Transition Pathways Towards a Carbon-Neutral Thuringia

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Abstract

Energy scenarios are used to better understand the effects of political or technological choices in the transformation of energy systems. These are complex calculations that, determine for example a cost- or emission-optimized configuration of an energy system under predefined boundary conditions. From them, both the need for action and the freedom of design can be derived. This paper presents an energy system model based on hourly load, generation and price profiles for the German state of Thuringia. The energy system was modelled in the open source energy modelling framework oemof. Taking into account the local energy potentials, the development of energy demands and prices, the results show how the climate policy goals of the federal state of Thuringia can be achieved and which transformation pathways are possible along the timelines 2030, 2040 and 2050.

Keywords: energy system, modelling, oemof, climate neutral, transition pathways, CO_2-price, energy scenarios, energy policy, Thuringia, sector coupling

1. Task

As a result of the World Climate Agreement in Paris, in which it was agreed to curb global warming, the Federal Government has set concrete CO_2 reduction targets for Germany. These targets can be broken down to Thuringia, although the Free State has set itself some more far-reaching targets in its Climate Act (ThürKlimaG, 2018): By 2030, Thuringia's greenhouse gas emissions are to be reduced by 70 % compared to 1990, by 2040 by 80 % and by 2050 by 95 %. In addition it is stipulated that 55 % of the total energy demand is to be covered by renewable energies in 2030 and 100 % since 2040. That means that the entire energy demand must be covered by renewable energies on the balance sheet, so that fossil energy sources may only be used if the same surplus of renewable energies is produced at another time. In 2030, moreover, 80 % of electricity demand is to be covered by renewable energy generation.[1]

How such a climate-neutral energy system can look like in 2050 for an industrialized region like Thuringia, which technologies are available to cover our energy demand for electricity, heat and mobility and finally, which steps politics and society must take to achieve this, can be answered by energy system models. They can be used to calculate which renewable energies are needed in which amount (i.e. with which output), and which composition of sector coupling technologies and storage systems is needed to optimize the energy system according to minimized economic costs, taking into account the given restrictions. The model results can be used to derive economic expansion pathways (transformation pathways) for technologies.

2. Approach

As a basis, the question arises as to how energy demand will develop in the future. To this end, various factors need to be illuminated, as shown in Tab. 1. The first is demographic change. Both the decline in population and the increase in the average age will lead to a decline in the number of private households and thus in the general energy demand. On the other hand, there is the factor of climate change: due to the higher average temperature, the heating demand will decrease. But this effect is overcompensated by a sharply rising air-conditioning demand and consequently the electricity demand will increase. Energy efficiency guidelines generally ensure lower energy

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[1] The targets, set out in the Thuringian Climate Act (ThürKlimaG, 2018), form the basis of the scenarios presented in this paper. The scenarios will continuously be adapted to the actual political discussion in Germany resp. Thuringia – for example carbon neutrality in 2045.

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Selection and/or peer review under responsibility of Scientific Committee
doi:10.18086/swc.2021.01.05 Available at http://proceedings.ises.org

demand. Building renovation reduces the demand for heat in particular. In the future, this will increasingly be provided by heat pumps, which, however, as Power-to-Heat (PtH) technology, generate a higher electricity demand. Electricity demand is also rising due to the increase in electro-mobility. The transport of goods will not decrease in the future, quite the contrary. All in all, this will lead to a lower energy demand, with electricity accounting for the largest proportion, while the energy supply from fossil sources will decrease significantly.

Tab. 1: Trends and their impact on useful and final energy demand until 2050

	useful energy			final energy	
Trends	**electricity**	**heating/ cooling**	**traction**	**electricity**	**Fossil energy**
demographic change	⬂	⬂	⬂	⬂	⬂
climate change	-	⇧	-	⇧	-
energy efficiency directive	⬂	⬂	-	⬂	⬂
building refurbishment	-	⇩	-	⬀	⇩
freight traffic	-	-	⇧	⇧	⬀
power-to-heat	-	-	-	⇧	⇩
electromobility	-	-	-	⇧	⇩

With the help of the trends mentioned in Tab. 1, an estimate of the future useful energy demand (Fig. 1) and final energy demand (Fig. 2) was generated.

