 92% to the total electricity generation by 2050 as shown in Figure 23. The share of renewable electricity production will already be around 38% in 2020 and reach 91% by 2030.

Figure 22: Sub-Saharan Africa – Cumulative installed capacities of various power generation technologies from 2015 to 2050 (left) and new installed capacities of various power generation technologies for every 5-year interval from 2015 to 2050 (right).

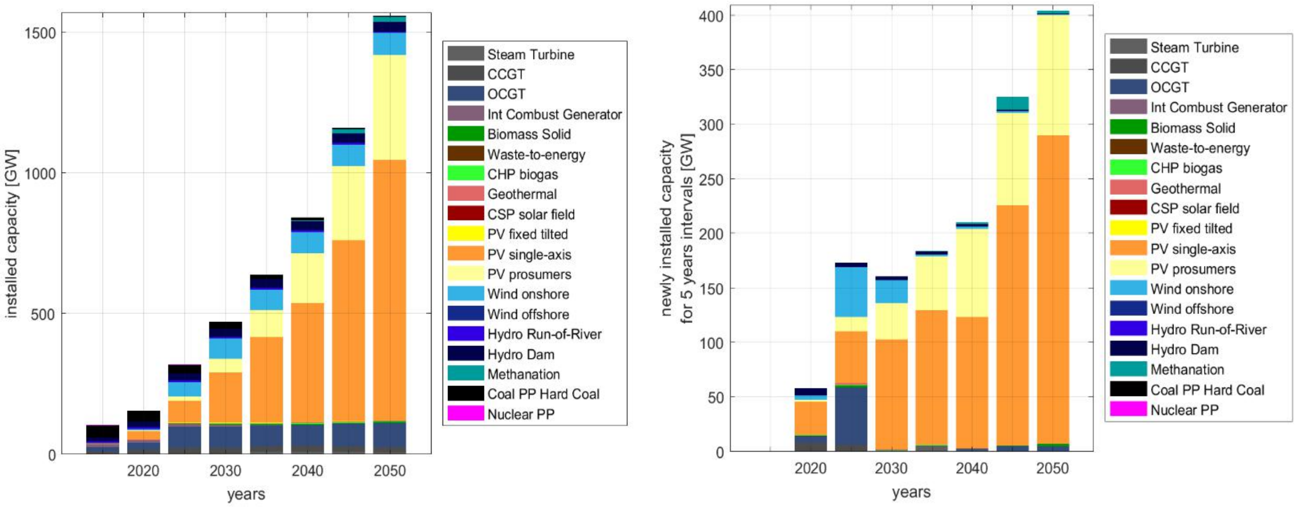


Figure 23: Sub-Saharan Africa – Net electricity generation by various power sources from 2015 to 2050 (left) and relative shares of electricity generation by various power sources from 2015 to 2050 (right).

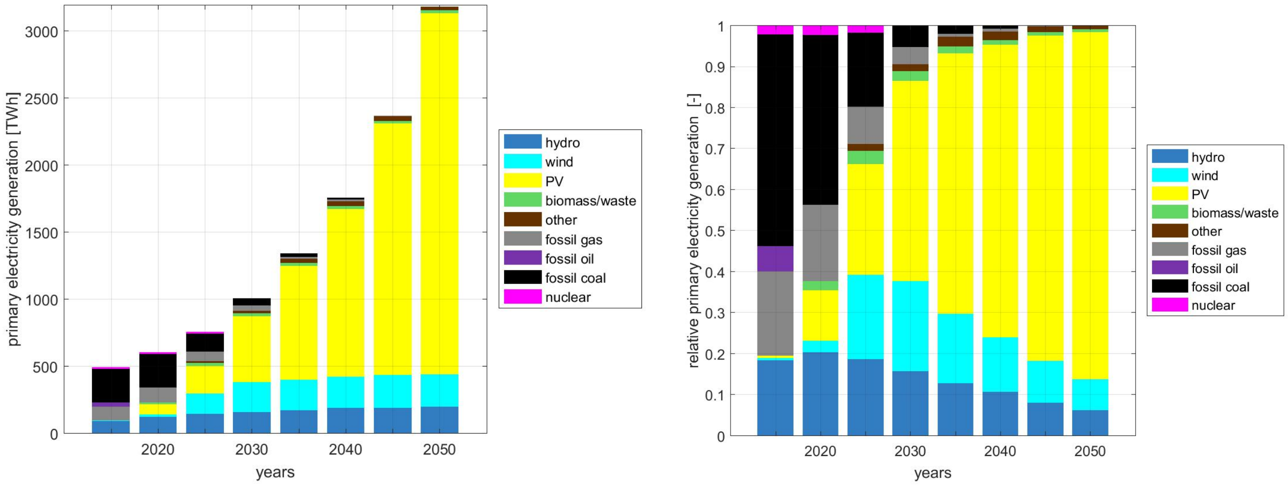
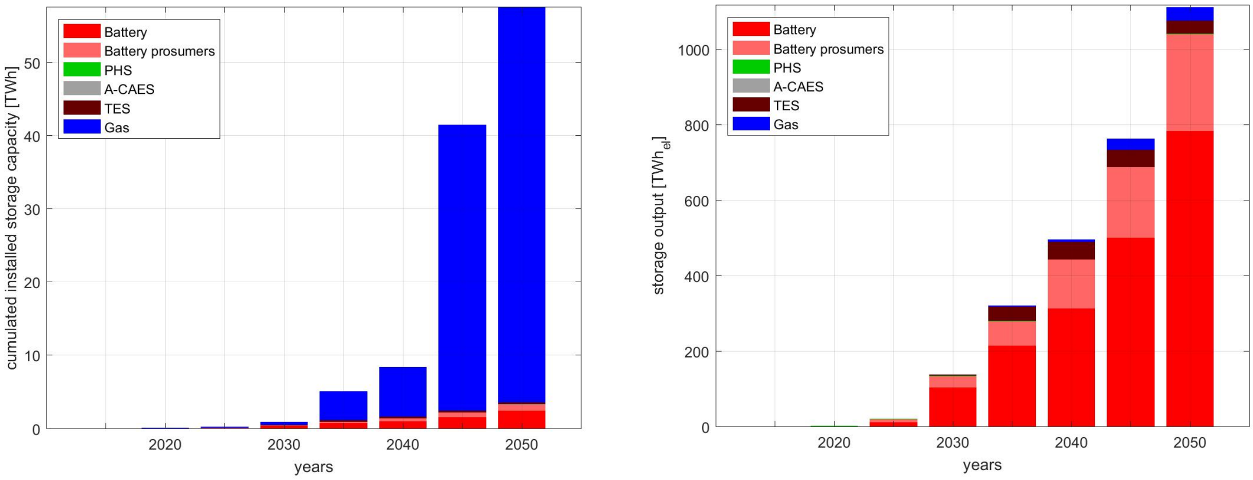


Figure 24: Sub-Saharan Africa – Cumulative installed capacities of various storage technologies from 2015 to 2050 (left) and net output by various storage technologies from 2015 to 2050 (right). Gas storage output (right) includes only stored SNG. The output of stored bio-methane is not classified as part of gas storage output even though it contributes significantly to the need of gas storage capacity (left). Bio-methane represents 8% of gas consumed in Sub-Saharan Africa, and is instead accounted as bioenergy generation.



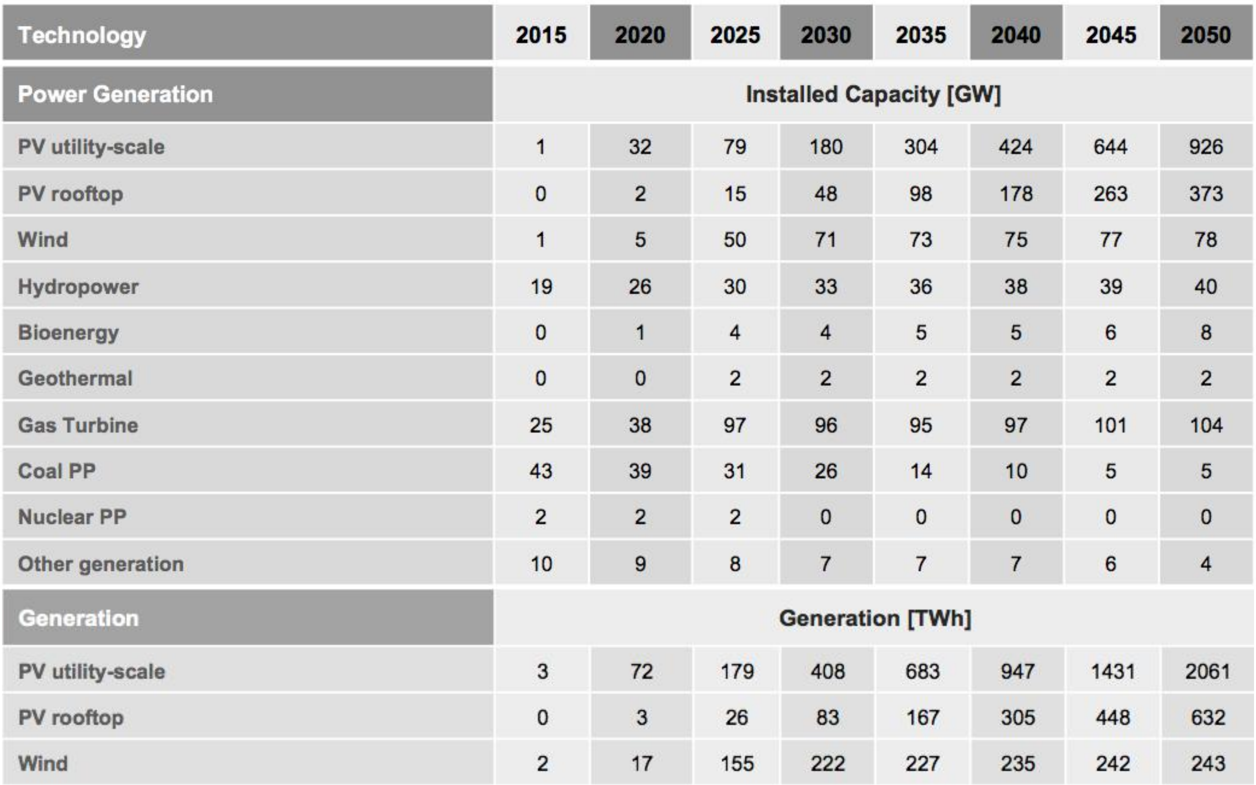
Storage technologies play a vital role in enabling the transition towards a fully renewable powered energy system. As shown in Figure 24, a significant share of gas storage is installed, which provides vital seasonal storage. However, batteries are even more critical as they provide the maximum output, combining with solar PV both in the form of prosumers as well as in large-scale battery storage. Other sources that have a minor share in the total output are PHS, TES and A-CAES.

The overall storage output covers around 40% of the total electricity demand in 2050, of which 95% is delivered by batteries. It should also be kept in mind that gas storage is also used for bio-methane, which represents 8% of all gas consumed in the region and contributes significantly to the need of gas storage capacity. However, only SNG is classified as gas storage output, while bio-methane is accounted as bioenergy generation. The technology-wise installed capacities and total output through the transition period of 2015 to 2050 are indicated in Table 7.

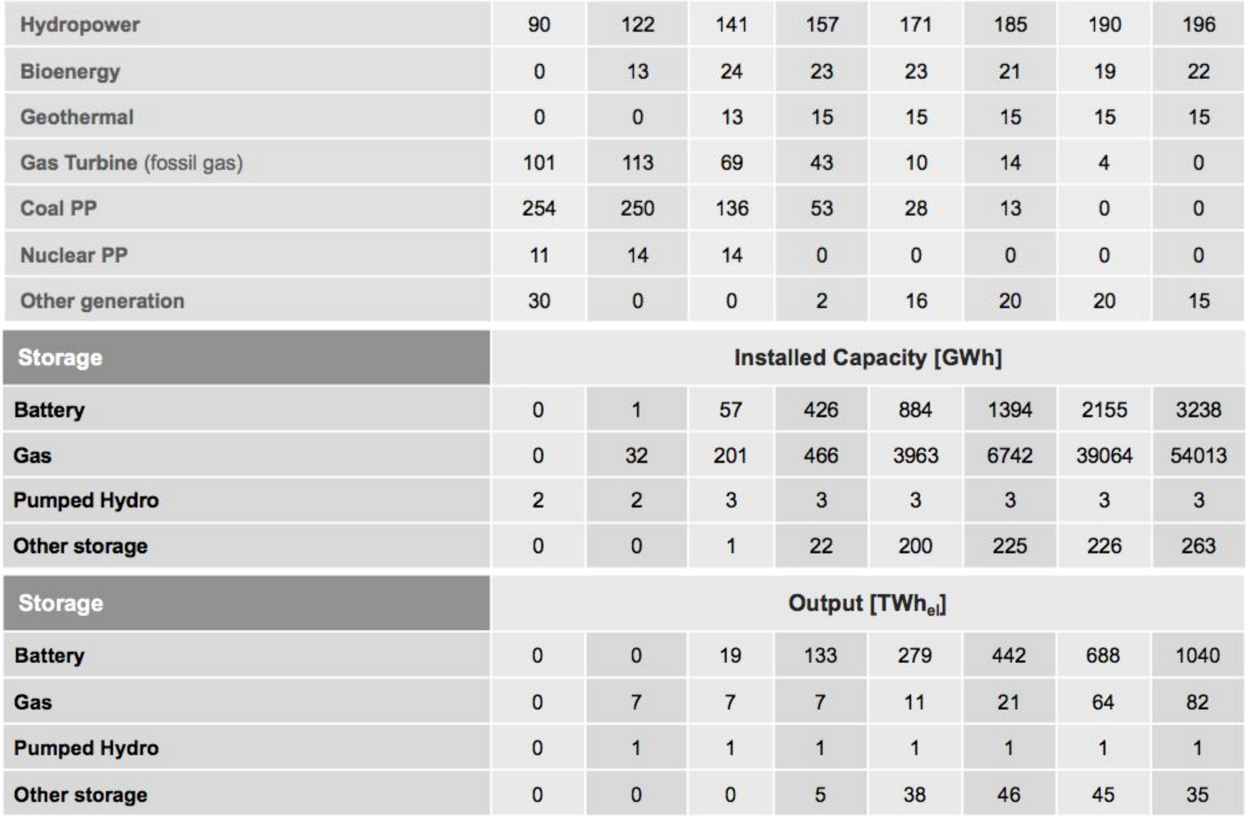
Solar PV and wind energy evolve to become the backbone of the Sub-Saharan Africa region's electricity supply system until 2050, growing from a supply share of 0.5% in 2015 to 94.4% in 2050. The contribution of CSP is found to be negligible, with around 40 GW of installed capacity by 2050, mainly due to the extremely high cost competiveness achieved by solar PV that is additionally well complemented by low-cost batteries. The share of wind energy increases rapidly until 2030, achieving around a 22% supply share of total electricity generation of Sub-Saharan Africa region. The very high cost competiveness of PV-battery systems limits further contribution from wind energy in the period from 2035 until 2040 and even forces a decline in terms of absolute electricity generation until 2050.

This is mainly because existing capacities are not repowered any longer, mainly in solar re-source rich regions with moderate seasonality. Hence, the relative electricity generation share of wind energy declines to 8% in the year 2050. The marginal increase of hydropower from 90 to 195 TWh is relatively low, as the overall resource constraint is taken into account,[76] also the comparably higher cost of new large-scale hydropower,[77] the respective risk of cost overruns[85] and the larger risk of violating societal and ecological sustainability criteria of large-scale hydropower projects. The generation of electricity from bio-based products increases from almost nothing to 22 TWh, and is not only limited by the availability of residual and waste energy resources but, also by the comparably higher costs. Geothermal power generation grows from almost nothing to 15 TWh and is impeded by limited resource availability and comparably higher costs.

Table 7: Sub-Saharan Africa – Installed capacities and net electricity generation by various power sources; installed capacities and net output of various storage sources during the energy transition from 2015 to 2050 at 5-year intervals.



Technology	2015	2020	2025	2030	2035	2040	2045	2050
Power Generation	Installed Capacity [GW]							
PV utility-scale	1	32	79	180	304	424	644	926
PV rooftop	0	2	15	48	98	178	263	373
Wind	1	5	50	71	73	75	77	78
Hydropower	19	26	30	33	36	38	39	40
Bioenergy	0	1	4	4	5	5	6	8
Geothermal	0	0	2	2	2	2	2	2
Gas Turbine	25	38	97	96	95	97	101	104
Coal PP	43	39	31	26	14	10	5	5
Nuclear PP	2	2	2	0	0	0	0	0
Other generation	10	9	8	7	7	7	6	4
Generation	Generation [TWh]							
PV utility-scale	3	72	179	408	683	947	1431	2061
PV rooftop	0	3	26	83	167	305	448	632
Wind	2	17	155	222	227	235	242	243



Hydropower	90	122	141	157	171	185	190	196
Bioenergy	0	13	24	23	23	21	19	22
Geothermal	0	0	13	15	15	15	15	15
Gas Turbine (fossil gas)	101	113	69	43	10	14	4	0
Coal PP	254	250	136	53	28	13	0	0
Nuclear PP	11	14	14	0	0	0	0	0
Other generation	30	0	0	2	16	20	20	15
Storage	**Installed Capacity [GWh]**							
Battery	0	1	57	426	884	1394	2155	3238
Gas	0	32	201	466	3963	6742	39064	54013
Pumped Hydro	2	2	3	3	3	3	3	3
Other storage	0	0	1	22	200	225	226	263
Storage	**Output [TWh_{el}]**							
Battery	0	0	19	133	279	442	688	1040
Gas	0	7	7	7	11	21	64	82
Pumped Hydro	0	1	1	1	1	1	1	1
Other storage	0	0	0	5	38	46	45	35

3.6 SOUTH ASIAN ASSOCIATION FOR REGIONAL COOPERATION (SAARC)

SAARC is a region with a number of fast-paced growing economies, with around a 9% share of global GDP[81] and 21% of the global population. With a rapidly growing population, unprecedented economic progress and need for reliable modern energy access, sustainable energy development is already on top of the agenda for many of the countries, led by progressive policies towards renewable energy development adopted by India in the recent years.[70, 86] The total electricity consumption is around 1694 TWh in 2015, which is estimated to rise to 6979 TWh by 2050.[70, 86] The energy sector in the SAARC region is vital to its overall development. Therefore, effective energy planning, optimal design, wise utilisation of all available renewable energy resources and maximum synergy between various regions of the SAARC countries will foster sustainable development in the region. The results indicate a steadily growing transition towards a 100% renewable powered energy system for the SAARC region with net installed capacity of renewables reaching 1200 GW in 2030 and close to 4000 GW by 2050 as shown in Figure 25.

A significant amount of solar PV and wind, roughly around 375 GW, is installed from 2020 to 2025 and 650 GW from 2025 to 2030. Solar PV drives the major share of installed capacities between 2035 and 2050, as it delivers the cheapest source of electricity as shown in Figure 25. Links to the results of all countries and regions in the SAARC region are provided in the appendix (Table 4.1).

The total electricity generation in the SAARC region is 1694 TWh in the year 2015 and is composed of 63.6% coal, 14.6% fossil gas, 4.3% oil, 2.0% nuclear energy, 11.8% hydropower, 2.3% wind energy and 0.6% solar PV.[6] The evolution towards 100% RE is visualised in Figure 26 and tabulated in Table 8. The share of renewable electricity in the overall mix will reach 99.7% of the electricity generated in the SAARC region by 2050. Renewable power generation technologies – mainly solar PV and wind – will contribute 93% to the total electricity generation by 2050 as shown in Figure 26. The share of renewable electricity production will already be around 31% in 2020 and reach 89% by 2030.

Figure 25: SAARC – Cumulative installed capacities of various power generation technologies from 2015 to 2050 (left) and new installed capacities of various power generation technologies for every 5-year interval from 2015 to 2050 (right).

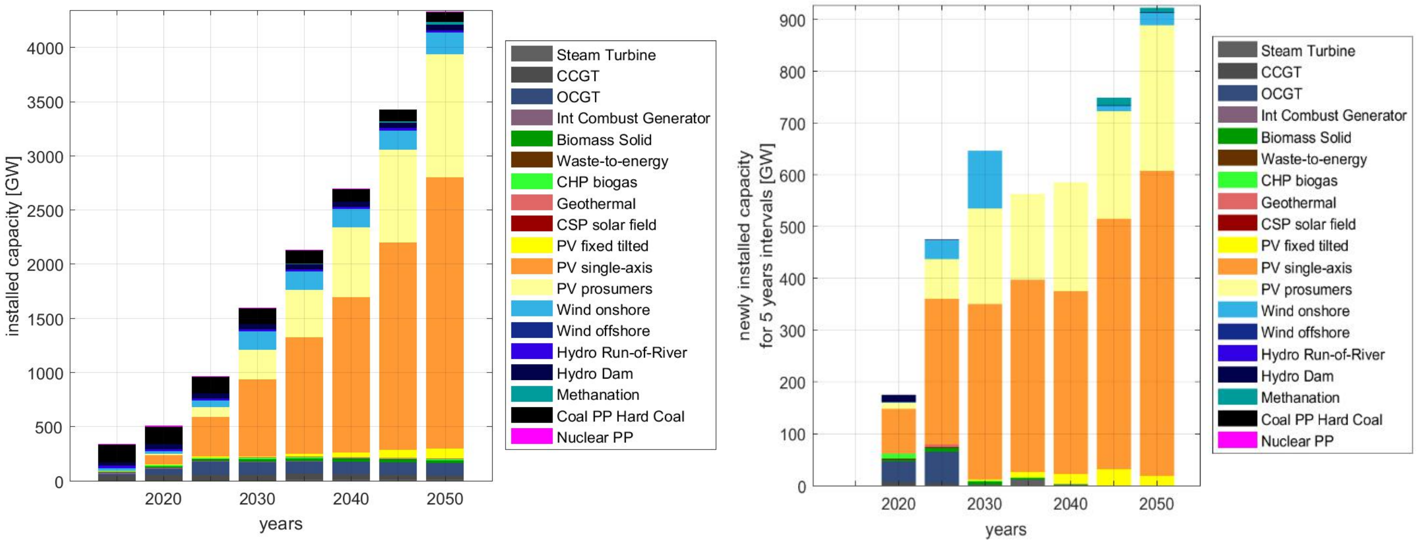


Figure 26: SAARC – Net electricity generation by various power sources from 2015 to 2050 (left) and relative shares of electricity generation by various power sources from 2015 to 2050 (right).

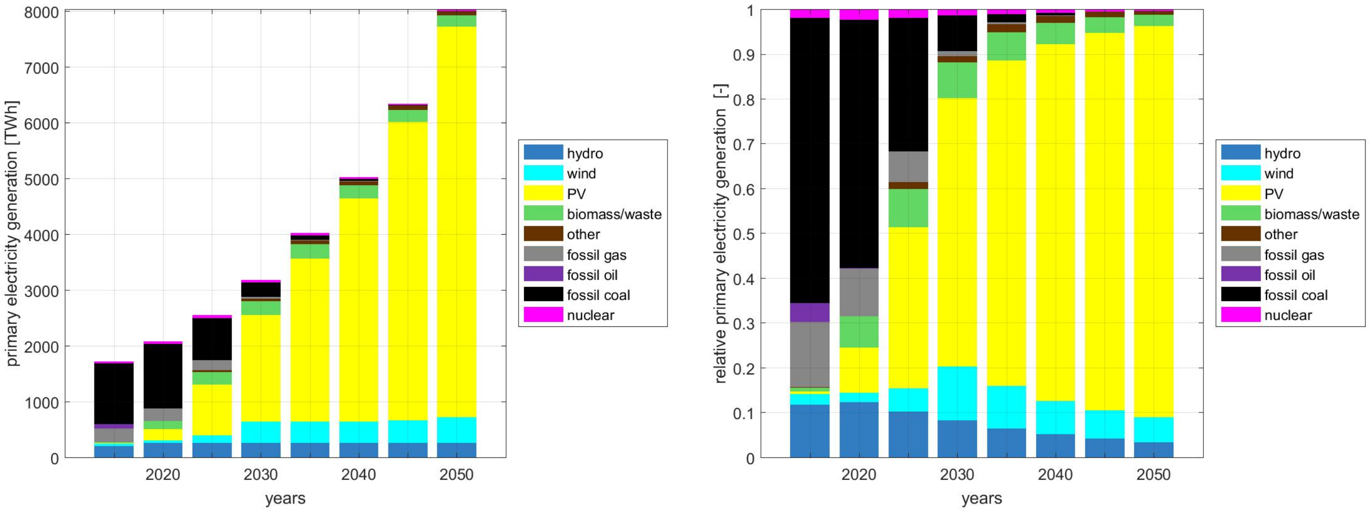
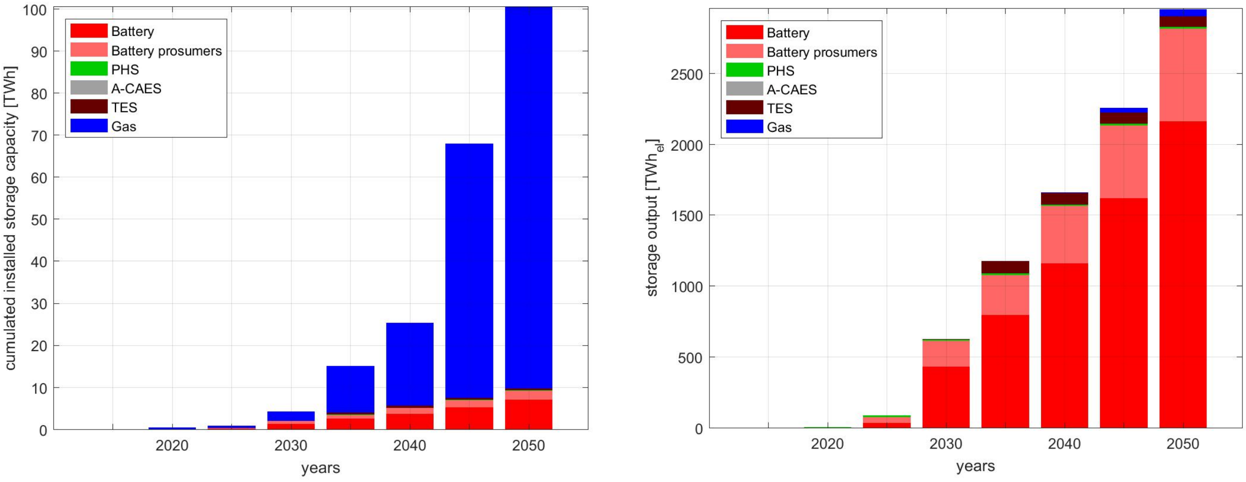


Figure 27: SAARC – Cumulative installed capacities of various storage technologies from 2015 to 2050 (left) and net output by various storage technologies from 2015 to 2050 (right). Gas storage output (right) includes only stored SNG. The output of stored bio-methane is not classified as part of gas storage output even though it contributes significantly to the need of gas storage capacity (left). Bio-methane represents 35% of gas consumed in SAARC, and is instead accounted as bioenergy generation.



Storage technologies play a vital role in enabling the transition towards a fully renewable powered energy system. As shown in Figure 27, a significant share of gas storage is installed, which provides vital seasonal storage. However, batteries are even more critical as they provide the maximum output, combining with solar PV both in the form of prosumers as well as in large-scale battery storage. Other sources that have a minor share in the total output are PHS, TES and A-CAES.

The overall storage output covers around 42% of the total electricity demand in 2050, of which 97% is delivered by batteries. It should also be kept in mind that gas storage is also used for bio-methane, which represents 35% of all gas consumed in the region and contributes significantly to the need of gas storage capacity. However, only SNG is classified as gas storage output, while bio-methane is accounted as bioenergy generation. The technology-wise installed capacities and total output through the transition period of 2015 to 2050 are indicated in Table 8.

Solar PV and wind energy evolve to become the backbone of the SAARC region's electricity supply system until 2050, growing from a supply share of just 2.9% in 2015 to 93% in 2050. The contribution of CSP is found to be negligible, with almost no installed capacity by 2050, mainly due to the extremely high cost competiveness achieved by solar PV that is additionally well complemented by low-cost batteries. The share of wind energy increases marginally until 2030, achieving around 12% supply share of total electricity generation of the SAARC region. The very high cost competiveness of PV-battery systems limits further contribution from wind energy in the period from 2035 until 2040 and even forces a decline in terms of absolute electricity generation until 2050. This is mainly because existing capacities are not repowered any longer, mainly in solar resource rich regions with moderate seasonality. Hence, the relative electricity generation share of wind energy declines to 6% in the year 2050. The marginal increase of hydropower from 202 to 263 TWh is relatively low, as the overall resource constraint is taken into account, also the comparably higher cost of new large-scale hydropower, the respective risk of cost overruns, and the larger risk of violating societal and ecological sustainability criteria of large-scale hydropower projects. The generation of electricity from bio-based products increases from 16 TWh to 202 TWh, and is not only limited by the availability of residual and waste energy resources but, also by the comparably higher costs. Geothermal power generation grows from almost nothing to 40 TWh and is impeded by limited resource availability and comparably higher costs.

Table 8: SAARC – Installed capacities and net electricity generation by various power sources; installed capacities and net output of various storage sources during the energy transition from 2015 to 2050 at 5-year intervals.

Technology	2015	2020	2025	2030	2035	2040	2045	2050
Power Generation	**Installed Capacity [GW]**							
PV utility-scale	6	93	375	717	1098	1471	1986	2593
PV rooftop	0	12	88	273	439	648	856	1137
Wind	24	25	61	172	169	166	176	200
Hydropower	54	68	69	69	69	69	70	70
Bioenergy	7	21	30	38	41	42	41	41
Geothermal	0	0	5	5	5	5	5	5
Gas Turbine	63	110	175	170	165	159	155	148
Coal PP	163	160	152	142	127	115	106	96
Nuclear PP	6	7	6	6	6	5	4	3
Other generation	16	12	5	5	14	14	13	12

Generation	Generation [TWh]							
PV utility-scale	10	190	776	1466	2224	2964	3978	5183
PV rooftop	0	19	141	438	704	1040	1373	1822
Wind	40	44	130	383	379	375	403	456
Hydropower	202	258	260	261	261	261	262	263
Bioenergy	16	145	218	254	249	235	217	202
Geothermal	0	0	40	40	40	40	40	40
Gas Turbine (fossil gas)	251	223	172	37	12	10	4	0
Coal PP	1093	1156	761	252	76	29	3	0
Nuclear PP	34	49	48	45	43	37	29	26
Other generation	74	1	0	2	37	37	36	34
Storage	**Installed Capacity [GWh]**							
Battery	0	0	225	1930	3428	5073	6928	9191
Gas	0	406	530	2224	11079	19723	60504	90806
Pumped Hydro	4	11	44	44	44	44	44	44
Other storage	0	4	4	20	465	500	498	498
Storage	**Output [TWh_{el}]**							
Battery	0	0	73	611	1077	1563	2133	2817
Gas	0	46	46	46	47	49	104	144
Pumped Hydro	1	3	13	12	11	10	10	10
Other storage	1	1	1	4	87	85	82	77

3.7 NORTHEAST ASIA

The Northeast Asian region is comprised of the fastest growing economies, with around a 25% share of global GDP and 22% of the global population.[54] With rapid industrialisation, unprecedented economic progress and a soaring appetite for energy, states across the region are stepping up their efforts to secure the energy supplies needed to sustain this rapid expansion. The total electricity consumption is around 6847 TWh in 2015, which is estimated to soar up to 15,078 TWh by 2050.[40] The energy sector in Northeast Asia is vital to its overall development. Therefore, effective energy planning, optimal design, wise utilisation of all available renewable energy resources and maximum synergy between various regions of the Northeast Asian countries will foster sustainable development in the region. In this context, China has been at the forefront of developing renewable energy, with 30% installed capacity and a 24% generation share of its total power generation in 2015.[3, 87] The results indicate a steadily growing transition towards a 100% renewable powered energy system for Northeast Asia, with net installed capacity of renewables reaching 3500 GW in 2030 and close to 9000 GW by 2050 as shown in Figure 28. A significant amount of solar PV and wind, roughly around 1400 GW, is installed from 2020 to 2025 and 1300 GW from 2025 to 2030. Solar PV drives the major share of installed capacities between 2035 and 2050, as it delivers the cheapest source of electricity as shown in Figure 28. Links to the results of all countries in Northeast Asia are provided in the appendix (Table 4.1).

The total electricity generation in Northeast Asia is 6847 TWh in the year 2015 and is composed of 58.6% coal, 14.3% fossil gas, 2.2% oil, 3.9% nuclear energy, 14% hydropower, 4.6% wind energy, 1.6% solar PV and 0.6% bioenergy.[6] The evolution towards 100% RE is visualised in Figure 29 and tabulated in Table 9. The share of renewable electricity in the overall mix will reach 99.2% of the electricity generated in Northeast Asia by 2050. Renewable power generation technologies – mainly solar PV and wind – will contribute 89% to the total electricity generation by 2050 as shown in Figure 28. The share of renewable electricity production will already be around 39% in 2020 and reach 90% by 2030.

Figure 28: Northeast Asia – Cumulative installed capacities of various power generation technologies from 2015 to 2050 (left) and new installed capacities of various power generation technologies for every 5-year interval from 2015 to 2050 (right).

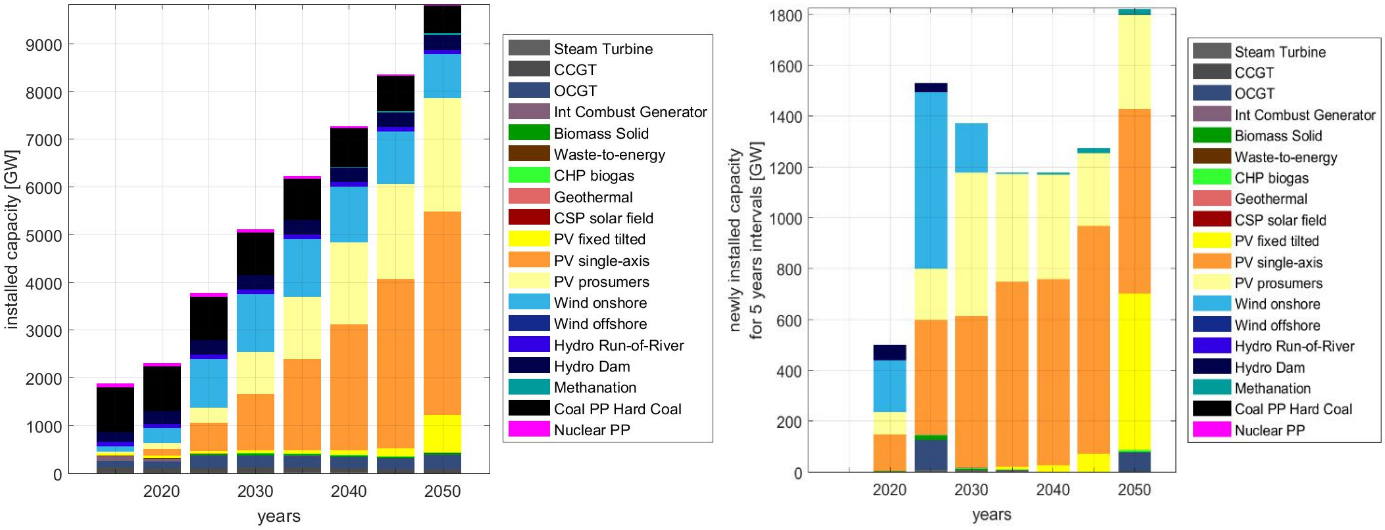


Figure 29: Northeast Asia – Net electricity generation by various power sources from 2015 to 2050 (left) and relative shares of electricity generation by various power sources from 2015 to 2050 (right).

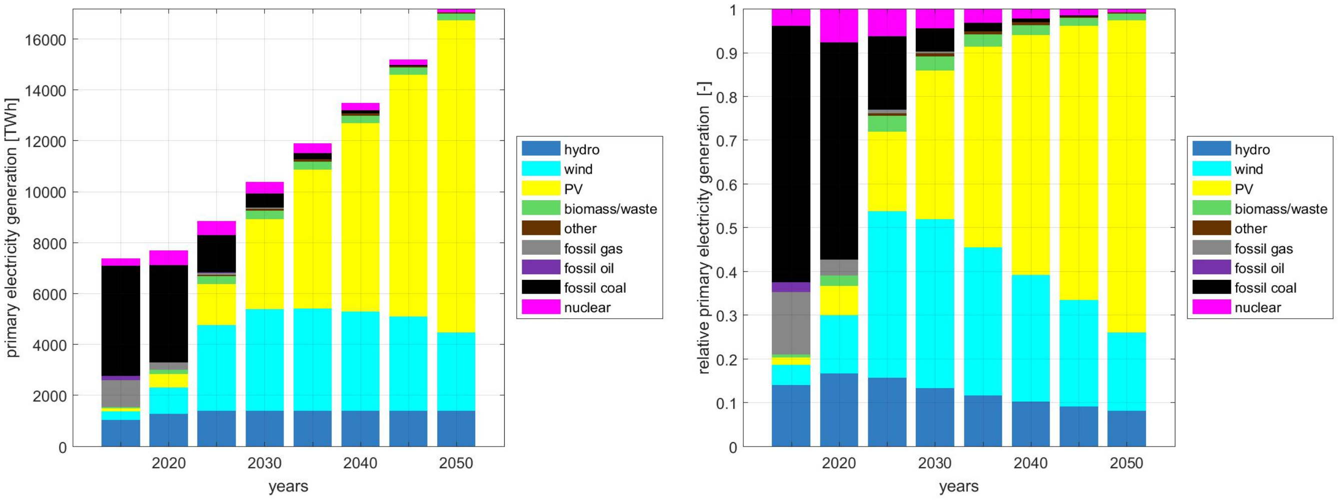
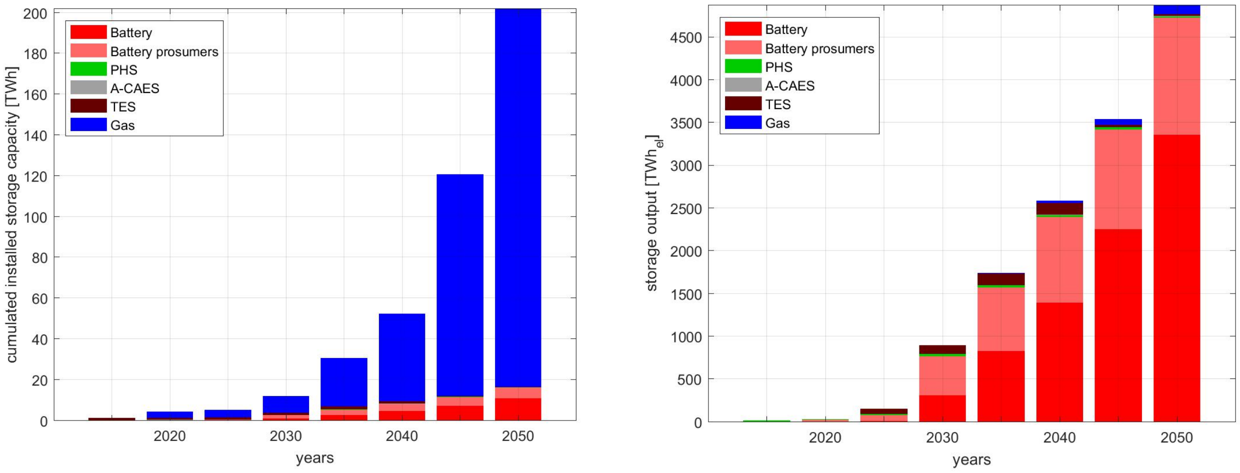


Figure 30: Northeast Asia – Cumulative installed capacities of various storage technologies from 2015 to 2050 (left) and net output by various storage technologies from 2015 to 2050 (right). Gas storage output (right) includes only stored SNG. The output of stored bio-methane is not classified as part of gas storage output even though it contributes significantly to the need of gas storage capacity (left). Bio-methane represents 33% of gas consumed in Northeast Asia, and is instead accounted as bioenergy generation.



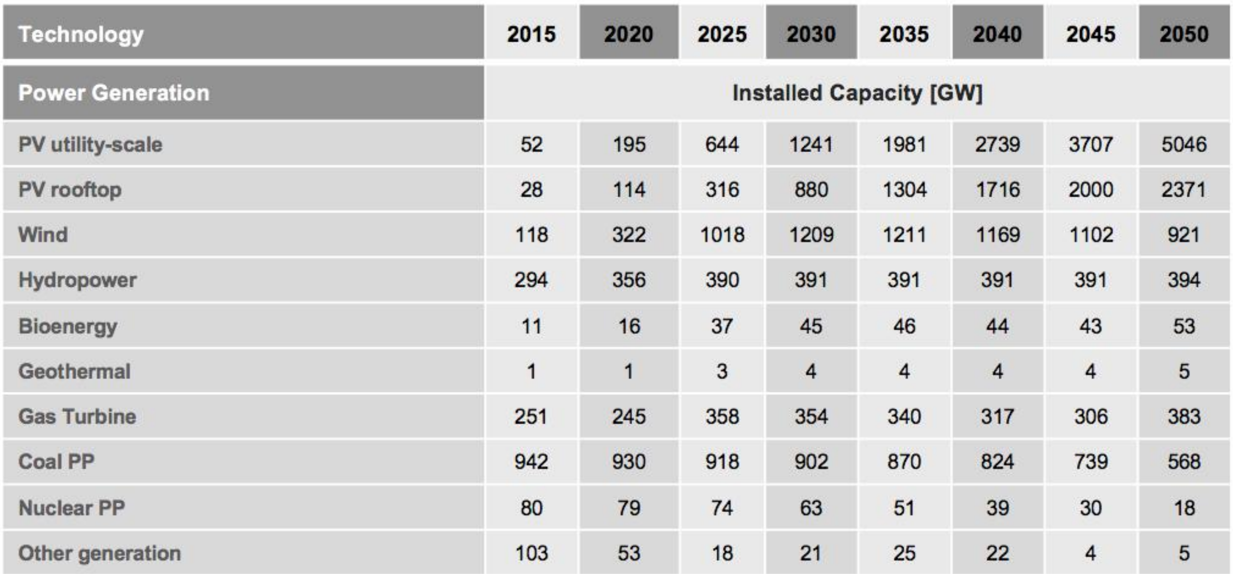
Storage technologies play a vital role in enabling the transition towards a fully renewable powered energy system. As shown in Figure 30, a significant share of gas storage is installed, which provides vital seasonal storage. However, batteries are even more critical as they provide the maximum output, combining with solar PV both in the form of prosumers as well as in large-scale battery storage. Other sources that have a minor share in the total output are PHS, TES and A-CAES.

The overall storage output covers around 32% of the total electricity demand in 2050, of which 97% is delivered by batteries. It should also be kept in mind that gas storage is also used for bio-methane, which represents 33% of all gas consumed in the region and contributes significantly to the need of gas storage capacity. However, only SNG is classified as gas storage output, while bio-methane is accounted as bioenergy generation. The technology-wise installed capacities and total output through

the transition period of 2015 to 2050 are indicated in Table 9.

Solar PV and wind energy evolve to become the backbone of Northeast Asia's electricity supply system until 2050, growing from a supply share of 6.2% in 2015 to 89% in 2050. The contribution of CSP is found to be negligible, with just 2 GW of installed capacity by 2050, mainly due to the extremely high cost competiveness achieved by solar PV that is additionally well complemented by low-cost batteries. The share of wind energy increases substantially until 2030, achieving around a 39% supply share of total electricity generation of Northeast Asia. The very high cost competiveness of PV-battery systems limits further contribution from wind energy in the period from 2035 until 2040 and even forces a decline in terms of absolute electricity generation until 2050. This is mainly because existing capacities are not repowered any longer, mainly in solar resource rich regions with moderate seasonality. Hence, the relative electricity generation share of wind energy declines to 18% in the year 2050. The marginal increase of hydropower from 1033 to 1390 TWh is relatively low, as the overall re-source constraint is taken into account, also the comparably higher cost of new large-scale hydropower, the respective risk of cost overruns, and the larger risk of violating societal and ecological sustainability criteria of large-scale hydropower projects. The generation of electricity from bio-based products increases from 51 TWh to 269 TWh, and is not only limited by the availability of residual and waste energy resources but, also by the comparably higher costs. Geothermal power generation grows from around 4 TWh to 29 TWh and is impeded by limited resource availability and comparably higher costs. Some regions of Northeast Asia face an area deficit to cover their power demand, as in the Republic of Korea, onshore wind installation reaches the upper limit, which implies that 4% of the country's territory is covered by wind turbines. This is a consequence of the applied social acceptance constraint, which leads to more PV and bioenergy utilisation and consistently higher electricity costs. However, if society would accept higher area occupation of wind energy, this could further reduce overall electricity costs and ensure a diverse renewable energy mix. The social acceptance of wind energy needs further research to better understand the real limitations, more so in countries which reach their constraint.

Table 9: Northeast Asia – Installed capacities and net electricity generation by various power sources; installed capacities and net output of various storage sources during the energy transition from 2015 to 2050 at 5-year intervals.