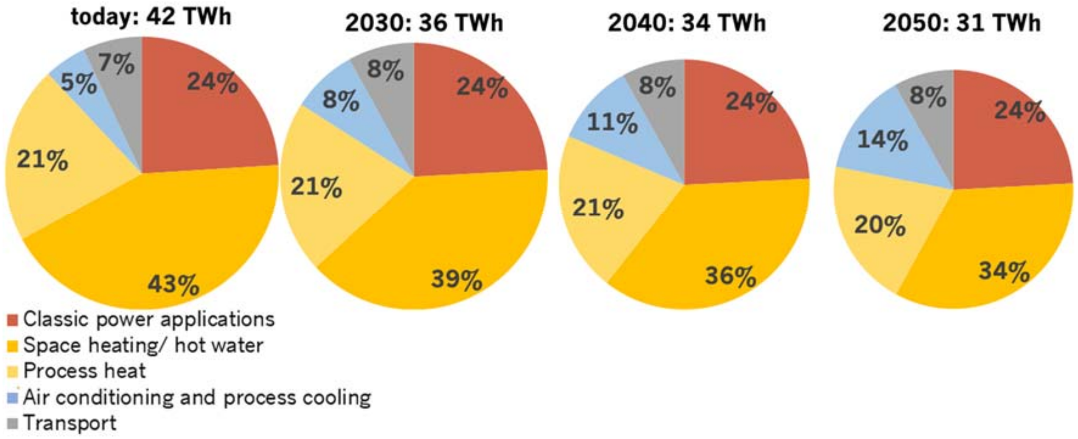

Fig. 1: Useful energy demand 2020 – 2050

At first glance, the useful energy demand will hardly change: from the current level of slightly more than 40 TWh, the useful energy demand will drop by about a quarter by 2050. The drivers here are demographic change and the various energy efficiency measures. The proportions of classic electricity applications, process heat and traction will remain almost unchanged. However, the proportion of space heating demand decreases significantly due to building renovation measures, while the demand for air conditioning increases at the same time.

The final energy demand shows a completely different picture. Here, the proportion of electricity has more than doubled from the current 20 percent to 44 percent, with a slight increase in the absolute amount of energy. The fossil energy sources coal, oil and natural gas are declining accordingly. While natural gas will still play a role in industrial processes and, to a lesser extent, for heating buildings in 2050, mineral oils will be used almost exclusively in the transport sector, which has not yet been electrified. Hard coal and lignite no longer play a role in 2040 due to the coal phase-out agreed for 2038. The final energy source "renewables" is dominated by solid biomass in the form of firewood and wood pellets, followed by solar and geothermal energy. The liquid or gaseous hydrocarbons that will still be needed by some energy converters in 2050 do not necessarily have to be of fossil origin. Power-to-X technologies can already provide climate-neutral fuels (Power-to-Liquid) or fuel gases (Power-to-Gas) today.

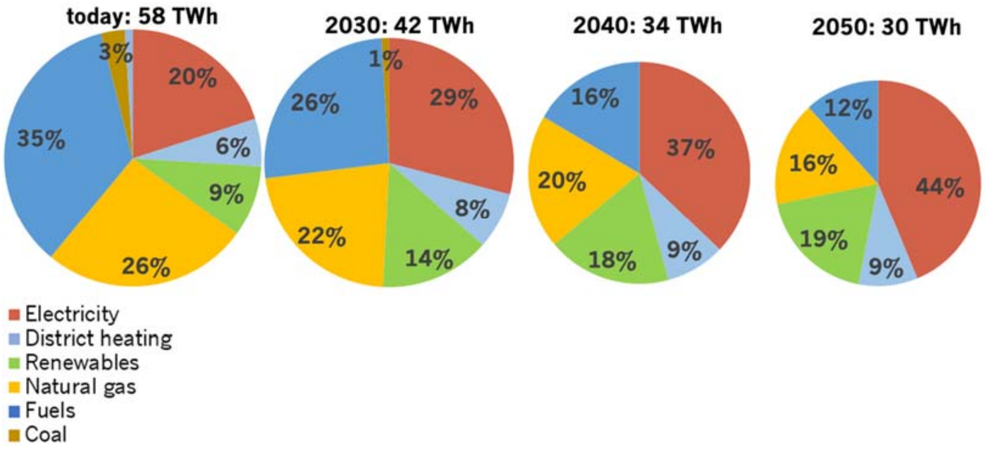

Fig. 2: Final energy demand 2020 – 2050

It can also be seen that in 2050 only 30 TWh of final energy would have to be used to provide 31 TWh of useful energy. This paradoxical ratio results from the strong integration of geothermal or ambient heat by means of PtH technologies, especially heat pumps. However, geothermal or ambient heat is not included in the final energy statistics.

To sum up: In the next 30 years, the demand for transport and heat as well as the demand for mechanical work and thermal energy in industrial production processes will continue to exist. However, there will be a fundamental change in the energy sources through whose conversion these benefits are generated: away from fossil energy sources towards renewably generated electricity and possibly also "green" fuels.

The demand for useful energy is generated by all sectors: The industry sector generates a demand for building heating, process heating, air-conditioning and process cooling, a demand for electricity for classic electricity applications as well as material use. In the commercial//retail/services sector, the material use is omitted, and in the household sector, process heating and cooling are omitted. The transport sector is divided into freight and passenger transport and quantified in passenger-km and ton-km.

3. Energy system modell

What is the best way to meet this final energy demand in 2050? To answer this question, a model of the Thuringian energy system was created. Energy system models are computational programs that determine how a given energy consumption can be covered at any given time by different generation, storage and sector coupling technologies, so they calculate an optimal interaction of the different technologies. Energy consumption and generation patterns as well as prices are available in an hourly temporal resolution[2]. The energy system can be optimized with respect to a predefined criterion. These can be, for example, minimum costs or CO_2 emissions.

The energy system model Thuringia was modelled with the open energy modelling framework oemof (oemof 2021) hourly-resolved for 1 year. Oemof is a framework implemented in Python, which can be used to solve linear problems with an open source solver. The object-oriented library solph was used, which is structured in blocks: There are sinks, which is the load, i.e. the demand that has to be covered. It can be covered by sources, by imports, self-generation i.e. renewable energy production and/or storage discharge. All sources are connected to the sinks via so-called buses, which serve as a busbar for each energy source. So there is a bus for electricity, one for heat, etc. In the model, each energy carrier - i.e. each different "bus" - is shown in a different color. The connecting link is formed by sector coupling technologies i.e. PtX, when, for example a heat pump converts electricity from the electricity bus into heat, which is fed to the heat bus. There is also storage that can store energy from a bus. For each technology, there is a block in which all photovoltaic systems, for example, are grouped together. The use of the individual options is controlled by an optimization criterion, like minimum costs. Fig. 6 shows the model of the energy system. The individual input data will be discussed below.

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[2] For the energy prices, data from an external service provider was used, which provides price time series up to 2050 via a merit order model of the European electricity market (brainreport 2019).

For implementation in the model, the useful energy demand per sector is calculated with standard load profiles, as shown in Fig. 3. The load profiles are scaled with the corresponding energy consumption for the analysis year. The electricity demands in green, red and brown and processes gas / process heating in purple have a weekday-dependent pattern, while room heating demands in blue and orange depends on the outdoor temperature and the seasons. The useful energy is provided by converters, which cause a final energy demand. The final energy demand for each energy source is summed up as a total load. These loads are shown on the bottom right of Fig. 6.

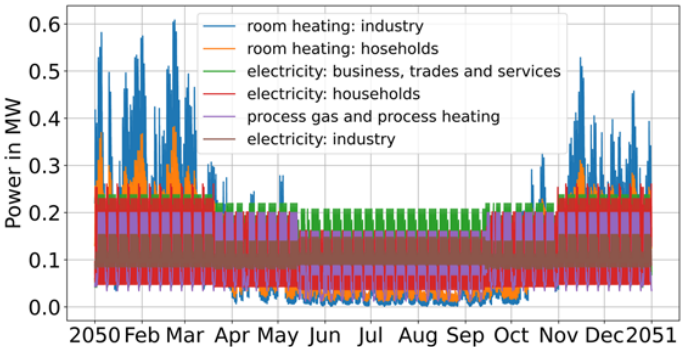


Fig. 3: Standard load profiles

As a transit state, Thuringia can import electricity, gas, oil, coal, etc. beyond its federal state borders (shown in the bottom left of Fig. 6), and also export them again (shown in the top right of Fig. 6). For this purpose, prices for the fossil energy sources are deposited. For electricity, a time-resolved price time series is used, which is correlated with photovoltaic and wind feed-in profiles, so that the electricity price is low when there is a lot of PV or wind in the grid (Fig. 4). Grid usage fees are also taken into account.