Technology	2015	2020	2025	2030	2035	2040	2045	2050
Power Generation	Installed Capacity [GW]							
PV utility-scale	52	195	644	1241	1981	2739	3707	5046
PV rooftop	28	114	316	880	1304	1716	2000	2371
Wind	118	322	1018	1209	1211	1169	1102	921
Hydropower	294	356	390	391	391	391	391	394
Bioenergy	11	16	37	45	46	44	43	53
Geothermal	1	1	3	4	4	4	4	5
Gas Turbine	251	245	358	354	340	317	306	383
Coal PP	942	930	918	902	870	824	739	568
Nuclear PP	80	79	74	63	51	39	30	18
Other generation	103	53	18	21	25	22	4	5

Generation	Generation [TWh]							
PV utility-scale	80	359	1157	2243	3546	4872	6570	8757
PV rooftop	38	161	452	1290	1912	2520	2940	3486
Wind	341	1026	3368	4000	4013	3899	3700	3087
Hydropower	1033	1279	1382	1384	1385	1385	1385	1391
Bioenergy	51	175	329	330	327	310	287	269
Geothermal	4	8	22	29	28	28	29	29
Gas Turbine (fossil gas)	1051	272	76	39	5	1	0	0
Coal PP	4322	3828	1482	552	226	120	45	0
Nuclear PP	287	587	552	467	381	288	222	136
Other generation	162	0	25	43	59	60	12	9

Storage	Installed Capacity [GWh]							
Battery	0	61	252	2467	5172	7910	11337	15707
Gas	0	3076	3738	8194	23693	42786	108734	185428
Pumped Hydro	56	56	61	98	98	98	98	98
Other storage	0	1113	1124	1210	1425	1428	332	589

Storage	Output [TWh_{el}]							
Battery	0	17	73	761	1569	2391	3418	4721
Gas	0	95	95	99	106	137	217	287
Pumped Hydro	14	10	14	26	23	24	21	19
Other storage	0	0	59	105	140	142	29	26

3.8 SOUTHEAST ASIA AND THE PACIFIC RIM

The Southeast Asian region including Australia, New Zealand and the Pacific Islands is comprised of rapidly growing economies, with around a 7% share of global GDP.[81] With rapid economic growth in most of the countries, the need for energy is ever increasing and some of the more developed countries have a high rate of consumption to sustain. The total electricity consumption is around 1208 TWh in 2015, which is estimated to soar up to 4222 TWh by 2050.[88] The energy sector in Southeast Asia is vital to its overall development. Therefore, effective energy planning, optimal design, wise utilisation of all available renewable energy resources and maximum synergy between various regions of the Southeast Asian countries will foster sustainable development in the region.[88] The results indicate a steadily growing transition towards a 100% renewables powered energy system for Southeast Asia, with net installed capacity of renewables reaching 900 GW in 2030 and close to 2750 GW by 2050 as shown in Figure 31. A significant amount of solar PV and wind, roughly around 300 GW, is installed from 2020 to 2025 and 450 GW from 2025 to 2030. Solar PV drives the major share of installed capacities between 2030 and 2050, as it delivers the cheapest source of electricity as shown in Figure 31. Links to the results of all countries and regions in Southeast Asia are provided in the appendix (Table 4.1).

The total electricity generation in Southeast Asia is 1208 TWh in the year 2015 and is composed of 39% coal, 38.4% fossil gas, 3.6% oil, 15.7% hydropower, 1.2% wind energy, 1.0% solar PV and 1.1% bioenergy.[6] The evolution towards 100% RE is visualised in Figure 31 and tabulated in Table 10. The share of renewable electricity in the overall mix will reach 100% of the electricity generated in Southeast Asia by 2050. Renewable power generation technologies – mainly solar PV and wind – will contribute 89% to the total electricity generation by 2050 as shown in Figure 32. The share of renewable electricity production will already be around 37% in 2020 and reach 88% by 2030.

Storage technologies play a vital role in enabling the transition towards a fully renewable powered energy system. As shown in Figure 33, a significant share of gas storage is installed, which provides vital seasonal storage.

Figure 31: Southeast Asia – Cumulative installed capacities of various power generation technologies from 2015 to 2050 (left) and new installed capacities of various power generation technologies for every 5-year interval from 2015 to 2050 (right).

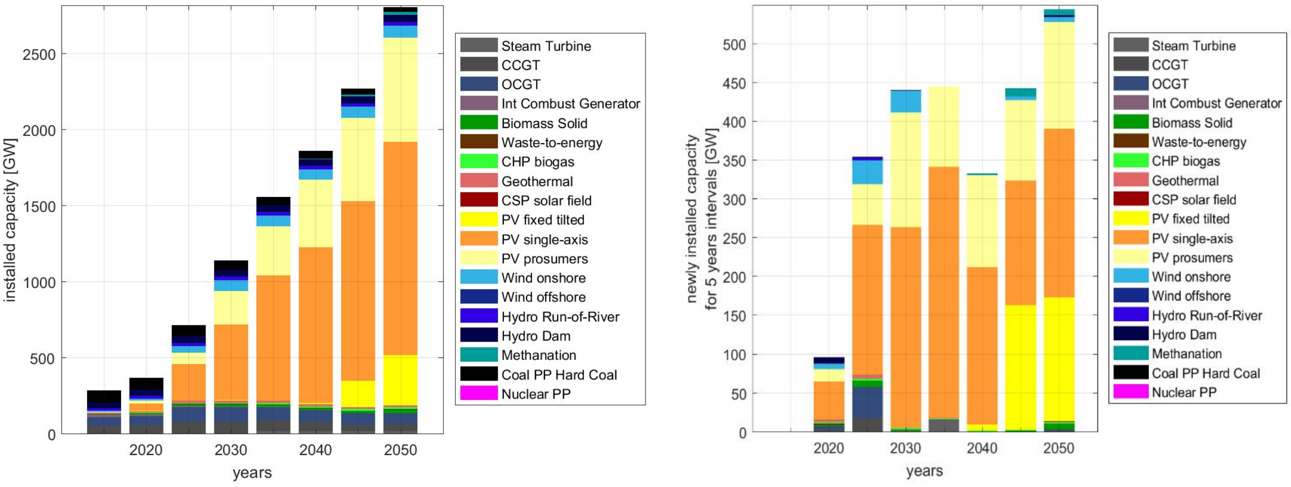


Figure 32: Southeast Asia – Net electricity generation by various power sources from 2015 to 2050 (left) and relative shares of electricity generation by various power sources from 2015 to 2050 (right).

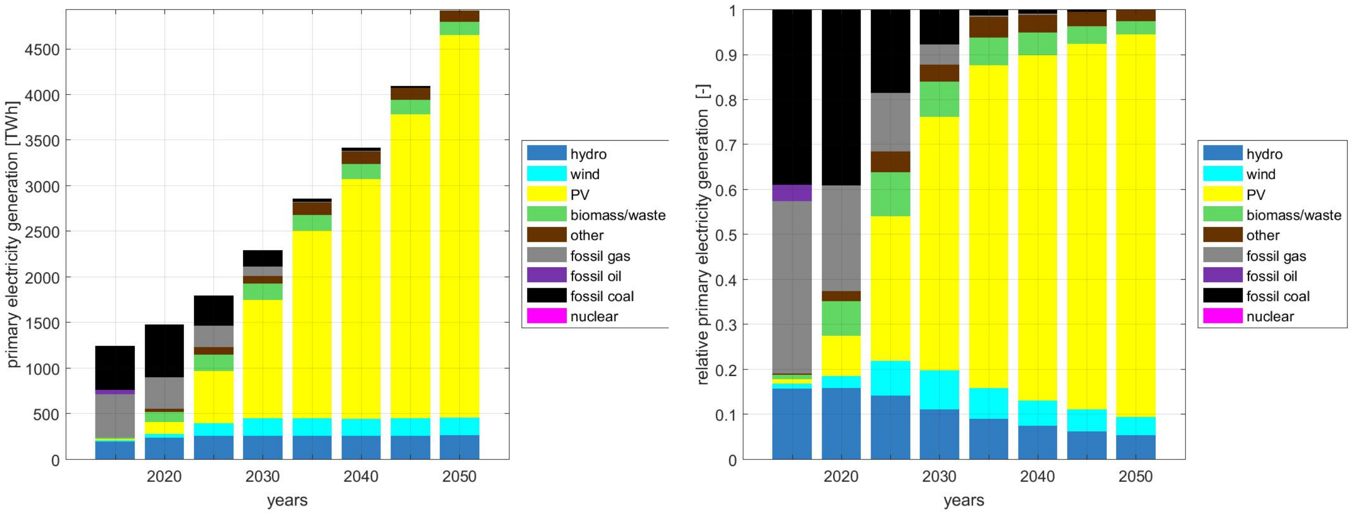
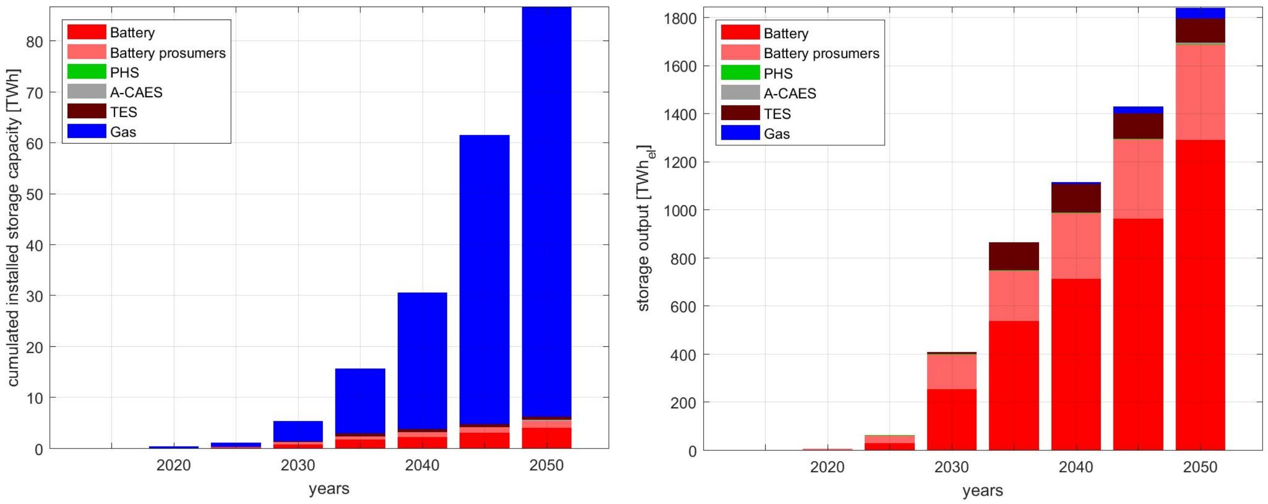


Figure 33: Southeast Asia – Cumulative installed capacities of various storage technologies from 2015 to 2050 (left) and net output by various storage technologies from 2015 to 2050 (right). Gas storage output (right) includes only stored SNG. The output of stored bio-methane is not classified as part of gas storage output even though it contributes significantly to the need of gas storage capacity (left). Bio-methane represents 44% of gas consumed in Southeast Asia, and is instead accounted as bioenergy generation.



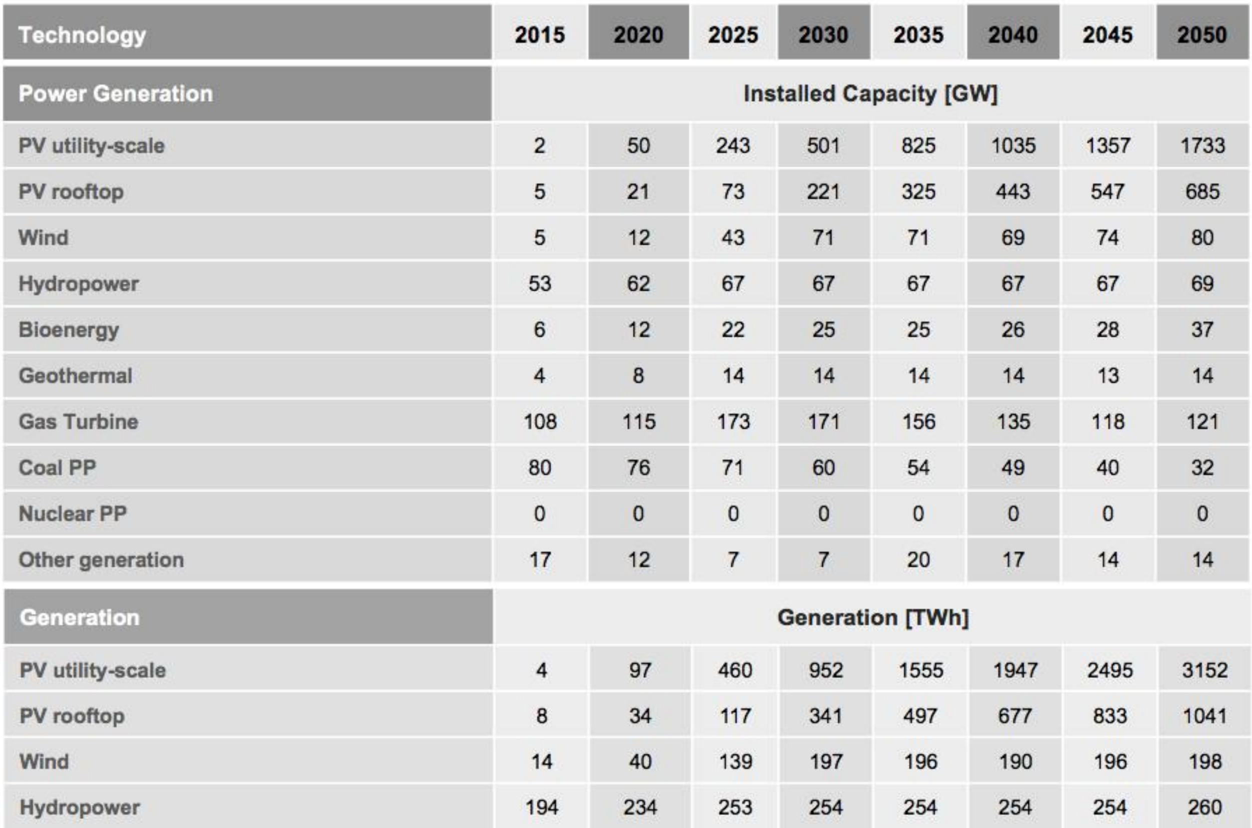
However, batteries are even more critical as they provide the maximum output, combining with solar PV both in the form of prosumers as well as in large-scale battery storage. Other sources that have a minor share in the total output are PHS, TES and A-CAES.

The overall storage output covers around 42% of the total electricity demand in 2050, of which 95% is delivered by batteries. It should also be kept in mind that gas storage is also used for bio-methane, which represents 44% of all gas consumed in the region and contributes significantly to the need of gas storage capacity. However, only SNG is classified as gas storage output, while bio-methane is accounted as bioenergy generation. The technology-wise installed capacities and total output through

the transition period of 2015 to 2050 are indicated in Table 10.

Solar PV, along with minimal levels of wind energy, evolves to become the backbone of Southeast Asia's electricity supply system until 2050, growing from a supply share of 2.2% in 2015 to 89% in 2050. The contribution of CSP is found to be non-existent even by 2050, mainly due to the extremely high cost competiveness achieved by solar PV that is additionally well complemented by low-cost batteries. The share of wind energy increases marginally until 2030, achieving around 9% supply share of total electricity generation of Southeast Asia. The very high cost competiveness of PV-battery systems limits further contribution from wind energy in the period from 2035 until 2040 and even forces a decline in terms of absolute electricity generation until 2050. This is mainly because existing capacities are not repowered any longer, mainly in solar resource rich regions with moderate seasonality. Hence, the relative electricity generation share of wind energy declines to 4% in the year 2050. The marginal increase of hydropower from 194 to 259 TWh is relatively low, as the overall re-source constraint is taken into account, also the comparably higher cost of new large-scale hydropower, the respective risk of cost overruns, and the larger risk of violating societal and ecological sustainability criteria of large-scale hydropower projects. The generation of electricity from bio-based products increases from 12 TWh to 144 TWh, and is not only limited by the availability of residual and waste energy resources but, also by the comparably higher costs. Geothermal power generation grows from around 2 TWh to 83 TWh and is impeded by limited resource availability and comparably higher costs.

Table 10: Southeast Asia – Installed capacities and net electricity generation by various power sources; installed capacities and net output of various storage sources during the energy transition from 2015 to 2050 at 5-year intervals.



Technology	2015	2020	2025	2030	2035	2040	2045	2050
Power Generation	Installed Capacity [GW]							
PV utility-scale	2	50	243	501	825	1035	1357	1733
PV rooftop	5	21	73	221	325	443	547	685
Wind	5	12	43	71	71	69	74	80
Hydropower	53	62	67	67	67	67	67	69
Bioenergy	6	12	22	25	25	26	28	37
Geothermal	4	8	14	14	14	14	13	14
Gas Turbine	108	115	173	171	156	135	118	121
Coal PP	80	76	71	60	54	49	40	32
Nuclear PP	0	0	0	0	0	0	0	0
Other generation	17	12	7	7	20	17	14	14
Generation	Generation [TWh]							
PV utility-scale	4	97	460	952	1555	1947	2495	3152
PV rooftop	8	34	117	341	497	677	833	1041
Wind	14	40	139	197	196	190	196	198
Hydropower	194	234	253	254	254	254	254	260

Bioenergy	13	114	172	178	176	168	159	144
Geothermal	2	34	83	83	83	83	83	83
Gas Turbine (fossil fuel)	476	348	234	101	8	8	1	0
Coal PP	483	578	333	179	38	33	22	0
Nuclear PP	0	0	0	0	0	0	0	0
Other generation	45	0	0	4	50	53	47	44
Storage	**Installed Capacity [GWh]**							
Battery	0	12	190	1234	2337	3110	4085	5288
Gas	0	302	836	4004	12729	26895	56822	80533
Pumped Hydro	4	4	7	8	8	8	8	8
Other storage	0	0	1	52	584	585	585	829
Storage	**Output [TWh_{el}]**							
Battery	0	4	59	397	745	986	1292	1688
Gas	0	74	74	74	75	83	114	148
Pumped Hydro	1	1	2	2	2	2	2	2
Other storage	0	0	0	9	117	120	108	105

3.9 NORTH AMERICA

North America is comprised of the major economic centers of the world, USA and Canada, with a 19% share in global GDP,[81] and is one of the largest energy consumption centers across the world, with total electricity consumption of around 5284 TWh in 2015.[89] This is estimated to rise to 7069 TWh by 2050, mainly driven by the rapid growth of Mexico as well as stable electricity demands from the USA and Canada. North America, led by some of the states in the USA such as California, North Carolina and Arizona, among others, have been at the forefront of the energy transition with significant contributions towards developing renewable energy. The USA has shares of installed power capacity at 18% and nearly 15% of electricity generation coming from renewables.[90] The results indicate an incremental transition to a 100% renewable powered energy system for North America, with net installed capacity of renewables reaching 2500 GW in 2030 and close to 4000 GW by 2050 as shown in Figure 34. A significant amount of wind and solar PV, roughly around 850 GW, is installed from 2020 to 2025 and 780 GW from 2025 to 2030. Solar PV drives the major share of installed capacities between 2040 and 2050, as it delivers the cheapest source of electricity as shown in Figure 34. Links to the results of all countries in North America are provided in the appendix (Table 4.1).

The total electricity generation of North America is 5284 TWh in the year 2015, which is comprised of 31.3% coal, 32.2% fossil gas, 1.3% oil, 17.0% nuclear energy, 12.2% hydropower, 4.1% wind energy, 0.8% solar PV, 0.9% bioenergy and 0.3% others (mainly geothermal and CSP).[6] The evolution towards 100% renewable electricity generation is visualised in Figure 35 and tabulated in Table 11. The share of renewable electricity in the overall mix will reach 100% of the total electricity generated across North America in 2050. Renewable power generation technologies – mainly solar PV and wind – will contribute nearly 75% to the total electricity generation by 2050 as shown in Figure 35. The share of renewable electricity production will already be around 50% in 2020 and reach over 85% by 2030.

Figure 34: North America – Cumulative installed capacities of various power generation technologies from 2015 to 2050 (left) and new installed capacities of various power generation technologies for every 5-year interval from 2015 to 2050 (right).

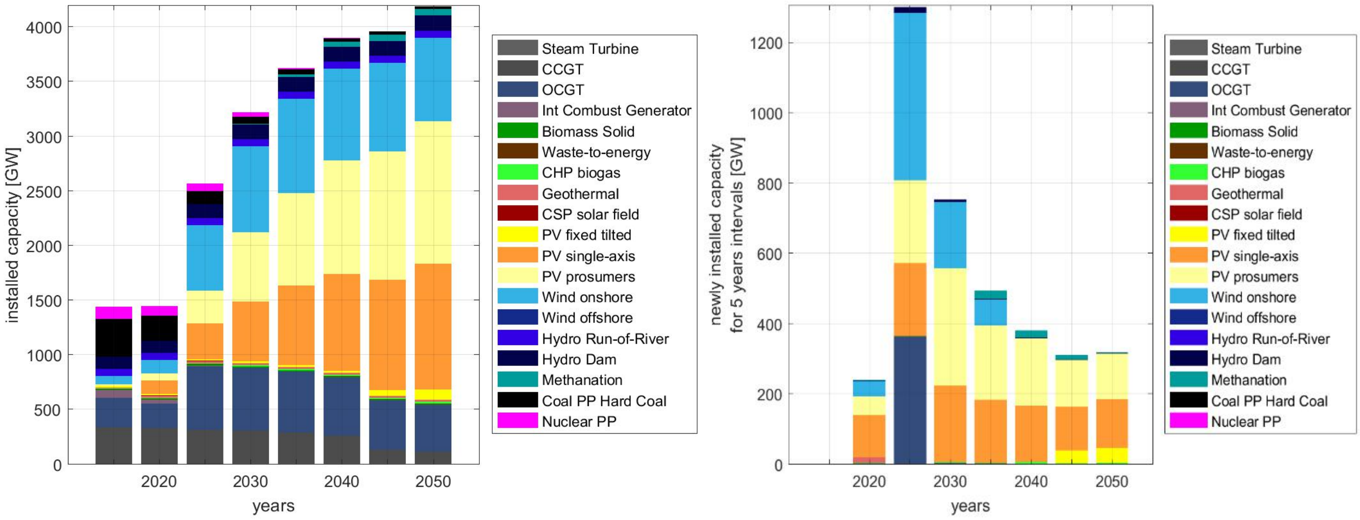


Figure 35: North America – Net electricity generation by various power sources from 2015 to 2050 (left) and relative shares of electricity generation by various power sources from 2015 to 2050 (right).

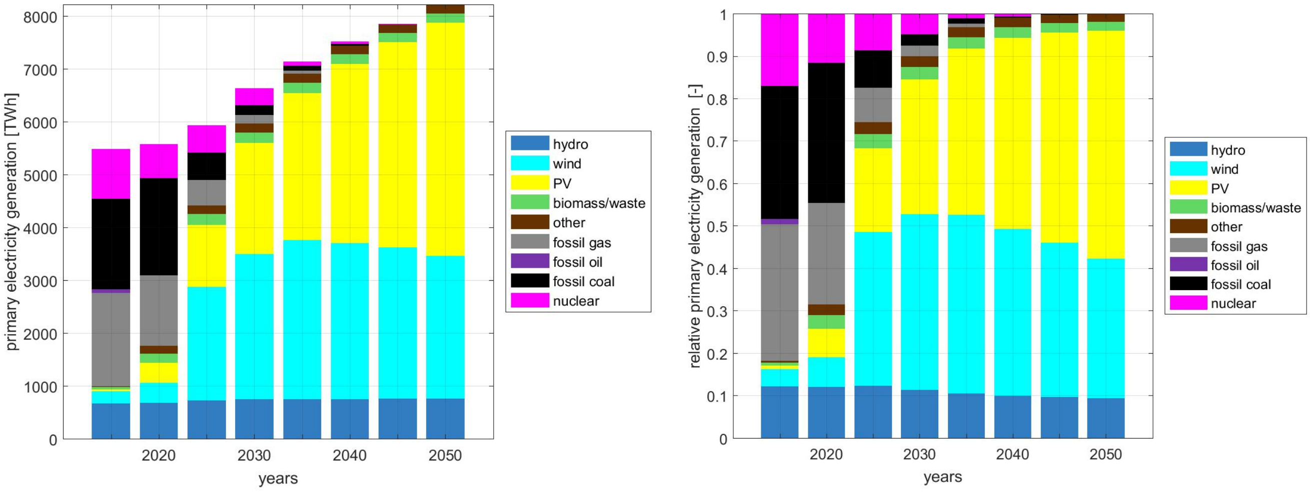
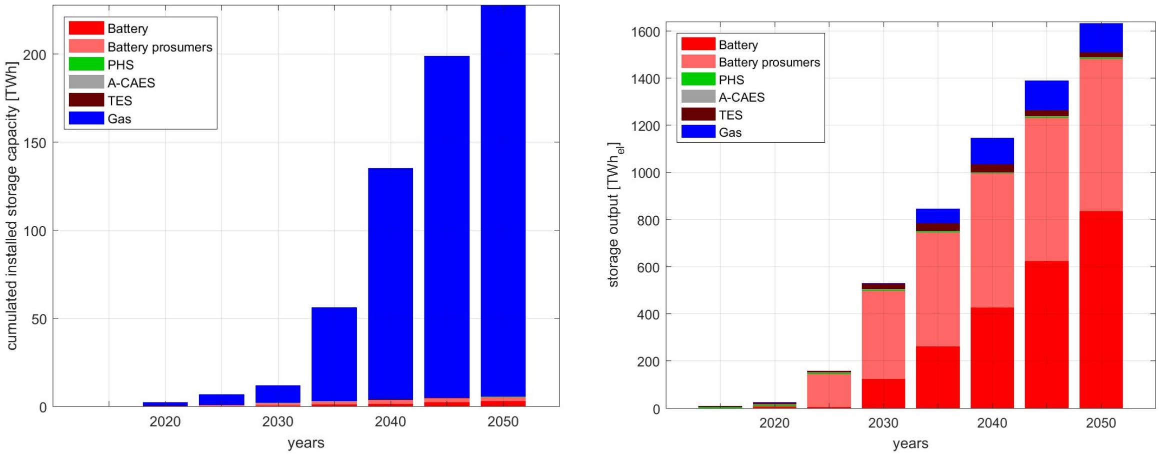


Figure 36: North America – Cumulative installed capacities of various storage technologies from 2015 to 2050 (left) and net output by various storage technologies from 2015 to 2050 (right). Gas storage output (right) includes only stored SNG. The output of stored bio-methane is not classified as part of gas storage output even though it contributes significantly to the need of gas storage capacity (left). Bio-methane represents 35% of gas consumed in North America, and is instead accounted as bioenergy generation.

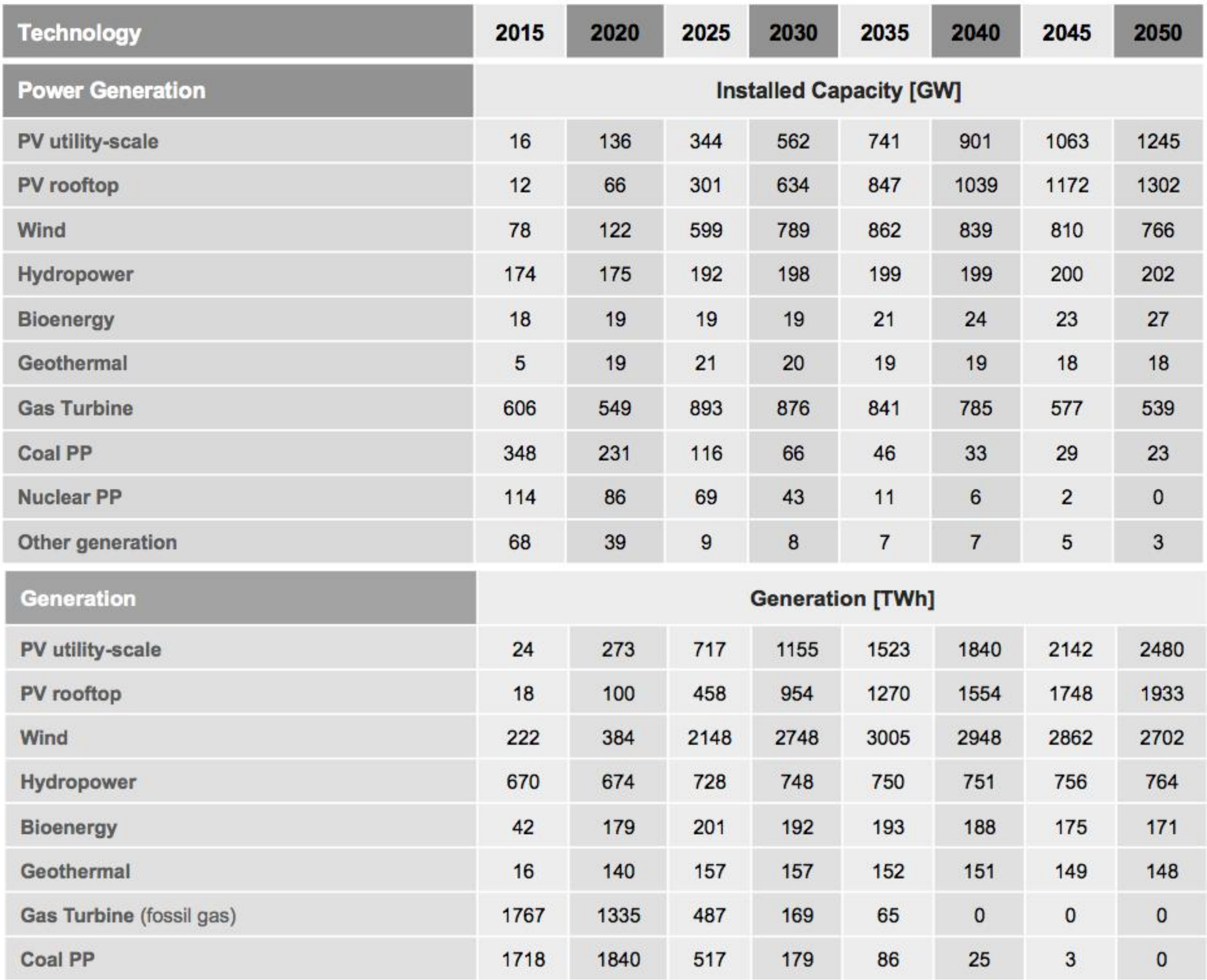


Storage technologies play a vital role in enabling the transition towards a fully renewable powered energy system. As shown in Figure 36, a significant share of gas storage is installed, which provides vital seasonal storage. However, batteries are even more critical as they provide the maximum output, combining with solar PV both in the form of prosumers as well as in large-scale battery storage. Other sources that have a minor share in the total output are PHS, TES and A-CAES.

The overall storage output covers 23% of the total electricity demand in 2050, of which 91% is delivered by batteries. It should also be kept in mind that gas storage is also used for bio-methane, which represents 35% of all gas consumed in the region and contributes significantly to the need of gas storage capacity. However, only SNG is classified as gas storage output, while bio-methane is accounted as bioenergy generation. The technology-wise installed capacities and total output through the transition period of 2015 to 2050 are indicated in Table 11.

Solar and wind energy evolve to become the backbone of the North American electricity supply system until 2050, growing steadily from a supply share of 4.9% in 2015 to 86.7% in 2050. The contribution of CSP is found to be negligible, mainly due to the extremely high cost competitiveness achieved by solar PV that is additionally well complemented by low-cost batteries. The share of wind energy increases significantly until 2035, achieving around a 42% supply share of total electricity generation across North America. Wind energy continues to contribute steadily, utilising the excellent potential in North America, while solar steadily increases in generation share to reach around 54% of the total in 2050. The hydropower electricity share declines from around 12% to just over 9%, as the overall resource constraint is taken into account, also most of the hydropower potential across North America has already been realised. The generation of electricity from bio-based products increases from 42 to 171 TWh, and is not only limited by the availability of residual and waste energy resources but, also by the comparably higher costs. Geothermal power generation grows from 16 to 148 TWh and is impeded by limited resource availability and comparably higher costs.

Table 11: North America – Installed capacities and net electricity generation by various power sources; installed capacities and net output of various storage sources during the energy transition from 2015 to 2050 at 5-year intervals.



Technology	2015	2020	2025	2030	2035	2040	2045	2050
Power Generation	**Installed Capacity [GW]**							
PV utility-scale	16	136	344	562	741	901	1063	1245
PV rooftop	12	66	301	634	847	1039	1172	1302
Wind	78	122	599	789	862	839	810	766
Hydropower	174	175	192	198	199	199	200	202
Bioenergy	18	19	19	19	21	24	23	27
Geothermal	5	19	21	20	19	19	18	18
Gas Turbine	606	549	893	876	841	785	577	539
Coal PP	348	231	116	66	46	33	29	23
Nuclear PP	114	86	69	43	11	6	2	0
Other generation	68	39	9	8	7	7	5	3
Generation	**Generation [TWh]**							
PV utility-scale	24	273	717	1155	1523	1840	2142	2480
PV rooftop	18	100	458	954	1270	1554	1748	1933
Wind	222	384	2148	2748	3005	2948	2862	2702
Hydropower	670	674	728	748	750	751	756	764
Bioenergy	42	179	201	192	193	188	175	171
Geothermal	16	140	157	157	152	151	149	148
Gas Turbine (fossil gas)	1767	1335	487	169	65	0	0	0
Coal PP	1718	1840	517	179	86	25	3	0

Nuclear PP	934	642	514	317	81	47	12	0
Other generation	72	5	3	10	14	14	11	9
Storage	**Installed Capacity [GWh]**							
Battery	0	18	501	1690	2592	3476	4364	5218
Gas	0	1940	6091	9899	53263	131255	194129	222194
Pumped Hydro	16	17	17	17	17	17	17	17
Other storage	0	174	175	232	299	300	283	248
Storage	**Output [TWh_{el}]**							
Battery	0	9	145	497	745	994	1232	1480
Gas	0	151	160	165	269	359	396	388
Pumped Hydro	5	5	4	5	4	4	4	5
Other storage	4	9	9	26	35	35	28	24

3.10 SOUTH AMERICA

The South American region including Central American countries is comprised of growing economies, with around a 6% share of global GDP.[81] With steady economic growth in most of the countries, the need for energy is increasing. The total electricity consumption is around 1180 TWh in 2015, which is estimated to increase up to 2420 TWh by 2050.[91] The energy sector in South America is a key ingredient to its overall develop-ment. Many of the countries have a well-developed hydropower sector, such as Brazil with more than 70% of its electricity generated through hydro,[87] and Paraguay runs its entire power sector based on hydropower and further exports excess generation to neighbouring countries. Overall, the region has amongst the least carbon intensive power sectors globa-lly. However, with growing needs and a need to en-sure security of supply, effective utilisation of all available renewable energy resources and maxi-mum synergy between various regions of the South American countries will foster sustainable development in the region. The results indicate a very swift transition towards a 100% renewables powered energy system for South America, with net installed capacity of renewables reaching 550 GW in 2030 and close to 1000 GW by 2050 as shown in Figure 37. A significant amount of solar PV and wind, roughly around 120 GW, is installed by 2020 and another 120 GW from 2025 to 2030. Solar PV drives the major share of installed capacities between 2030 and 2050, as it delivers the cheapest source of electricity as shown in Figure 37. Links to the results of all countries and regions in South America are provided in the appendix (Table 4.1).

The total electricity generation in South America is 1180 TWh in the year 2015 and is composed of 6.1% coal, 26.5% fossil gas, 7.7% oil, 51.8% hydropower, 1.9% wind energy, 0.3% solar PV and 4.0% bioenergy.[6] The evolution towards 100% RE is visualised in Figure 38 and tabulated in Table 12. The share of renewable electricity in the overall mix will reach 100% of the electricity generated in South America by 2050. Renewable power generation technologies – mainly solar PV and wind – will contribute 67% to the total electricity generation by 2050 as shown in Figure 38. The share of renewable electricity production will already be around 91% in 2020 and already reach 99% by 2030.

Figure 37: South America – Cumulative installed capacities of various power generation technologies from 2015 to 2050 (left) and new installed capacities of various power generation technologies for every 5-year interval from 2015 to 2050 (right).

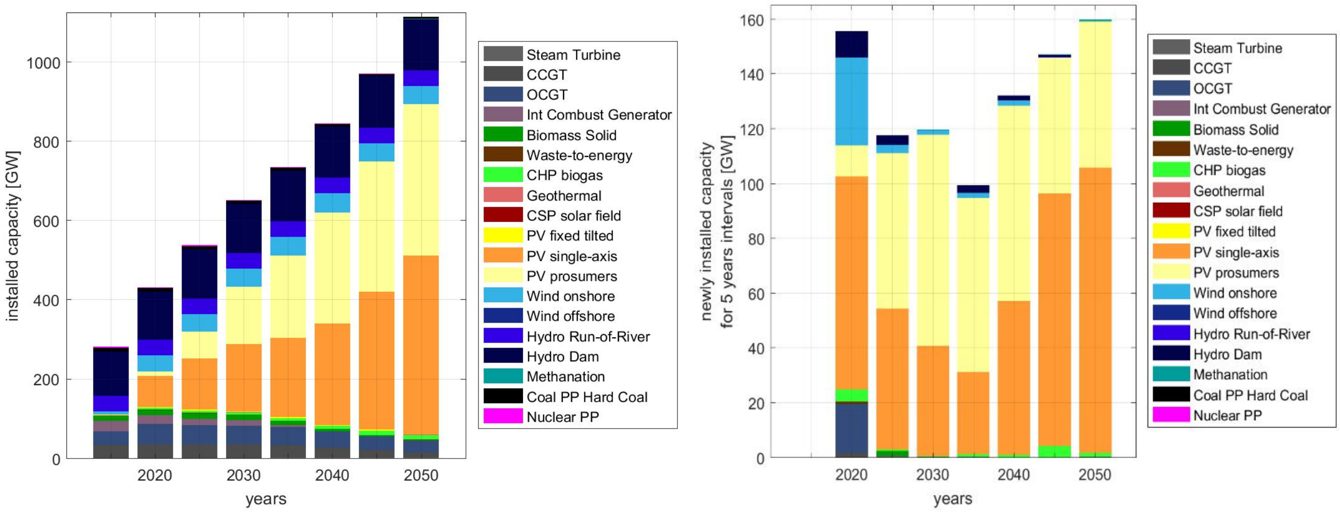


Figure 38: South America – Net electricity generation by various power sources from 2015 to 2050 (left) and relative shares of electricity generation by various power sources from 2015 to 2050 (right).

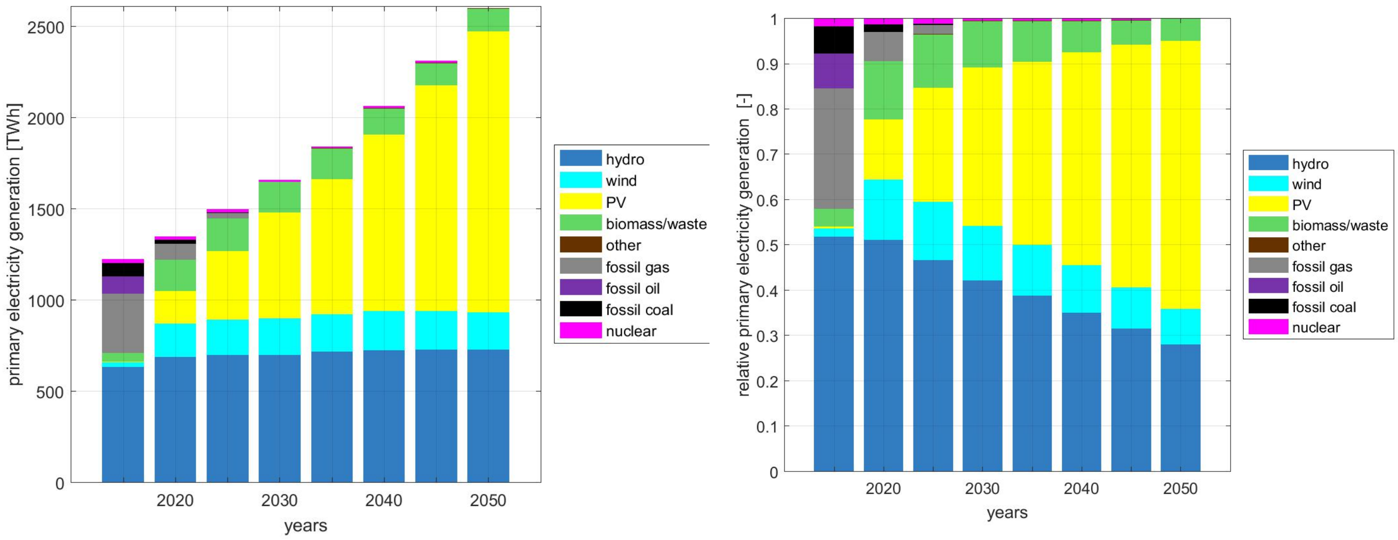
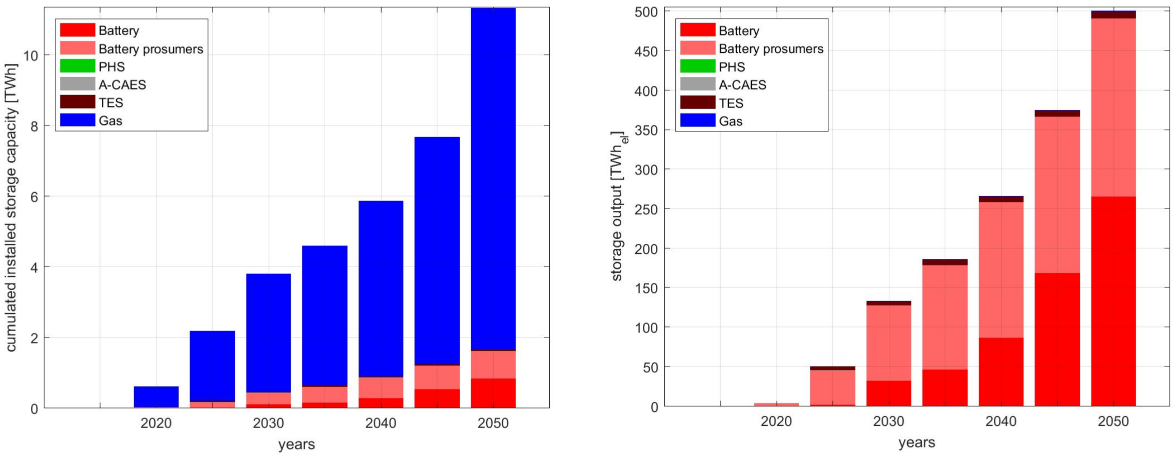


Figure 39: South America – Cumulative installed capacities of various storage technologies from 2015 to 2050 (left) and net output by various storage technologies from 2015 to 2050 (right). Gas storage output (right) includes only stored SNG. The output of stored bio-methane is not classified as part of gas storage output even though it contributes significantly to the need of gas storage capacity (left). Bio-methane represents 94% of gas consumed in South America, and is instead accounted as bioenergy generation.



Storage technologies play a vital role in enabling the transition towards a fully renewable powered energy system. As shown in Figure 39, a significant share of gas storage is installed, which provides vital seasonal storage. However, batteries are even more critical as they provide the maximum output, combining with solar PV both in the form of prosumers as well as in large-scale battery storage. Other sources that have a minor share in the total output are PHS, TES and A-CAES.

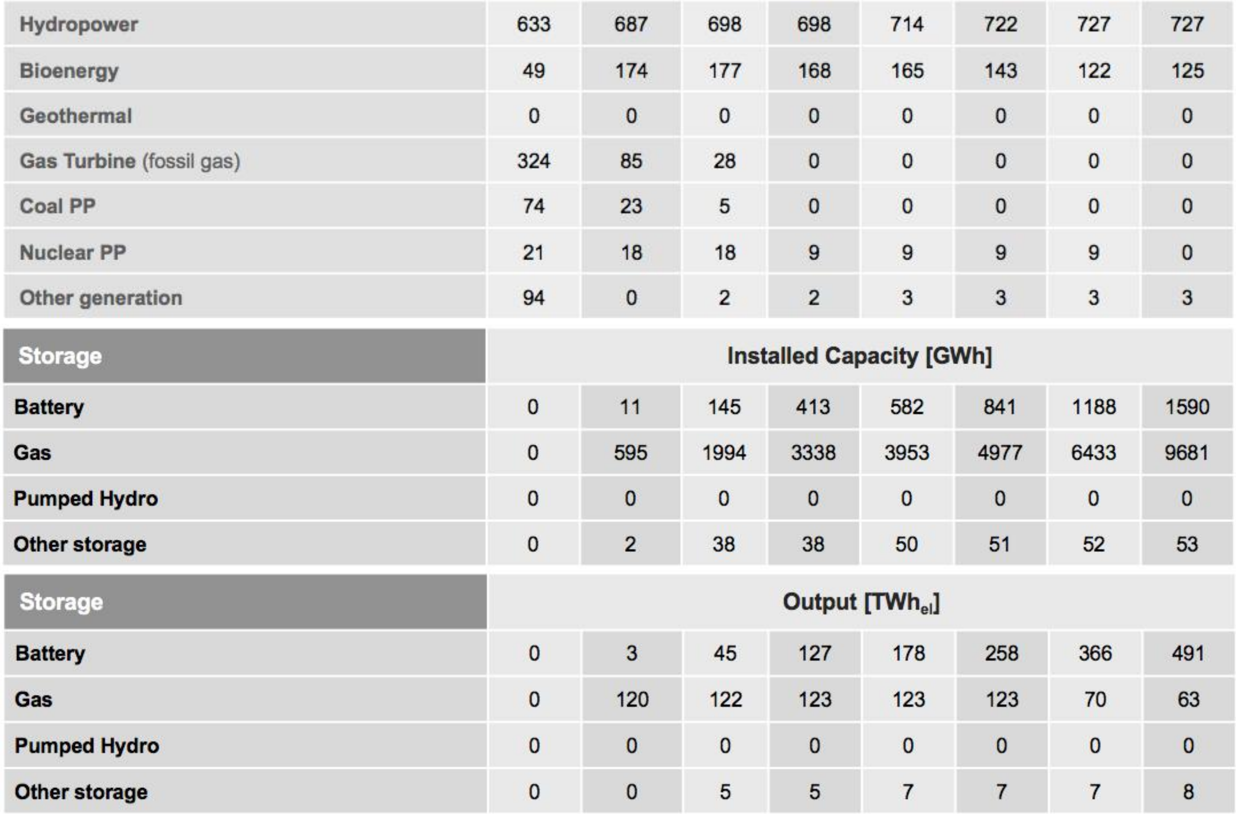
The overall storage output covers around 21% of the total electricity demand in 2050, of which 99% is delivered by batteries. It should also be kept in mind that gas storage is also used for bio-methane, which represents 94% of all gas consumed in the region and contributes significantly to the need of gas storage capacity. However, only SNG is classified as gas storage output, while bio-methane is accounted as bioenergy generation. The technology-wise installed capacities and total output through

the transition period of 2015 to 2050 are indicated in Table 12.

Solar PV, hydropower and minimal levels of wind energy evolve to become the backbone of South America's electricity supply system until 2050, growing from a supply share of 54% in 2015 to 95% in 2050. The contribution of CSP is found to be non-existent even by 2050, mainly due to the extremely high cost competiveness achieved by solar PV that is additionally well complemented by low-cost batteries. The share of wind energy increases marginally until 2020, achieving around a 13% supply share of total electricity generation of South America. The very high cost competiveness of PV-battery systems limits further contribution from wind energy from 2040 onwards and even forces a decline in terms of absolute electricity generation until 2050. This is mainly because existing capacities are not repowered any longer, mainly in solar resource rich regions with moderate seasonality. Hence, the relative electricity generation share of wind energy declines to 8% in the year 2050. Despite being the main source of electricity generation for the region, hydropower declines from 52% of the share in 2015 to 28% in 2050. Some of the reasons for the decline are the overall resource constraint as most of the resource has been utilised, also the comparably higher cost of new large-scale hydropower, the respective risk of cost overruns, and the larger risk of violating societal and ecological sustainability criteria of large-scale hydropower projects. The generation of electricity from bio-based products increases from 49 TWh to 125 TWh, and is not only limited by the availability of residual and waste energy resources but, also by the comparably higher costs. Geothermal power generation is very negligible, as it is impeded by very limited resource availability in the region and comparably higher costs.

Table 12: South America – Installed capacities and net electricity generation by various power sources; installed capacities and net output of various storage sources during the energy transition from 2015 to 2050 at 5-year intervals.

Technology	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Power Generation	**Installed Capacity [GW]**							
PV utility-scale	2	80	131	172	202	258	350	452
PV rooftop	0	11	68	145	209	280	330	383
Wind	8	41	44	45	47	49	46	44
Hydropower	151	160	164	164	167	168	169	169
Bioenergy	13	18	20	20	17	13	14	15
Geothermal	1	1	1	0	0	0	0	0
Gas Turbine	67	86	82	81	77	67	55	42
Coal PP	10	10	8	8	7	7	5	5
Nuclear PP	3	2	2	1	1	1	1	0
Other generation	27	22	17	15	6	1	1	1
Generation	**Generation [TWh]**							
PV utility-scale	4	161	268	348	410	525	715	931
PV rooftop	0	18	109	232	332	445	523	606
Wind	23	180	193	199	206	215	210	204



Hydropower	633	687	698	698	714	722	727	727
Bioenergy	49	174	177	168	165	143	122	125
Geothermal	0	0	0	0	0	0	0	0
Gas Turbine (fossil gas)	324	85	28	0	0	0	0	0
Coal PP	74	23	5	0	0	0	0	0
Nuclear PP	21	18	18	9	9	9	9	0
Other generation	94	0	2	2	3	3	3	3
Storage	**Installed Capacity [GWh]**							
Battery	0	11	145	413	582	841	1188	1590
Gas	0	595	1994	3338	3953	4977	6433	9681
Pumped Hydro	0	0	0	0	0	0	0	0
Other storage	0	2	38	38	50	51	52	53
Storage	**Output [TWh_{el}]**							
Battery	0	3	45	127	178	258	366	491
Gas	0	120	122	123	123	123	70	63
Pumped Hydro	0	0	0	0	0	0	0	0
Other storage	0	0	5	5	7	7	7	8

4. COST PROJECTIONS OF THE GLOBAL 100% RENEWABLE ELECTRICITY SYSTEM

As the distinct ways of generating electricity across the world incur significantly different costs, a cost perspective of the global energy transition towards 100% renewable energy is a vital indicator.[92] As discussed earlier, the LCOE methodology is utlised to estimate costs of the various technologies that are part of the global power system.[87]

The cost estimates in this reserach consider local, regional as well as global factors influencing the overall cost of electricity generation. The following sections present the results from a cost perespective for the globally aggregated scenario, which is followed by and based on regional scenarios for the nine major regions. Links to the results of all countries and regions are provided in the appendix (Table 4.1).

4.1 GLOBAL

The global energy system LCOE remains rather stable for the first periods, showing a gradual decline from 70 €/MWh to 59 €/MWh from 2015 to 2040, including all generation, storage, curtailment and parts of the grid costs, i.e. all transmission and distribution losses and full costs of connecting individually modelled regions of the same country, which is shown in Table 13. Beyond 2040 the LCOE further declines to 52 €/MWh in 2050 as indicated in Figure 40.

If the energy system mix for the year 2050 would have been built with the assumptions for the year 2050, the LCOE would further decline to 41 €/MWh, a cost level that can be expected in the years beyond 2050. The LCOE composition in the beginning is dominated by amortisation requirements of coal, nuclear and gas power plants and the respective fossil and nuclear fuel expenditures. The LCOE in the year 2050 is mainly composed of solar PV and batteries, complemented by some wind energy and hydropower as can be observed from Figure 40, which shows the LCOE composition based on different power generation and storage technologies. Also, the fuel cost component of the LCOE decreases significantly from 2015 to 2030, mainly with the phase out of expensive coal and nuclear electricty.

Figure 40: Global – Composition of LCOE with shares of LCOS, LCOC and LCOT along with fuel and CO2 costs from 2015 to 2050 (left) and composition of LCOE by various power generation technologies from 2015 to 2050 (right).

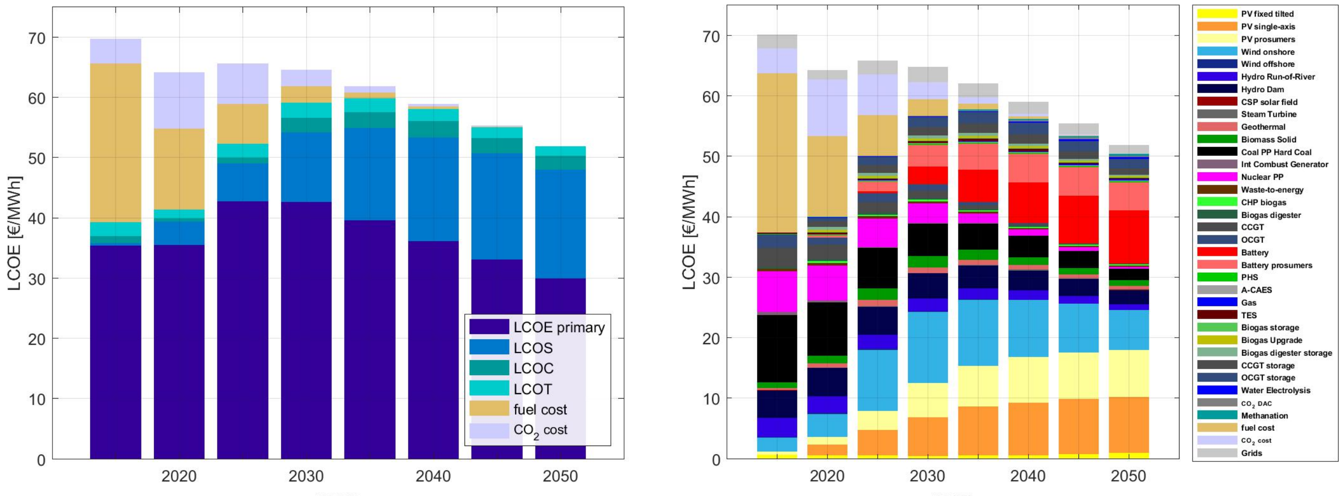
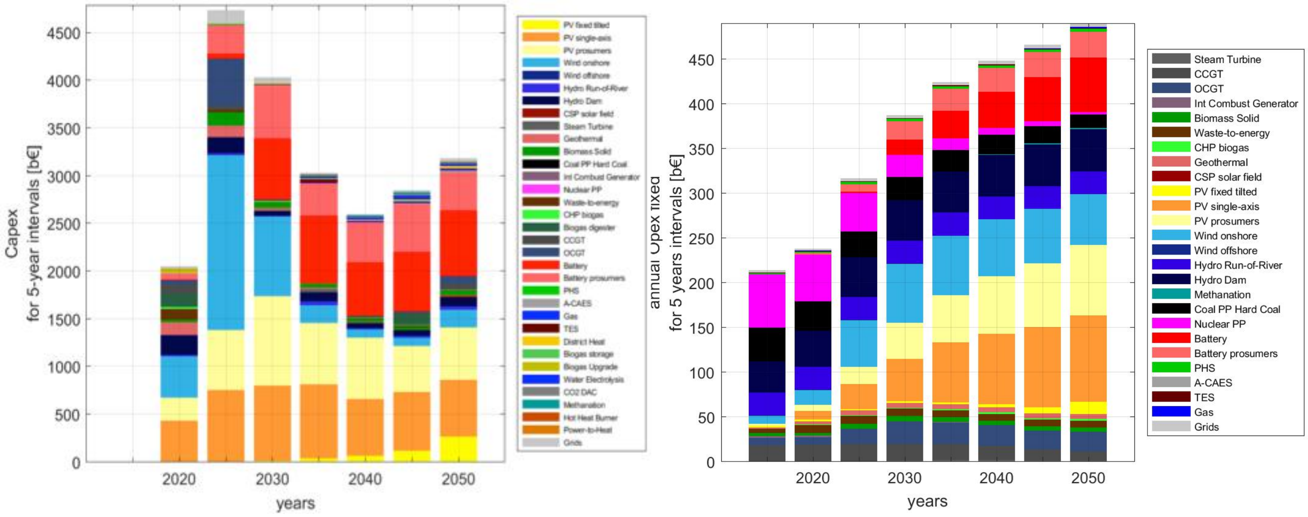


Figure 41: Global - Capital investments required in power generation and storage technologies for every 5-year interval from 2020 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).



The capital investment required for each 5-year interval during the energy transition from 2015 to 2050 is shown in Figure 41 and Table 13. The period between 2020 and 2030 is when high investments are required with 4735 b€ during 2020-25 and 4034 b€ during 2025-30, mainly in wind, solar PV and battery technologies. Beyond this the investment requirements decline to 3027 b€ in 2035 and later gradually increases with invest-ments around 2592 b€ in 2040 to 3184 b€ until 2050. Whereas, the operational expenditures increase from around 200 b€ in 2015 to 500 b€ in 2050 as shown in Figure 41.

Table 13: Global – LCOE and investment requirements during the energy transition for every 5-year interval from 2015 to 2050.

	Total LCOE [€/MWh]							
Composition	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
LCOE - Generation	65.8	58.2	56.0	48.2	41.5	37.0	33.4	29.9
LCOC - Curtailment	1.2	0.5	0.9	2.4	2.7	2.7	2.6	2.3
LCOS - Storage	0.4	3.8	6.4	11.5	15.3	17.2	17.6	18.1
LCOT - Transmission	2.3	1.6	2.3	2.5	2.3	2.0	1.7	1.5
Total LCOE	**69.7**	**64.1**	**65.6**	**64.6**	**61.8**	**58.9**	**55.3**	**51.8**
	Investments for 5-year periods [b€]							
Capital Expenditure (CAPEX)		2053	4735	4034	3027	2592	2847	3184

4.2 EUROPE

The European energy system LCOE remains rather stable for the first couple of decades until 2030, afterwards showing a gradual decline from 67 €/MWh to 56 €/MWh from 2015 to 2050, including all generation, storage, curtailment and parts of the grid costs, i.e. all transmission and distribution losses and full costs of connecting individually modelled regions of the same country, which is shown in Figure 42 and Table 14. If the energy system mix for the year 2050 would have been built with the assumptions for the year 2050, the LCOE would further decline to around 43 €/MWh, a cost level that can be expected in the years beyond 2050 in Europe.

The LCOE in the year 2050 is mainly composed of wind energy, solar PV and batteries, along with some hydropower and bioenergy as shown in Figure 42. Also, the fuel cost component of the LCOE decreases significantly from 2015 to 2030, mainly with the phase out of expensive coal and nuclear electricty in Europe.

The capital investment required for each 5-year interval during the energy transition from 2015 to 2050 is shown in Figure 43 and Table 14. The period between 2020 and 2030 is when high investments are required, with 584 b€ during 2020-25 and 437 b€ during 2025-30, mainly in wind, solar PV and battery technologies. Beyond this the investment requirements continue to decline steadily, with investment needs dropping to just about 300 b€ until 2050. Whereas, the operational expenditures increase until 2025 and beyond this remain stable up to 2050 as shown in Figure 43.

Figure 42: Europe – Composition of LCOE with shares of LCOS, LCOC and LCOT along with fuel and CO2 costs from 2015 to 2050 (left) and composition of LCOE by various power generation technologies from 2015 to 2050 (right).

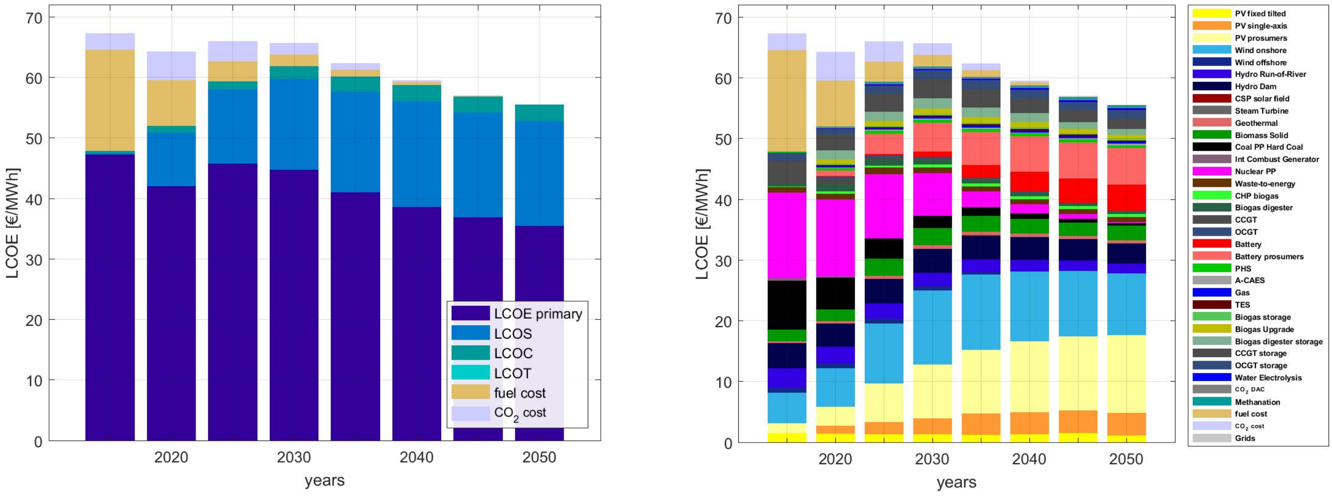


Figure 43: Europe - Capital investments required in power generation and storage technologies for every 5-year interval from 2020 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).

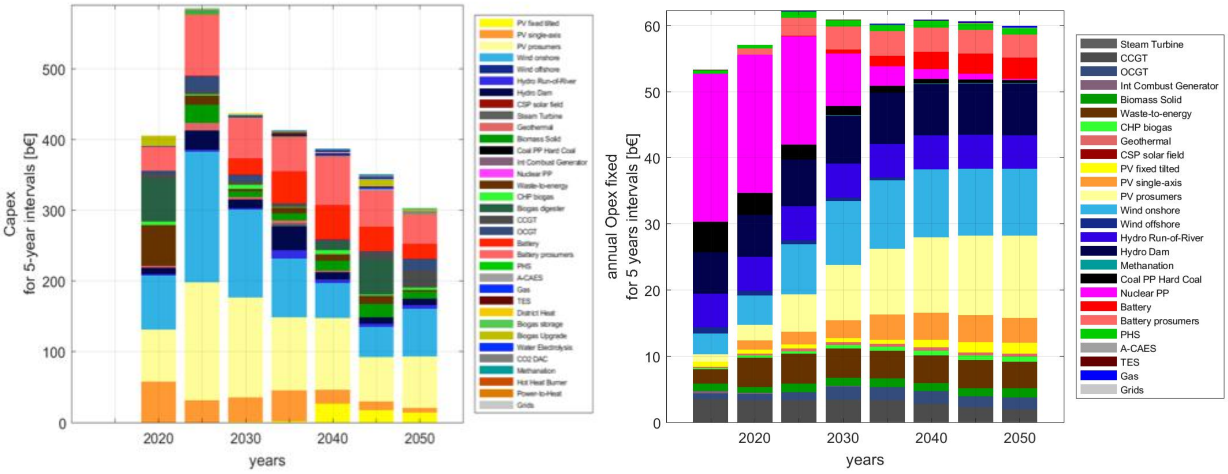


Table 14: Europe – LCOE and investment requirements during the energy transition for every 5-year interval from 2015 to 2050.

	Total LCOE [€/MWh]							
Composition	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
LCOE - Generation	66.6	54.2	52.4	48.5	43.2	39.4	37.0	35.6
LCOC - Curtailment	0.5	1.2	1.3	2.2	2.6	2.8	2.7	2.6
LCOS - Storage	0.2	8.9	12.2	15.0	16.6	17.4	17.3	17.3
LCOT - Transmission	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total LCOE	**67.3**	**64.3**	**65.9**	**65.7**	**62.4**	**59.6**	**57.0**	**55.5**
	Investments for 5-year periods [b€]							
Capital Expenditure (CAPEX)		404	584	437	413	385	351	300

4.3 EURASIA

The Eurasian energy system LCOE drops initially to 60 €/MWh in 2020 and then onwards shows a stable decline until 2050. The LCOE is observed to reduce from 70 €/MWh to 50 €/MWh during the entire transition period from 2015 to 2050, including all generation, storage, curtailment and parts of the grid costs, i.e. all transmission and distribution losses and full costs of connecting individually modelled regions of the same country, which is shown in Figure 44 and Table 15. If the energy system mix for the year 2050 would have been built with the assumptions for the year 2050, the LCOE would further decline to around 45 €/MWh, a cost level that can be expected in the years beyond 2050 in Eurasia.

The LCOE in the year 2050 is mainly composed of largely wind energy with some solar PV and batteries, along with hydropower and gas turbines with a combination of bio-methane and SNG as shown in Figure 44. Also, the fuel cost component of the LCOE decreases significantly from 2015 to 2030, mainly with the phase out of expensive coal and nuclear electricty in Eurasia.

The capital investment required for each 5-year interval during the energy transition from 2015 to 2050 is shown in Figure 45 and Table 15. The period between 2020 and 2025 is when high investments are required, with 284 b€, mainly large investments in wind energy capacity. Along with new installations, old, pre-1990 built capacities reach their end of technical lifetimes and have to be reinvested in, adding to the overall investment requirements. Beyond this the investment requirements drop to 84 b€ in 2030 and continue to decline steadily with investment needs dropping to just about 54 b€ in 2045 and increasing again to 86 b€ in 2050. Whereas, the annual operational expenditures increase from around 11 b€ in 2015 to just over 18 b€ in 2050 as shown in Figure 45.

Figure 44: Eurasia – Composition of LCOE with shares of LCOS, LCOC and LCOT along with fuel and CO2 costs from 2015 to 2050 (left) and composition of LCOE by various power generation technologies from 2015 to 2050 (right).

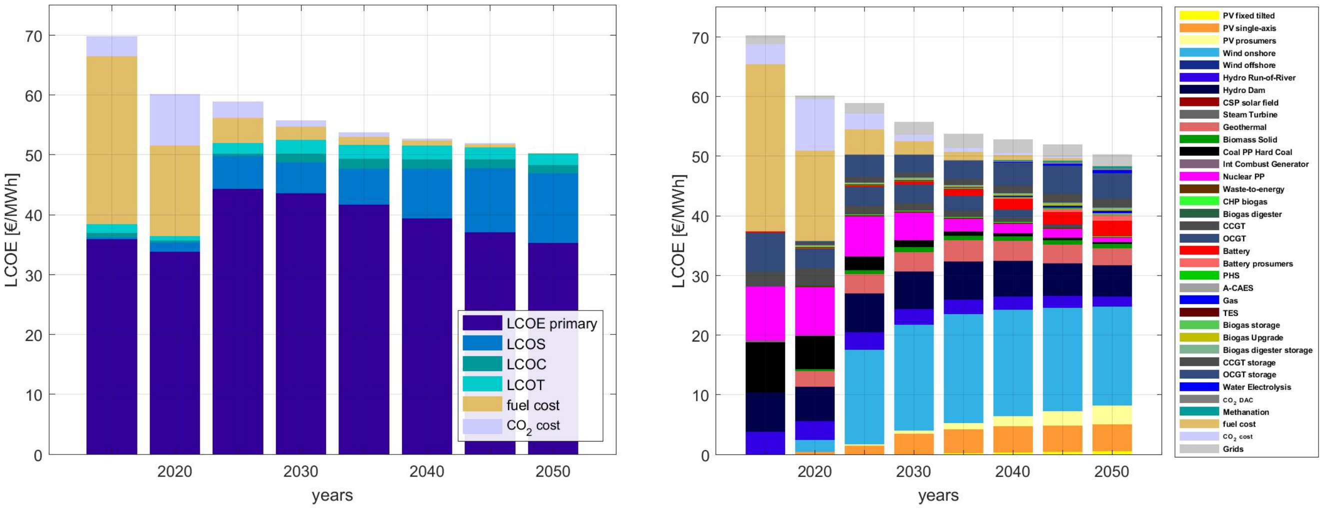


Figure 45: Eurasia - Capital investments required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).

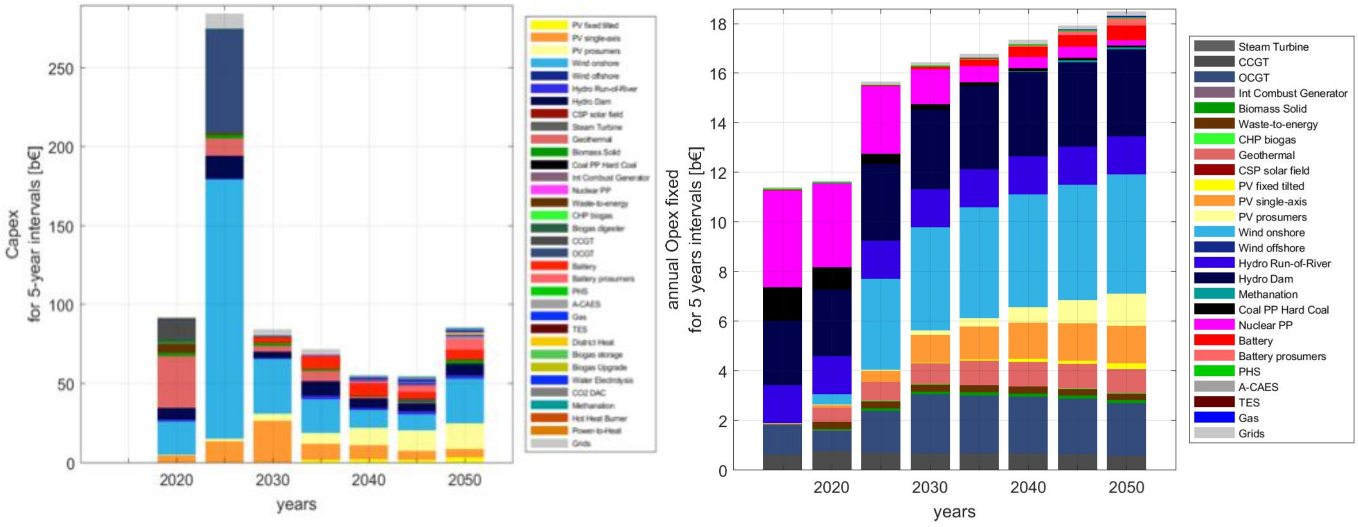


Table 15: Eurasia – LCOE and investment requirements during the energy transition for every 5-year interval from 2015 to 2050.

	Total LCOE [€/MWh]							
Composition	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
LCOE - Generation	67.3	57.5	51.0	46.8	43.7	40.6	37.7	35.3
LCOC - Curtailment	0.8	0.3	0.5	1.5	1.6	1.6	1.4	1.4
LCOS - Storage	0.2	1.6	5.5	5.2	6.0	8.3	10.7	11.7
LCOT - Transmission	1.5	0.7	1.8	2.2	2.4	2.2	2.1	1.9
Total LCOE	**69.8**	**60.1**	**58.8**	**55.7**	**53.7**	**52.7**	**51.9**	**50.3**
	Investments for 5-year periods [b€]							
Capital Expenditure (CAPEX)		90	284	84	71	56	54	86

4.4 MENA

The energy system LCOE of the MENA region drops significantly from 97 €/MWh in 2015 to 64 €/MWh in 2020 and then onwards shows a stable decline until 2050. The LCOE is observed to reduce from 97 €/MWh to 51 €/MWh during the entire transition period from 2015 to 2050, including all generation, storage, curtailment and parts of the grid costs, i.e. all transmission and distribution losses and full costs of connecting individually modelled regions of the same country, which is shown in Figure 46 and Table 16. If the energy system mix for the year 2050 would have been built with the assumptions for the year 2050, the LCOE would further decline to around 40 €/MWh, a cost level that can be ex-pected in the years beyond 2050 in the MENA region.

The LCOE in the year 2050 is mainly composed of solar PV and batteries, complemented by some thermal energy energy from CSP and wind energy as show in Figure 46. Also, the fuel cost component of the LCOE decreases hugely from 2015 to 2035, mainly with the phase out of expensive oil and gas, with some coal and nuclear electricty in the MENA region.

The capital investment required for each 5-year interval during the energy transition from 2015 to 2050 is shown in Figure 47 and Table 16. The period between 2020 and 2035 is when high investments are required, with 340 b€ during 2020-25 and 321 b€ during 2025-30, mainly in wind, solar PV and battery technologies, along with some in SNG. Beyond this the investment requirements decline to 254 b€ in 2035 and later stablise with investments around 166 b€ in 2040 to 186 b€ until 2050. Whereas, the operational expenditures increase from around 5 b€ in 2015 to just over 30 b€ in 2050 as shown in Figure 47.

Figure 46: MENA – Composition of LCOE with shares of LCOS, LCOC and LCOT along with fuel and CO2 costs from 2015 to 2050 (left) and composition of LCOE by various power generation technologies from 2015 to 2050 (right).

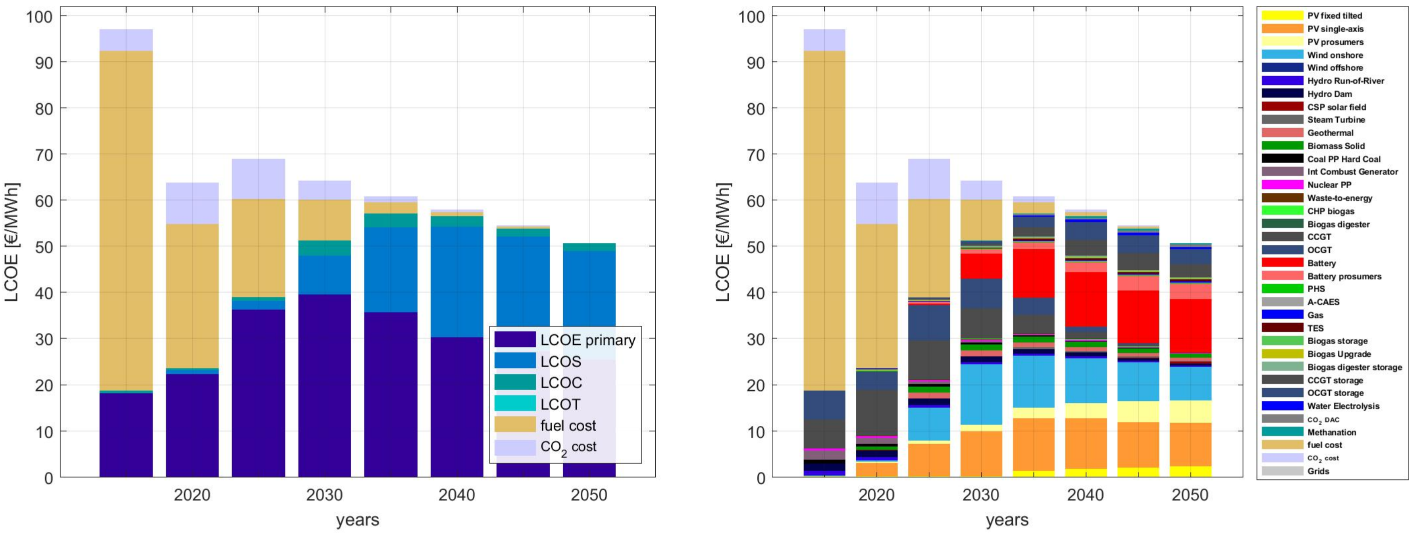


Figure 47: MENA - Capital investments required in power generation and storage technologies for every 5-year interval from 2020 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).

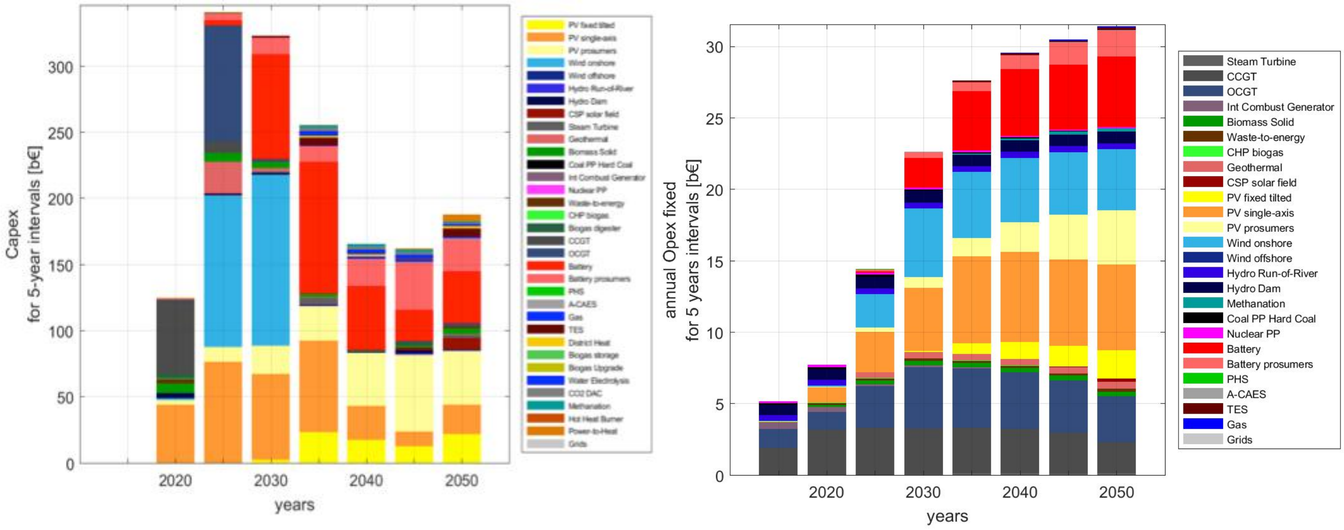


Table 16: MENA – LCOE and investment requirements during the energy transition for every 5-year interval from 2015 to 2050.

	Total LCOE [€/MWh]							
Composition	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
LCOE - Generation	96.5	62.5	66.3	52.6	39.4	31.6	28.0	25.3
LCOC - Curtailment	0.6	0.4	0.8	3.2	3.0	2.3	1.7	1.7
LCOS - Storage	0.0	0.9	1.8	8.4	18.4	24.0	24.8	23.7
LCOT - Transmission	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total LCOE	**97.1**	**63.8**	**68.9**	**64.2**	**60.8**	**57.9**	**54.5**	**50.7**
	Investments for 5-year periods [b€]							
Capital Expenditure (CAPEX)		116	340	321	254	166	162	186

4.5 SUB-SAHARAN AFRICA

The energy system LCOE of the Sub-Saharan Africa region drops from 61 €/MWh in 2015 to 55 €/MWh in 2020 and then onwards continues with a decline from 2030 until 2050. The LCOE is observed to reduce from 61 €/MWh to 43 €/MWh during the entire transition period from 2015 to 2050, including all generation, storage, curtailment and parts of the grid costs, i.e. all transmission and distribution losses and full costs of connecting individually modelled regions of the same country, which is shown in Figure 48 and Table 17. If the energy system mix for the year 2050 would have been built with the assumptions for the year 2050, the LCOE would further decline to around 35 €/MWh, a cost level that can be expected in the years beyond 2050 in Sub-Saharan Africa.

The LCOE in the year 2050 is mainly composed of solar PV and batteries, along with some bioenergy, hydropower and wind energy as shown in Figure 48. Also, the fuel cost component of the LCOE decreases significantly from 2015 to 2035, mainly with the phase out of expensive oil, gas and coal based electricty in Sub-Saharan Africa.

The capital investment required for each 5-year interval during the energy transition from 2015 to 2050 is shown in Figure 49 and Table 17. The investment required increases substantially from 52 b€ in 2020 to 143 b€ in 2025, then onwards it stabilises in the period between 2025 and 2040, initially driven mainly by investments in wind, solar PV and battery technologies, along with some in hydropower. Beyond this the invest-ment requirements again increase to 194 b€ in 2045 and further to 246 b€ until 2050. This increase in investment requirement is characte-ristied by the high growth potential in Africa. Whereas, the operational expenditures increase gradually from around 3 b€ in 2015 to around 30 b€ in 2050 as shown in Figure 49.

Figure 48: Sub-Saharan Africa – Composition of LCOE with shares of LCOS, LCOC and LCOT along with fuel and CO2 costs from 2015 to 2050 (left) and composition of LCOE by various power generation technologies from 2015 to 2050 (right).

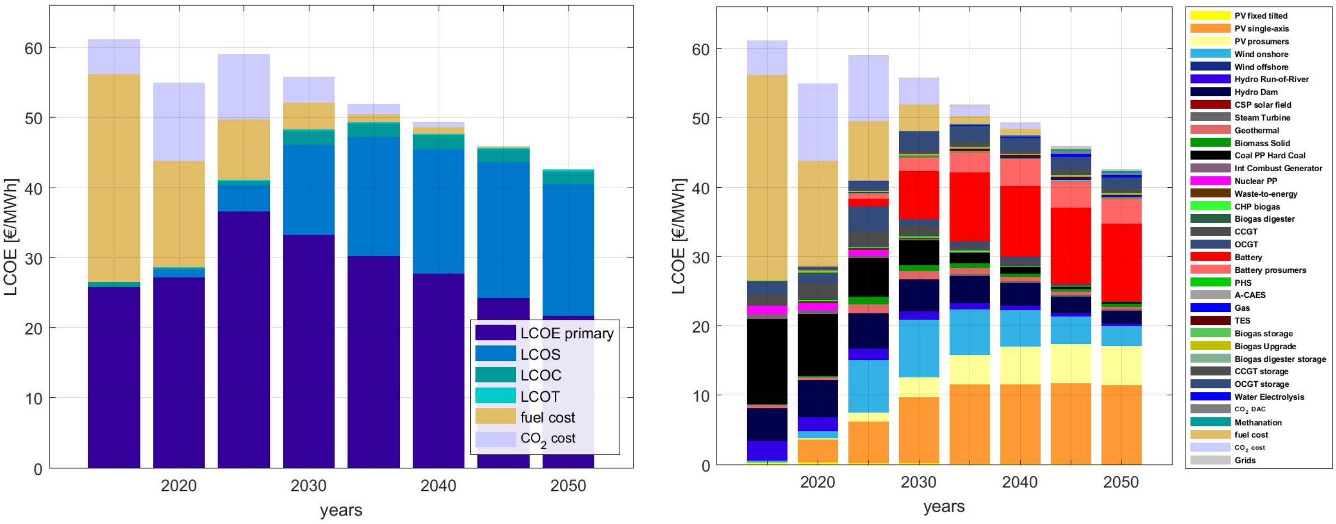


Figure 49: Sub-Saharan Africa - Capital investments required in power generation and storage technologies for every 5-year interval from 2020 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).

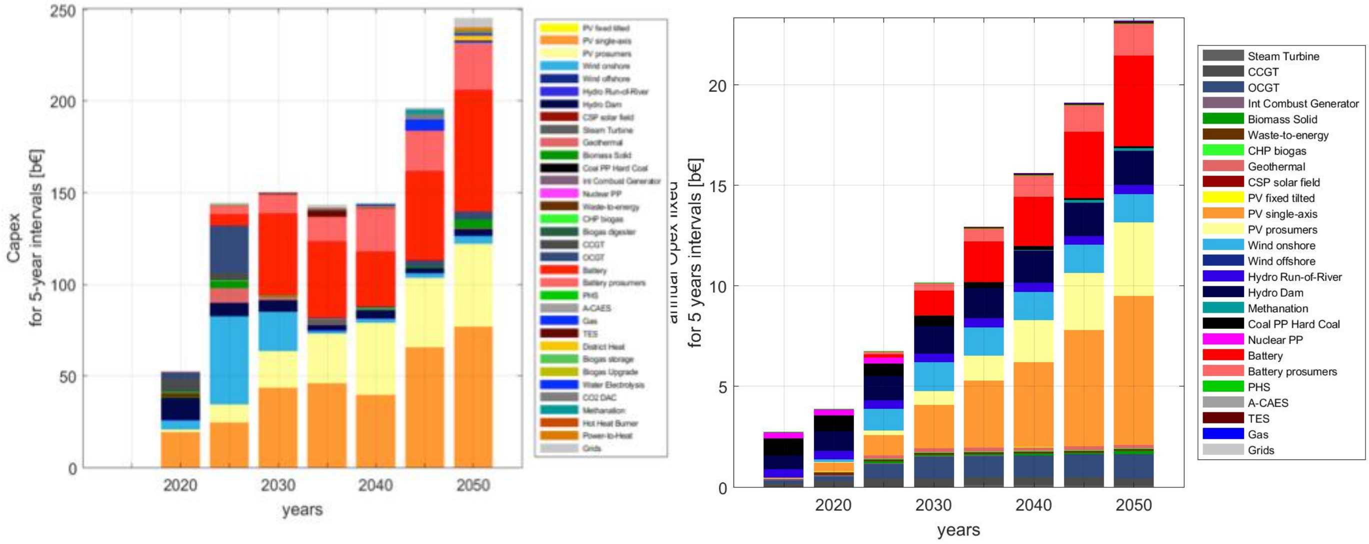


Table 17: Sub-Saharan Africa – LCOE and investment requirements during the energy transition for every 5-year interval from 2015 to 2050.

	Total LCOE [€/MWh]							
Composition	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
LCOE - Generation	60.4	53.6	54.5	40.7	32.8	29.3	24.4	21.7
LCOC - Curtailment	0.7	0.3	0.5	2.1	1.9	2.1	1.9	1.8
LCOS - Storage	0.1	1.1	3.8	12.8	17.0	17.7	19.4	18.8
LCOT - Transmission	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.3
Total LCOE	**61.2**	**55.0**	**59.0**	**55.8**	**51.9**	**49.3**	**45.9**	**42.6**
	Investments for 5-year periods [b€]							
Capital Expenditure (CAPEX)		52	143	148	142	143	194	246

4.6 SAARC

The energy system LCOE of the SAARC region increases intially from 60 €/MWh in 2015 to 66 €/MWh in 2025 and then onwards continues with a decline from 2025 until 2050. The LCOE is observed to reduce from 60 €/MWh to 50 €/MWh during the entire transition period from 2015 to 2050, including all generation, storage, curtailment and parts of the grid costs, i.e. all transmission and distribution losses and full costs of connecting individually modelled regions of the same country, which is shown in Figure 50 and Table 18. If the energy system mix for the year 2050 would have been built with the assumptions for the year 2050, the LCOE would further decline to around 39 €/MWh, a cost level that can be expected in the years beyond 2050 in the SAARC region.

The LCOE in the year 2050 is mainly composed of solar PV and batteries, along with some wind energy, bioenergy and hydropower as shown in Figure 50. Also, the fuel cost component of the LCOE decreases substantially from 2015 to 2030, mainly with the phase out of expensive and polluting coal and gas based electricty in the SAARC region.

The capital investment required for each 5-year interval during the energy transition from 2015 to 2050 is shown in Figure 51 and Table 18. The investment required increases substantially from 157 b€ in 2020 to 380 b€ in 2025, and further increase to 656 b€ between 2025 and 2030. Beyond this it drops to 414 b€ in 2040 and increases in the period between 2040 to 2050 to 530 b€, initially driven mainly by investments in wind, solar PV and battery technologies, along with some in hydropower. This substantial increase in investment requirement is characteristied by the high growth in the South Asian region. Whereas, the operational expenditures increases gradually from around 10 b€ in 2015 to around 65 b€ in 2050 as shown in Figure 51.

Figure 50: SAARC – Composition of LCOE with shares of LCOS, LCOC and LCOT along with fuel and CO2 costs from 2015 to 2050 (left) and composition of LCOE by various power generation technologies from 2015 to 2050 (right).

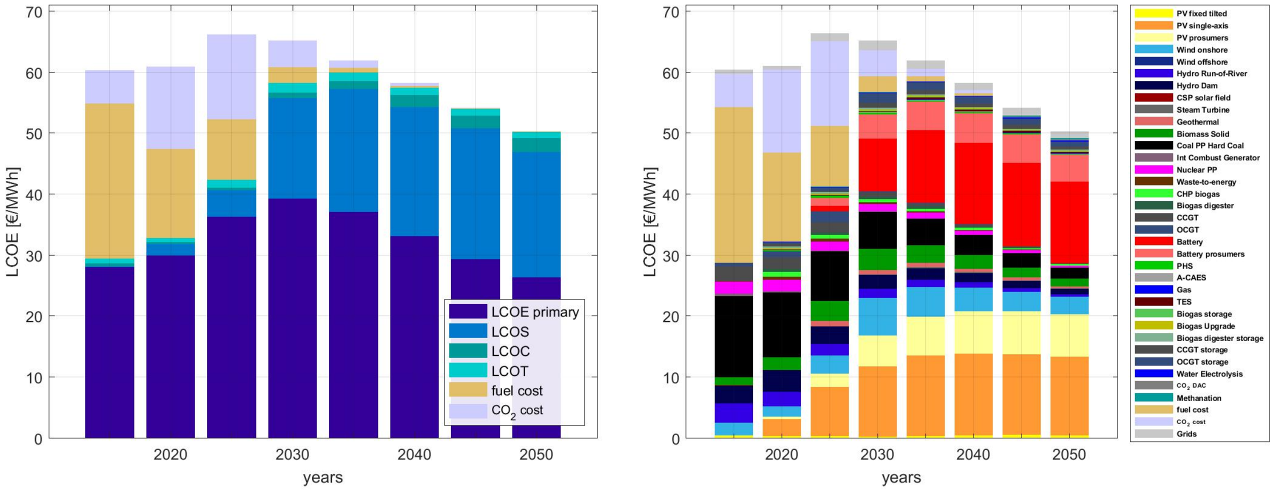


Figure 51: SAARC - Capital investments required in power generation and storage technologies for every 5-year interval from 2020 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).