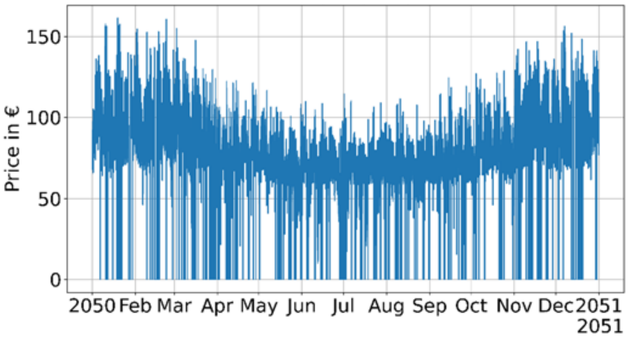


Fig. 4: Electricity import price, hourly resolved time serie

Furthermore, the energy demand is covered by generation from renewable energies. These are listed in the model to the right of the natural gas bus. For wind power and photovoltaics, feed-in profiles are also stored, as showed in Fig. 5 for photovoltaics for 4 different planning regions for a period of 2 weeks, so that one peak at midday can be seen for each day. It is also possible to use solar thermal energy. Furthermore, hydropower can be used, the output of which is fixed because the entire potential has already been used in Thuringia. Biogas substrate can be converted into electricity and heat in a CHP plant, solid biomass (e.g. wood) can also be used for electricity or heat production - with

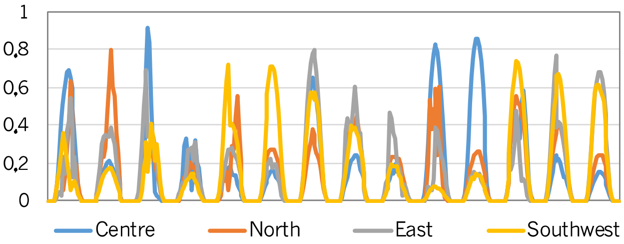


Fig. 5: Photovoltaic feed-in profiles for Thuringia's planning regions for 2 weeks

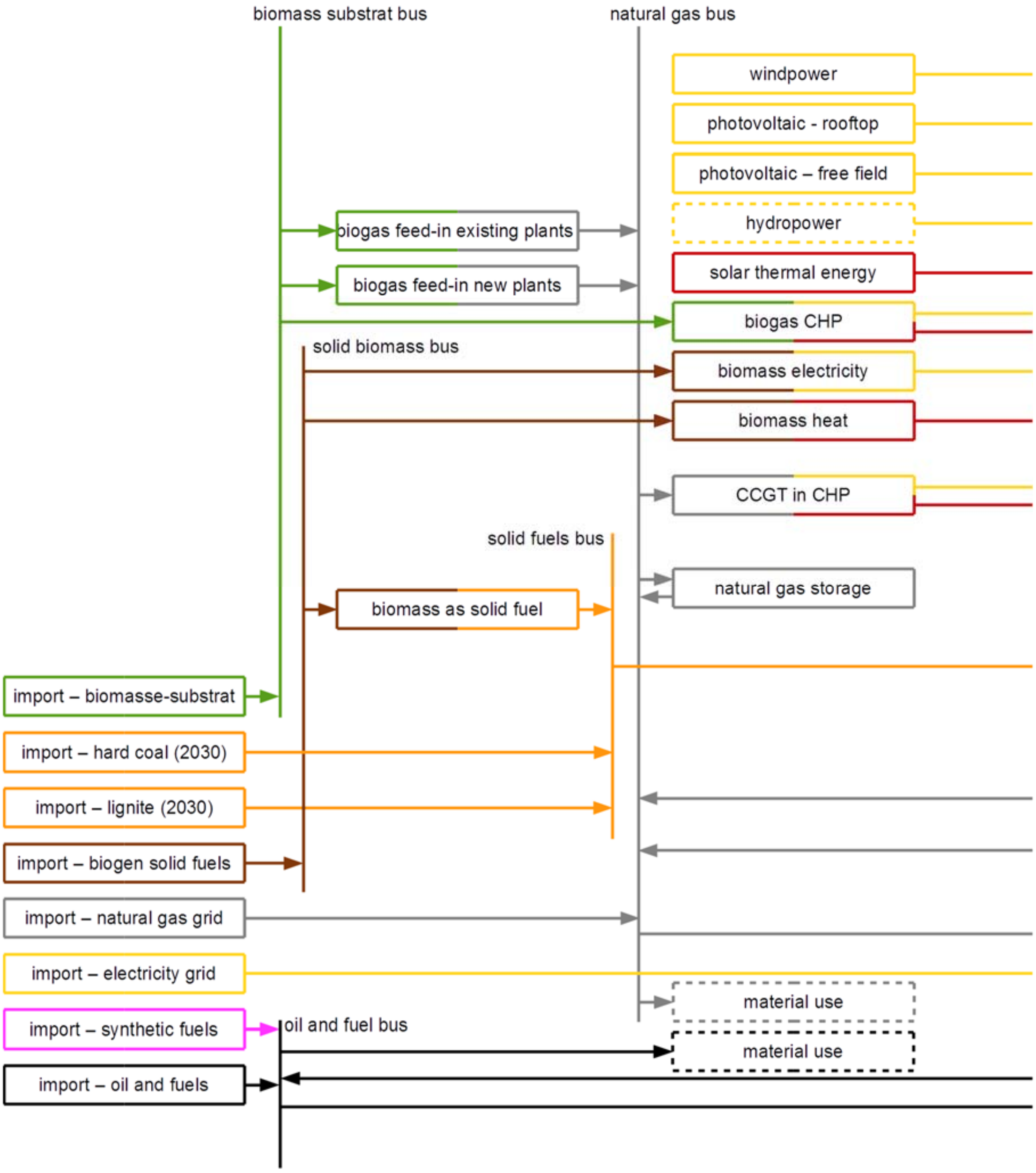
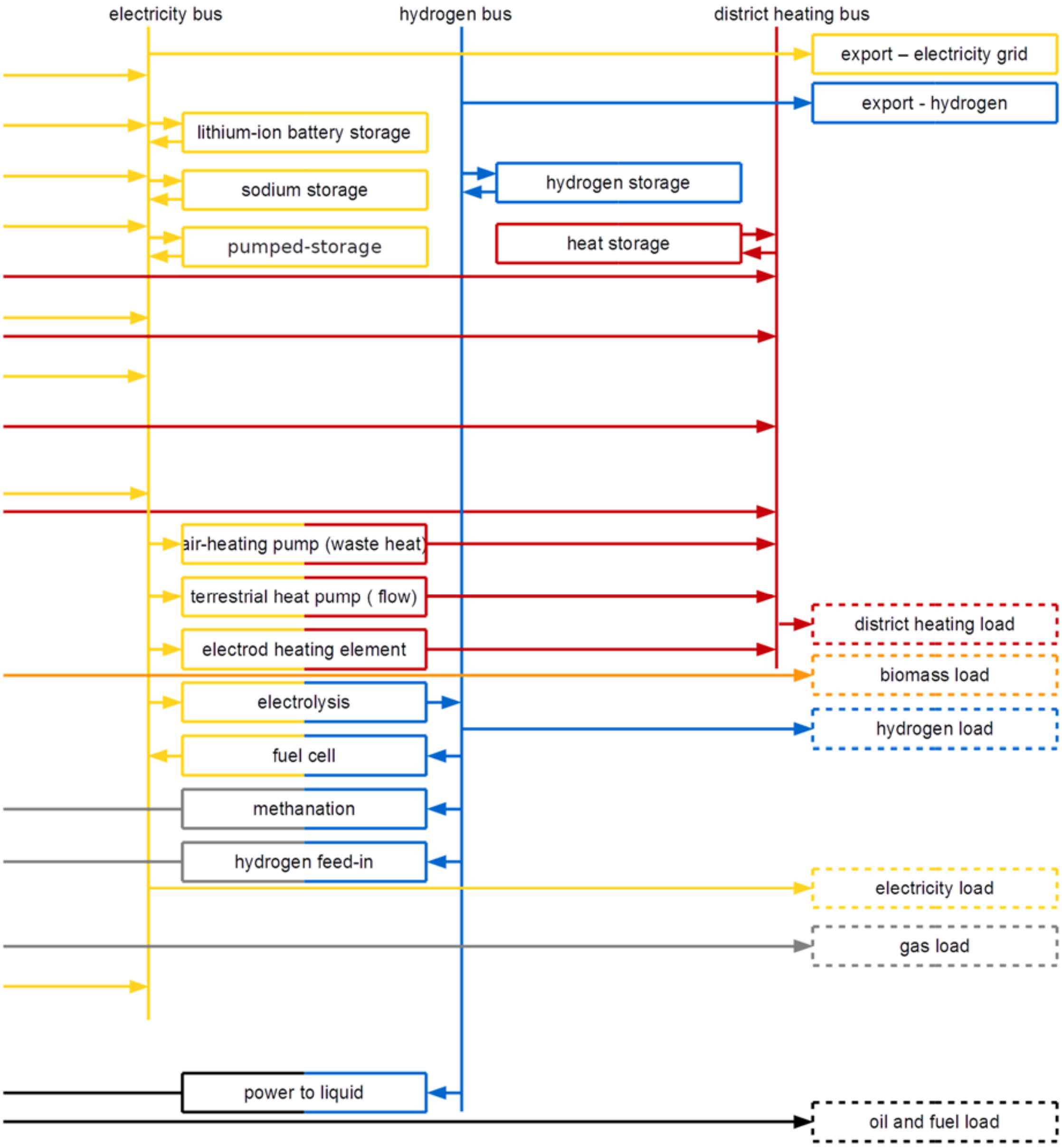