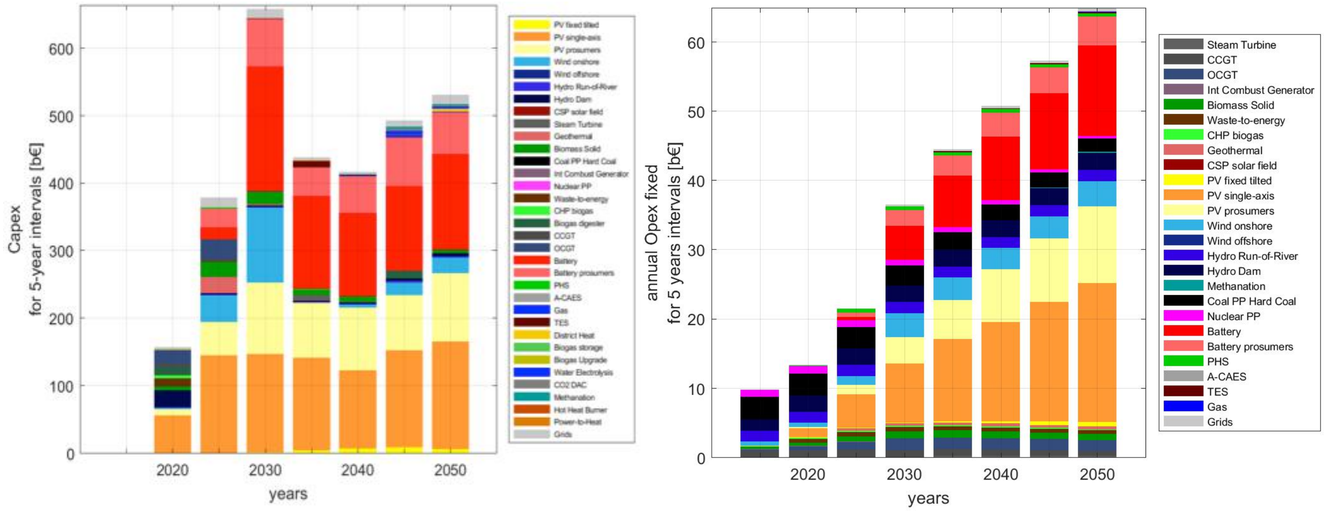


Table 18: SAARC – LCOE and investment requirements during the energy transition for every 5-year interval from 2015 to 2050.

	Total LCOE [€/MWh]							
Composition	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
LCOE - Generation	59.0	58.1	60.2	46.1	39.1	33.9	29.4	26.4
LCOC - Curtailment	0.5	0.3	0.4	1.0	1.3	2.0	2.1	2.2
LCOS - Storage	0.1	1.9	4.4	16.4	20.1	21.1	21.5	20.5
LCOT - Transmission	0.7	0.6	1.2	1.6	1.4	1.2	1.1	1.1
Total LCOE	**60.3**	**60.9**	**66.2**	**65.1**	**61.9**	**58.2**	**54.1**	**50.2**
	Investments for 5-year periods [b€]							
Capital Expenditure (CAPEX)		157	380	656	437	414	490	530

4.7 NORTHEAST ASIA

The Northeast Asian energy system LCOE remains rather stable after a slight drop for the first couple of decades until 2030, afterwards showing a gradual decline from 74 €/MWh to 55 €/MWh from 2015 to 2050, including all generation, storage, curtailment and parts of the grid costs, i.e. all transmission and distribution losses and full costs of connecting individually modelled regions of the same country, which is shown in Figure 52 and Table 19. If the energy system mix for the year 2050 would have been built with the assumptions for the year 2050, the LCOE would further decline to around 45 €/MWh, a cost level that can be expected in the years beyond 2050 in Northeast Asia.

The LCOE in the year 2050 is mainly composed of solar PV and batteries, along with some wind energy and hydropower as shown in Figure 52.

Also, the fuel cost component of the LCOE decreases substantially from 2015 to 2030, mainly with the phase out of expensive and polluting coal, gas and nuclear based electricty in Northeast Asia.

The capital investment required for each 5-year interval during the energy transition from 2015 to 2050 is shown in Figure 53 and Table 19. The period between 2020 and 2030 is when high investments are required, with 1345 b€ during 2020-25 and 1162 b€ during 2025-30, mainly in wind, solar PV and battery technologies. Beyond this the investment requirements continue to decline steadily with investment needs dropping to about 750 b€ in 2040 and then increasing to 1098 b€ in 2050. Whereas, the operational expen-ditures increase gradually from around 60 b€ in 2015 to 155 b€ in 2050 as shown in Figure 53.

Figure 52: Northeast Asia – Composition of LCOE with shares of LCOS, LCOC and LCOT along with fuel and CO2 costs from 2015 to 2050 (left) and composition of LCOE by various power generation technologies from 2015 to 2050 (right).

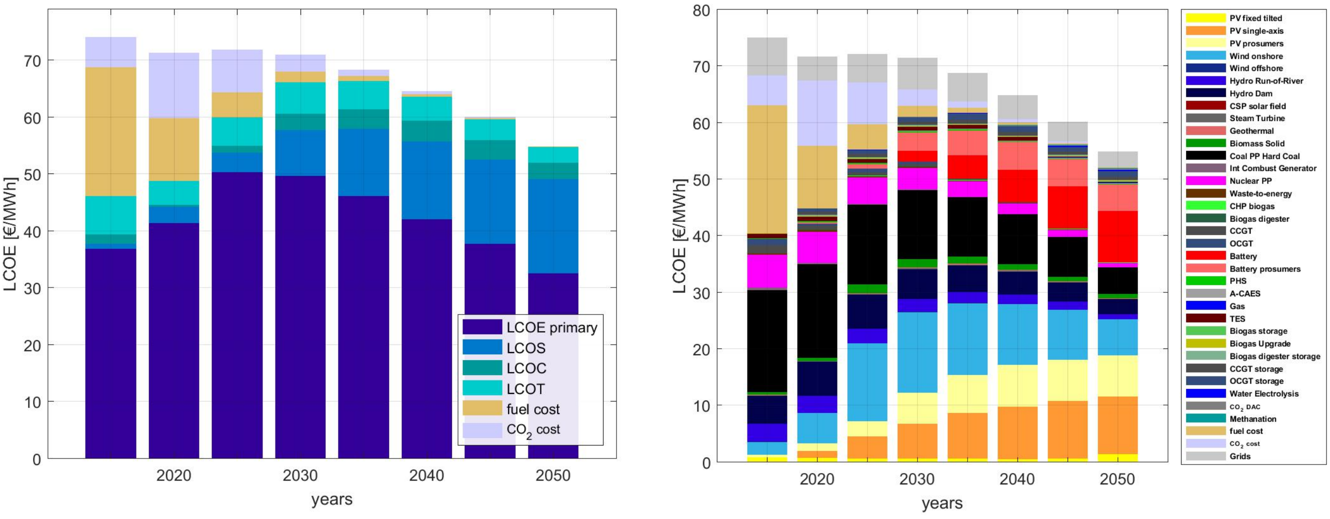


Figure 53: Northeast Asia - Capital investments required in power generation and storage technologies for every 5-year interval from 2020 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).

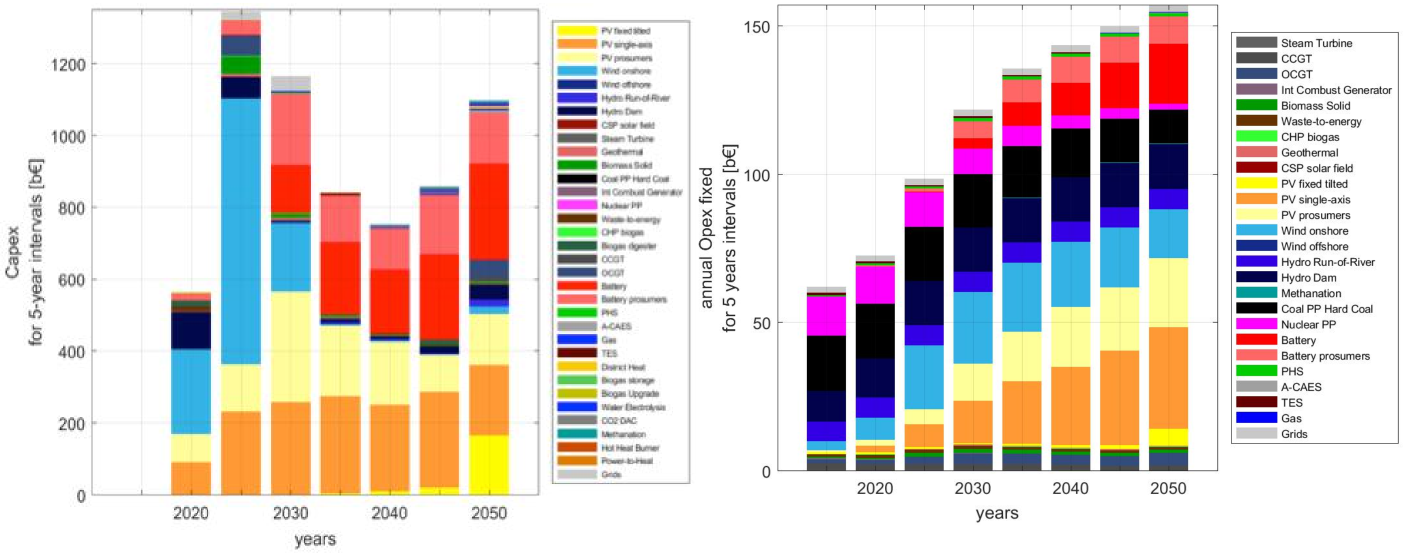


Table 19: Northeast Asia – LCOE and investment requirements during the energy transition for every 5-year interval from 2015 to 2050.

	Total LCOE [€/MWh]							
Composition	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
LCOE - Generation	64.6	64.0	62.2	54.4	48.1	43.1	38.1	32.5
LCOC - Curtailment	1.6	0.3	1.2	2.9	3.4	3.6	3.4	2.8
LCOS - Storage	1.0	2.9	3.4	8.1	11.8	13.7	14.9	16.7
LCOT - Transmission	6.8	4.1	5.0	5.6	5.0	4.2	3.6	2.8
Total LCOE	**74.0**	**71.3**	**71.8**	**71.0**	**68.3**	**64.6**	**60.0**	**54.8**
	Investments for 5-year periods [b€]							
Capital Expenditure (CAPEX)		560	1345	1162	840	750	856	1098

4.8 SOUTHEAST ASIA

The Southeast Asian energy system LCOE remains rather stable after a slight drop for the first couple of decades until 2030, afterwards showing a gradual decline from 66 €/MWh to 53 €/MWh from 2015 to 2050, including all generation, storage, curtailment and parts of the grid costs, i.e. all transmission and distribution losses and full costs of connecting individually modelled regions of the same country, which is shown in Figure 54 and Table 20. If the energy system mix for the year 2050 would have been built with the assumptions for the year 2050, the LCOE would further decline to around 40 €/MWh, a cost level that can be expected in the years beyond 2050 in the region of Southeast Asia.

The LCOE in the year 2050 is mainly composed of solar PV and batteries, along with some wind energy and bioenergy as shown in Figure 54.

Also, the fuel cost component of the LCOE decreases significantly from 2015 to 2030, mainly with the phase out of expensive and polluting coal and gas based electricty in Southeast Asia.

The capital investment required for each 5-year interval during the energy transition from 2015 to 2050 is shown in Figure 55 and Table 20. The period between 2020 and 2035 is when high investments are required with 302 b€ during 2020-25, 407 b€ during 2025-30 and 337 b€ during 2030-35, mainly in wind, solar PV and battery technologies. Beyond this the investment requirements drop to 224 b€ in 2040 and continue to increase steadily with investment needs increasing to 361 b€ in 2050. Whereas, the operational expenditures increase gradually from around 6 b€ in 2015 to over 40 b€ in 2050 as shown in Figure 55.

Figure 54: Southeast Asia – Composition of LCOE with shares of LCOS, LCOC and LCOT along with fuel and CO2 costs from 2015 to 2050 (left) and composition of LCOE by various power generation technologies from 2015 to 2050 (right).

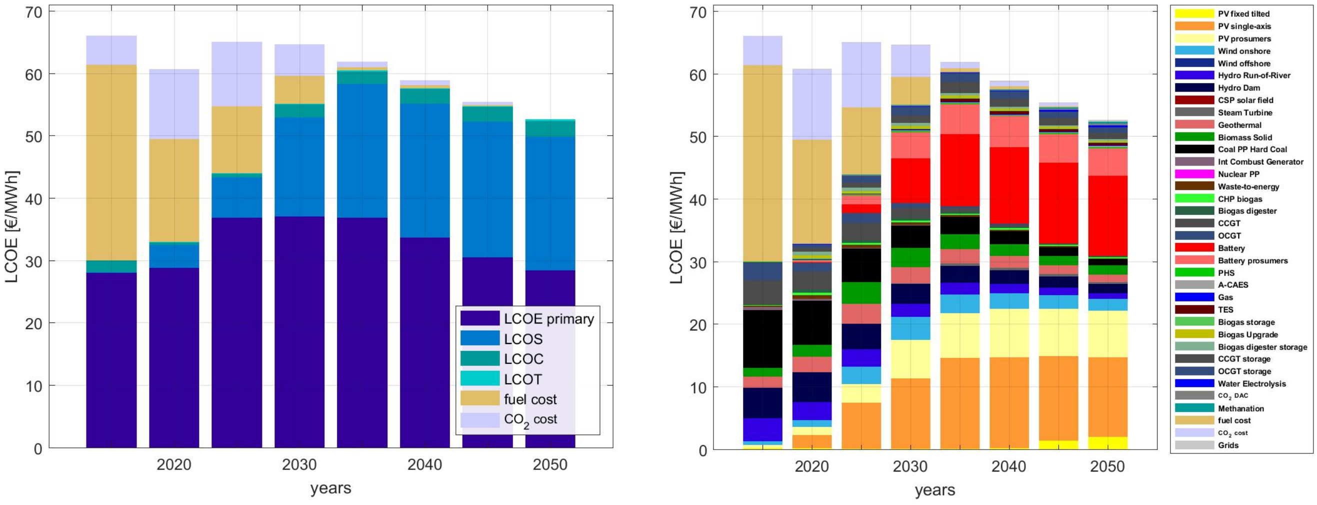


Figure 55: Southeast Asia - Capital investments required in power generation and storage technologies for every 5-year interval from 2020 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).

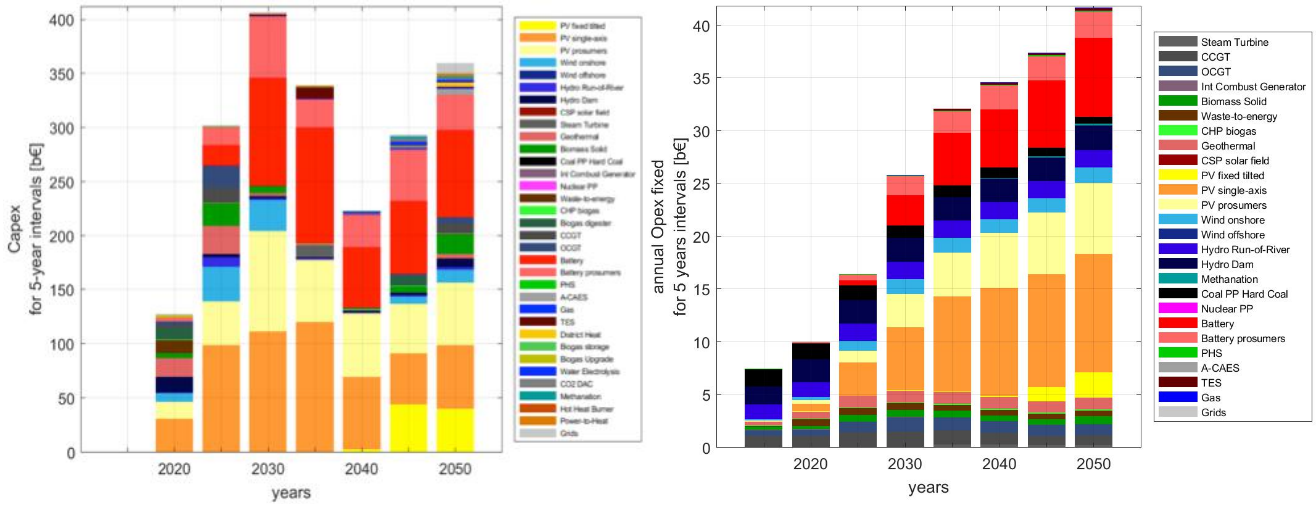


Table 20: Southeast Asia – LCOE and investment requirements during the energy transition for every 5-year interval from 2015 to 2050.

	Total LCOE [€/MWh]							
Composition	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
LCOE - Generation	64.2	56.6	57.9	46.7	38.2	34.9	31.2	28.4
LCOC - Curtailment	1.8	0.4	0.6	2.0	2.0	2.4	2.4	2.5
LCOS - Storage	0.1	3.7	6.4	15.9	21.6	21.5	21.7	21.4
LCOT - Transmission	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.3
Total LCOE	**66.1**	**60.7**	**65.0**	**64.7**	**61.9**	**58.9**	**55.4**	**52.6**
	Investments for 5-year periods [b€]							
Capital Expenditure (CAPEX)		127	302	407	337	224	291	361

4.9 NORTH AMERICA

The North American energy system LCOE remains rather stable after a slight drop intially for the first couple of decades until 2030, post that showing a gradual decline from 64 €/MWh to 53 €/MWh from 2015 to 2050, including all generation, storage, curtailment and parts of the grid costs, i.e. all transmission and distribution losses and full costs of connecting individually modelled regions of the same country, which is shown in Figure 56 and Table 21. If the energy system mix for the year 2050 would have been built with the assumptions for the year 2050, the LCOE would further decline to around 41 €/MWh, a cost level that can be expected in the years beyond 2050 in North America.

The LCOE in the year 2050 is mainly composed of solar PV and batteries, along with some wind energy and hydropower as shown in Figure 56.

Also, the fuel cost component of the LCOE decreases substantially from 2015 to 2035, mainly with the phase out of expensive and polluting coal, gas and nuclear based electricty in North America.

The capital investment required for each 5-year interval during the energy transition from 2015 to 2050 is shown in Figure 57 and Table 21. The period between 2020 and 2030 is when high investments are required with 1228 b€ during 2020-25 and 696 b€ during 2025-30, mainly in wind, solar PV and battery technologies. Beyond this the investment requirements continue to decline steadily with investment needs dropping to about 234 b€ in 2050. Whereas, the operational expenditures intially increase from around 50 b€ in 2015 to over 70 b€ in 2030 and reamins stable until 2050 as shown in Figure 57.

Figure 56: North America – Composition of LCOE with shares of LCOS, LCOC and LCOT along with fuel and CO2 costs from 2015 to 2050 (left) and composition of LCOE by various power generation technologies from 2015 to 2050 (right).

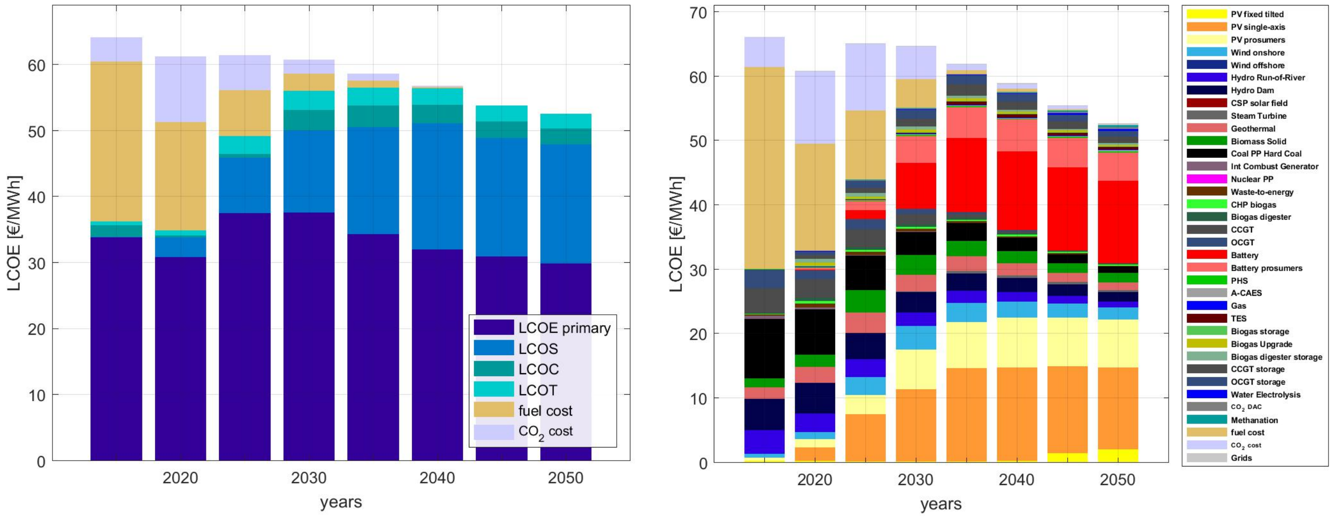


Figure 57: North America - Capital investments required in power generation and storage technologies for every 5-year interval from 2020 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).

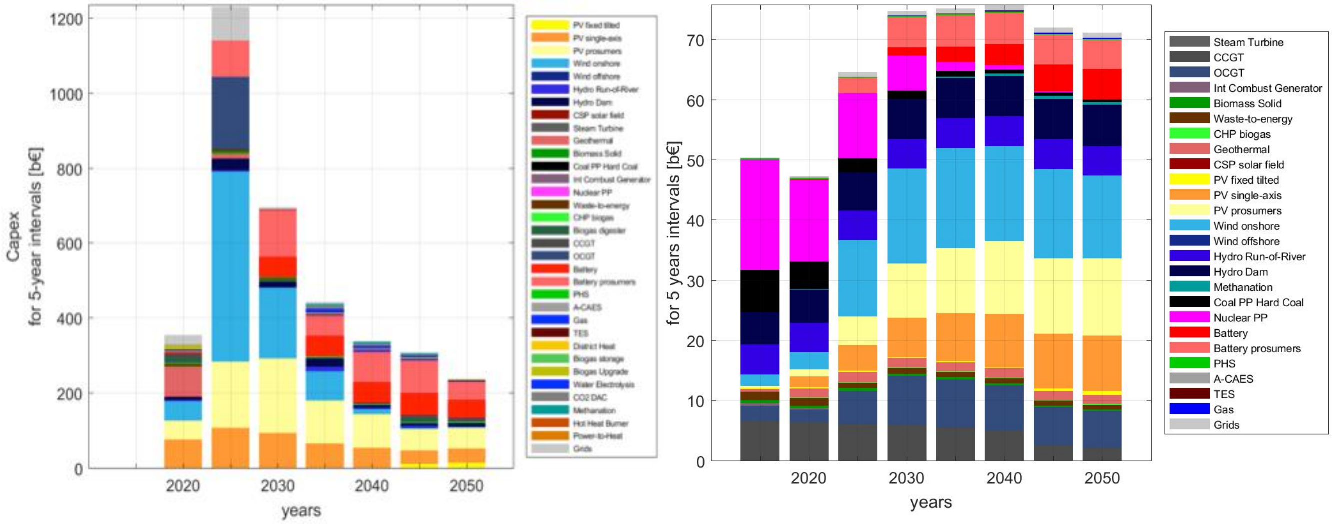


Table 21: North America – LCOE and investment requirements during the energy transition for every 5-year interval from 2015 to 2050.

	Total LCOE [€/MWh]							
Composition	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
LCOE - Generation	61.8	57.1	49.7	42.3	36.4	32.4	30.9	29.9
LCOC - Curtailment	1.7	0.3	0.6	3.1	3.3	2.8	2.5	2.4
LCOS - Storage	0.1	3.0	8.4	12.4	16.2	19.1	18.0	18.0
LCOT - Transmission	0.5	0.8	2.7	2.9	2.7	2.5	2.4	2.2
Total LCOE	**64.1**	**61.2**	**61.4**	**60.7**	**58.6**	**56.8**	**53.8**	**52.5**
	Investments for 5-year periods [b€]							
Capital Expenditure (CAPEX)		354	1228	696	442	337	307	234

4.10 SOUTH AMERICA

The South American energy system LCOE drops substantially from 68 €/MWh in 2015 to 51 €/MWh in 2020. Beyond this the LCOE gradually declines from 51 €/MWh to 39 €/MWh from 2020 to 2050, including all generation, storage, curtailment and parts of the grid costs, i.e. all transmission and distribution losses and full costs of connecting individually modelled regions of the same country, which is shown in Figure 58 and Table 22. If the energy system mix for the year 2050 would have been built with the assumptions for the year 2050, the LCOE would further decline to around 32 €/MWh, a cost level that can be expected in the years beyond 2050 in South America.

The LCOE in the year 2050 is mainly composed of solar PV, hydropopwer and batteries, along with some bioenergy and wind energy as shown in Figure 58. Also, the fuel cost component of the LCOE decreases rapidly from 2015 to 2020, mainly with the phase out of expensive and polluting coal and gas based electricty in South

The capital investment required for each 5-year interval during the energy transition from 2015 to 2050 is shown in Figure 59 and Table 22. The investment requirements are in two periods between 2015-2030 when higher investments are required with 177 b€ during 2015-20 and 125 b€ during 2025-30, mainly in wind, solar PV and battery technologies. During the second period between 2030 and 2050, investment requirements drop to about 83 b€ during 2030-35 and increase to 133 b€ until 2050. Whereas, the operational expenditures increase gradually from about 11 b€ to around 25 b€ in 2050 as shown in Figure 59.

Figure 58: South America – Composition of LCOE with shares of LCOS, LCOC and LCOT along with fuel and CO2 costs from 2015 to 2050 (left) and composition of LCOE by various power generation technologies from 2015 to 2050 (right).

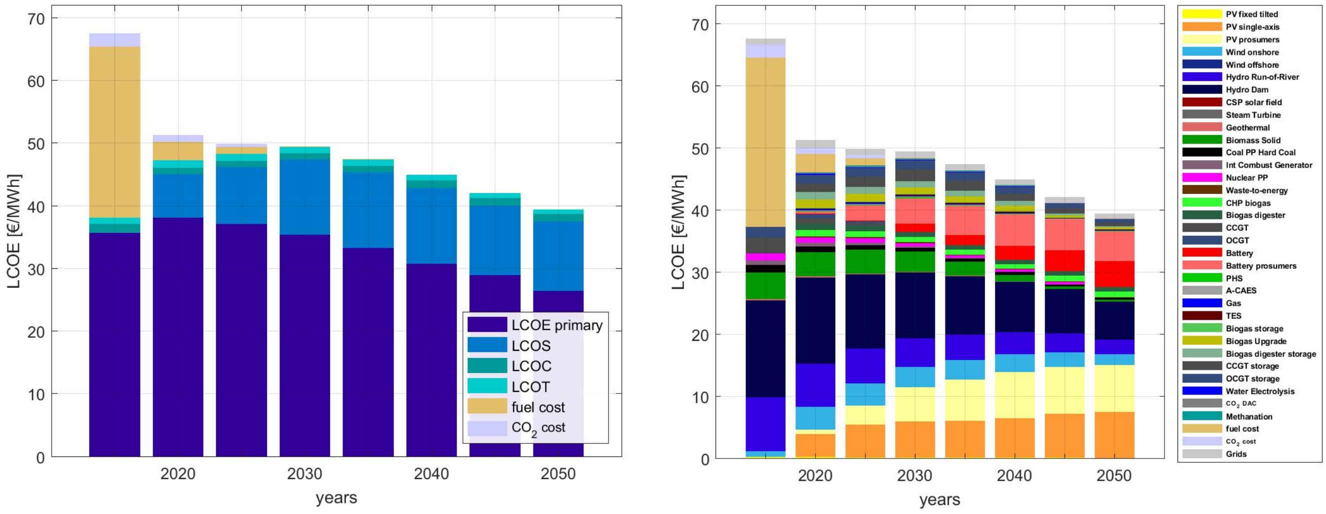


Figure 59: South America - Capital investments required in power generation and storage technologies for every 5-year interval from 2020 to 2050 (left) and annual operational expenditure required in power generation and storage technologies for every 5-year interval from 2015 to 2050 (right).

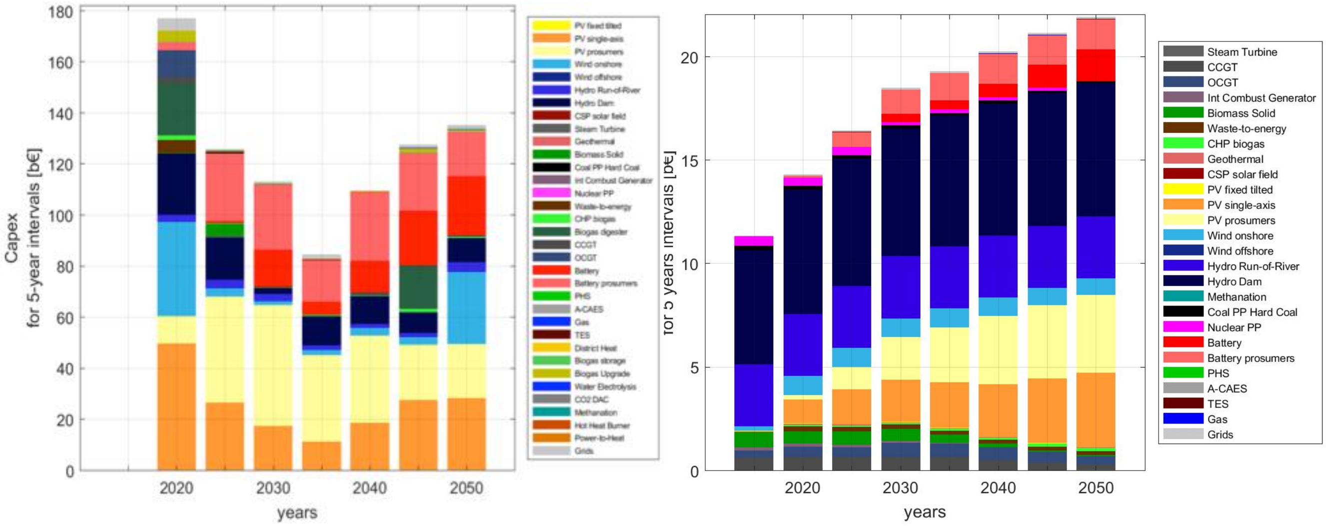


Table 22: South America – LCOE and investment requirements during the energy transition for every 5-year interval from 2015 to 2050.

	Total LCOE [€/MWh]							
Composition	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
LCOE - Generation	65.1	42.0	38.8	35.4	33.3	30.9	29.1	26.3
LCOC - Curtailment	1.4	1.0	1.0	1.0	1.0	1.2	1.2	1.2
LCOS - Storage	0.0	7.0	9.1	12.0	12.1	12.1	11.0	11.1
LCOT - Transmission	1.0	1.2	1.0	1.0	1.0	0.9	0.8	0.8
Total LCOE	**67.5**	**51.2**	**49.9**	**49.4**	**47.4**	**44.9**	**42.1**	**39.4**
	Investments for 5-year periods [b€]							
Capital Expenditure (CAPEX)		177	125	113	83	108	128	133

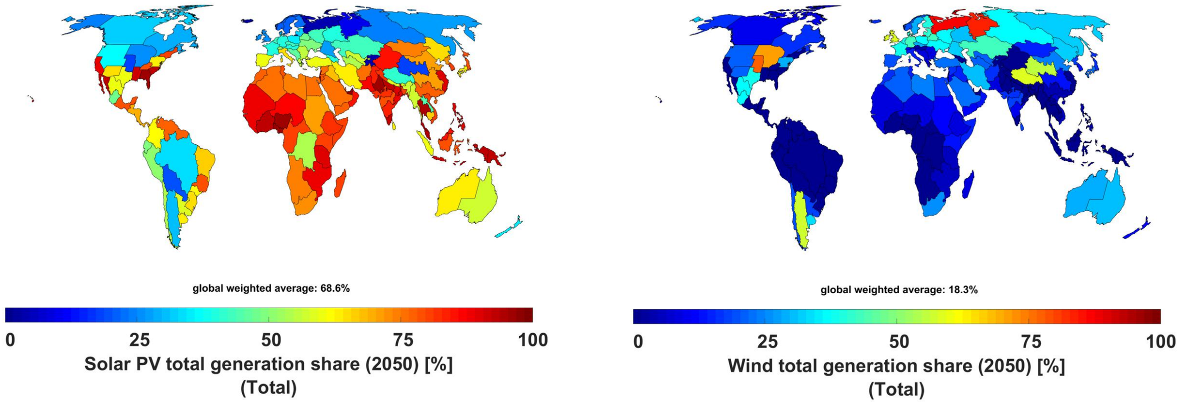
5. SOCIO-ECONOMIC BENEFITS OF THE GLOBAL 100% RENEWABLE ELECTRICITY SYSTEM

As this research indicates, a global 100% renewable electricty system will not only ensure meeting the goals set by the Paris Agreement by achieving deep decarbonisation of the global power sector earlier than 2050 and achieving zero GHG emissions by 2050, but also bring about a multitude of socio-economic benefits to the global society.[93, 94, 95]

The global average solar PV electricity generation share of 69% is comprised of Sun Belt countries with a typical solar PV electricity share of 90% and more. Some countries have a lower share of solar PV due to strong or very strong seasonality, or excellent availability of other RE resources and partly due to limited future electricity demand growth as indiacted in Figure 60. Regions around the latitudes of 45° N and higher show a strong seasonality effect, i.e. parts of North America, Europe and Eurasia. The effects of excellent potential among other RE resources can be observed for instance in Russia, with excellent wind, and hydropower in Siberia and the Far Eastern region.

Similary, Brazil has excellent hydropower potential, parts of Canada and Laos also have vast hydropower generation as shown in Figure 61, and Sumatra in Indonesia has excellent geothermal energy resources. Seasonality leads to a well balanced mix of solar PV and wind energy in some of these regions. Whereas, for regions at lower latitudes and not in the proximity of the equator a very good combination of solar PV and wind energy throughout the year is displayed, in particular until 2030.

Figure 60: Shares of solar PV (left) and wind (right) electricity generation across the world in 2050.



Batteries are the most important supporting technology for the energy transition, since storage output covers 31% of the total demand in 2050, of which 95% is contributed solely by batteries as show in Figure 62. Batteries not only complement PV prosumers, but also complement large-scale installations as costs continue to decline during the transition period. Along with this, gas storage in combination with electrolysers that utilise electricity to pro-duce SNG through methanation play a critical role in addressing the seasonality effects as the produced SNG is utlised as fuel for flexible gas turbines. Since the demand is mainly in few regions, the supply shares across the world are quite low as indicated in Figure 62 in comparision to batteries. This is due to the fact that bio-methane can be also used for seasonal balancing with a composition of 51% bio-methane and 49% SNG for sustainable gas supply in 2050. Along with the right mix of tranmission grid lines, storage technologies can play a vital role in enhancing solar-wind complementarity to ensure year round power supply based entirely on renewables, as shown by research for India in mitigating the monsoon effect.[96]

As the results have indicated, a 100% renewable electricty system globally is not a technical challenge anymore and neither is it an economic one. On the contrary, it is techninally feasible, resulting in a far more effcient and smart global energy system, while also economically viable, with energy costs declining through the year across the various regions of the world as shown earlier. A 100% renewable electricty system can deliver an affordable, more efficient, job-creating and zero-emission global power system.

Figure 61: Shares of hydro electricity generation across the world in 2050.

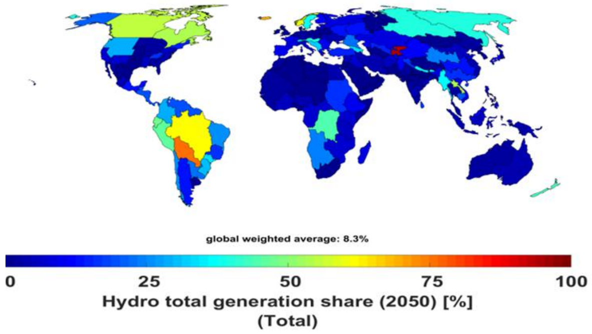
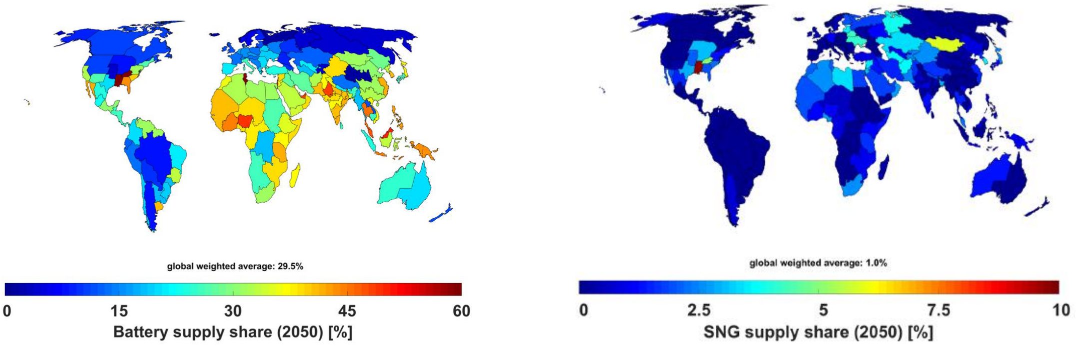


Figure 62: Shares of battery storage supply (left) and SNG supply (right) of the total electricity supply across the world in 2050.



Affordable global power system

The achieved global average energy system LCOE of 52 €/MWh is highly competitive. Only some cost related to grids are missing, but other research[97] shows that this cost is about 10-15% of the total cost of power systems. Hence, no major distortion of the obtained results can be expected and the low LCOE is observed a-cross the different regions of the world with a few excpetions that have slightly higher LCOEs as shown in Figure 63.

A slower energy system transition may most likely induce a higher total energy system cost, as indicated by respective research results for the case of Iran.[98] As shown by Fig. 64, primary electricity generation contributes 60% to the total electricity system cost in 2050 and the cost for storage contributes 30% to the total electricity system cost.

Theoretically, other available energy system options, such as fossil-CCS and nuclear energy cannot compete at that cost level at all, since their individual LCOEs are around 100 €/MWh and higher.[99, 100] These other technologies also involve further risks for society and also require additional subsidies not included in the mentioned cost level.[87] Furthermore, nuclear energy and fossil-CCS do not adhere to sustainability guardrails that should form a framework of resilient energy system design.[101] Nevertheless, it could be taken into account to accept some active nuclear power plant construction sites for commissioning in the period till 2020. The strict sustainability criteria have been weighted as more relevant in this research, and the risk of stranded nuclear power plant construction sites is not

Figure 63: Total LCOE in 2050 across the different regions of the world.

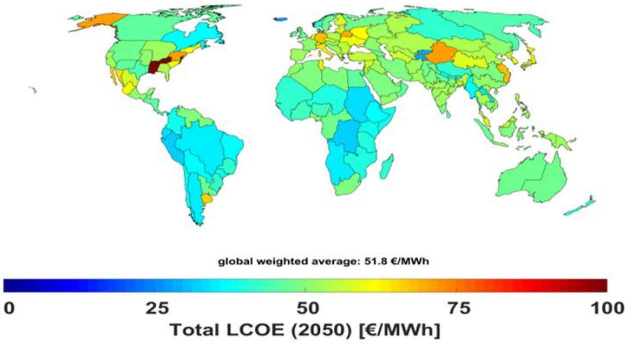
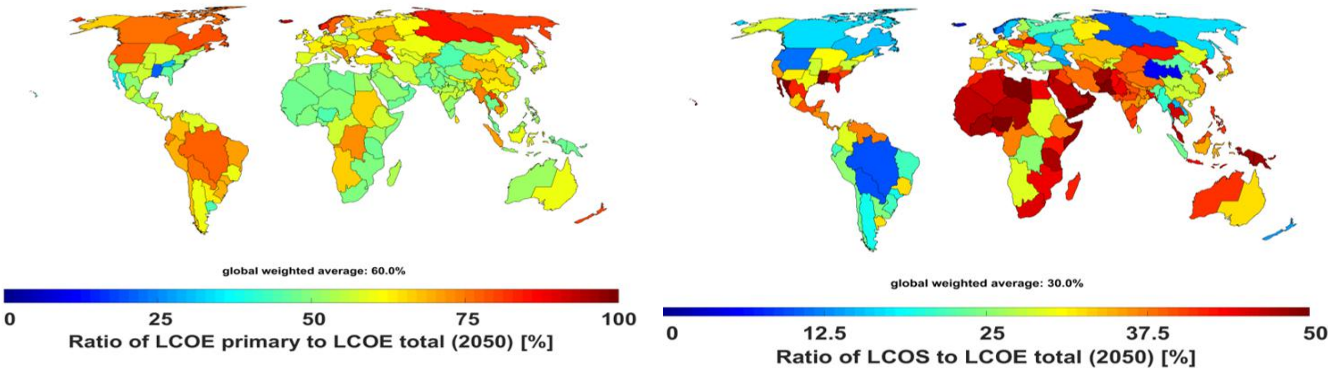


Figure 64: The ratios of LCOE primary to the Total LCOE (left) and LCOS to Total LCOE (right) across the different regions of the world in 2050.



negligible as recently documented by two stranded construction sites in South Carolina in the US, after 9 bUSD investments and due to economic reasons, since a continuation would have further increased the losses for the involved utilities with no hope for amortisation of the invested capital.[102] Coal-based power plants are still commissioned in several countries. However, large capacities which had been permitted or were even under construction have been cancelled, and recently added plants have already become stranded assets.[87] On the whole, a 100% renewable electricty system can bring down costs in the long run and ensure economic growth globally

More efficient global power system

The overall energy system losses referenced to the final electricity demand decrease drastically from around 139% in 2015 to just about 26% in 2050 (equivalent to 58% and 20% of primary energy input) as shown in Figure 65, indicating a huge efficiency gain globally with the energy transition. The large losses during primary energy to secondary energy conversion of present power plants (mainly based on nuclear, coal, gas, oil, biomass) drastically reduce by about 88%. This is mainly due to the phase out of thermal power plants during the energy transition. Also, transmission and distribution grid losses decrease globally to an average of 5.8% in relation to the final electricty demand by 2050 (equivalent to 4.9% of total electricity generation) as shown in Figure 65. This is mainly attributed to advanced grid management in presently emerging and developing countries.

Whereas, curtailment and storage losses increase to around 8.5% and 4.8% of the final electricity demand, respectively, (equivalent to 7.2% and 4.0% of the electricity generation) as shown in Figure 66. The shares of curtailment increase after 2030, mainly due to the prevailing low costs of renewable electricity, which enables curtailment as a low-cost flexibility option. The high efficiency of batteries ensures a low percentage of storage losses.

Figure 65: Total losses in reference to the final electricity demand during the energy transition from 2015 to 2050 (left) and grid losses across the different regions of the world in 2050 (right).

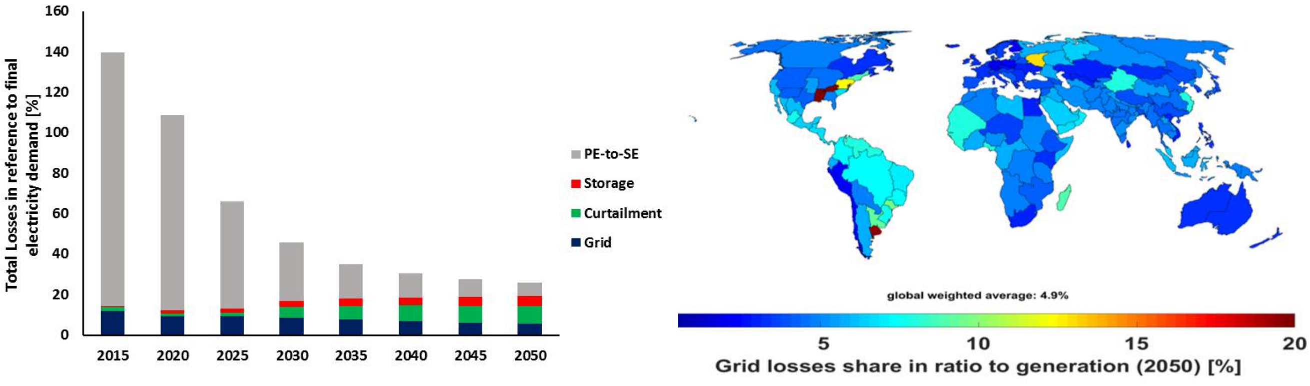
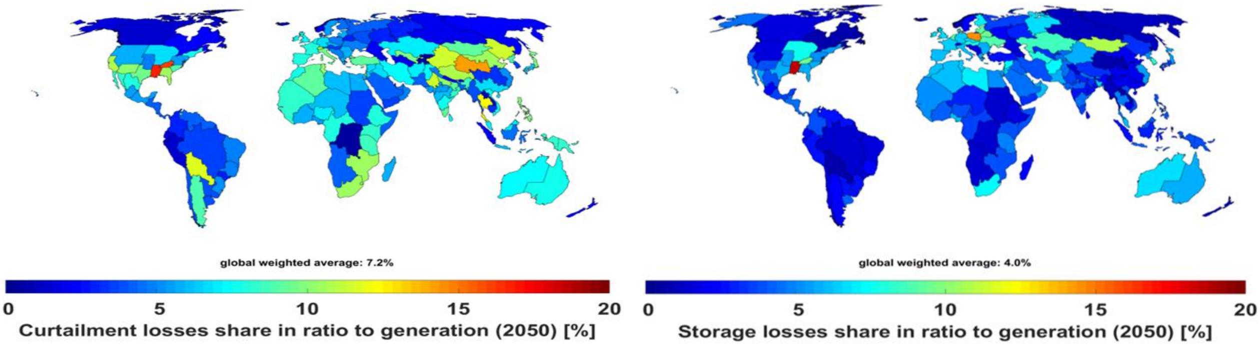


Figure 66: Share of curtailment losses in comparison to the generation (left) and storage losses in comparison to the generation (right) across the different regions of the world in 2050.