Fig. 6: Energy System Model Thuringia

Sector coupling or PtX technologies (to the left of the renewables and at the bottom center of the model) offer the possibility of feeding biogas into the natural gas grid. Hydrogen can also be fed into the natural gas grid up to a certain percentage. PtH options include integrated air and terrestrial heat pumps and electrode heating elements. There are stationary fuel cells with which electricity can be generated from hydrogen if the reverse technology electrolysis has previously produced the hydrogen from electricity as a PtG technology. Another PtG technology is methanation, whereby methane is produced from hydrogen and fed into the natural gas grid. Last but not least, PtL can also be used to produce synthetic fuel from hydrogen. The material use to the left of the PtX technologies is industry.

Electricity storage facilities are available, including lithium-ion storages, sodium storages and pumped storage power plants, as well as heat, hydrogen and gas storages. In the model, these can be seen to the right of the renewables.



Various parameters are included in the model, for each technology investment costs (so Capital Expenditures), operating and maintenance costs (so Operational Expenditures) and Efficiencies, which are mainly taken from the dena study (dena, 2018), where these parameters were determined for the whole of Germany. In addition, regional potentials (i.e. capacity limits) are specified for each technology. Fig. 7 illustrates the potential of photovoltaic free field for the four planning regions of Thuringia. There is significant potential along the federal motorway (in orange) and the railway tracks (in black). Some potentials are limited, such as that of wind power to 1 % of the state area of Thuringia. The other restrictions are those already mentioned in the Thuringian Climate Act, which prescribes reductions in greenhouse gas emissions and sets CO_2 budgets for each year on the basis of this: In 2030, a maximum of 9 million tons of CO_2 may still be emitted, in 2040 6 and in 2050 only 1.5 million tons of CO_2. In addition, the question was addressed of what a climate-neutral energy system with 0 CO_2 emissions would look like. The condition "balance renewable" is also mentioned here, or the 55 % of renewables in the electricity demand in 2030.