It is not yet well reported in scientific literature as to how efficient a 100% renewable electricity system will turn out to be. This is mainly a consequence of limited methodologies, in which full hourly resolution for energy transistion analyses is not yet state-of-the-art, in particular for global analyses.[10] Also, inadequate technology portfolios are used in the analyses, particularly lacking long-term storage options and having sub-optimal system designs.[103-105] Furthermore, outdated cost assumptions, especially for solar PV and batteries, lead to less balanced and less efficient energy systems. This report is the very first research on the high efficiency levels of 100% renewable electricity systems, whereas the significantly high primary to secondary energy losses of the current energy system, mainly based on thermal power plants, are neglected in many studies.

Job-creating global power system

A strong growth in the renewable sector leads to an increase of around 80% more direct energy sector jobs by 2030, and job numbers are nearly twice as high in 2050 as compared to 2015. Job numbers continue to rise after 2020, to reach around 34 million direct energy jobs by 2030. Beyond this point they stabilise around the 30 million range until 2045 and then increase to 36 million by 2050 as shown in Figure 67. This is mainly due to large capacities being replaced and reinvested in as they would reach end of their lifetimes. Renewable energy accounts for around 90% of total direct energy jobs by 2030. Solar PV, batteries and wind energy are the major job creating technologies during the energy transition from 2015 to 2050. Solar PV replaces coal as the most job creating energy resource with around 22 million jobs in 2050 in comparision to 2.6 million in 2015. Additionally, it is well complemented by battery storage creating around 5.8 million jobs by 2050 as shown in Figure 67.

A category-wise classification of jobs in manufacturing, construction and installation, operation and maintenance, fuel supply and transmission created during the energy transition from 2015 to 2050 is shown in Figure 68. It can be observed that by 2050 operation and maintenance jobs have the most significant share of the total jobs. This indicates that the transition towards a 100% RE power system enables more stable jobs, which can contribute to stable economic growth of countries mainly in the developing regions of the world. Furthermore, Figure 68 also illustrates the development of the electricity demand specific jobs, which is the ratio of the jobs created to the total electricty demand of the respective year. It can be observed that this remains quite stable through the transition, with 820 jobs/TWhel in 2015 and rising up to 1100 jobs/TWhel in 2030 due to larger investments during this period and around 740 jobs/TWhel in 2050.

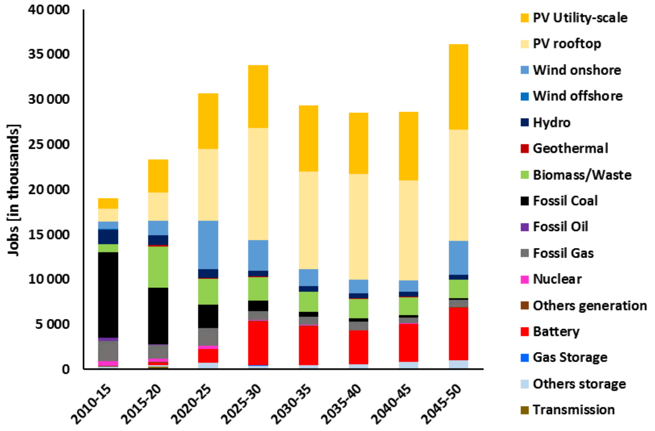


Figure 67: Jobs created by the various power generation and storage technologies during the energy transition from 2015 to 2050.

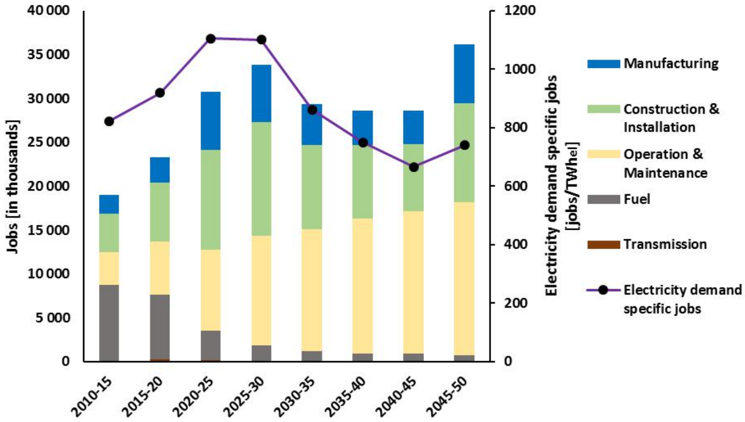


Figure 68: Jobs created based on different categories and the development of electricity demand specific jobs during the energy transition from 2015 to 2050.

Development of the global power system to zero GHG emissions

GHG emissions can be reduced from about 11 GtCO2eq in 2015 to zero by 2050 (Figure 69), while the total LCOE of the power system declines (Figure 40). The presented 100% RE scenario for the global power sector supports the Paris Agreement very well. What is even more important is the observation that a deep decarbonisation of 95% to 0.5 GtCO2eq by 2035 and 98% to 0.2 GtCO2eq by 2040 is possible, which is well before 2050, while gradually lowering the energy system LCOE.

Similarly, Europe shows a gradual decline from 1200 MtCO2eq in 2015 to around 150 MtCO2eq by 2030 as indicated in Figure 70. Meanwhile, the region of Eurasia shows a dramatic reduction from around 350 MtCO2eq in 2020 to around 25 MtCO2eq in 2030 as shown in Figure 70.

In the case of the MENA region, a steady reduction in emissions from 700 MtCO2eq in 2015 to just over 100 MtCO2eq in 2030 is achieved during the energy transition as shown in Figure 71. Similarly, Sub-Saharan Africa also shows a gradual reduction in GHG emissions from around 275 MtCO2eq to around 50 MtCO2eq in 2030 as shown in Figure 71.

Figure 69: Global - CO2 emission reduction during the energy transition from 2015 to 2050.

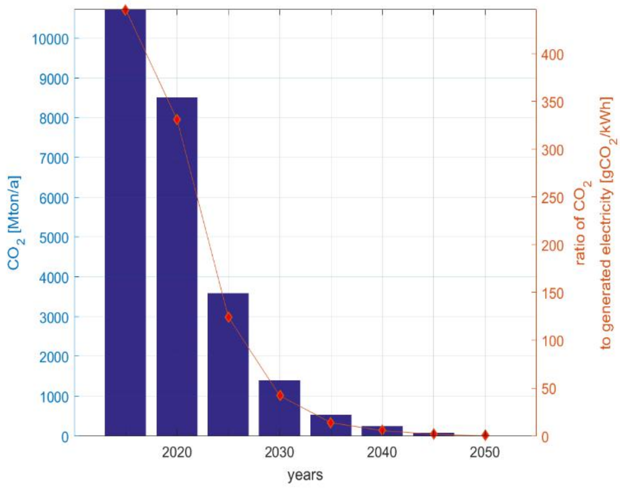


Figure 70: Europe (left) and Eurasia (right) - CO2 emission reduction during the energy transition from 2015 to 2050.

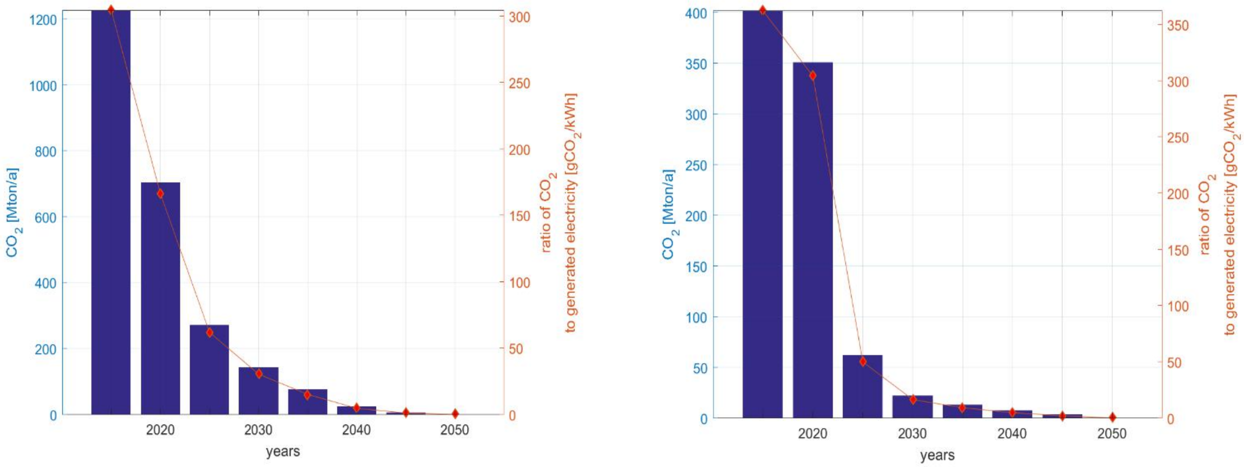


Figure 71: MENA (left) and Sub-Saharan Africa (right) - CO2 emission reduction during the energy transition from 2015 to 2050.

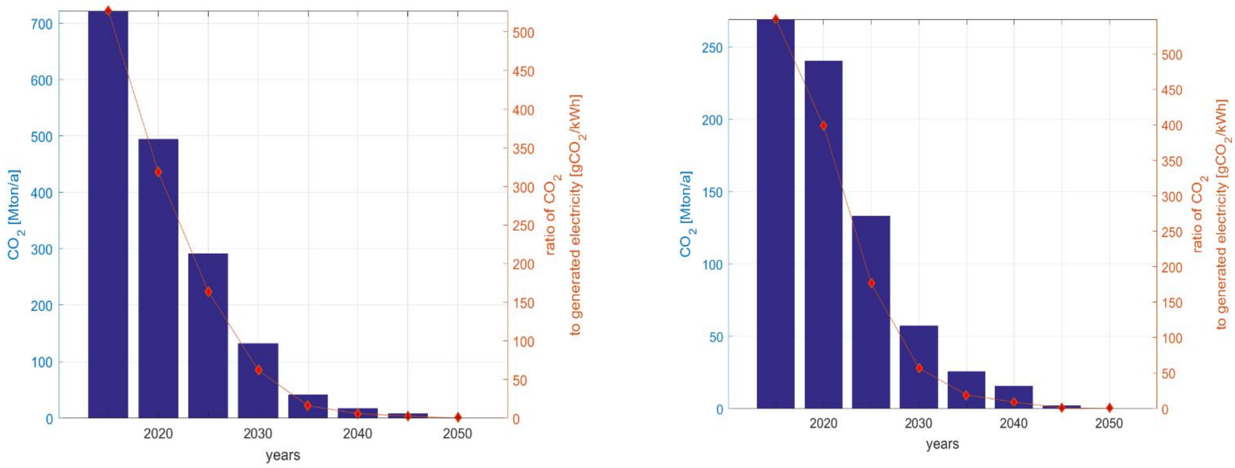


Figure 72: SAARC - CO2 emission reduction during the energy transition from 2015 to 2050.

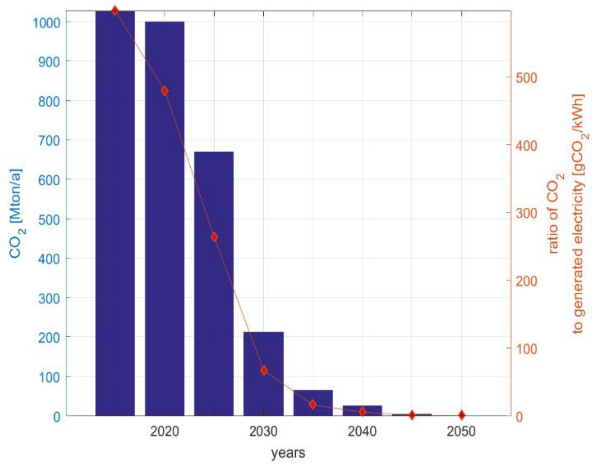


Figure 73: Northeast Asia (left) and Southeast Asia (right) - CO2 emission reduction during the energy transition from 2015 to 2050.

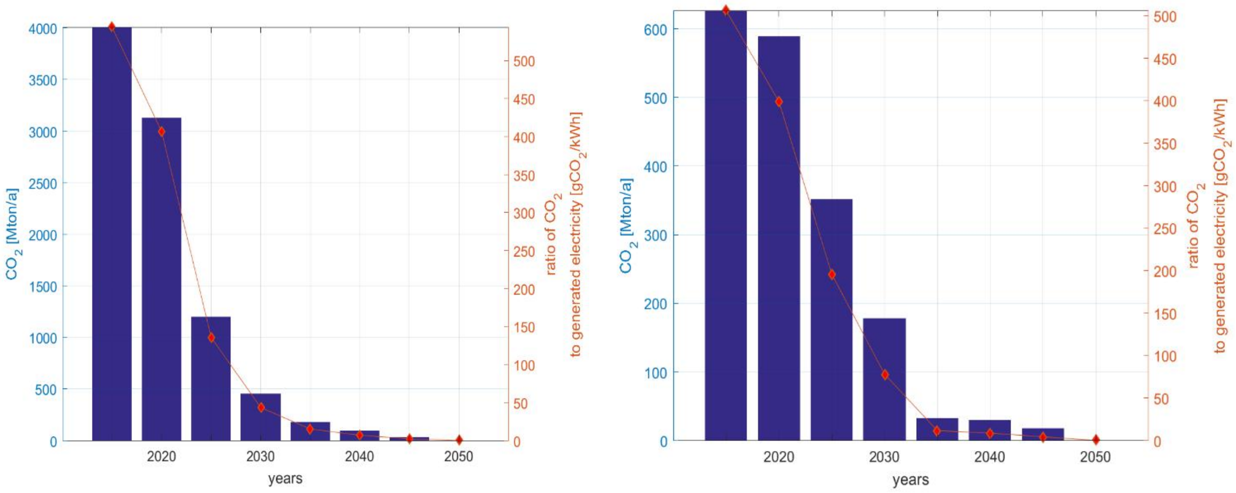
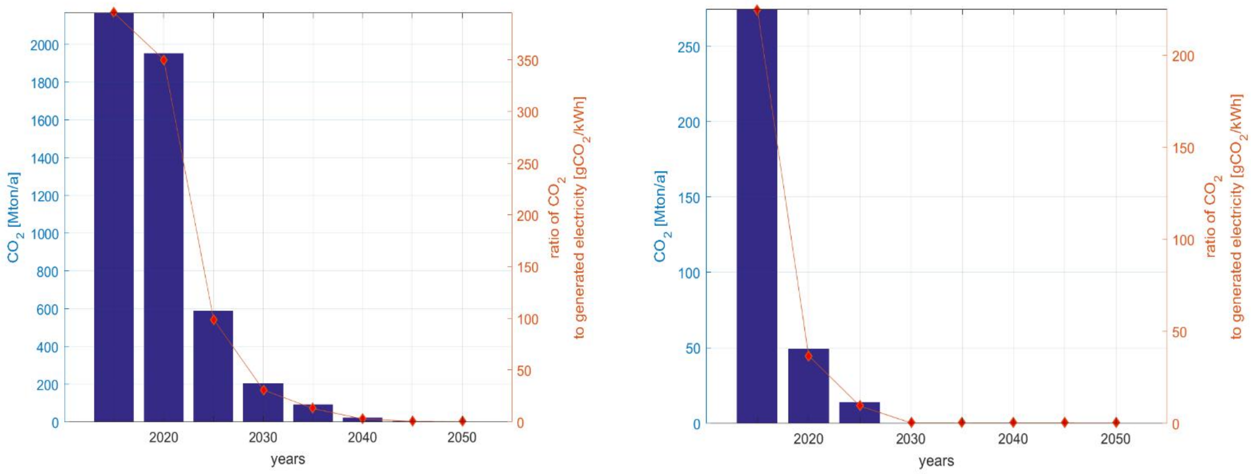


Figure 74: North America (left) and South America (right) - CO2 emission reduction during the energy transition from 2015 to 2050.



Whereas in the case of the SAARC region, a rapid reduction in emissions from 1000 MtCO2eq in 2015 to just over 200 MtCO2eq in 2030 is achieved during the energy transition as shown in Figure 72.

In the case of Northeast Asia, GHG emissions show a gradual decline from 4000 MtCO2eq in 2015 to around 400 MtCO2eq by 2030 as indiacted in Figure 73. Meanwhile, Southeast Asia shows a dramatic reduction from around 600 MtCO2eq in 2015 to around 25 MtCO2eq in 2035 as shown in Figure 73.

In the case of North America, GHG emissions decline quite rapidly from over 2000 MtCO2eq in 2015 to around 200 MtCO2eq by 2030 as shown in Figure 74. Meanwhile, Sounth America shows a dramatic reduction from around 300 MtCO2eq in 2015 to zero emissions in 2030 as shown in Figure 74.

6. POLICY RECOMMENDATIONS TOWARDS A RAPID TRANSITION TO 100% RENEWABLE ENERGY

The global movement for 100% renewable energy has been rapidly growing. On a global scale, hundreds of cities, including Vancouver, San Francisco, Munich, Frankfurt, Barcelona, Geneva, Doha and Sydney as well as entire nations like Sweden, Denmark, New Zeeland and Iceland have set the bold goal for 100% renewable energy. At the Marrakesh climate change conference in 2016, a group of 48 developing countries most vulnerable to climate change committed to 100% renewable energy by 2050.

The first decisive prerequisite for a transition to renewable energy is public support. The second prerequisite is a clear legislative framework promoting the fast and steady growth of renewables on the one hand and the phasing out all subsidies to fossil fuel and nuclear energy generation on the other hand.

To ensure a smooth, fast and cost-effective transition to 100% renewable energy, governments need to adopt national legislative acts, which ensure the sufficient flow of private investment in renewable energy and storage technologies. Although public financing is indispensable, private investment is instrumental in enabling competition and a rapid scaling-up of the renewable energy sector. The following political measures and instruments are key:

1. Instruments, enabling direct private investments in renewable energy and other zero-emission technologies.

The German Renewable Energy Sources Act (EEG) with a fixed feed-in-tariff is one of the best-known and proven successful policy frameworks. It played a major role in reducing costs for initially cost intensive wind and solar PV technologies. It is imperative that an EEG law includes a privileged guaranteed feed-in-tariff for renewable energy generation.

Over the last years, a range of countries have introduced tenders instead of feed-in-tariffs. A recent analysis[A] by the Energy Watch Group has shown that tenders are limiting the deployment of renewable energy sources and lead to higher costs for customers. Furthermore, tenders limit investors to large companies and exclude investment from decentralized actors, such as cooperatives. Tendering procedures should therefore only apply for capacities above 40 MW. In cases below 40 MW, feed-in-tariffs should apply.

We also need to implement new, innovative political mechanisms encouraging investment in renewable energy, storage and network integration simultaneously. A “hybrid renewable power plant remuneration”, a reformed version of the feed-in-tariff scheme,[B] enables just that.

2. Phasing-out all state subsidies to fossil fuel and nuclear energy generation

To accelerate the growth of renewable energy sources, all subsidies and tax exemptions for conventional fossil energy plants, foremost coal power plants, need to be phased out. This would save public money, which could be instead spent on education and research.

A: See the link: http://energywatchgroup.org/wp-content/uploads/2017/09/FIT-Tender_Fell_PolicyPaper_EN_final.pdf

B: For more information about hybrid renewable power plant renumeration see the link: https://www.hans-josef-fell.de/content/index.php/dokumente/beschluss-und-positionspapiere/918-eckpunktepapier-kombikraftwerksverguetung

3. Tax exemptions for investments in renewable energy

Renewable energy generation needs to be subject to tax exemptions on property and trade. In the new markets they are crucial to ensure the market growth of renewable energy sources and overall return on investment.

4. Introducing carbon and radioactivity tax

Carbon and radioactivity taxes will sanction energy companies, generating electricity based on fossil fuel and nuclear energy. As a result of a carbon tax, the costs of fossil fuel based electricity generation should exceed the average renewable electricity cost. It does not directly promote renewable electricity generation as a renewable energy support scheme does, but would reflect the real costs of fossil fuel and nuclear energy (including hidden environmental, social and economic costs) and will make it economically unviable over time. A continuously rising carbon and radioactivity tax should replace the emission trading system, which has proven to be an ineffective climate change policy.

5. Promoting research and education in the sphere of renewable energy and zero-emission technologies

Research, education and training on renewable energy and zero-emission technology at all levels, including schools, universities, vocational training for professionals in economics, engineering and social sciences needs to be strengthened. Furthermore, it is important to promote research in engineering and technology assessment as well as to enable an exchange of know-how across the world.

7. ABBREVIATIONS

BAU	Business-As-Usual
BECCS	Bioenergy Carbon Capture and Storage
BEV	Battery Electric Vehicle
BNEF	Bloomberg New Energy Finance
CAES	Compressed Air Energy Storage
CBM	Coal Bed Methane
CCS	Carbon Capture and Storage
CCGT	Combined Cycle Gas Turbine
COP	Conference of the Parties
CSP	Concentrated Solar Thermal Power
DACCS	Direct Air Carbon Capture and Storage
DME	Dimethyl Ether
EU	European Union
FLH	Full Load Hours
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GPFG	Government Pension Fund Global
GW	Gigawatts
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IPCC	International Panel on Climate Change
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Electricity
LCOC	Levelised Cost of Curtailment
LCOS	Levelised Cost of Storage
LCOT	Levelised Cost of Transmission
MW	Megawatt
OCGT	Open Cycle Gas Turbine
PHEV	Plug-in Hybrid Electric Vehicle
PHS	Pumped Hydroelectric Storage
PtL	Power-to-Liquids
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable Energy, partly used in the sense of Renewable Energy
SDGs	Sustainable Development Goals
SNG	Synthetic Natural Gas
TPED	Total Primary Energy Demand
TW	Terawatt
USD	United States Dollar
WBGU	German Advisory Council on Global Change
WEC	World Energy Council
WEO	World Energy Outlook (flagship report of the IEA)
WWF	World Wide Fund for Nature

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10. APPENDIX

1. Methodology

The optimisation model of the energy system is based on a linear optimisation of the system parameters under a set of applied constraints with the assumption of a perfect foresight of RE power generation and power demand. A multi-node approach enables the description of any desired configuration of sub-regions and power transmission interconnections. The main constraints for the optimisation is the matching of total power generation and total power demand values for every hour of the applied year and the optimisation criteria is the minimum of the total annual cost of the system. The hourly resolution of the model significantly increases the computation time. However, it guarantees that for every hour of the year the total supply within a sub-region covers the local demand and enables a more precise system description including synergy effects of different system components. The optimisation is performed in a third party solver. Currently, the main option is MOSEK ver. 8, but other solvers (Gurobi, CPLEX, etc.) can also be used. The model is compiled in the Matlab environment in the LP file format, so that the model can be read by most of the available solvers. After the simulation, results are parsed back to the Matlab data structure and post-processed.

Target function

The target of the system optimisation is the minimisation of the total annual cost of the integrated system, calculated as the sum of the annual costs of installed capacities of the different technologies, costs of energy and products generation and production ramping. This target function includes annual costs of all the elements of the power sector. The target function of the applied energy model of minimising annual costs is presented in Eq. (1) using the abbreviations: sub-regions (r, reg), generation, storage and transmission technologies (t, tech), capital expenditures for technology t (CAPEXt), capital recovery factor for technology t (crft), fixed operational expenditures for technology t (OPEXfixt), variable operational expenditures technology t (OPEXvart), installed capacity in the region r of technology t (instCapt,r), annual generation by technology t in region r (Egen,t,r), cost of ramping of technology t (rampCostt) and sum of power ramping values during the year for the technology t in the region r (totRampt,r).

$$\min_{\square}\left(\sum_{r=1}^{reg}\sum_{t=1}^{tech}(CAPEX_t \cdot crf_t + OPEXfix_t)\cdot instCap_{t,r} + OPEXvar_t \cdot E_{gen,t,r} + rampCost_t \cdot totRamp_{t,r}\right) \qquad (1)$$

The prosumer system is realised in an independent sub-model with a slightly different target function. The prosumer system is optimised for each sub-region independently, even if the sub-region is connected to neighbours inside the region. The target function includes annual costs of prosumer power generation and storage, the cost of electricity bought from the distribution grid; the cost of electricity sold to the distribution grid is deducted from the total annual cost. The target function of the applied energy model of minimising annual costs is presented in Eq. (2) using the abbreviations: generation and storage technologies (t, tech), capital expenditures for technology t (CAPEXt), capital recovery factor for technology t (crft), fixed operational expenditures for technology t (OPEXfixt), variable operational expenditures technology t (OPEXvart), installed capacity of technology t (instCapt), annual generation by technology t (Egen,t), retail price of electricity (elCost), feed-in price of electricity (elFeedIn), annual amount of electricity bought from the grid (E_grid), annual amount of electricity sold from the grid (E_curt).

$$\min_{\square}\left(\sum_{t=1}^{tech}(CAPEX_t \cdot crf_t + OPEXfix_t)\cdot instCap_t + OPEXvar_t \cdot E_{gen,t} + elCost \cdot E_{grid} - elFeedIn \cdot E_{curt}\right) \tag{2}$$

Energy balance constraints The main constraint for the power sector optimisation is the matching of the power generation and demand for every hour of the applied year. For every hour of the year the total generation within a sub-region and electricity import minus electricity export cover the local electricity demand.

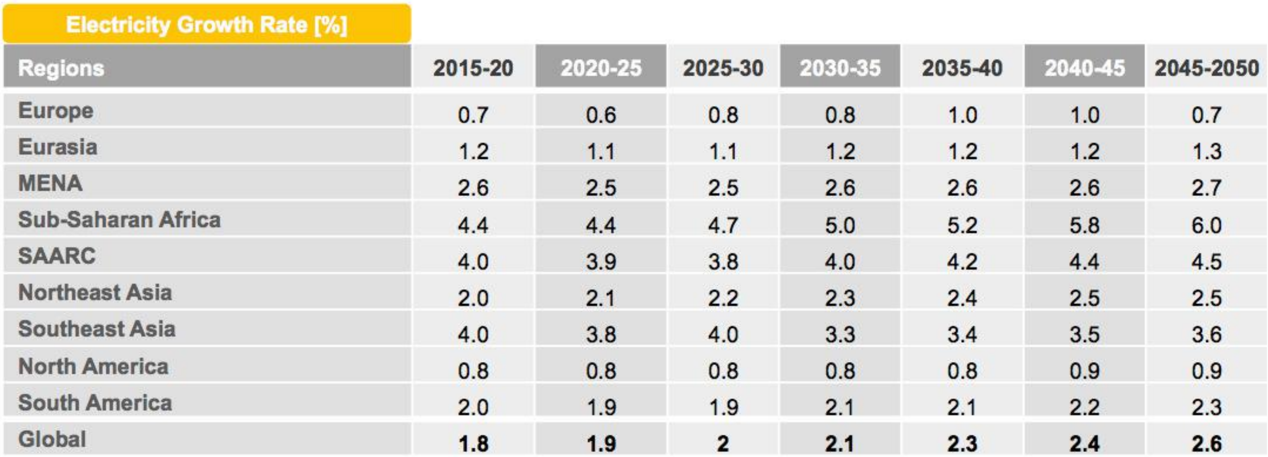
$$\forall h \in \underset{\square}{[1{,}8760]} \sum_{t}^{tech} E_{gen,t} + \sum_{r}^{reg} E_{imp,r} + \sum_{t}^{stor} E_{stor,disch} = E_{demand} + \sum_{r}^{reg} E_{exp,r} + \sum_{t}^{stor} E_{stor,ch} + E_{curt} \tag{3}$$

Eq. (3) describes constraints for the energy flows of a sub-region. Abbreviations: hours (h), technology (t), all modelled power generation technologies (tech), sub-region (r), all sub-regions (reg), electricity generation (Egen), electricity import (Eimp), storage technologies (stor), electricity from discharging storage (Estor,disch), electricity demand (Edemand), electricity exported (Eexp), electricity for charging storage (Estor,ch), curtailed excess energy (Ecurt). The energy loss in the high voltage direct current (HVDC) and alternating current (HVAC) transmission grids and energy storage technologies are considered in storage discharge and grid import value calculations. Apart from this, various financial and technical assumptions that are utilised for the cost optimisation of the model are presented in the next section.

2. Technical and financial assumptions

The following tables show the various technical and financial assumptions that were factored into the modelling of the global energy transition.

Table 2.1: *Electricity demand growth rates across the nine major regions assumed for the energy transition from 2015 to 2050*



Electricity Growth Rate [%]							
Regions	**2015-20**	**2020-25**	**2025-30**	**2030-35**	**2035-40**	**2040-45**	**2045-2050**
Europe	0.7	0.6	0.8	0.8	1.0	1.0	0.7
Eurasia	1.2	1.1	1.1	1.2	1.2	1.2	1.3
MENA	2.6	2.5	2.5	2.6	2.6	2.6	2.7
Sub-Saharan Africa	4.4	4.4	4.7	5.0	5.2	5.8	6.0
SAARC	4.0	3.9	3.8	4.0	4.2	4.4	4.5
Northeast Asia	2.0	2.1	2.2	2.3	2.4	2.5	2.5
Southeast Asia	4.0	3.8	4.0	3.3	3.4	3.5	3.6
North America	0.8	0.8	0.8	0.8	0.8	0.9	0.9
South America	2.0	1.9	1.9	2.1	2.1	2.2	2.3
Global	**1.8**	**1.9**	**2**	**2.1**	**2.3**	**2.4**	**2.6**

Table 2.2: *Technical and financial assumptions of energy system technologies used in the energy transition from 2015 to 2050. Assumptions are taken from Pleßmann et al. (48) and European Commission (49) and further references are individually mentioned. All technical and financial assumptions are given in currency values of the year 2015.*

Technologies		Units	2015	2020	2025	2030	2035	2040	2045	2050	REF
PV rooftop – residential	Capex	€/kW$_{,el}$	1360	1169	966	826	725	650	589	537	50
	Opex fix	€/(kW$_{,el}$ a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - commercial	Capex	€/kW$_{,el}$	1360	907	737	623	542	484	437	397	50
	Opex fix	€/(kW$_{,el}$ a)	20	17.6	15.7	14.2	12.8	11.7	10.7	9.8	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV rooftop - industrial	Capex	€/kW$_{,el}$	1360	682	548	459	397	353	318	289	50
	Opex fix	€/(kW$_{,el}$ a)	20	17,6	15,7	14,2	12,8	11,7	10.7	9.8	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV optimally tilted	Capex	€/kW$_{,el}$	1000	580	466	390	337	300	270	246	50
	Opex fix	€/(kW$_{,el}$ a)	15	13.2	11.8	10.6	9.6	8.8	8.0	7.4	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
PV single-axis tracking	Capex	€/kW$_{,el}$	1150	638	513	429	371	330	297	271	50,106
	Opex fix	€/(kW$_{,el}$ a)	17.3	15.0	13.0	12.0	11.0	10.0	9.0	8.0	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	30	30	35	35	35	40	40	40	
Wind onshore	Capex	€/kW$_{,el}$	1250	1150	1060	1000	965	940	915	900	107
	Opex fix	€/(kW$_{,el}$ a)	25	23	21	20	19	19	18	18	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	25	25	25	25	
CSP (solar field, parabolic trough)	Capex	€/kW$_{,th}$	547.8	427.8	369.2	326.9	304	283.6	265.4	249.5	54,55
	Opex fix	€/(kW$_{,th}$ a)	12.6	9.8	8.5	7.5	7	6.5	6.1	5.7	
	Opex var	€/(kWh$_{,th}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	30	30	30	30	
Geothermal power	Capex	€/kW$_{,el}$	5250	4970	4720	4470	4245	4020	3815	3610	56,49
	Opex fix	€/(kW$_{,el}$ a)	80.0	80.0	80.0	80.0	80.0	80.0	80.0	80.0	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Lifetime	years	40	40	40	40	40	40	40	40	
Water electrolysis	Capex	€/kW$_{,H2}$	800	685	500	363	325	296	267	248	57,58
	Opex fix	€/(kW$_{,H2}$ a)	32	27	20	12.7	11.4	10.4	9.4	8.7	
	Opex var	€/(kWh$_{,H2}$)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Lifetime	years	30	30	30	30	30	30	30	30	
Methanation	Capex	€/kW$_{,CH4}$	492	421	310	278	247	226	204	190	57,58
	Opex fix	€/(kW$_{,CH4}$ a)	19.7	16.8	12.4	11.1	9.9	9.0	8.2	7.6	
	Opex var	€/(kWh$_{,CH4}$)	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	
	Lifetime	years	30	30	30	30	30	30	30	30	

Technologies		Units	2015	2020	2025	2030	2035	2040	2045	2050	REF
Coal PP	Opex fix	€/(kW$_{el}$ a)	20	20	20	20	20	20	20	20	
	Opex var	€/(kWh)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	43	43	43	43	43	43	43	43	
	Lifetime	years	40	40	40	40	40	40	40	40	
	Capex	€/(kW$_{,el}$)	1500	1500	1500	1500	1500	1500	1500	1500	
ICG	Capex	€/(kW$_{el}$)	310	310	310	310	310	310	310	310	
	Opex fix	€/(kW$_{el}$ a)	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	30	30	30	30	30	30	30	30	
	Lifetime	years	20	20	20	20	20	20	20	20	
Nuclear PP	Capex	€/(kW$_{el}$)	6210	6003	6003	5658	5658	5244	5244	5175	
	Opex fix	€/(kW$_{el}$ a)	162	157	157	137	137	116	116	109	
	Opex var	€/(kWh$_{,el}$)	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025	
	Efficiency	%	37	37	37	38	38	38	38	38	
	Lifetime	years	40	40	40	40	40	40	40	40	
CCGT	Capex	€/(kW$_{el}$)	775	775	775	775	775	775	775	775	59
	Opex fix	€/(kW$_{el}$ a)	19.4	19.4	19.4	19.4	19.4	19.4	19.4	19.4	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	58	58	58	58	59	60	60	60	
	Lifetime	years	35	35	35	35	35	35	35	35	
OCGT	Capex	€/(kW$_{el}$)	475	475	475	475	475	475	475	475	59
	Opex fix	€/(kW$_{el}$ a)	14.25	14.25	14.25	14.25	14.25	14.25	14.25	14.25	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	43	43	43	43	43	43	43	43	
	Lifetime	years	35	35	35	35	35	35	35	35	
Steam turbine (CSP)	Capex	€/(kW$_{el}$)	760	740	720	700	670	640	615	600	
	Opex fix	€/(kW$_{el}$ a)	15.2	14.8	14.4	14	13.4	12.8	12.3	12	
	Opex var	€/(kWh$_{,el}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	42	42	42	43	44	44	45	45	
	Lifetime	years	25	25	25	25	30	30	30	30	
Biomass CHP	Capex	€/kW$_{,el}$	2755	2620	2475	2330	2195	2060	1945	1830	
	Opex fix	€/(kW$_{,el}$ a)	55.4	47.2	44.6	41.9	39.5	37.1	35	32.9	
	Opex var	€/(kWh$_{,el}$)	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	
	Efficiency	%	35	36	36.5	37	37.5	38	38.5	39	
	Lifetime	years	25	25	25	25	25	25	25	25	
Biogas CHP	Capex	€/kW$_{,el}$	503	429	400	370	340	326	311	296	
	Opex fix	€/(kW$_{,el}$ a)	20.1	17.2	16.0	14.8	13.6	13.0	12.4	11.8	
	Opex var	€/(kWh$_{,el}$)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Efficiency	%	33.5	34.4	37.2	40.0	41.9	43.7	44.2	44.7	
	Lifetime	years	30	30	30	30	30	30	30	30	

Technologies		Units	2015	2020	2025	2030	2035	2040	2045	2050	REF
Waste incinerator	Capex	€/kW$_{,el}$	5940	5630	5440	5240	5030	4870	4690	4540	
	Opex fix	€/(kW$_{,el}$ a)	267.3	253.35	244.8	235.8	226.35	219.15	211.05	204.3	
	Opex var	€/(kWh$_{,el}$)	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	0.0069	
	Efficiency	%	27	31	32.5	34	35.5	37	37	42	
	Lifetime	years	30	30	30	30	30	30	30	30	
Biogas digester	Capex	€/kW$_{,th}$	771	731	706	680	653	632	609	589	
	Opex fix	€/(kW$_{,th}$ a)	30.8	29.2	28.2	27.2	26.1	25.3	24.3	23.6	
	Opex var	€/(kWh$_{,th}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	100	100	100	100	100	100	100	100	
	Lifetime	years	20	20	20	20	25	25	25	25	
Biogas upgrade	Capex	€/kW$_{,th}$	340	290	270	250	230	220	210	200	61
	Opex fix	€/(kW$_{,th}$ a)	27.2	23.2	21.6	20	18.4	17.6	16.8	16	
	Opex var	€/(kWh$_{,th}$)	0	0	0	0	0	0	0	0	
	Efficiency	%	98	98	98	98	98	98	98	98	
	Lifetime	years	20	20	20	20	25	25	25	25	
Battery, Li-ion	Capex	€/(kWh$_{el}$)	600	300	200	150	120	100	85	75	62,108
	Opex fix	€/(kWh$_{el}$ a)	24	9	5	3.75	3	2.5	2.125	1.875	
	Opex var	€/(kWh$_{,el}$)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Efficiency	%	90	91	92	93	94	95	95	95	
	Lifetime	years	15	20	20	20	20	20	20	20	
Adiabatic compressed air energy storage (A-CAES)	Capex	€/kWh$_{,el}$	35.0	35.0	33.0	31.1	30.4	29.8	28.0	26.3	
	Opex fix	€/(kWh$_{,el}$ a)	0.46	0.46	0.43	0.40	0.40	0.39	0.36	0.34	
	Opex var	€/(kWh$_{,el}$)	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	
	Efficiency	%	54	59	65	70	70	70	70	70	
	Lifetime	years	40	55	55	55	55	55	55	55	
Gas storage	Capex	€/kWh$_{,el}$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	
	Opex fix	€/(kWh a)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	
Pumped hydro storage (PHS)	Capex	€/kWh$_{,el}$	70	70	70	70	70	70	70	70	
	Opex fix	€/(kWh a)	11	11	11	11	11	11	11	11	
	Opex var	€/(kWh)	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	
	Lifetime	years	50	50	50	50	50	50	50	50	
Thermal energy storage (TES)	Capex	€/kWh$_{,th}$	50	40	30	30	20	20	20	20	
	Opex fix	€/(kWh a)	0.75	0.6	0.45	0.45	0.3	0.3	0.3	0.3	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	25	25	25	25	30	30	30	30	
High voltage alternating current transmission line (HVAC)	Capex	€/(kW km)	0.458	0.458	0.458	0.458	0.458	0.458	0.458	0.458	
	Opex fix	€/(kW km)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
	Opex var	€/(kWh km)	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	
High voltage direct current transmission line (HVDC)	Capex	€/(kW km)	1.044	1.044	1.044	1.044	1.044	1.044	1.044	1.044	
	Opex fix	€/(kW km)	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	
	Opex var	€/(kWh km)	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	

Technologies		Units	2015	2020	2025	2030	2035	2040	2045	2050	REF
HVDC Converter pair	Capex	€/kW	180	180	180	180	180	180	180	180	
	Opex fix	€/(kW a)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	
	Opex var	€/(kWh)	0	0	0	0	0	0	0	0	
	Lifetime	years	50	50	50	50	50	50	50	50	

Table 2.3: *Energy to power ratio and self-discharge rates of storage technologies. Efficiency values are given for 2015.*

Technology	Efficiency [%]	Energy/Power Ratio [h]	Self-Discharge [%/h]	References
Battery	90	6	0	62, 108
PHS	85	8	0	49
A-CAES	54	100	0.1	49
TES	90	8	0.2	48
Gas storage	100	80*24	0	48

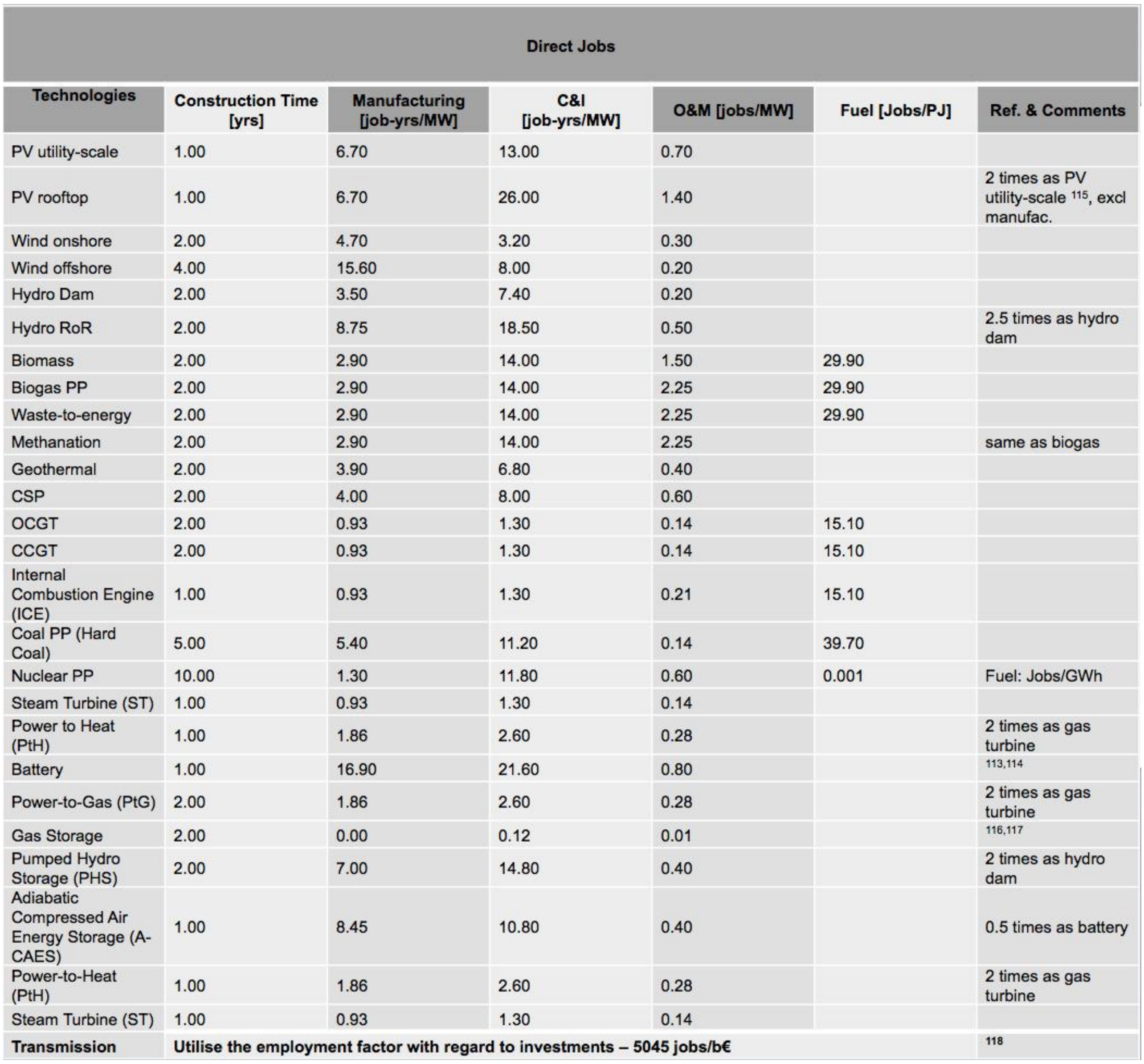
Table 2.4: *Financial assumptions for the fossil-nuclear fuel prices and GHG emission cost. The referenced values are all till 2040 and are kept stable for later periods (fuels) or are assumed to further increase for matching the Paris Agreement (GHG emissions).*

Name of component	Unit	2015	2020	2025	2030	2035	2040	2045	2050	References
Coal	€/MWh$_{th}$	7.7	7.7	8.4	9.2	10.2	11.1	11.1	11.1	109
Fuel oil	€/MWh$_{th}$	52.5	35.2	39.8	44.4	43.9	43.5	43.5	43.5	110
Fossil gas	€/MWh$_{th}$	21.8	22.2	30.0	32.7	36.1	40.2	40.2	40.2	109
Uranium	€/MWh$_{th}$	2.6	2.6	2.6	2.6	2.6	2.6	2.6	2.6	111
GHG emissions	€/tCO$_{2eq}$	9	28	52	61	68	75	100	150	109

Table 2.5: *Efficiency assumptions for HVDC and HVAC transmission for all years 112.*

Component	Power losses
HVDC line	1.6 % / 1000 km
HVDC converter pair	1.4%
HVAC line	9.4 % / 1000 km

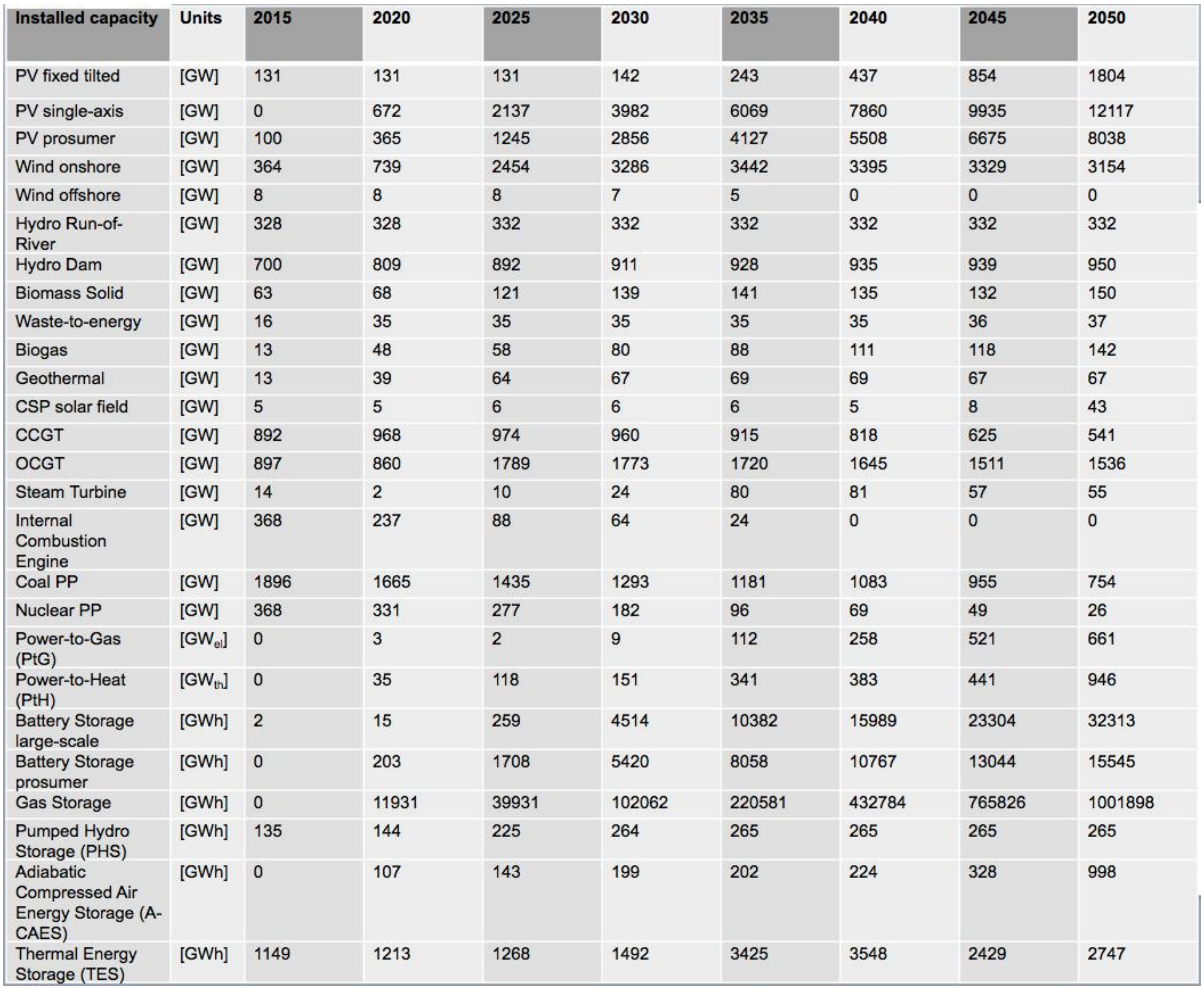
Table 2.6: *Employment factors used in the estimation of jobs generated during the energy transition from 2015 to 2050. Employment factors for batteries are LUT estimates based on US DOE 113 and Hart 2016 114. Most values are from Rutovitz 2015 73, others are referenced specifically.*



Direct Jobs						
Technologies	**Construction Time [yrs]**	**Manufacturing [job-yrs/MW]**	**C&I [job-yrs/MW]**	**O&M [jobs/MW]**	**Fuel [Jobs/PJ]**	**Ref. & Comments**
PV utility-scale	1.00	6.70	13.00	0.70		
PV rooftop	1.00	6.70	26.00	1.40		2 times as PV utility-scale [115], excl manufac.
Wind onshore	2.00	4.70	3.20	0.30		
Wind offshore	4.00	15.60	8.00	0.20		
Hydro Dam	2.00	3.50	7.40	0.20		
Hydro RoR	2.00	8.75	18.50	0.50		2.5 times as hydro dam
Biomass	2.00	2.90	14.00	1.50	29.90	
Biogas PP	2.00	2.90	14.00	2.25	29.90	
Waste-to-energy	2.00	2.90	14.00	2.25	29.90	
Methanation	2.00	2.90	14.00	2.25		same as biogas
Geothermal	2.00	3.90	6.80	0.40		
CSP	2.00	4.00	8.00	0.60		
OCGT	2.00	0.93	1.30	0.14	15.10	
CCGT	2.00	0.93	1.30	0.14	15.10	
Internal Combustion Engine (ICE)	1.00	0.93	1.30	0.21	15.10	
Coal PP (Hard Coal)	5.00	5.40	11.20	0.14	39.70	
Nuclear PP	10.00	1.30	11.80	0.60	0.001	Fuel: Jobs/GWh
Steam Turbine (ST)	1.00	0.93	1.30	0.14		
Power to Heat (PtH)	1.00	1.86	2.60	0.28		2 times as gas turbine
Battery	1.00	16.90	21.60	0.80		[113,114]
Power-to-Gas (PtG)	2.00	1.86	2.60	0.28		2 times as gas turbine
Gas Storage	2.00	0.00	0.12	0.01		[116,117]
Pumped Hydro Storage (PHS)	2.00	7.00	14.80	0.40		2 times as hydro dam
Adiabatic Compressed Air Energy Storage (A-CAES)	1.00	8.45	10.80	0.40		0.5 times as battery
Power-to-Heat (PtH)	1.00	1.86	2.60	0.28		2 times as gas turbine
Steam Turbine (ST)	1.00	0.93	1.30	0.14		
Transmission	**Utilise the employment factor with regard to investments – 5045 jobs/b€**					[118]

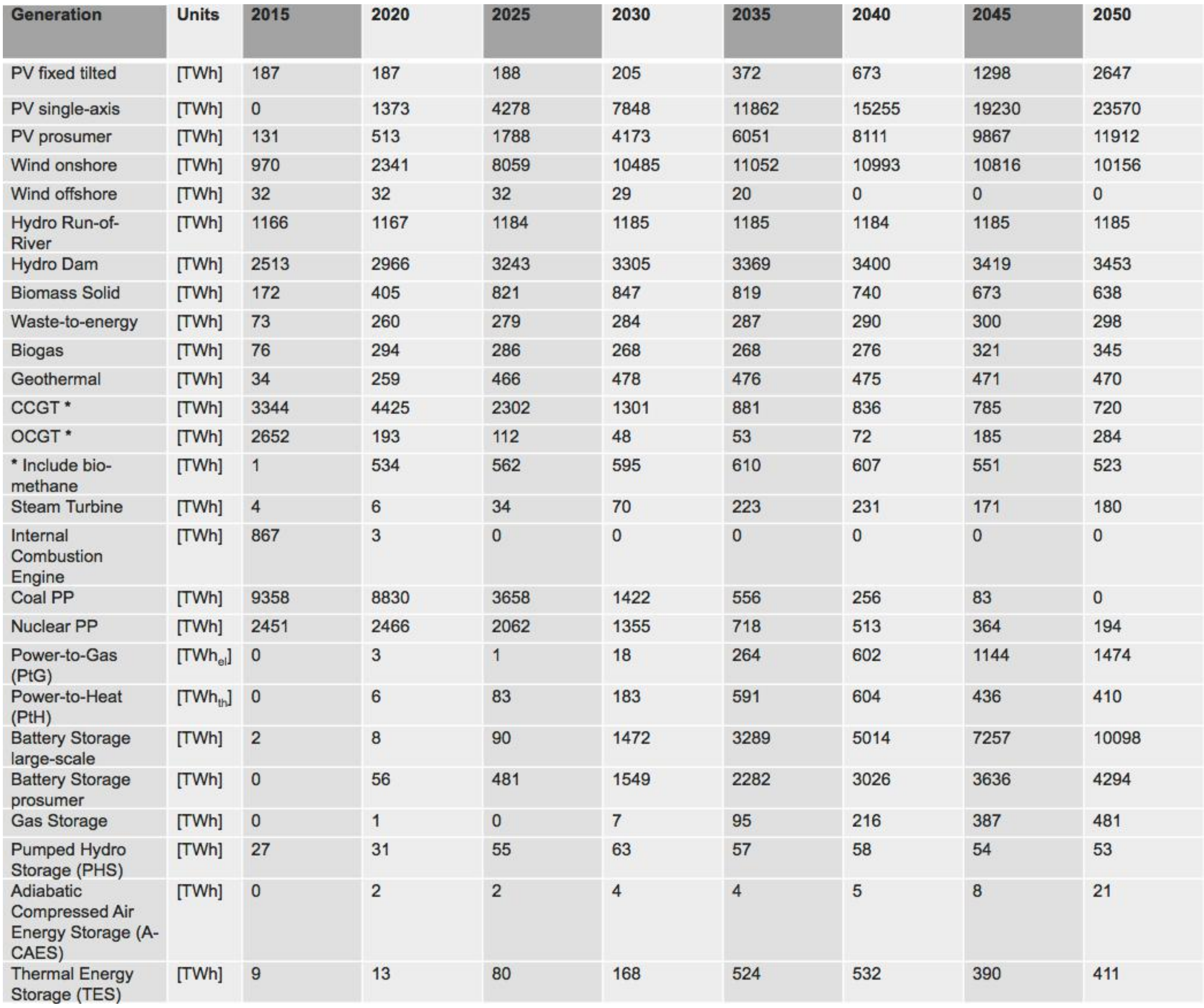
3. Results of the energy transition 2015-2050

Table 3.1: ***Global*** *- Installed capacities of power and storage technologies during the energy transition from 2015 to 2050.*



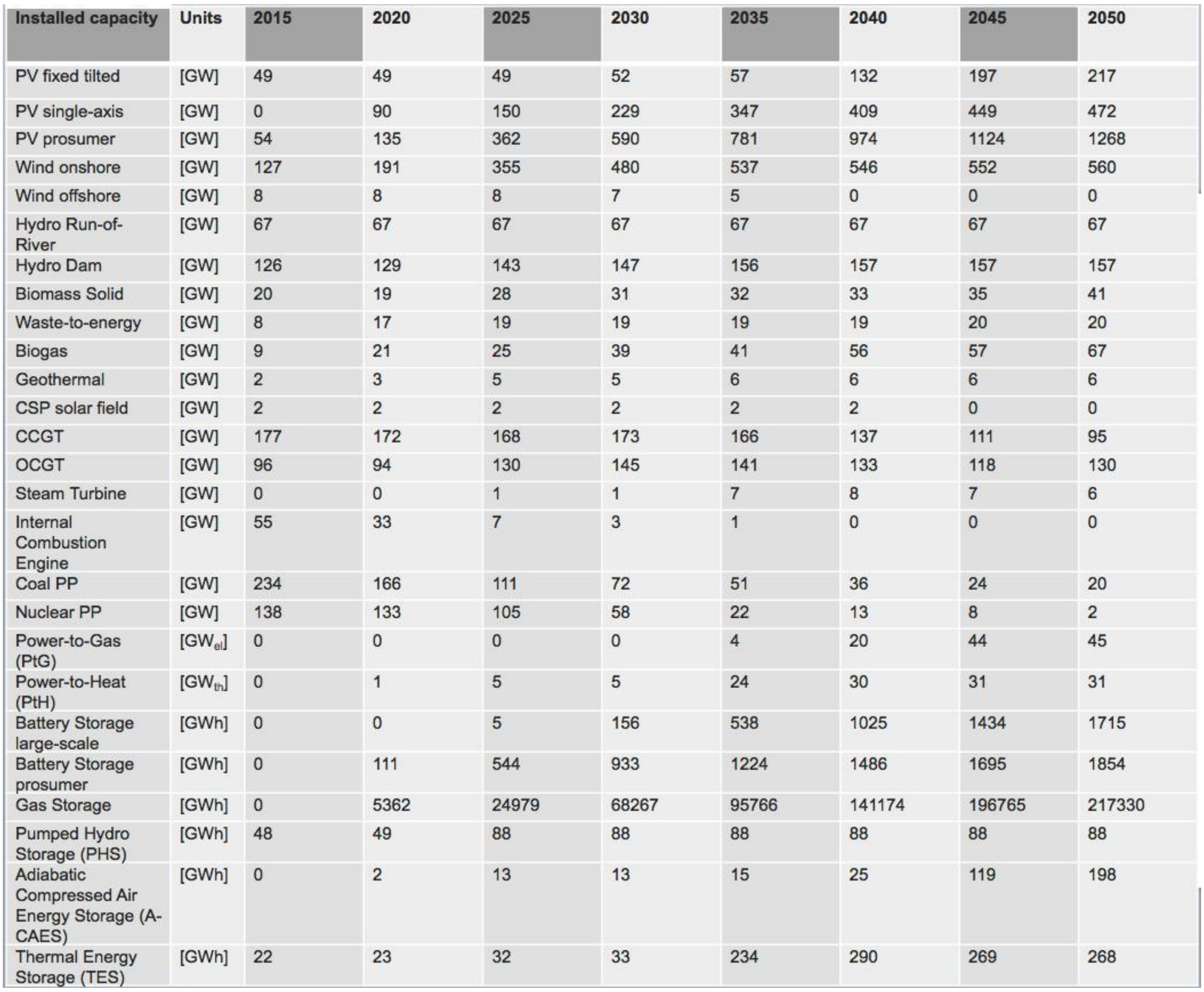
Installed capacity	**Units**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV fixed tilted	[GW]	131	131	131	142	243	437	854	1804
PV single-axis	[GW]	0	672	2137	3982	6069	7860	9935	12117
PV prosumer	[GW]	100	365	1245	2856	4127	5508	6675	8038
Wind onshore	[GW]	364	739	2454	3286	3442	3395	3329	3154
Wind offshore	[GW]	8	8	8	7	5	0	0	0
Hydro Run-of-River	[GW]	328	328	332	332	332	332	332	332
Hydro Dam	[GW]	700	809	892	911	928	935	939	950
Biomass Solid	[GW]	63	68	121	139	141	135	132	150
Waste-to-energy	[GW]	16	35	35	35	35	35	36	37
Biogas	[GW]	13	48	58	80	88	111	118	142
Geothermal	[GW]	13	39	64	67	69	69	67	67
CSP solar field	[GW]	5	5	6	6	6	5	8	43
CCGT	[GW]	892	968	974	960	915	818	625	541
OCGT	[GW]	897	860	1789	1773	1720	1645	1511	1536
Steam Turbine	[GW]	14	2	10	24	80	81	57	55
Internal Combustion Engine	[GW]	368	237	88	64	24	0	0	0
Coal PP	[GW]	1896	1665	1435	1293	1181	1083	955	754
Nuclear PP	[GW]	368	331	277	182	96	69	49	26
Power-to-Gas (PtG)	$[GW_{el}]$	0	3	2	9	112	258	521	661
Power-to-Heat (PtH)	$[GW_{th}]$	0	35	118	151	341	383	441	946
Battery Storage large-scale	[GWh]	2	15	259	4514	10382	15989	23304	32313
Battery Storage prosumer	[GWh]	0	203	1708	5420	8058	10767	13044	15545
Gas Storage	[GWh]	0	11931	39931	102062	220581	432784	765826	1001898
Pumped Hydro Storage (PHS)	[GWh]	135	144	225	264	265	265	265	265
Adiabatic Compressed Air Energy Storage (A-CAES)	[GWh]	0	107	143	199	202	224	328	998
Thermal Energy Storage (TES)	[GWh]	1149	1213	1268	1492	3425	3548	2429	2747

Table 3.2: ***Global*** *- Generation of electricity and storage output during the energy transition from 2015 to 2050.*



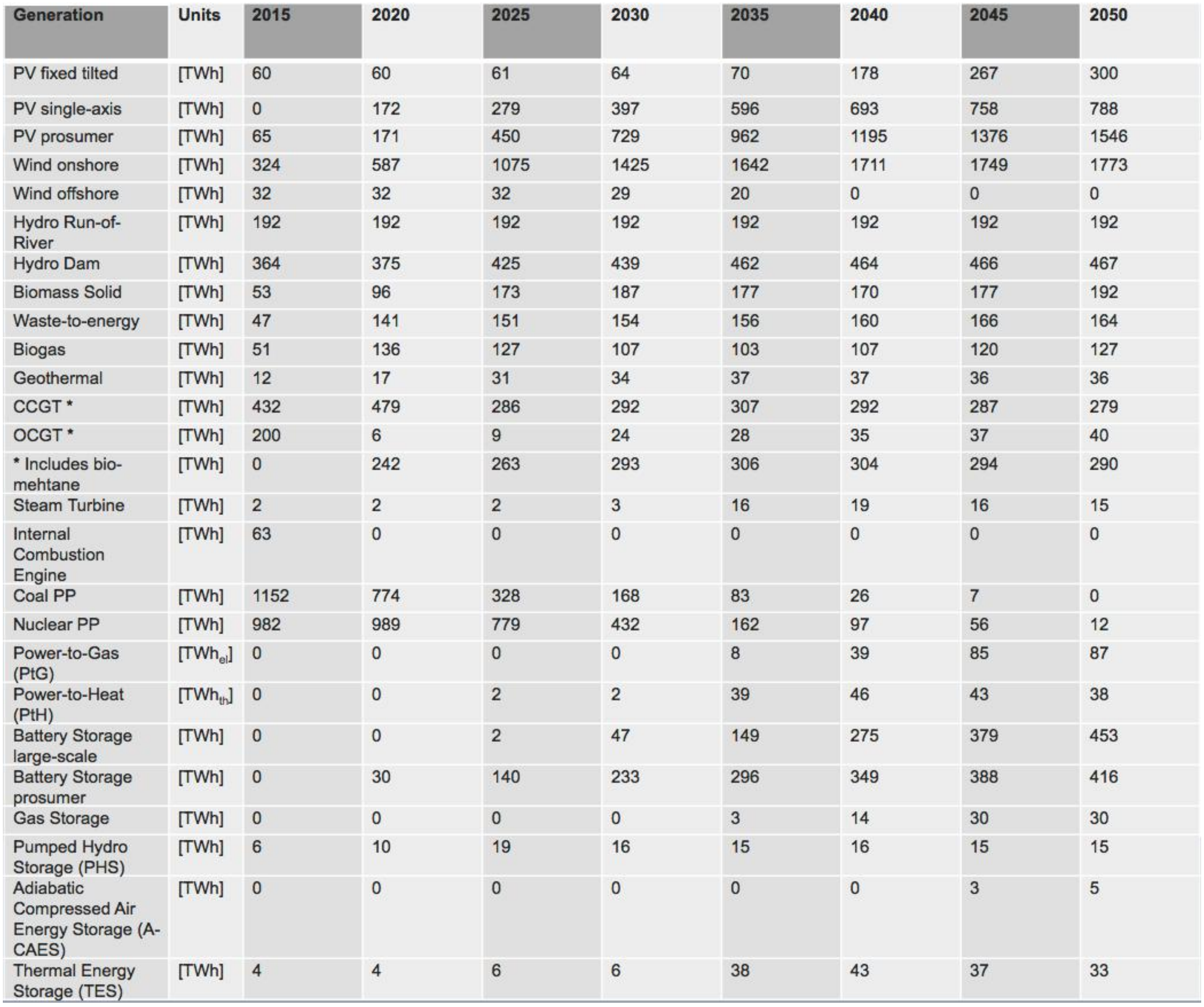
Generation	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[TWh]	187	187	188	205	372	673	1298	2647
PV single-axis	[TWh]	0	1373	4278	7848	11862	15255	19230	23570
PV prosumer	[TWh]	131	513	1788	4173	6051	8111	9867	11912
Wind onshore	[TWh]	970	2341	8059	10485	11052	10993	10816	10156
Wind offshore	[TWh]	32	32	32	29	20	0	0	0
Hydro Run-of-River	[TWh]	1166	1167	1184	1185	1185	1184	1185	1185
Hydro Dam	[TWh]	2513	2966	3243	3305	3369	3400	3419	3453
Biomass Solid	[TWh]	172	405	821	847	819	740	673	638
Waste-to-energy	[TWh]	73	260	279	284	287	290	300	298
Biogas	[TWh]	76	294	286	268	268	276	321	345
Geothermal	[TWh]	34	259	466	478	476	475	471	470
CCGT *	[TWh]	3344	4425	2302	1301	881	836	785	720
OCGT *	[TWh]	2652	193	112	48	53	72	185	284
* Include bio-methane	[TWh]	1	534	562	595	610	607	551	523
Steam Turbine	[TWh]	4	6	34	70	223	231	171	180
Internal Combustion Engine	[TWh]	867	3	0	0	0	0	0	0
Coal PP	[TWh]	9358	8830	3658	1422	556	256	83	0
Nuclear PP	[TWh]	2451	2466	2062	1355	718	513	364	194
Power-to-Gas (PtG)	[TWh$_{el}$]	0	3	1	18	264	602	1144	1474
Power-to-Heat (PtH)	[TWh$_{th}$]	0	6	83	183	591	604	436	410
Battery Storage large-scale	[TWh]	2	8	90	1472	3289	5014	7257	10098
Battery Storage prosumer	[TWh]	0	56	481	1549	2282	3026	3636	4294
Gas Storage	[TWh]	0	1	0	7	95	216	387	481
Pumped Hydro Storage (PHS)	[TWh]	27	31	55	63	57	58	54	53
Adiabatic Compressed Air Energy Storage (A-CAES)	[TWh]	0	2	2	4	4	5	8	21
Thermal Energy Storage (TES)	[TWh]	9	13	80	168	524	532	390	411

Table 3.3: ***Europe*** *- Installed capacities of power and storage technologies during the energy transition from 2015 to 2050.*



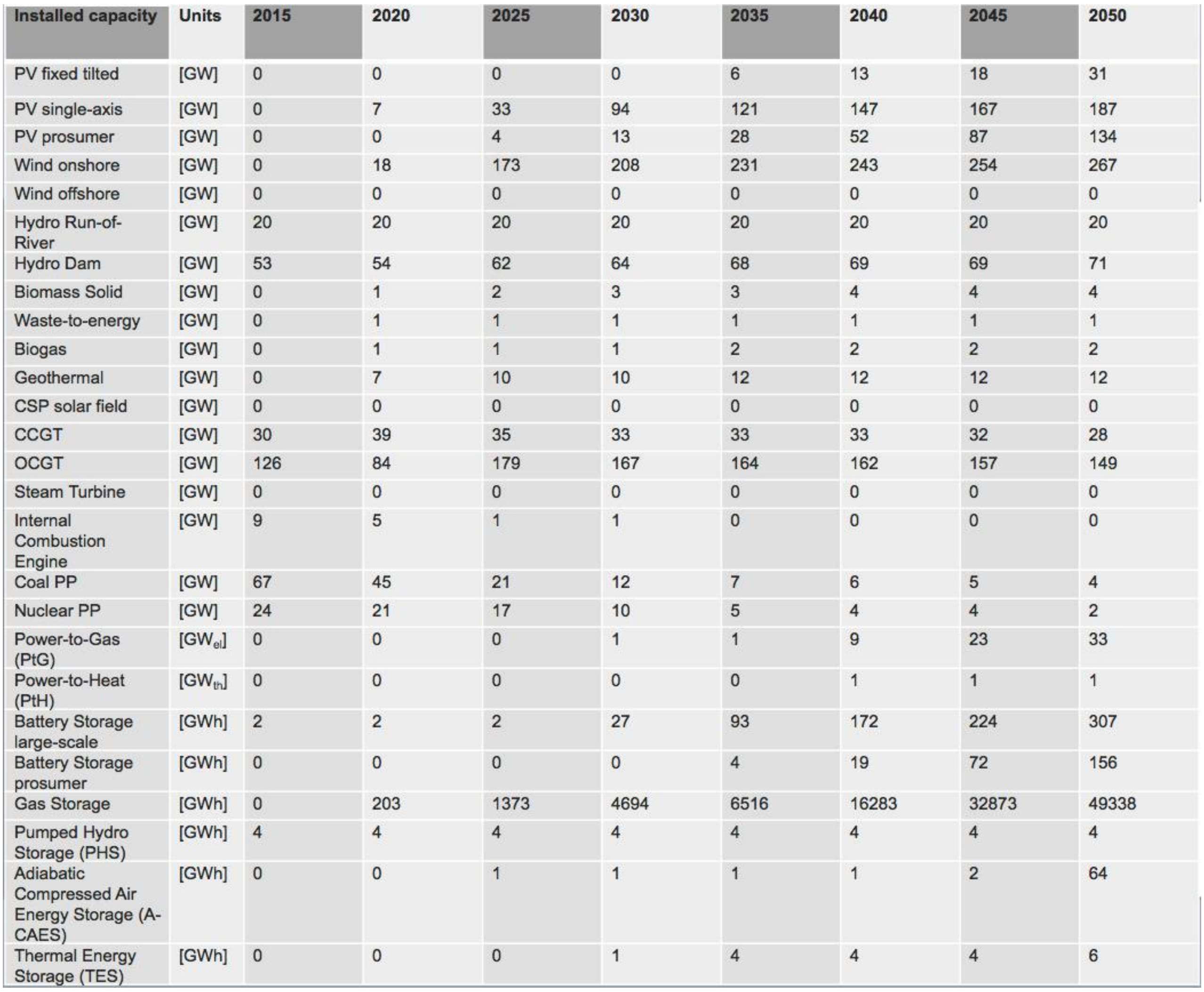
Installed capacity	**Units**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PV fixed tilted	[GW]	49	49	49	52	57	132	197	217
PV single-axis	[GW]	0	90	150	229	347	409	449	472
PV prosumer	[GW]	54	135	362	590	781	974	1124	1268
Wind onshore	[GW]	127	191	355	480	537	546	552	560
Wind offshore	[GW]	8	8	8	7	5	0	0	0
Hydro Run-of-River	[GW]	67	67	67	67	67	67	67	67
Hydro Dam	[GW]	126	129	143	147	156	157	157	157
Biomass Solid	[GW]	20	19	28	31	32	33	35	41
Waste-to-energy	[GW]	8	17	19	19	19	19	20	20
Biogas	[GW]	9	21	25	39	41	56	57	67
Geothermal	[GW]	2	3	5	5	6	6	6	6
CSP solar field	[GW]	2	2	2	2	2	2	0	0
CCGT	[GW]	177	172	168	173	166	137	111	95
OCGT	[GW]	96	94	130	145	141	133	118	130
Steam Turbine	[GW]	0	0	1	1	7	8	7	6
Internal Combustion Engine	[GW]	55	33	7	3	1	0	0	0
Coal PP	[GW]	234	166	111	72	51	36	24	20
Nuclear PP	[GW]	138	133	105	58	22	13	8	2
Power-to-Gas (PtG)	$[GW_{el}]$	0	0	0	0	4	20	44	45
Power-to-Heat (PtH)	$[GW_{th}]$	0	1	5	5	24	30	31	31
Battery Storage large-scale	[GWh]	0	0	5	156	538	1025	1434	1715
Battery Storage prosumer	[GWh]	0	111	544	933	1224	1486	1695	1854
Gas Storage	[GWh]	0	5362	24979	68267	95766	141174	196765	217330
Pumped Hydro Storage (PHS)	[GWh]	48	49	88	88	88	88	88	88
Adiabatic Compressed Air Energy Storage (A-CAES)	[GWh]	0	2	13	13	15	25	119	198
Thermal Energy Storage (TES)	[GWh]	22	23	32	33	234	290	269	268

Table 3.4: ***Europe*** *- Generation of electricity and storage output during the energy transition from 2015 to 2050.*



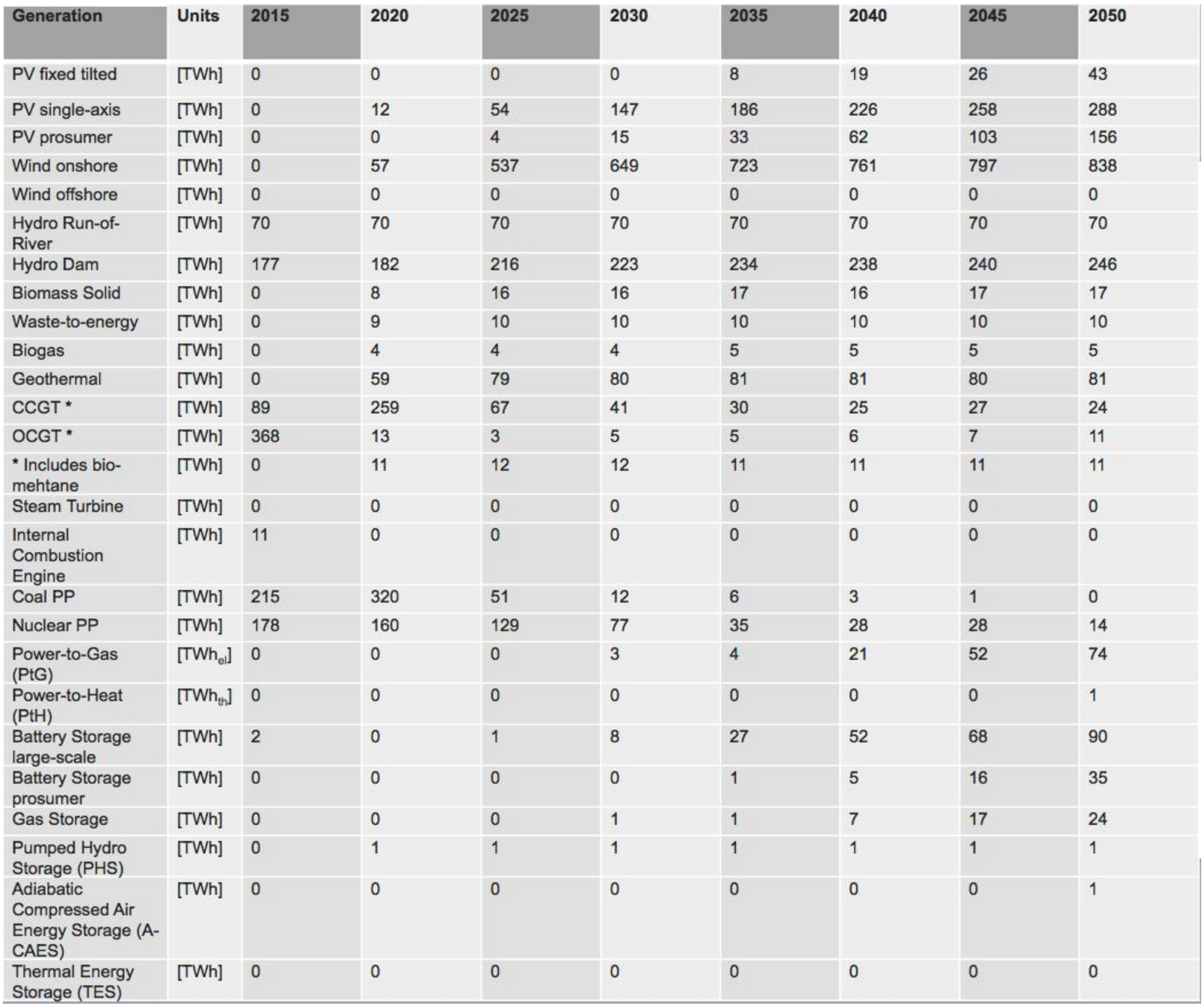
Generation	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[TWh]	60	60	61	64	70	178	267	300
PV single-axis	[TWh]	0	172	279	397	596	693	758	788
PV prosumer	[TWh]	65	171	450	729	962	1195	1376	1546
Wind onshore	[TWh]	324	587	1075	1425	1642	1711	1749	1773
Wind offshore	[TWh]	32	32	32	29	20	0	0	0
Hydro Run-of-River	[TWh]	192	192	192	192	192	192	192	192
Hydro Dam	[TWh]	364	375	425	439	462	464	466	467
Biomass Solid	[TWh]	53	96	173	187	177	170	177	192
Waste-to-energy	[TWh]	47	141	151	154	156	160	166	164
Biogas	[TWh]	51	136	127	107	103	107	120	127
Geothermal	[TWh]	12	17	31	34	37	37	36	36
CCGT *	[TWh]	432	479	286	292	307	292	287	279
OCGT *	[TWh]	200	6	9	24	28	35	37	40
* Includes bio-mehtane	[TWh]	0	242	263	293	306	304	294	290
Steam Turbine	[TWh]	2	2	2	3	16	19	16	15
Internal Combustion Engine	[TWh]	63	0	0	0	0	0	0	0
Coal PP	[TWh]	1152	774	328	168	83	26	7	0
Nuclear PP	[TWh]	982	989	779	432	162	97	56	12
Power-to-Gas (PtG)	[$\mathrm{TWh_{el}}$]	0	0	0	0	8	39	85	87
Power-to-Heat (PtH)	[$\mathrm{TWh_{th}}$]	0	0	2	2	39	46	43	38
Battery Storage large-scale	[TWh]	0	0	2	47	149	275	379	453
Battery Storage prosumer	[TWh]	0	30	140	233	296	349	388	416
Gas Storage	[TWh]	0	0	0	0	3	14	30	30
Pumped Hydro Storage (PHS)	[TWh]	6	10	19	16	15	16	15	15
Adiabatic Compressed Air Energy Storage (A-CAES)	[TWh]	0	0	0	0	0	0	3	5
Thermal Energy Storage (TES)	[TWh]	4	4	6	6	38	43	37	33

Table 3.5: ***Eurasia*** *- Installed capacities of power and storage technologies during the energy transition from 2015 to 2050.*



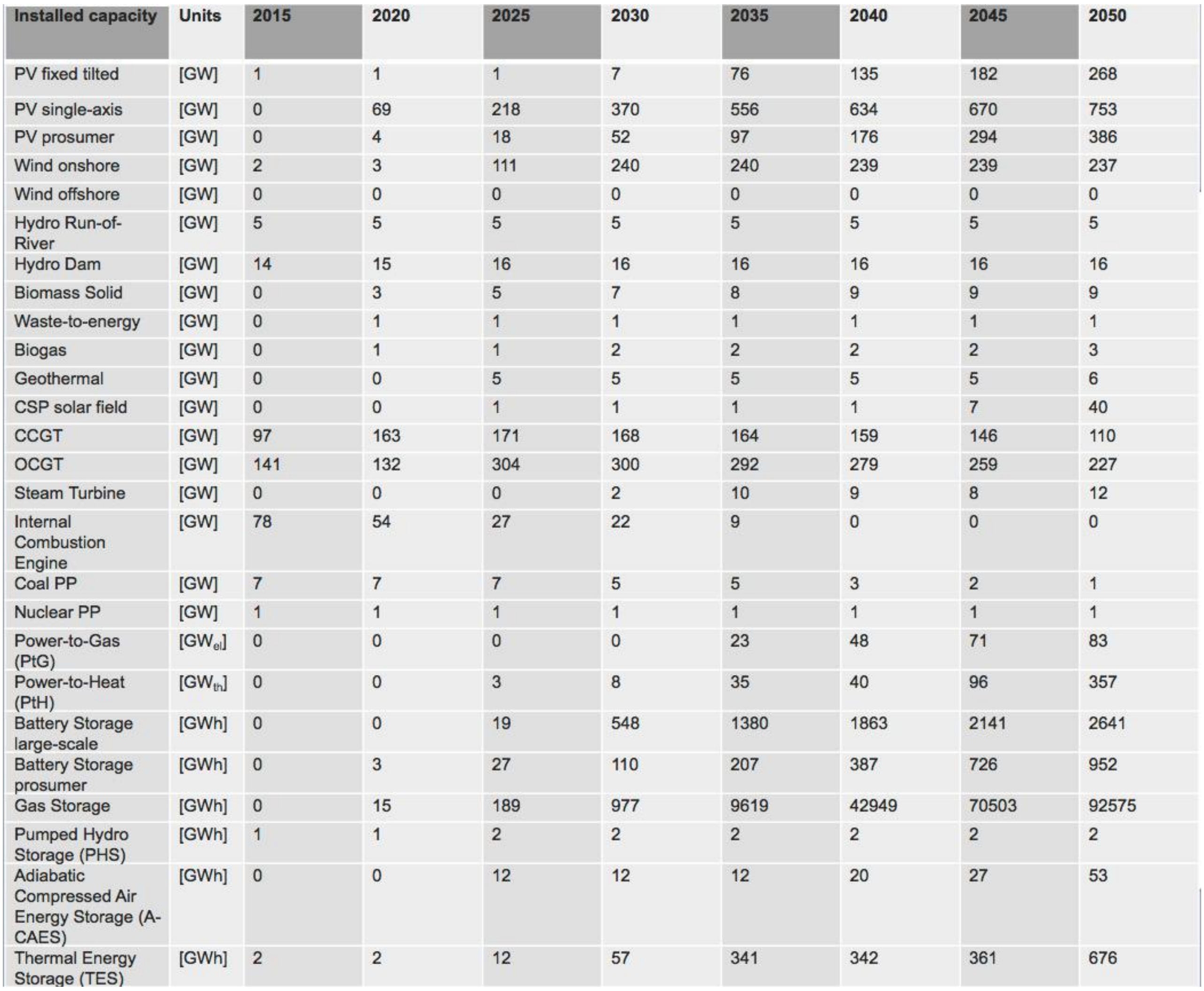
Installed capacity	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[GW]	0	0	0	0	6	13	18	31
PV single-axis	[GW]	0	7	33	94	121	147	167	187
PV prosumer	[GW]	0	0	4	13	28	52	87	134
Wind onshore	[GW]	0	18	173	208	231	243	254	267
Wind offshore	[GW]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[GW]	20	20	20	20	20	20	20	20
Hydro Dam	[GW]	53	54	62	64	68	69	69	71
Biomass Solid	[GW]	0	1	2	3	3	4	4	4
Waste-to-energy	[GW]	0	1	1	1	1	1	1	1
Biogas	[GW]	0	1	1	1	2	2	2	2
Geothermal	[GW]	0	7	10	10	12	12	12	12
CSP solar field	[GW]	0	0	0	0	0	0	0	0
CCGT	[GW]	30	39	35	33	33	33	32	28
OCGT	[GW]	126	84	179	167	164	162	157	149
Steam Turbine	[GW]	0	0	0	0	0	0	0	0
Internal Combustion Engine	[GW]	9	5	1	1	0	0	0	0
Coal PP	[GW]	67	45	21	12	7	6	5	4
Nuclear PP	[GW]	24	21	17	10	5	4	4	2
Power-to-Gas (PtG)	[GW$_{el}$]	0	0	0	1	1	9	23	33
Power-to-Heat (PtH)	[GW$_{th}$]	0	0	0	0	0	1	1	1
Battery Storage large-scale	[GWh]	2	2	2	27	93	172	224	307
Battery Storage prosumer	[GWh]	0	0	0	0	4	19	72	156
Gas Storage	[GWh]	0	203	1373	4694	6516	16283	32873	49338
Pumped Hydro Storage (PHS)	[GWh]	4	4	4	4	4	4	4	4
Adiabatic Compressed Air Energy Storage (A-CAES)	[GWh]	0	0	1	1	1	1	2	64
Thermal Energy Storage (TES)	[GWh]	0	0	0	1	4	4	4	6

Table 3.6: ***Eurasia*** *- Generation of electricity and storage output during the energy transition from 2015 to 2050.*



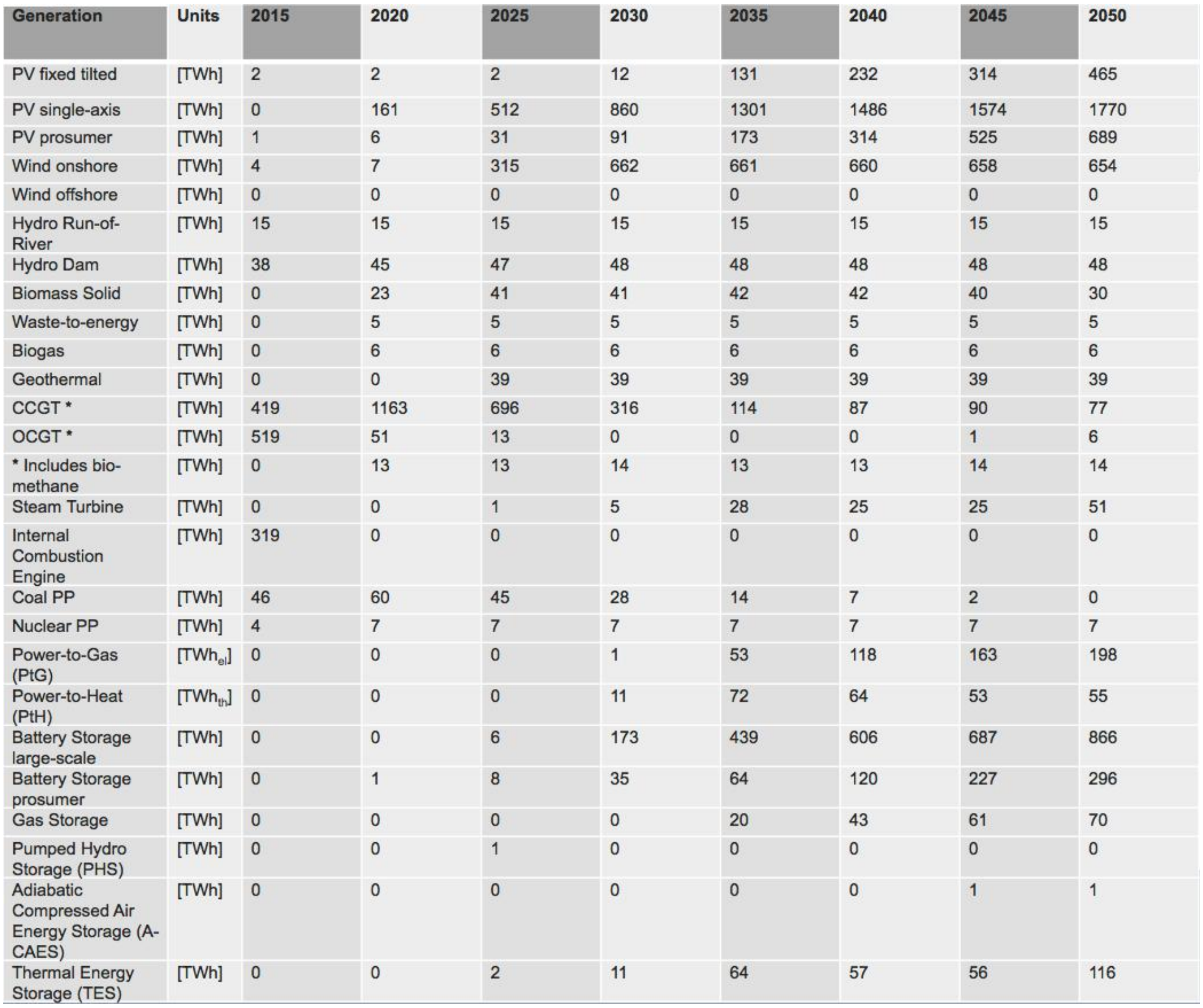
Generation	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[TWh]	0	0	0	0	8	19	26	43
PV single-axis	[TWh]	0	12	54	147	186	226	258	288
PV prosumer	[TWh]	0	0	4	15	33	62	103	156
Wind onshore	[TWh]	0	57	537	649	723	761	797	838
Wind offshore	[TWh]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[TWh]	70	70	70	70	70	70	70	70
Hydro Dam	[TWh]	177	182	216	223	234	238	240	246
Biomass Solid	[TWh]	0	8	16	16	17	16	17	17
Waste-to-energy	[TWh]	0	9	10	10	10	10	10	10
Biogas	[TWh]	0	4	4	4	5	5	5	5
Geothermal	[TWh]	0	59	79	80	81	81	80	81
CCGT *	[TWh]	89	259	67	41	30	25	27	24
OCGT *	[TWh]	368	13	3	5	5	6	7	11
* Includes bio-mehtane	[TWh]	0	11	12	12	11	11	11	11
Steam Turbine	[TWh]	0	0	0	0	0	0	0	0
Internal Combustion Engine	[TWh]	11	0	0	0	0	0	0	0
Coal PP	[TWh]	215	320	51	12	6	3	1	0
Nuclear PP	[TWh]	178	160	129	77	35	28	28	14
Power-to-Gas (PtG)	[$\mathrm{TWh_{el}}$]	0	0	0	3	4	21	52	74
Power-to-Heat (PtH)	[$\mathrm{TWh_{th}}$]	0	0	0	0	0	0	0	1
Battery Storage large-scale	[TWh]	2	0	1	8	27	52	68	90
Battery Storage prosumer	[TWh]	0	0	0	0	1	5	16	35
Gas Storage	[TWh]	0	0	0	1	1	7	17	24
Pumped Hydro Storage (PHS)	[TWh]	0	1	1	1	1	1	1	1
Adiabatic Compressed Air Energy Storage (A-CAES)	[TWh]	0	0	0	0	0	0	0	1
Thermal Energy Storage (TES)	[TWh]	0	0	0	0	0	0	0	0