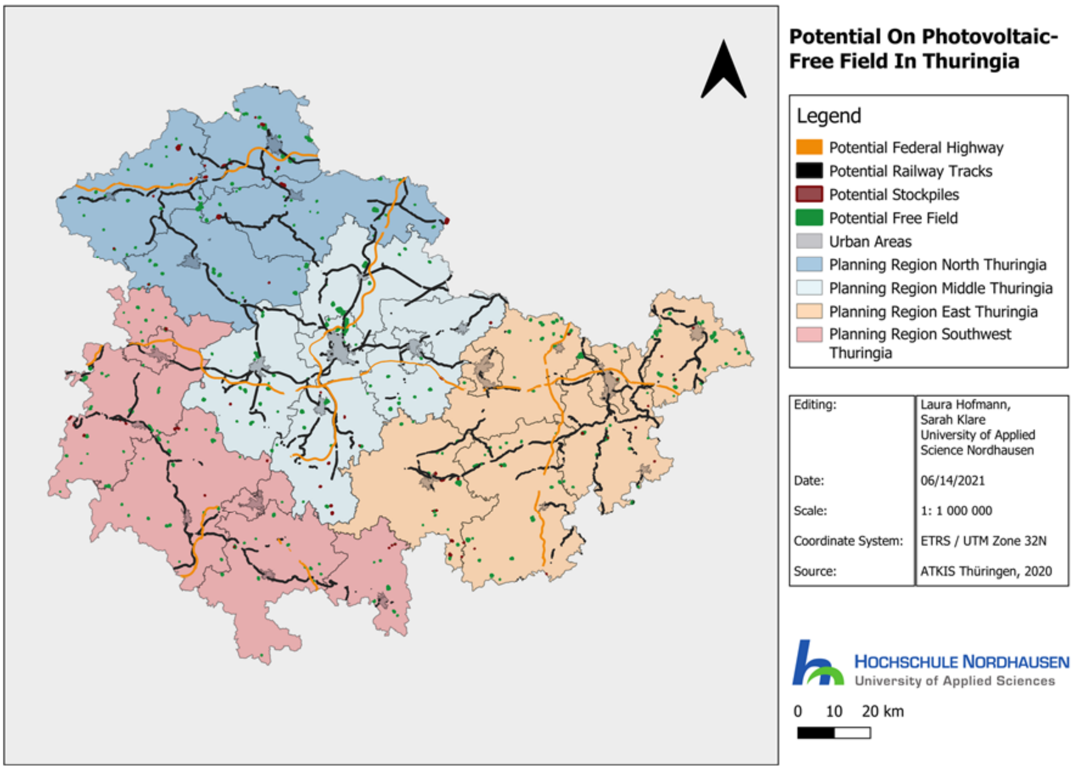


Fig. 7: Potential of photovoltaic free field

4. Scenarios

Two scenarios were modelled: Scenario B is the baseline scenario. It has conservative assumptions regarding renovation rate, energy efficiency and openness towards PtX technologies. It also assumes no hydrogen demand. A CO_2 price is applied to the import of fossil energy sources, and only the fossil share to the import of electricity. The CO_2 price is approx. 80 €/tCO_2 for 2030, approx. 110 €/tCO_2 for 2040 and approx. 120 €/tCO_2 for 2050. Another assumption is that from 2050 onwards, electricity imports, i.e. the German electricity mix, will be CO_2-free and will no longer be subject to the CO_2 price.

In contrast, the innovative scenario A assumes increased efficiency, more PtX and a higher renovation rate, and thus a lower energy demand than in the baseline scenario. Scenario A also includes hydrogen-based mobility and therefore a hydrogen load.

The years 2030, 2040 and 2050 were modelled.

5. Results

This chapter describes which technologies are needed with which output in order to obtain a cost-optimal energy system under all the conditions mentioned. The first technology is wind power, as shown in Fig. 8. On the y-axis, the power is plotted over the years shown on the x-axis. 2050 "c" here stands for a climate-neutral energy system in 2050, i.e. 100 % CO_2 reduction. In the case of wind power, the basic scenario B in blue and the innovative scenario A in orange are both above the potential limit in red dashed lines, which means that the full wind power potential will be exploited as early as 2030, which corresponds to a tripling of the current capacity.

A higher capacity is also required for photovoltaics (Fig. 9), approx. 7-8 times as much as at present, especially in the year 2040, from which the condition applies that the entire energy demand must be covered by renewable energies on balance. However, the potential limits of fallow land and roadside areas are not reached. The fact that so much PV is needed in 2040 means that less electricity has to be imported, as can be seen in 10. In the innovative scenario A, on the other hand, less PV is needed compared to the conservative scenario B, and instead more electricity is imported to meet demand.