Table 3.7: ***MENA*** *- Installed capacities of power and storage technologies during the energy transition from 2015 to 2050.*



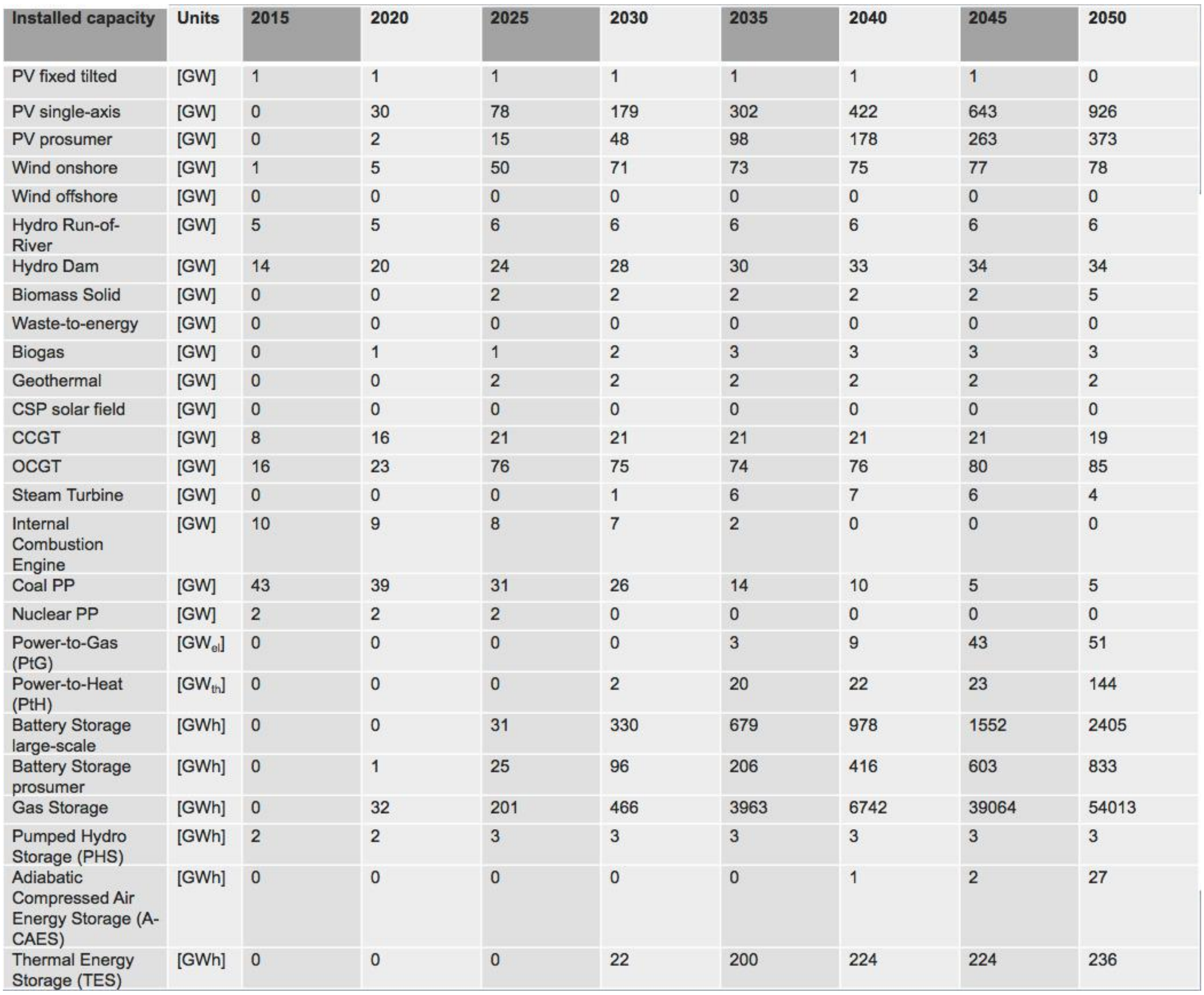
Installed capacity	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[GW]	1	1	1	7	76	135	182	268
PV single-axis	[GW]	0	69	218	370	556	634	670	753
PV prosumer	[GW]	0	4	18	52	97	176	294	386
Wind onshore	[GW]	2	3	111	240	240	239	239	237
Wind offshore	[GW]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[GW]	5	5	5	5	5	5	5	5
Hydro Dam	[GW]	14	15	16	16	16	16	16	16
Biomass Solid	[GW]	0	3	5	7	8	9	9	9
Waste-to-energy	[GW]	0	1	1	1	1	1	1	1
Biogas	[GW]	0	1	1	2	2	2	2	3
Geothermal	[GW]	0	0	5	5	5	5	5	6
CSP solar field	[GW]	0	0	1	1	1	1	7	40
CCGT	[GW]	97	163	171	168	164	159	146	110
OCGT	[GW]	141	132	304	300	292	279	259	227
Steam Turbine	[GW]	0	0	0	2	10	9	8	12
Internal Combustion Engine	[GW]	78	54	27	22	9	0	0	0
Coal PP	[GW]	7	7	7	5	5	3	2	1
Nuclear PP	[GW]	1	1	1	1	1	1	1	1
Power-to-Gas (PtG)	[GW_{el}]	0	0	0	0	23	48	71	83
Power-to-Heat (PtH)	[GW_{th}]	0	0	3	8	35	40	96	357
Battery Storage large-scale	[GWh]	0	0	19	548	1380	1863	2141	2641
Battery Storage prosumer	[GWh]	0	3	27	110	207	387	726	952
Gas Storage	[GWh]	0	15	189	977	9619	42949	70503	92575
Pumped Hydro Storage (PHS)	[GWh]	1	1	2	2	2	2	2	2
Adiabatic Compressed Air Energy Storage (A-CAES)	[GWh]	0	0	12	12	12	20	27	53
Thermal Energy Storage (TES)	[GWh]	2	2	12	57	341	342	361	676

Table 3.8: ***MENA*** *- Generation of electricity and storage output during the energy transition from 2015 to 2050.*



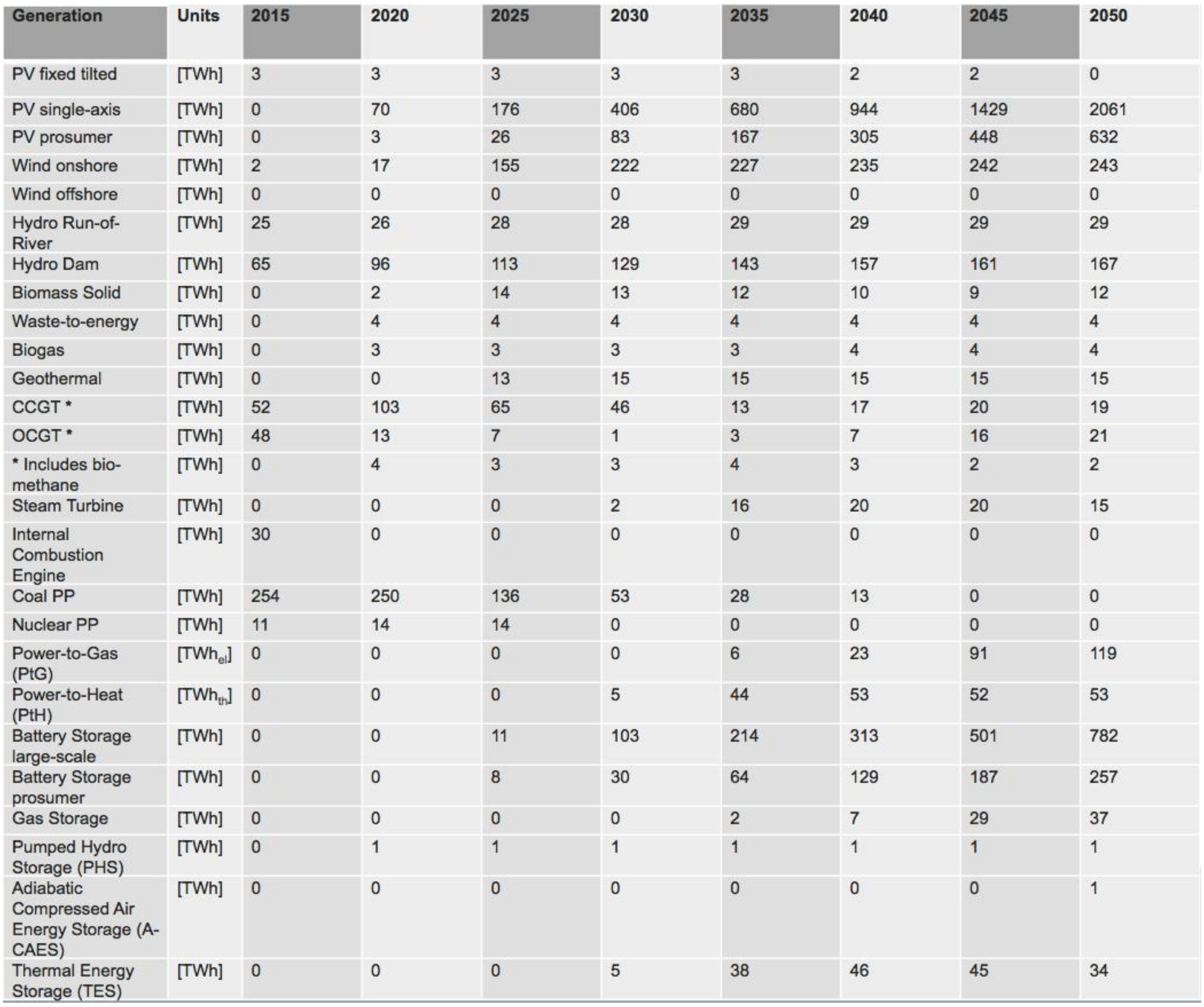
Generation	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[TWh]	2	2	2	12	131	232	314	465
PV single-axis	[TWh]	0	161	512	860	1301	1486	1574	1770
PV prosumer	[TWh]	1	6	31	91	173	314	525	689
Wind onshore	[TWh]	4	7	315	662	661	660	658	654
Wind offshore	[TWh]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[TWh]	15	15	15	15	15	15	15	15
Hydro Dam	[TWh]	38	45	47	48	48	48	48	48
Biomass Solid	[TWh]	0	23	41	41	42	42	40	30
Waste-to-energy	[TWh]	0	5	5	5	5	5	5	5
Biogas	[TWh]	0	6	6	6	6	6	6	6
Geothermal	[TWh]	0	0	39	39	39	39	39	39
CCGT *	[TWh]	419	1163	696	316	114	87	90	77
OCGT *	[TWh]	519	51	13	0	0	0	1	6
* Includes bio-methane	[TWh]	0	13	13	14	13	13	14	14
Steam Turbine	[TWh]	0	0	1	5	28	25	25	51
Internal Combustion Engine	[TWh]	319	0	0	0	0	0	0	0
Coal PP	[TWh]	46	60	45	28	14	7	2	0
Nuclear PP	[TWh]	4	7	7	7	7	7	7	7
Power-to-Gas (PtG)	[$\mathrm{TWh_{el}}$]	0	0	0	1	53	118	163	198
Power-to-Heat (PtH)	[$\mathrm{TWh_{th}}$]	0	0	0	11	72	64	53	55
Battery Storage large-scale	[TWh]	0	0	6	173	439	606	687	866
Battery Storage prosumer	[TWh]	0	1	8	35	64	120	227	296
Gas Storage	[TWh]	0	0	0	0	20	43	61	70
Pumped Hydro Storage (PHS)	[TWh]	0	0	1	0	0	0	0	0
Adiabatic Compressed Air Energy Storage (A-CAES)	[TWh]	0	0	0	0	0	0	1	1
Thermal Energy Storage (TES)	[TWh]	0	0	2	11	64	57	56	116

Table 3.9: ***Sub-Saharan Africa*** *- Installed capacities of power and storage technologies during the energy transition from 2015 to 2050.*



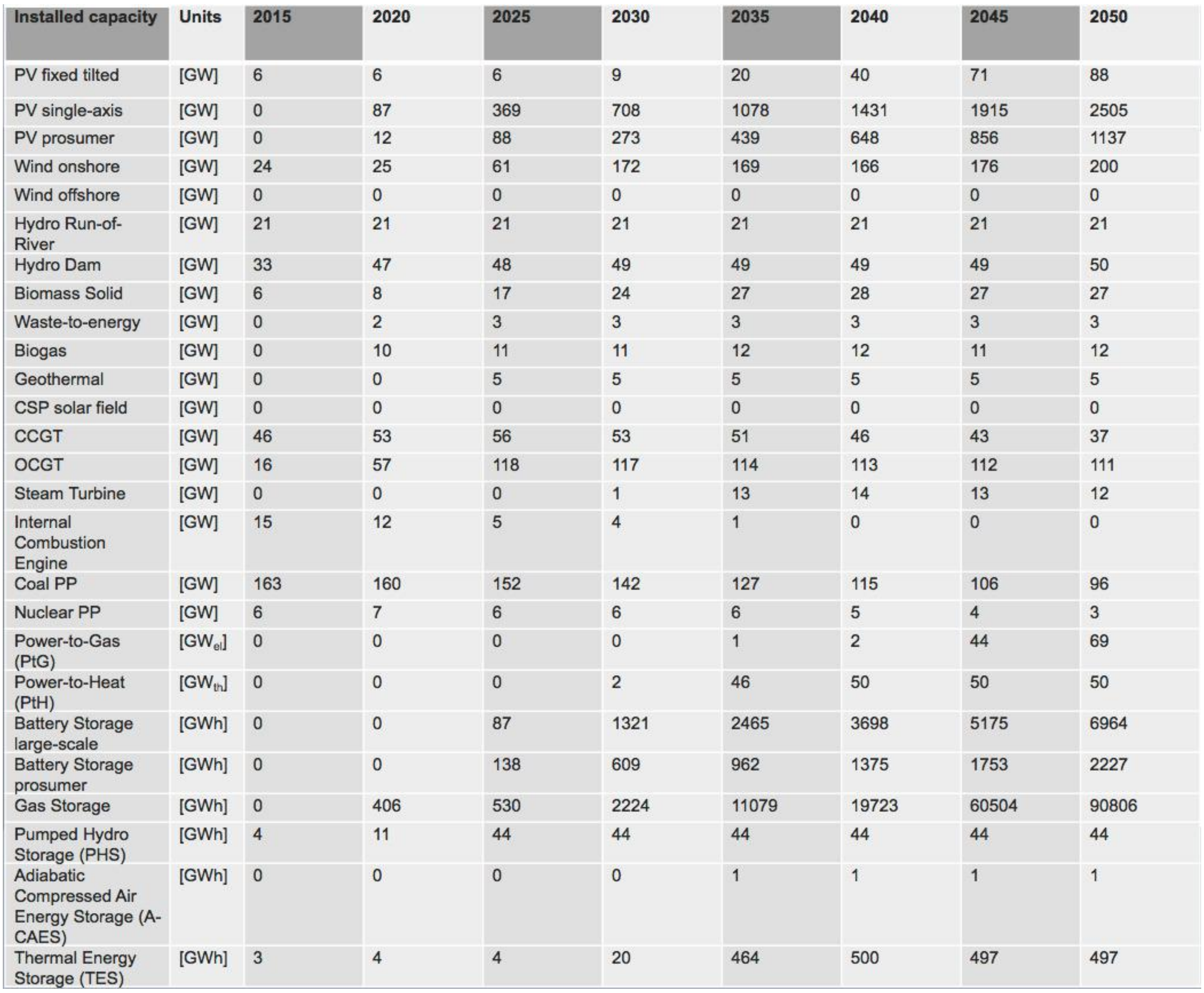
Installed capacity	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[GW]	1	1	1	1	1	1	1	0
PV single-axis	[GW]	0	30	78	179	302	422	643	926
PV prosumer	[GW]	0	2	15	48	98	178	263	373
Wind onshore	[GW]	1	5	50	71	73	75	77	78
Wind offshore	[GW]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[GW]	5	5	6	6	6	6	6	6
Hydro Dam	[GW]	14	20	24	28	30	33	34	34
Biomass Solid	[GW]	0	0	2	2	2	2	2	5
Waste-to-energy	[GW]	0	0	0	0	0	0	0	0
Biogas	[GW]	0	1	1	2	3	3	3	3
Geothermal	[GW]	0	0	2	2	2	2	2	2
CSP solar field	[GW]	0	0	0	0	0	0	0	0
CCGT	[GW]	8	16	21	21	21	21	21	19
OCGT	[GW]	16	23	76	75	74	76	80	85
Steam Turbine	[GW]	0	0	0	1	6	7	6	4
Internal Combustion Engine	[GW]	10	9	8	7	2	0	0	0
Coal PP	[GW]	43	39	31	26	14	10	5	5
Nuclear PP	[GW]	2	2	2	0	0	0	0	0
Power-to-Gas (PtG)	$[GW_{el}]$	0	0	0	0	3	9	43	51
Power-to-Heat (PtH)	$[GW_{th}]$	0	0	0	2	20	22	23	144
Battery Storage large-scale	[GWh]	0	0	31	330	679	978	1552	2405
Battery Storage prosumer	[GWh]	0	1	25	96	206	416	603	833
Gas Storage	[GWh]	0	32	201	466	3963	6742	39064	54013
Pumped Hydro Storage (PHS)	[GWh]	2	2	3	3	3	3	3	3
Adiabatic Compressed Air Energy Storage (A-CAES)	[GWh]	0	0	0	0	0	1	2	27
Thermal Energy Storage (TES)	[GWh]	0	0	0	22	200	224	224	236

Table 3.10: ***Sub-Saharan Africa -*** *Generation of electricity and storage output during the energy transition from 2015 to 2050.*



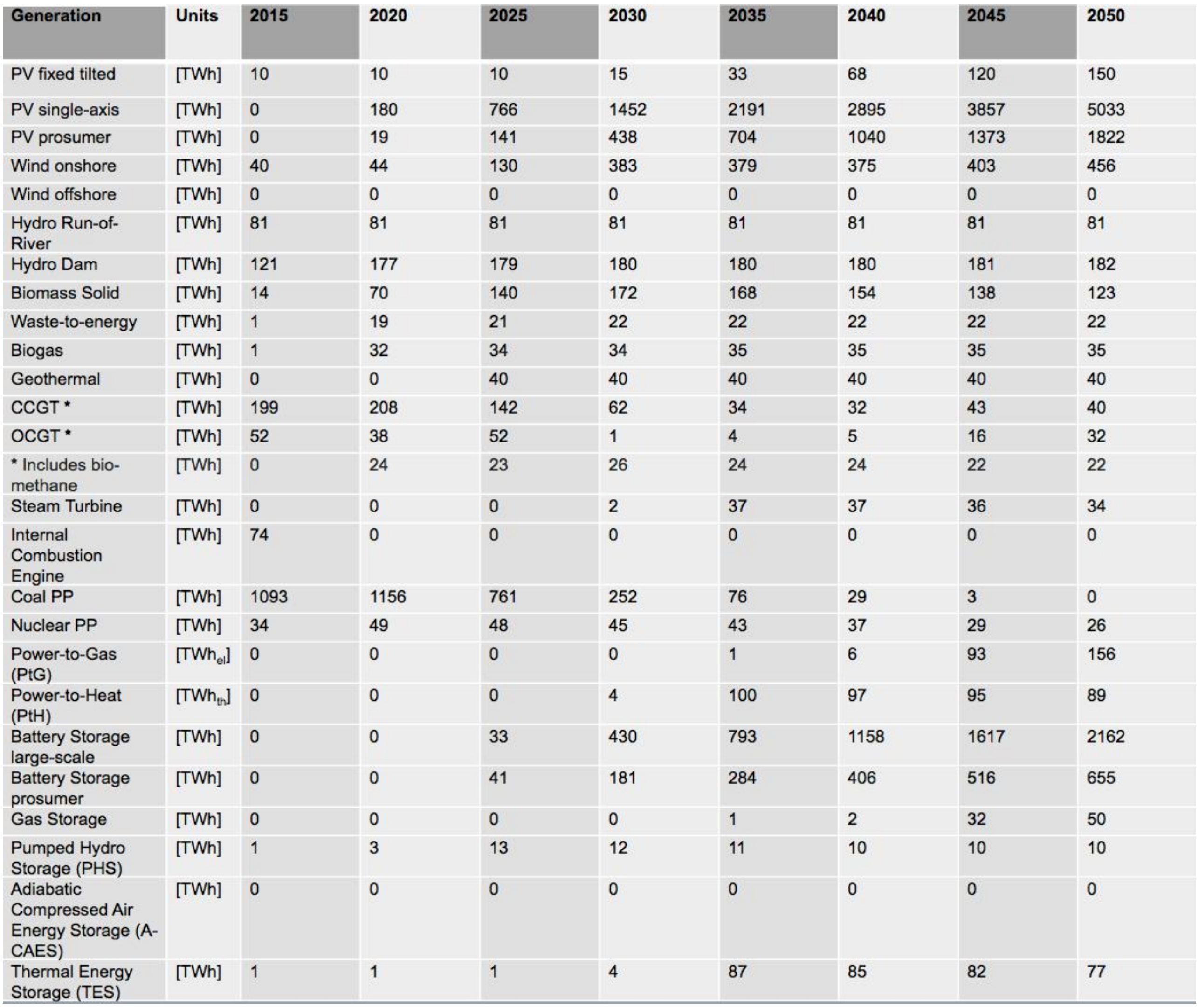
Generation	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[TWh]	3	3	3	3	3	2	2	0
PV single-axis	[TWh]	0	70	176	406	680	944	1429	2061
PV prosumer	[TWh]	0	3	26	83	167	305	448	632
Wind onshore	[TWh]	2	17	155	222	227	235	242	243
Wind offshore	[TWh]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[TWh]	25	26	28	28	29	29	29	29
Hydro Dam	[TWh]	65	96	113	129	143	157	161	167
Biomass Solid	[TWh]	0	2	14	13	12	10	9	12
Waste-to-energy	[TWh]	0	4	4	4	4	4	4	4
Biogas	[TWh]	0	3	3	3	3	4	4	4
Geothermal	[TWh]	0	0	13	15	15	15	15	15
CCGT *	[TWh]	52	103	65	46	13	17	20	19
OCGT *	[TWh]	48	13	7	1	3	7	16	21
* Includes bio-methane	[TWh]	0	4	3	3	4	3	2	2
Steam Turbine	[TWh]	0	0	0	2	16	20	20	15
Internal Combustion Engine	[TWh]	30	0	0	0	0	0	0	0
Coal PP	[TWh]	254	250	136	53	28	13	0	0
Nuclear PP	[TWh]	11	14	14	0	0	0	0	0
Power-to-Gas (PtG)	[TWh_{el}]	0	0	0	0	6	23	91	119
Power-to-Heat (PtH)	[TWh_{th}]	0	0	0	5	44	53	52	53
Battery Storage large-scale	[TWh]	0	0	11	103	214	313	501	782
Battery Storage prosumer	[TWh]	0	0	8	30	64	129	187	257
Gas Storage	[TWh]	0	0	0	0	2	7	29	37
Pumped Hydro Storage (PHS)	[TWh]	0	1	1	1	1	1	1	1
Adiabatic Compressed Air Energy Storage (A-CAES)	[TWh]	0	0	0	0	0	0	0	1
Thermal Energy Storage (TES)	[TWh]	0	0	0	5	38	46	45	34

Table 3.11: ***SAARC*** *- Installed capacities of power and storage technologies during the energy transition from 2015 to 2050.*



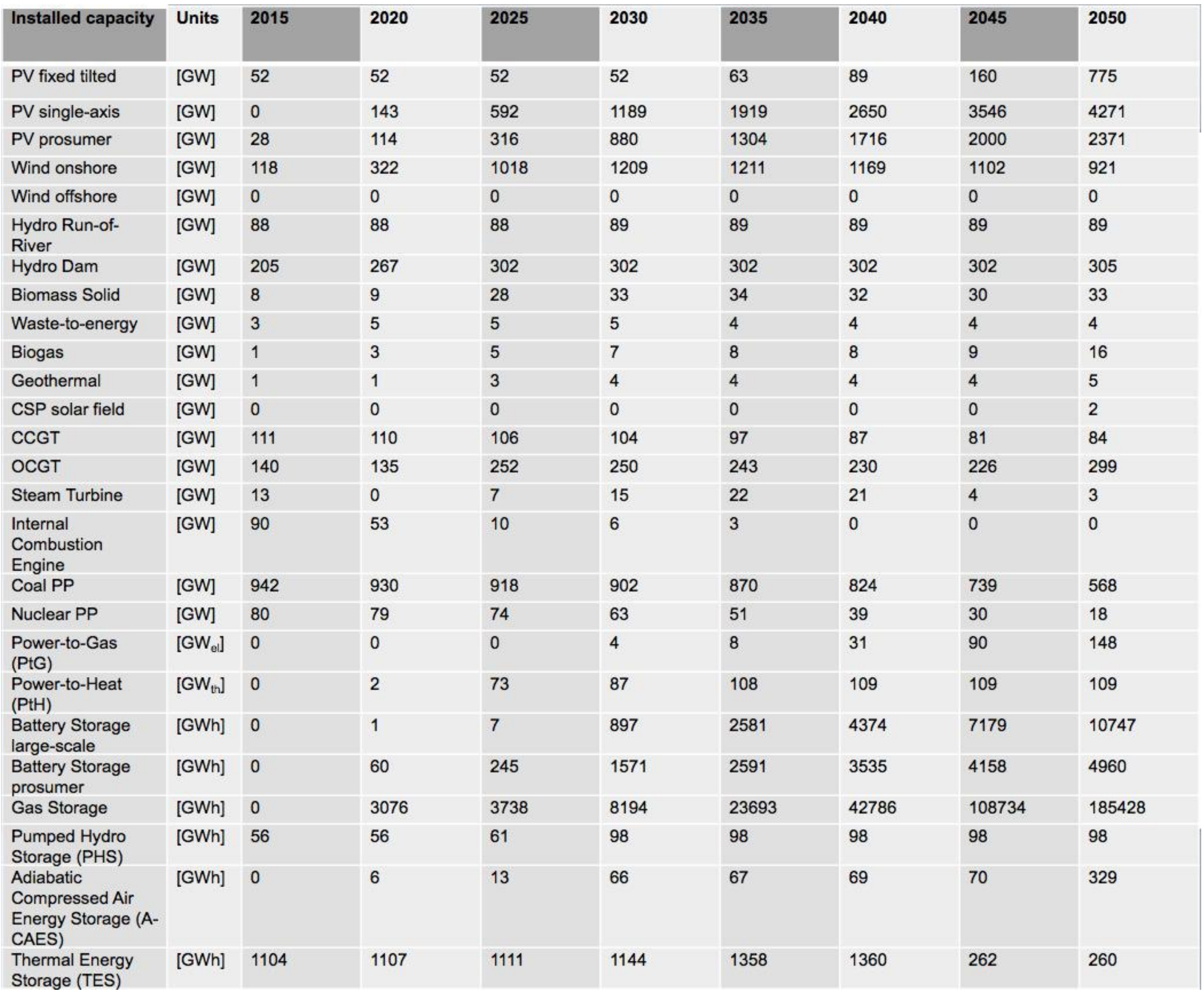
Installed capacity	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[GW]	6	6	6	9	20	40	71	88
PV single-axis	[GW]	0	87	369	708	1078	1431	1915	2505
PV prosumer	[GW]	0	12	88	273	439	648	856	1137
Wind onshore	[GW]	24	25	61	172	169	166	176	200
Wind offshore	[GW]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[GW]	21	21	21	21	21	21	21	21
Hydro Dam	[GW]	33	47	48	49	49	49	49	50
Biomass Solid	[GW]	6	8	17	24	27	28	27	27
Waste-to-energy	[GW]	0	2	3	3	3	3	3	3
Biogas	[GW]	0	10	11	11	12	12	11	12
Geothermal	[GW]	0	0	5	5	5	5	5	5
CSP solar field	[GW]	0	0	0	0	0	0	0	0
CCGT	[GW]	46	53	56	53	51	46	43	37
OCGT	[GW]	16	57	118	117	114	113	112	111
Steam Turbine	[GW]	0	0	0	1	13	14	13	12
Internal Combustion Engine	[GW]	15	12	5	4	1	0	0	0
Coal PP	[GW]	163	160	152	142	127	115	106	96
Nuclear PP	[GW]	6	7	6	6	6	5	4	3
Power-to-Gas (PtG)	[GW$_{el}$]	0	0	0	0	1	2	44	69
Power-to-Heat (PtH)	[GW$_{th}$]	0	0	0	2	46	50	50	50
Battery Storage large-scale	[GWh]	0	0	87	1321	2465	3698	5175	6964
Battery Storage prosumer	[GWh]	0	0	138	609	962	1375	1753	2227
Gas Storage	[GWh]	0	406	530	2224	11079	19723	60504	90806
Pumped Hydro Storage (PHS)	[GWh]	4	11	44	44	44	44	44	44
Adiabatic Compressed Air Energy Storage (A-CAES)	[GWh]	0	0	0	0	1	1	1	1
Thermal Energy Storage (TES)	[GWh]	3	4	4	20	464	500	497	497

Table 3.12: ***SAARC*** *- Generation of electricity and storage output during the energy transition from 2015 to 2050.*



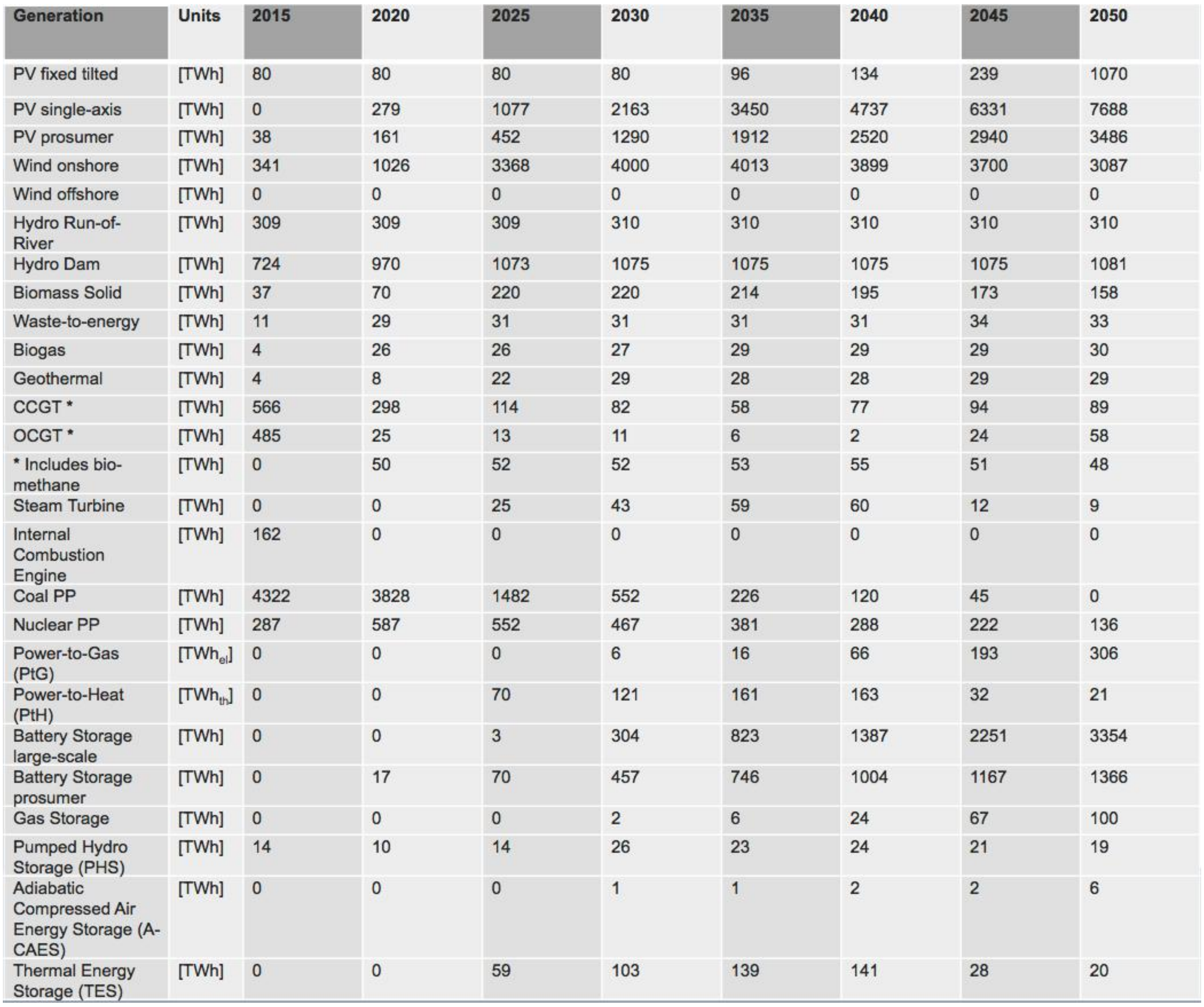
Generation	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[TWh]	10	10	10	15	33	68	120	150
PV single-axis	[TWh]	0	180	766	1452	2191	2895	3857	5033
PV prosumer	[TWh]	0	19	141	438	704	1040	1373	1822
Wind onshore	[TWh]	40	44	130	383	379	375	403	456
Wind offshore	[TWh]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[TWh]	81	81	81	81	81	81	81	81
Hydro Dam	[TWh]	121	177	179	180	180	180	181	182
Biomass Solid	[TWh]	14	70	140	172	168	154	138	123
Waste-to-energy	[TWh]	1	19	21	22	22	22	22	22
Biogas	[TWh]	1	32	34	34	35	35	35	35
Geothermal	[TWh]	0	0	40	40	40	40	40	40
CCGT *	[TWh]	199	208	142	62	34	32	43	40
OCGT *	[TWh]	52	38	52	1	4	5	16	32
* Includes bio-methane	[TWh]	0	24	23	26	24	24	22	22
Steam Turbine	[TWh]	0	0	0	2	37	37	36	34
Internal Combustion Engine	[TWh]	74	0	0	0	0	0	0	0
Coal PP	[TWh]	1093	1156	761	252	76	29	3	0
Nuclear PP	[TWh]	34	49	48	45	43	37	29	26
Power-to-Gas (PtG)	[TWh$_{el}$]	0	0	0	0	1	6	93	156
Power-to-Heat (PtH)	[TWh$_{th}$]	0	0	0	4	100	97	95	89
Battery Storage large-scale	[TWh]	0	0	33	430	793	1158	1617	2162
Battery Storage prosumer	[TWh]	0	0	41	181	284	406	516	655
Gas Storage	[TWh]	0	0	0	0	1	2	32	50
Pumped Hydro Storage (PHS)	[TWh]	1	3	13	12	11	10	10	10
Adiabatic Compressed Air Energy Storage (A-CAES)	[TWh]	0	0	0	0	0	0	0	0
Thermal Energy Storage (TES)	[TWh]	1	1	1	4	87	85	82	77

Table 3.13: ***Northeast Asia*** *- Installed capacities of power and storage technologies during the energy transition from 2015 to 2050.*



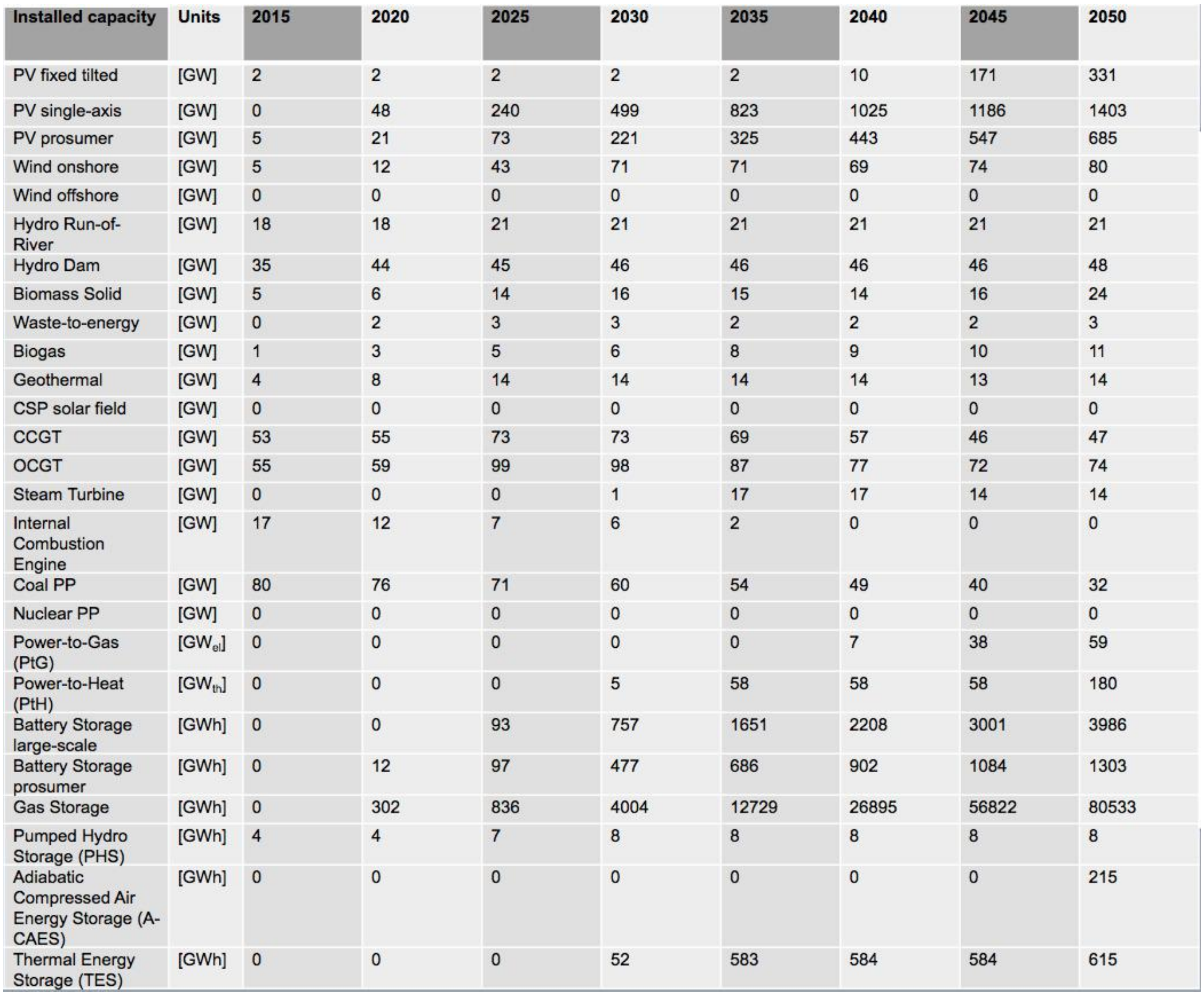
Installed capacity	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[GW]	52	52	52	52	63	89	160	775
PV single-axis	[GW]	0	143	592	1189	1919	2650	3546	4271
PV prosumer	[GW]	28	114	316	880	1304	1716	2000	2371
Wind onshore	[GW]	118	322	1018	1209	1211	1169	1102	921
Wind offshore	[GW]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[GW]	88	88	88	89	89	89	89	89
Hydro Dam	[GW]	205	267	302	302	302	302	302	305
Biomass Solid	[GW]	8	9	28	33	34	32	30	33
Waste-to-energy	[GW]	3	5	5	5	4	4	4	4
Biogas	[GW]	1	3	5	7	8	8	9	16
Geothermal	[GW]	1	1	3	4	4	4	4	5
CSP solar field	[GW]	0	0	0	0	0	0	0	2
CCGT	[GW]	111	110	106	104	97	87	81	84
OCGT	[GW]	140	135	252	250	243	230	226	299
Steam Turbine	[GW]	13	0	7	15	22	21	4	3
Internal Combustion Engine	[GW]	90	53	10	6	3	0	0	0
Coal PP	[GW]	942	930	918	902	870	824	739	568
Nuclear PP	[GW]	80	79	74	63	51	39	30	18
Power-to-Gas (PtG)	[GW$_{el}$]	0	0	0	4	8	31	90	148
Power-to-Heat (PtH)	[GW$_{th}$]	0	2	73	87	108	109	109	109
Battery Storage large-scale	[GWh]	0	1	7	897	2581	4374	7179	10747
Battery Storage prosumer	[GWh]	0	60	245	1571	2591	3535	4158	4960
Gas Storage	[GWh]	0	3076	3738	8194	23693	42786	108734	185428
Pumped Hydro Storage (PHS)	[GWh]	56	56	61	98	98	98	98	98
Adiabatic Compressed Air Energy Storage (A-CAES)	[GWh]	0	6	13	66	67	69	70	329
Thermal Energy Storage (TES)	[GWh]	1104	1107	1111	1144	1358	1360	262	260

Table 3.14: ***Northeast Asia*** *- Generation of electricity and storage output during the energy transition from 2015 to 2050.*



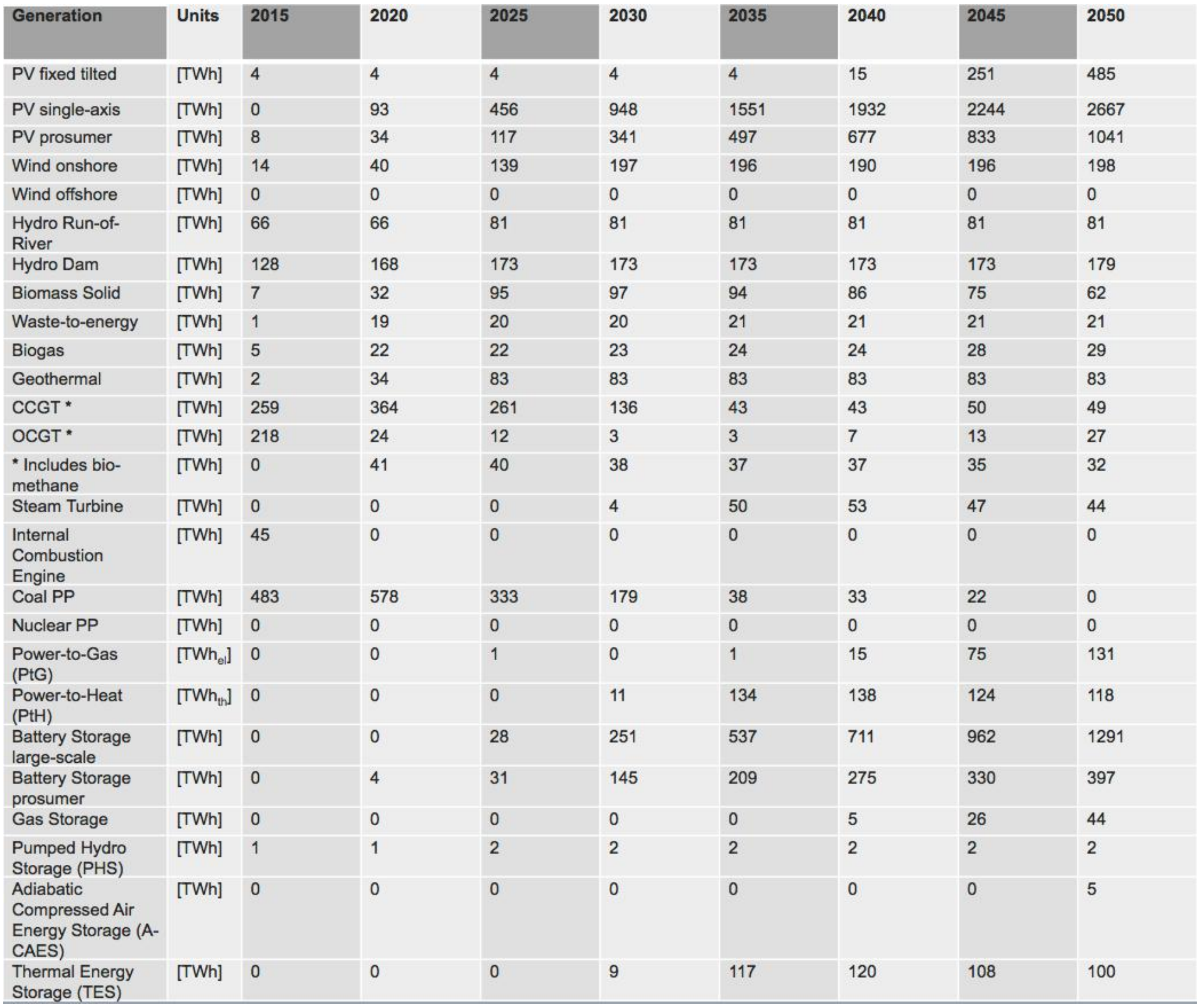
Generation	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[TWh]	80	80	80	80	96	134	239	1070
PV single-axis	[TWh]	0	279	1077	2163	3450	4737	6331	7688
PV prosumer	[TWh]	38	161	452	1290	1912	2520	2940	3486
Wind onshore	[TWh]	341	1026	3368	4000	4013	3899	3700	3087
Wind offshore	[TWh]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[TWh]	309	309	309	310	310	310	310	310
Hydro Dam	[TWh]	724	970	1073	1075	1075	1075	1075	1081
Biomass Solid	[TWh]	37	70	220	220	214	195	173	158
Waste-to-energy	[TWh]	11	29	31	31	31	31	34	33
Biogas	[TWh]	4	26	26	27	29	29	29	30
Geothermal	[TWh]	4	8	22	29	28	28	29	29
CCGT *	[TWh]	566	298	114	82	58	77	94	89
OCGT *	[TWh]	485	25	13	11	6	2	24	58
* Includes bio-methane	[TWh]	0	50	52	52	53	55	51	48
Steam Turbine	[TWh]	0	0	25	43	59	60	12	9
Internal Combustion Engine	[TWh]	162	0	0	0	0	0	0	0
Coal PP	[TWh]	4322	3828	1482	552	226	120	45	0
Nuclear PP	[TWh]	287	587	552	467	381	288	222	136
Power-to-Gas (PtG)	[TWh$_{el}$]	0	0	0	6	16	66	193	306
Power-to-Heat (PtH)	[TWh$_{th}$]	0	0	70	121	161	163	32	21
Battery Storage large-scale	[TWh]	0	0	3	304	823	1387	2251	3354
Battery Storage prosumer	[TWh]	0	17	70	457	746	1004	1167	1366
Gas Storage	[TWh]	0	0	0	2	6	24	67	100
Pumped Hydro Storage (PHS)	[TWh]	14	10	14	26	23	24	21	19
Adiabatic Compressed Air Energy Storage (A-CAES)	[TWh]	0	0	0	1	1	2	2	6
Thermal Energy Storage (TES)	[TWh]	0	0	59	103	139	141	28	20

Table 3.15: ***Southeast Asia*** *- Installed capacities of power and storage technologies during the energy transition from 2015 to 2050.*



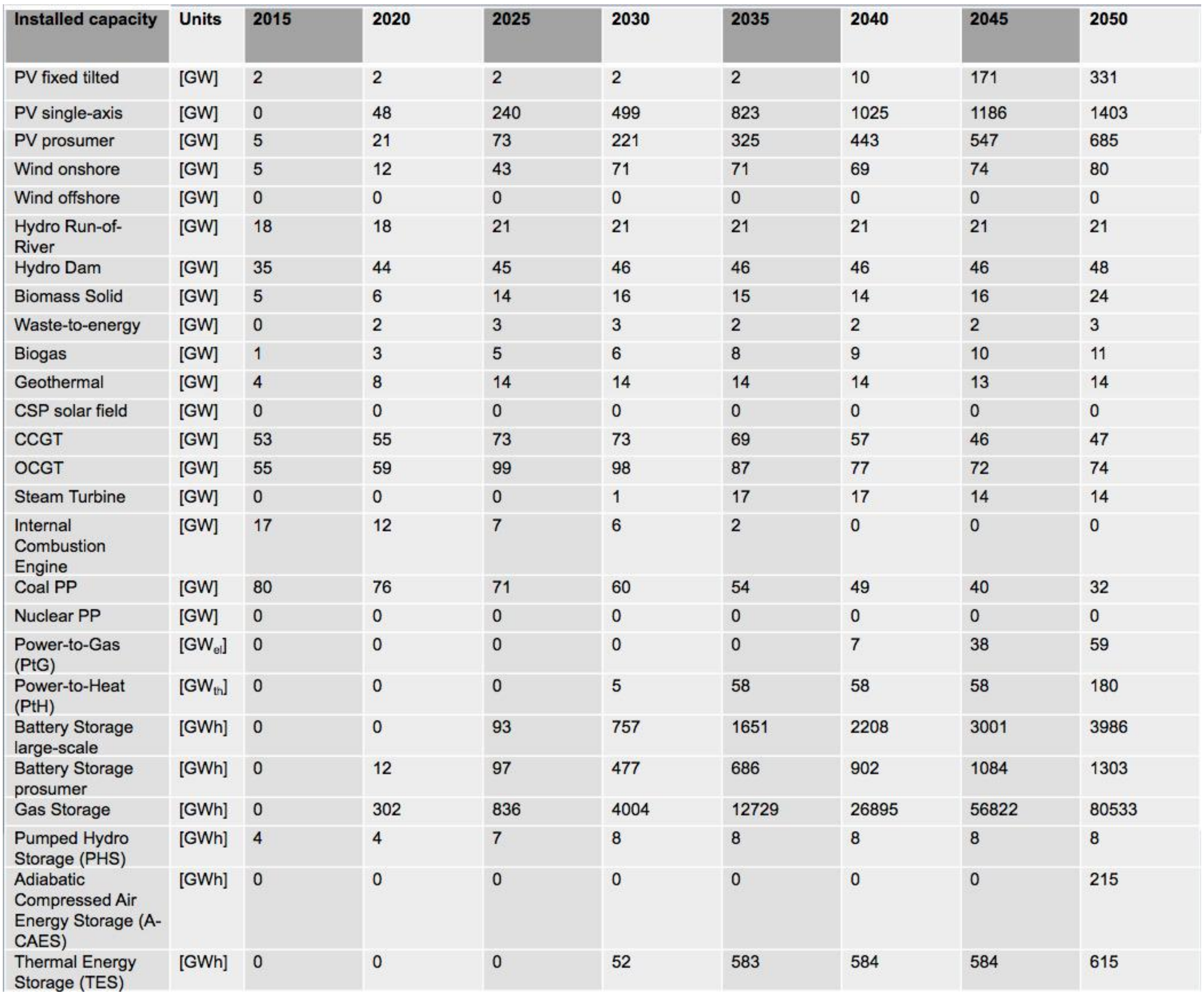
Installed capacity	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[GW]	2	2	2	2	2	10	171	331
PV single-axis	[GW]	0	48	240	499	823	1025	1186	1403
PV prosumer	[GW]	5	21	73	221	325	443	547	685
Wind onshore	[GW]	5	12	43	71	71	69	74	80
Wind offshore	[GW]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[GW]	18	18	21	21	21	21	21	21
Hydro Dam	[GW]	35	44	45	46	46	46	46	48
Biomass Solid	[GW]	5	6	14	16	15	14	16	24
Waste-to-energy	[GW]	0	2	3	3	2	2	2	3
Biogas	[GW]	1	3	5	6	8	9	10	11
Geothermal	[GW]	4	8	14	14	14	14	13	14
CSP solar field	[GW]	0	0	0	0	0	0	0	0
CCGT	[GW]	53	55	73	73	69	57	46	47
OCGT	[GW]	55	59	99	98	87	77	72	74
Steam Turbine	[GW]	0	0	0	1	17	17	14	14
Internal Combustion Engine	[GW]	17	12	7	6	2	0	0	0
Coal PP	[GW]	80	76	71	60	54	49	40	32
Nuclear PP	[GW]	0	0	0	0	0	0	0	0
Power-to-Gas (PtG)	[GW_{el}]	0	0	0	0	0	7	38	59
Power-to-Heat (PtH)	[GW_{th}]	0	0	0	5	58	58	58	180
Battery Storage large-scale	[GWh]	0	0	93	757	1651	2208	3001	3986
Battery Storage prosumer	[GWh]	0	12	97	477	686	902	1084	1303
Gas Storage	[GWh]	0	302	836	4004	12729	26895	56822	80533
Pumped Hydro Storage (PHS)	[GWh]	4	4	7	8	8	8	8	8
Adiabatic Compressed Air Energy Storage (A-CAES)	[GWh]	0	0	0	0	0	0	0	215
Thermal Energy Storage (TES)	[GWh]	0	0	0	52	583	584	584	615

Table 3.16: ***Southeast Asia*** *- Generation of electricity and storage output during the energy transition from 2015 to 2050.*



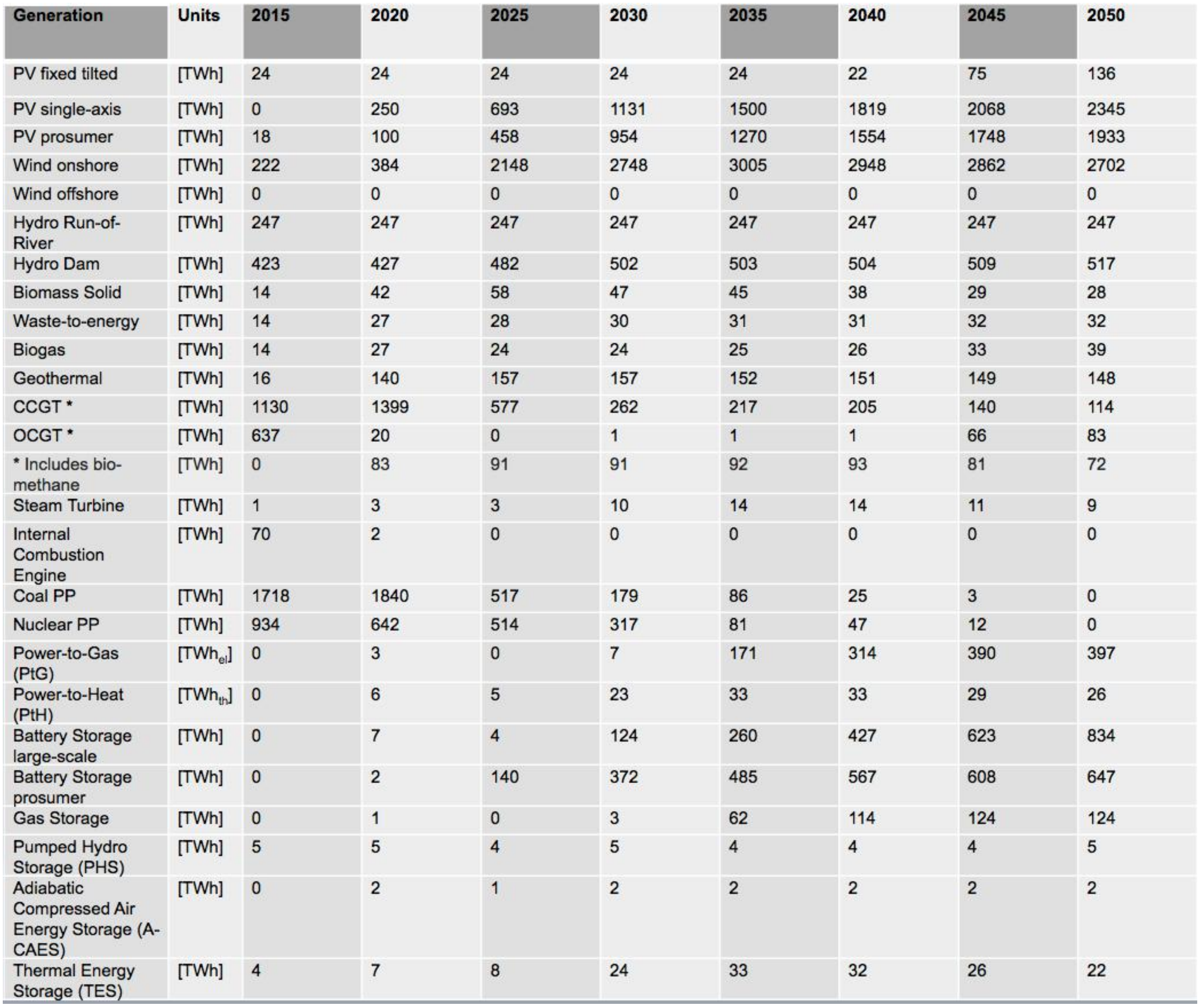
Generation	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[TWh]	4	4	4	4	4	15	251	485
PV single-axis	[TWh]	0	93	456	948	1551	1932	2244	2667
PV prosumer	[TWh]	8	34	117	341	497	677	833	1041
Wind onshore	[TWh]	14	40	139	197	196	190	196	198
Wind offshore	[TWh]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[TWh]	66	66	81	81	81	81	81	81
Hydro Dam	[TWh]	128	168	173	173	173	173	173	179
Biomass Solid	[TWh]	7	32	95	97	94	86	75	62
Waste-to-energy	[TWh]	1	19	20	20	21	21	21	21
Biogas	[TWh]	5	22	22	23	24	24	28	29
Geothermal	[TWh]	2	34	83	83	83	83	83	83
CCGT *	[TWh]	259	364	261	136	43	43	50	49
OCGT *	[TWh]	218	24	12	3	3	7	13	27
* Includes bio-methane	[TWh]	0	41	40	38	37	37	35	32
Steam Turbine	[TWh]	0	0	0	4	50	53	47	44
Internal Combustion Engine	[TWh]	45	0	0	0	0	0	0	0
Coal PP	[TWh]	483	578	333	179	38	33	22	0
Nuclear PP	[TWh]	0	0	0	0	0	0	0	0
Power-to-Gas (PtG)	[TWh_{el}]	0	0	1	0	1	15	75	131
Power-to-Heat (PtH)	[TWh_{th}]	0	0	0	11	134	138	124	118
Battery Storage large-scale	[TWh]	0	0	28	251	537	711	962	1291
Battery Storage prosumer	[TWh]	0	4	31	145	209	275	330	397
Gas Storage	[TWh]	0	0	0	0	0	5	26	44
Pumped Hydro Storage (PHS)	[TWh]	1	1	2	2	2	2	2	2
Adiabatic Compressed Air Energy Storage (A-CAES)	[TWh]	0	0	0	0	0	0	0	5
Thermal Energy Storage (TES)	[TWh]	0	0	0	9	117	120	108	100

Table 3.17: ***North America*** *- Installed capacities of power and storage technologies during the energy transition from 2015 to 2050.*



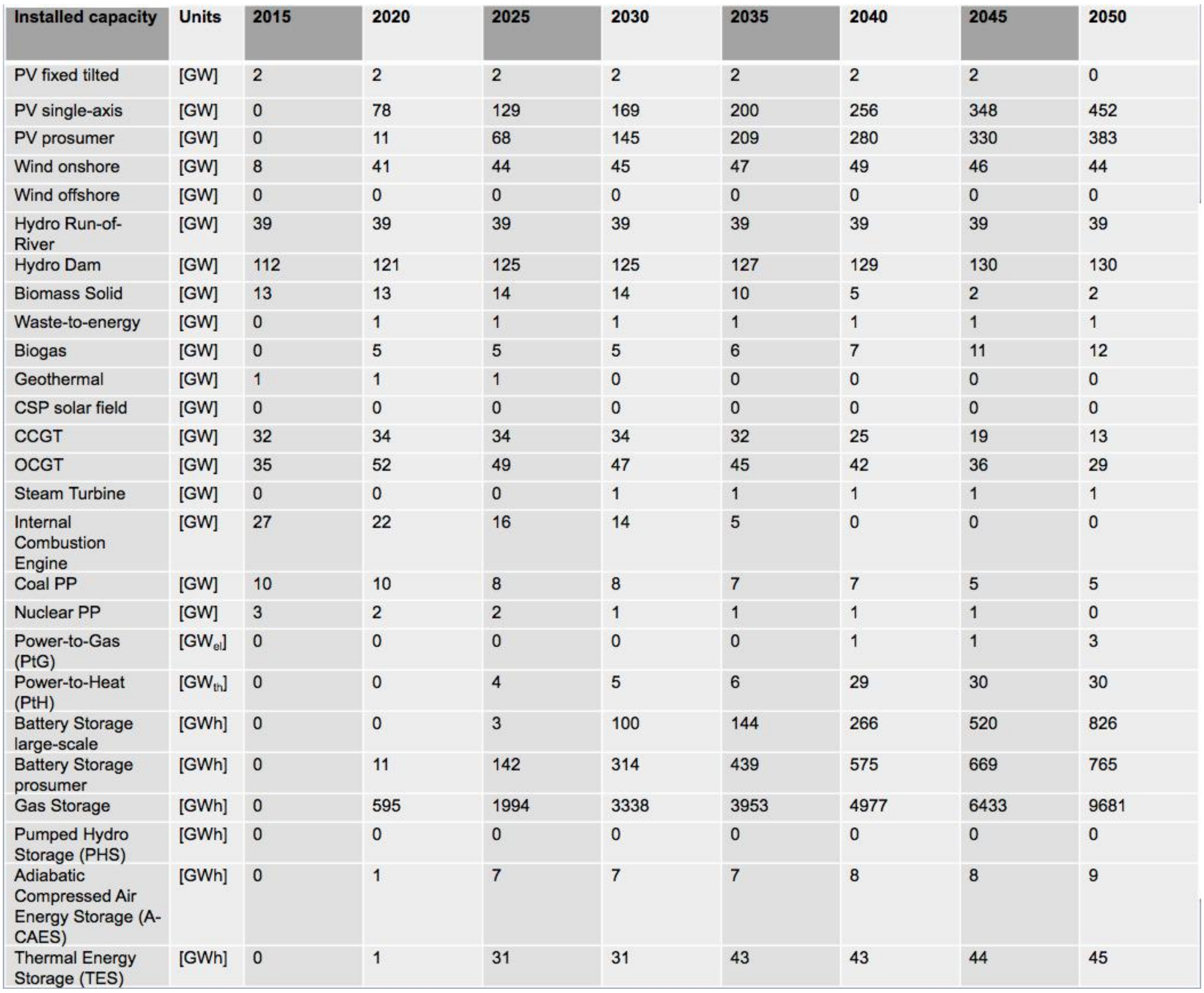
Installed capacity	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[GW]	2	2	2	2	2	10	171	331
PV single-axis	[GW]	0	48	240	499	823	1025	1186	1403
PV prosumer	[GW]	5	21	73	221	325	443	547	685
Wind onshore	[GW]	5	12	43	71	71	69	74	80
Wind offshore	[GW]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[GW]	18	18	21	21	21	21	21	21
Hydro Dam	[GW]	35	44	45	46	46	46	46	48
Biomass Solid	[GW]	5	6	14	16	15	14	16	24
Waste-to-energy	[GW]	0	2	3	3	2	2	2	3
Biogas	[GW]	1	3	5	6	8	9	10	11
Geothermal	[GW]	4	8	14	14	14	14	13	14
CSP solar field	[GW]	0	0	0	0	0	0	0	0
CCGT	[GW]	53	55	73	73	69	57	46	47
OCGT	[GW]	55	59	99	98	87	77	72	74
Steam Turbine	[GW]	0	0	0	1	17	17	14	14
Internal Combustion Engine	[GW]	17	12	7	6	2	0	0	0
Coal PP	[GW]	80	76	71	60	54	49	40	32
Nuclear PP	[GW]	0	0	0	0	0	0	0	0
Power-to-Gas (PtG)	[GW_{el}]	0	0	0	0	0	7	38	59
Power-to-Heat (PtH)	[GW_{th}]	0	0	0	5	58	58	58	180
Battery Storage large-scale	[GWh]	0	0	93	757	1651	2208	3001	3986
Battery Storage prosumer	[GWh]	0	12	97	477	686	902	1084	1303
Gas Storage	[GWh]	0	302	836	4004	12729	26895	56822	80533
Pumped Hydro Storage (PHS)	[GWh]	4	4	7	8	8	8	8	8
Adiabatic Compressed Air Energy Storage (A-CAES)	[GWh]	0	0	0	0	0	0	0	215
Thermal Energy Storage (TES)	[GWh]	0	0	0	52	583	584	584	615

Table 3.18: ***North America*** *- Generation of electricity and storage output during the energy transition from 2015 to 2050.*



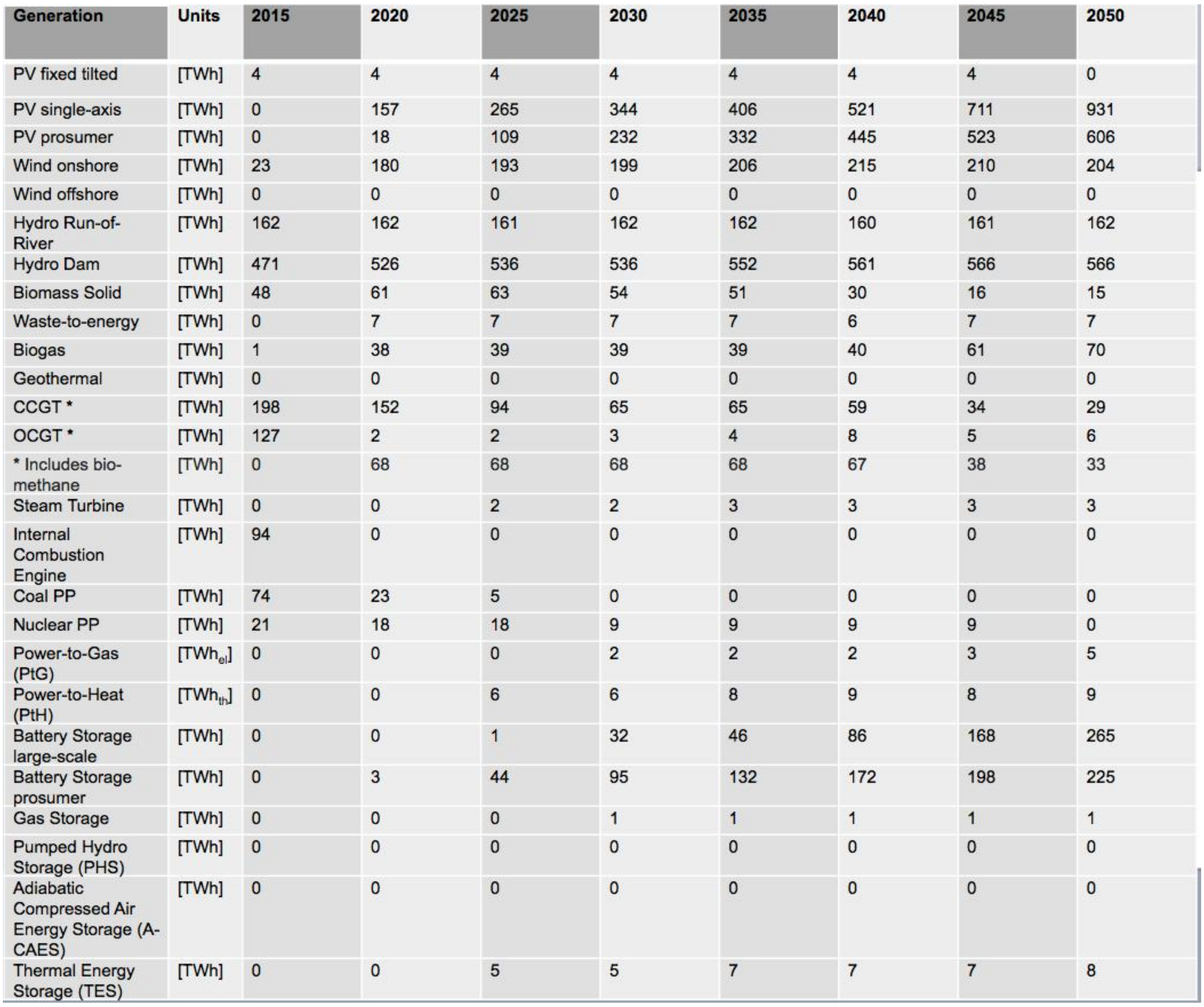
Generation	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[TWh]	24	24	24	24	24	22	75	136
PV single-axis	[TWh]	0	250	693	1131	1500	1819	2068	2345
PV prosumer	[TWh]	18	100	458	954	1270	1554	1748	1933
Wind onshore	[TWh]	222	384	2148	2748	3005	2948	2862	2702
Wind offshore	[TWh]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[TWh]	247	247	247	247	247	247	247	247
Hydro Dam	[TWh]	423	427	482	502	503	504	509	517
Biomass Solid	[TWh]	14	42	58	47	45	38	29	28
Waste-to-energy	[TWh]	14	27	28	30	31	31	32	32
Biogas	[TWh]	14	27	24	24	25	26	33	39
Geothermal	[TWh]	16	140	157	157	152	151	149	148
CCGT *	[TWh]	1130	1399	577	262	217	205	140	114
OCGT *	[TWh]	637	20	0	1	1	1	66	83
* Includes bio-methane	[TWh]	0	83	91	91	92	93	81	72
Steam Turbine	[TWh]	1	3	3	10	14	14	11	9
Internal Combustion Engine	[TWh]	70	2	0	0	0	0	0	0
Coal PP	[TWh]	1718	1840	517	179	86	25	3	0
Nuclear PP	[TWh]	934	642	514	317	81	47	12	0
Power-to-Gas (PtG)	[TWh$_{el}$]	0	3	0	7	171	314	390	397
Power-to-Heat (PtH)	[TWh$_{th}$]	0	6	5	23	33	33	29	26
Battery Storage large-scale	[TWh]	0	7	4	124	260	427	623	834
Battery Storage prosumer	[TWh]	0	2	140	372	485	567	608	647
Gas Storage	[TWh]	0	1	0	3	62	114	124	124
Pumped Hydro Storage (PHS)	[TWh]	5	5	4	5	4	4	4	5
Adiabatic Compressed Air Energy Storage (A-CAES)	[TWh]	0	2	1	2	2	2	2	2
Thermal Energy Storage (TES)	[TWh]	4	7	8	24	33	32	26	22

Table 3.19: ***South America*** *- Installed capacities of power and storage technologies during the energy transition from 2015 to 2050.*



Installed capacity	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[GW]	2	2	2	2	2	2	2	0
PV single-axis	[GW]	0	78	129	169	200	256	348	452
PV prosumer	[GW]	0	11	68	145	209	280	330	383
Wind onshore	[GW]	8	41	44	45	47	49	46	44
Wind offshore	[GW]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[GW]	39	39	39	39	39	39	39	39
Hydro Dam	[GW]	112	121	125	125	127	129	130	130
Biomass Solid	[GW]	13	13	14	14	10	5	2	2
Waste-to-energy	[GW]	0	1	1	1	1	1	1	1
Biogas	[GW]	0	5	5	5	6	7	11	12
Geothermal	[GW]	1	1	1	0	0	0	0	0
CSP solar field	[GW]	0	0	0	0	0	0	0	0
CCGT	[GW]	32	34	34	34	32	25	19	13
OCGT	[GW]	35	52	49	47	45	42	36	29
Steam Turbine	[GW]	0	0	0	1	1	1	1	1
Internal Combustion Engine	[GW]	27	22	16	14	5	0	0	0
Coal PP	[GW]	10	10	8	8	7	7	5	5
Nuclear PP	[GW]	3	2	2	1	1	1	1	0
Power-to-Gas (PtG)	[GW_{el}]	0	0	0	0	0	1	1	3
Power-to-Heat (PtH)	[GW_{th}]	0	0	4	5	6	29	30	30
Battery Storage large-scale	[GWh]	0	0	3	100	144	266	520	826
Battery Storage prosumer	[GWh]	0	11	142	314	439	575	669	765
Gas Storage	[GWh]	0	595	1994	3338	3953	4977	6433	9681
Pumped Hydro Storage (PHS)	[GWh]	0	0	0	0	0	0	0	0
Adiabatic Compressed Air Energy Storage (A-CAES)	[GWh]	0	1	7	7	7	8	8	9
Thermal Energy Storage (TES)	[GWh]	0	1	31	31	43	43	44	45

Table 3.20: ***South America*** *- Generation of electricity and storage output during the energy transition from 2015 to 2050.*



Generation	Units	2015	2020	2025	2030	2035	2040	2045	2050
PV fixed tilted	[TWh]	4	4	4	4	4	4	4	0
PV single-axis	[TWh]	0	157	265	344	406	521	711	931
PV prosumer	[TWh]	0	18	109	232	332	445	523	606
Wind onshore	[TWh]	23	180	193	199	206	215	210	204
Wind offshore	[TWh]	0	0	0	0	0	0	0	0
Hydro Run-of-River	[TWh]	162	162	161	162	162	160	161	162
Hydro Dam	[TWh]	471	526	536	536	552	561	566	566
Biomass Solid	[TWh]	48	61	63	54	51	30	16	15
Waste-to-energy	[TWh]	0	7	7	7	7	6	7	7
Biogas	[TWh]	1	38	39	39	39	40	61	70
Geothermal	[TWh]	0	0	0	0	0	0	0	0
CCGT *	[TWh]	198	152	94	65	65	59	34	29
OCGT *	[TWh]	127	2	2	3	4	8	5	6
* Includes bio-methane	[TWh]	0	68	68	68	68	67	38	33
Steam Turbine	[TWh]	0	0	2	2	3	3	3	3
Internal Combustion Engine	[TWh]	94	0	0	0	0	0	0	0
Coal PP	[TWh]	74	23	5	0	0	0	0	0
Nuclear PP	[TWh]	21	18	18	9	9	9	9	0
Power-to-Gas (PtG)	[TWh$_{el}$]	0	0	0	2	2	2	3	5
Power-to-Heat (PtH)	[TWh$_{th}$]	0	0	6	6	8	9	8	9
Battery Storage large-scale	[TWh]	0	0	1	32	46	86	168	265
Battery Storage prosumer	[TWh]	0	3	44	95	132	172	198	225
Gas Storage	[TWh]	0	0	0	1	1	1	1	1
Pumped Hydro Storage (PHS)	[TWh]	0	0	0	0	0	0	0	0
Adiabatic Compressed Air Energy Storage (A-CAES)	[TWh]	0	0	0	0	0	0	0	0
Thermal Energy Storage (TES)	[TWh]	0	0	5	5	7	7	7	8

4 Supplementary information

Table 4.1: Links to presentation slide sets for Global, the 9 Major regions and 92 Countries/ Regions directly related to this study.

Global	results for all 145 sub-regions	http://bit.ly/2gQIY6p
Major Regions		
Europe	results for all 20 sub-regions	http://bit.ly/2zonZ6a
Eurasia	results for all 13 sub-regions	http://bit.ly/2zlUVfC
MENA	results for all 17 sub-regions	http://bit.ly/2lDUib0
Sub-Saharan Africa	results for all 16 sub-regions	http://bit.ly/2A5QgeQ
SAARC	results for all 16 sub-regions	http://bit.ly/2iS2TGi
Northeast Asia	results for all 13 sub-regions	http://bit.ly/2gRKghh
Southeast Asia	results for all 15 sub-regions	http://bit.ly/2A44Ao6
North America	results for all 20 sub-regions	http://bit.ly/2zn0IS3
South America	results for all 15 sub-regions	http://bit.ly/2iiWu2O
Countries/ Regions		
Europe	Norway	http://bit.ly/2ylpMc9
Europe	Denmark	http://bit.ly/2yl3189
Europe	Sweden	http://bit.ly/2iSDigs
Europe	Finland	http://bit.ly/2z5edmo
Europe	Baltic: Estonia, Latvia, Lithuania	http://bit.ly/2xLPnXg
Europe	Poland	http://bit.ly/2xMGXPu
Europe	Iberia: Portugal, Spain, Gibraltar	http://bit.ly/2iTLRYr
Europe	France, Monaco, Andorra	http://bit.ly/2ylKcBG
Europe	Belgium, Netherlands, Luxembourg	http://bit.ly/2gUzHdy
Europe	British Isles: Ireland, United Kingdom, Isle of Man, Guernsey, Jersey	http://bit.ly/2imJQQE
Europe	Germany	http://bit.ly/2ilWKhJ

Europe	Czech Republic, Slovakia	**http://bit.ly/2zYxlSx**
Europe	Austria, Hungary	**http://bit.ly/2zbWonZ**
Europe	Balkan-West: Slovenia, Croatia, Bosnia & Hertzegovina, Serbia, Kosova, Montenegro, Macedonia, Albania	**http://bit.ly/2z6t4j6**
Europe	Balkan-East: Romania, Bulgaria, Greece	**http://bit.ly/2xKNryb**
Europe	Italy, San Marino, Vatican	**http://bit.ly/2zoCerl**
Europe	Switzerland, Liechtenstein	**http://bit.ly/2ylSObu**
Europe	Turkey, Cyprus	**http://bit.ly/2gUt7Uc**
Europe	Ukraine, Moldova	**http://bit.ly/2h5W5o7**
Europe	Iceland	**http://bit.ly/2z3VffT**
Eurasia	Russia	**http://bit.ly/2xIeIRK**
Eurasia	Belarus	**http://bit.ly/2zX6XIq**
Eurasia	Armenia, Azerbaijan, Georgia	http://bit.ly/2A4k0sG
Eurasia	Kazakhstan	http://bit.ly/2il1Zht
Eurasia	Tajikistan, Kyrgyzstan	http://bit.ly/2ijTvHq
Eurasia	Uzbekistan	http://bit.ly/2iR3Hvb
Eurasia	Turkmenistan	http://bit.ly/2z3cqR6
MENA	Algeria	http://bit.ly/2xIA3L5
MENA	Bahrain, Qatar	http://bit.ly/2zX7qup
MENA	Egypt	http://bit.ly/2imgT79
MENA	Iran	http://bit.ly/2ijnSxV
MENA	Iraq	http://bit.ly/2lChFSF
MENA	Israel	http://bit.ly/2A7i8iU
MENA	Jordan, State of Palestine (West Bank & Gaza Strip)	http://bit.ly/2gSuW3Z
MENA	Kuwait	http://bit.ly/2xJ1uEx
MENA	Lebanon	http://bit.ly/2h25dd4
MENA	Libya	http://bit.ly/2htCQ4L
MENA	Morocco	http://bit.ly/2xJ2BUJ
MENA	Oman	http://bit.ly/2gUbRyH
MENA	Saudi Arabia	http://bit.ly/2z3KtZt

MENA	Tunisia	http://bit.ly/2htPQai
MENA	United Arab Emirates	http://bit.ly/2zW2UMI
MENA	Yemen	http://bit.ly/2zZylpj
MENA	Syria	http://bit.ly/2lCky5X
Sub-Saharan Africa	Senegal, Gambia, Cape Verde Islands, Guinea Bissau, Guinea, Sierra Leone, Liberia, Mali, Mauritania, Western Sahara	http://bit.ly/2lGJNDY
Sub-Saharan Africa	Ghana, Cote D'Ivoire, Benin, Burkina Faso, Togo	http://bit.ly/2lJHVKK
Sub-Saharan Africa	Niger, Chad	http://bit.ly/2hyJmHt
Sub-Saharan Africa	Nigeria	http://bit.ly/2lIZlHt
Sub-Saharan Africa	Sudan, Eritrea	http://bit.ly/2hz7ObB
Sub-Saharan Africa	Ethiopia	http://bit.ly/2lJynQ3
Sub-Saharan Africa	Djibouti, Somalia	http://bit.ly/2zb7sja
Sub-Saharan Africa	Kenya, Uganda	http://bit.ly/2xSDcb8
Sub-Saharan Africa	Rwanda, Burundi, Tanzania	http://bit.ly/2h6WTsK
Sub-Saharan Africa	Central African Republic, Cameroon, Equatorial Guinea, São Tomé and Príncipe, Congo, Republic of (Brazzaville), Gabon	http://bit.ly/2A1yd8J
Sub-Saharan Africa	Congo, Democratic Republic (Kinshasa)	http://bit.ly/2hyZ7Op
Sub-Saharan Africa	Angola, Namibia, Botswana	http://bit.ly/2z8q2bn
Sub-Saharan Africa	Republic of South Africa, Lesotho	http://bit.ly/2zenF9g
Sub-Saharan Africa	Malawi, Mozambique, Zambia, Zimbabwe, Swaziland	http://bit.ly/2iXHknR
Sub-Saharan Africa	Madagascar, Comoros Islands, Mauritius, Mayotte, Seychelles	http://bit.ly/2z96GTD
SAARC	India	**http://bit.ly/2h2zzwg**
SAARC	Bangladesh	**http://bit.ly/2z3WOKU**
SAARC	Nepal, Bhutan	**http://bit.ly/2zZ9HFc**
SAARC	Pakistan	**http://bit.ly/2zX2w0d**
SAARC	Afghanistan	**http://bit.ly/2za2MvQ**

SAARC	Sri Lanka	http://bit.ly/2iR034v
Northeast Asia	Japan	http://bit.ly/2ijP5jP
Northeast Asia	Republic of Korea	http://bit.ly/2z51sZi
Northeast Asia	DPR Korea	http://bit.ly/2iQRaaQ
Northeast Asia	China	http://bit.ly/2gRvjMf
Northeast Asia	Mongolia	http://bit.ly/2zakQpC
Southeast Asia	New Zealand	http://bit.ly/2z94MEt
Southeast Asia	Australia	http://bit.ly/2z8b7jM
Southeast Asia	Indonesia, Papua New Guinea	http://bit.ly/2lEs6oO
Southeast Asia	Malaysia, Singapore, Brunei	http://bit.ly/2iTpMsL
Southeast Asia	Philippines	http://bit.ly/2zmS6Lr
Southeast Asia	Myanmar	http://bit.ly/2gRcYyZ
Southeast Asia	Thailand	http://bit.ly/2zb1twu
Southeast Asia	Laos	http://bit.ly/2h20ZSY
Southeast Asia	Vietnam	http://bit.ly/2z9uKbg
Southeast Asia	Cambodia	http://bit.ly/2gZFrq0
North America	Canada	http://bit.ly/2z7TK2t
North America	United States of America	http://bit.ly/2A4ZW9y
North America	Mexico	http://bit.ly/2zmcD2K
South America	Panama, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala, Belize	http://bit.ly/2ikbrlr
South America	Colombia	http://bit.ly/2z9FHcP
South America	Venezuela, Guyana, French Guiana, Suriname	http://bit.ly/2ykuFCk
South America	Ecuador	http://bit.ly/2A4NPJu
South America	Peru	http://bit.ly/2huf2xs
South America	Bolivia and Paraguay	http://bit.ly/2lBNxGZ
South America	Brazil	http://bit.ly/2zW0q0V
South America	Argentina, Uruguay	http://bit.ly/2A2T7oZ

South America	Chile	http://bit.ly/2ijqCuW

Table 4.2: Further publications of the LUT team in close relation to this study. The types of publications are scientific journals (J), scientific conferences (C) and technical reports (R).

Region	Reference	Year	Type	Link
Global	Breyer Ch., Bogdanov D., Aghahosseini A., Gulagi A., Child M., Oyewo A.S., Farfan J., Sadovskaia K., Vainikka P., 2017. Solar Photovoltaics Demand for the Global Energy Transition in the Power Sector, Progress in Photovoltaics: Research and Applications, accepted, DOI: 10.1002/pip.2950	2017	J	https://goo.gl/zsdFZi
Global	Breyer Ch., Bogdanov D., Gulagi A., Aghahosseini A., Barbosa L.S.N.S., Koskinen O., Barasa M., Caldera U., Afanasyeva S., Child M., Farfan J., Vainikka P., 2017. On the Role of Solar Photovoltaics in Global Energy Transition Scenarios, Progress in Photovoltaics: Research and Applications, 25, 727-745, DOI: 10.1002/pip.2885	2017	J	**http://bit.ly/2nUVCpw**
Global	Farfan J. and Breyer Ch., 2017. Structural changes of global power generation capacity towards sustainability and the risk of stranded investments supported by a sustainability indicator, Journal of Cleaner Production, 141, 370-384, DOI: 10.1016/j.jclepro.2016.09.068	2017	J	**http://bit.ly/2k4Jhhq**
Global	Breyer Ch., Heinonen S., Ruotsalainen J., 2017. New Consciousness: A societal and energetic vision for rebalancing humankind within the limits of planet Earth, Technological Forecasting and Social Change, 114, 7-15, DOI: 10.1016/j.techfore.2016.06.029	2017	J	**http://bit.ly/2iSBpQX**
Global	Solomon A.A., Child M., Caldera U., Breyer Ch., 2017. How much energy storage is needed to incorporate very high large intermittent renewables?, Energy Procedia, 135, 283-293, DOI: 10.1016/j.egypro.2017.09.520	2017	J	**http://bit.ly/2iSx1kS**
Global	Fasihi M., Bogdanov D., Breyer Ch., 2016. Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants, Energy Procedia, 99, 243-268, DOI: 10.1016/j.egypro.2016.10.115	2016	J	**http://bit.ly/2oDE4uN**

Global	Koskinen O. and Breyer Ch., 2016. Energy Storage in Global and Transcontinental Energy Scenarios: A Critical Review, Energy Procedia, 99, 53-63, DOI: 10.1016/j.egypro.2016.10.097	2016	J	http://bit.ly/2uKTsf6
Global	Caldera U., Bogdanov D., Breyer Ch., 2016. Local cost of seawater RO desalination based on solar PV and wind energy: A global estimate, Desalination, 385, 207-216, DOI: 10.1016/j.desal.2016.02.004	2016	J	http://bit.ly/2g7Bcpc
Global	Breyer Ch., Koskinen O., Blechinger P., 2015. Profitable climate change mitigation: The case of greenhouse gas emission reduction benefits enabled by solar photovoltaic systems, Renewable and Sustainable Energy Reviews, 49, 610-628, DOI: 10.1016/j.rser.2015.04.061	2015	J	http://bit.ly/2xKLDW2
Global	Manish Ram, Michael, Child, Arman Aghahosseini, Dmitrii Bogdanov, Alena Poleva, Breyer Ch., 2017. Comparing electricity production costs of renewables to fossil and nuclear power plants in G20 countries, study commissioned by Greenpeace Deutschland e.V., July 5	2017	R	http://bit.ly/2u28u0L
Global	Werner Ch., Gerlach A., Breyer Ch., Masson G., 2017. Growth Regions in Photovoltaics 2016 – Update on latest Global Solar Market Development, 33rd European Photovoltaic Solar Energy Conference, Amsterdam, September 25-29	2017	C	http://bit.ly/2xT4i6e
Global	Keiner D. and Breyer Ch., 2017. Modelling of PV Prosumers using a stationary battery, heat pump, thermal energy storage and electric vehicle for optimizing self-consumption ratio and total cost of energy, 33rd European Photovoltaic Solar Energy Conference, Amsterdam, September 25-29	2017	C	http://bit.ly/2huro8N
Global	Fasihi M. and Breyer Ch., 2017. Synthetic Methanol and Dimethyl Ether Production based on Hybrid PV-Wind Power Plants, 11th International Renewable Energy Storage Conference (IRES 2017), Düsseldorf, March 14-16	2017	C	http://bit.ly/2qvsLYf

Global	Solomon A.A., Child M., Caldera U., Breyer Ch., 2017. Exploiting resource complementarities to reduce energy storage need, 11th International Renewable Energy Storage Conference (IRES 2017), Düsseldorf, March 14-16	2017	C	http://bit.ly/2zacLBx
Global	Bogdanov D., Gulagi A., Breyer Ch., 2016. PV generation share in the energy system and battery utilisation correlation in a net zero emission world, 6th Solar Integration Workshop, Vienna, November 14-15	2016	C	http://bit.ly/2iujITo
Global	Fasihi M., Bogdanov D., Breyer Ch., 2015. Economics of global gas-to-liquids (GtL) fuels trading based on hybrid PV-Wind power plants, ISES Solar World Congress 2015, Daegu, Korea, November 8-12	2015	C	http://bit.ly/2huFJlV
Global	Fasihi M., Bogdanov D., Breyer Ch., 2015. Economics of global LNG trading based on hybrid PV-Wind power plants, 31st EU PVSEC, Hamburg, September 14-18, DOI: 10.4229/31stEUPVSEC2015-7DO.15.6	2015	C	http://bit.ly/2e0qe24
Global	Metayer M., Breyer Ch., Fell H.-J., 2015. The projections for the future and quality in the past of the World Energy Outlook for solar PV and other Renewable Energy technologies, 31st EU PVSEC, Hamburg, September 14-18, DOI: 10.4229/31stEUPVSEC2015-7DV.4.61	2015	C	http://bit.ly/2izWUUJ
Europe	Child M., Bogdanov D., Breyer Ch., Fell H.-J., 2017. Role of storage technologies for the transition to a 100% renewable energy system in Ukraine, Energy Procedia, 135, 410-423, DOI: 10.1016/j.egypro.2017.09.513	2017	J	http://bit.ly/2imPouf
Europe	Kilickaplan A., Bogdanov D., Peker O., Caldera U., Aghahosseini A., Breyer Ch., 2017. An Energy Transition Pathway for Turkey to Achieve 100% Renewable Energy Powered Electricity, Desalination and Non-energetic Industrial Gas Demand Sectors by 2050, Solar Energy, 158, 218-235, DOI: 10.1016/j.solener.2017.09.030	2017	J	http://bit.ly/2imdkhB

Europe	Farfan J. and Breyer Ch., 2017. Aging of European Power Plant Infrastructure as an Opportunity to evolve towards Sustainability, International Journal of Hydrogen Energy, 42, 18081-18091, DOI: 10.1016/j.ijhydene.2016.12.138	2017	J	http://bit.ly/2oDtGmU
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