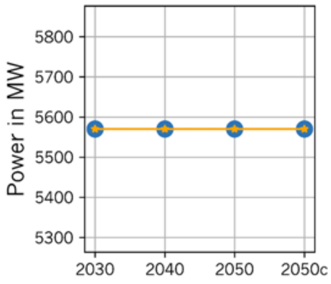


Fig. 8: Windpower

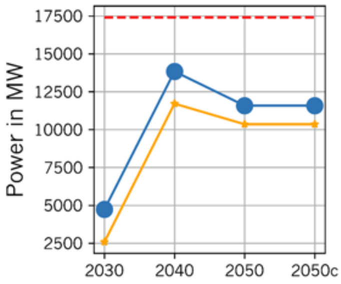


Fig. 9: Photovoltaic free field

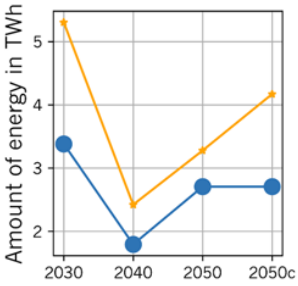


Fig. 10: Import electricity grid

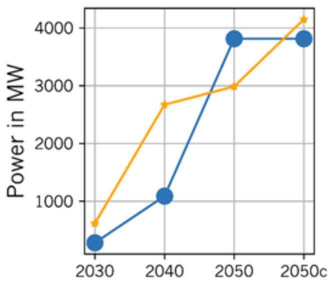


Fig. 11: Electrode heating element

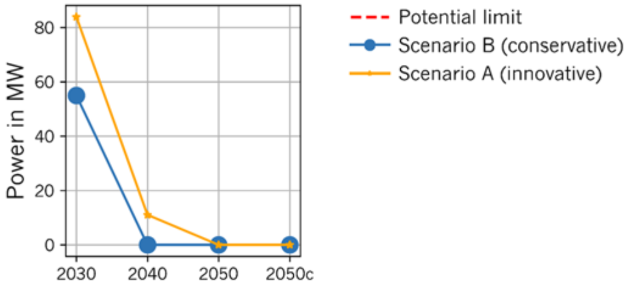


Fig. 12: Heat pumps

There is also generation from hydropower plants, which, as already mentioned, is at a constant 31 MW capacity, because the potential has already been reached.

Electrode heating elements (Fig. 11) are increasingly used as a sector coupling technology. Large-scale heat pumps (Fig. 12) are no longer used in 2050[3]. The energy demand decreases over the years due to the factors mentioned at the beginning, which is why the energy demand is still highest in 2030; in 2050, the energy demand has decreased to such an extent that electrode heating elements are sufficient.

As far as biotechnologies are concerned, a more complex picture emerges in Fig. 13, which is only shown for the baseline scenario B, as in the innovative scenario A the relevant results are the same. In blue, the electrical output of the biogas in combined heat and power (CHP) is shown, which decreases over the years, as does the electrical output of the combined cycle gas turbine (CCGT) in CHP in purple. At the same time, the capacities of the biogas feed-in, of existing and new plants in both shades of green, increase, as does the capacity of the gas storage facility in orange, which is the only one related to the secondary axis on the right. In 2050, with little or no import of fossil gas, especially in the climate-neutral scenario, the gas storage is used for biomethane processed from biogas, not for fossil gas. A change in the use of biogas is thus emerging, away from pure electricity and heat production towards a substitution of natural gas.

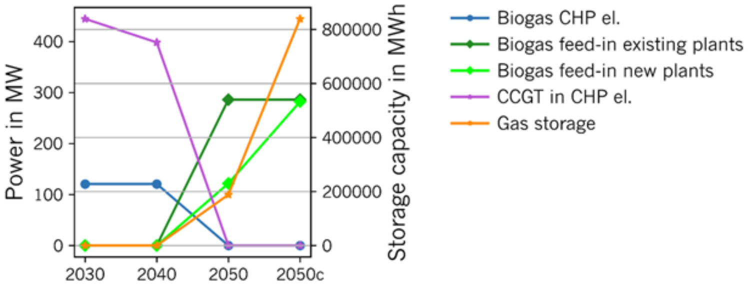


Fig. 13: Bio- and gas technologies

As storage technologies, electricity storage technologies are needed. Here, sodium storages (Fig. 14) are preferred to lithium-ion battery storages, and ever larger capacities are needed. In the case of pumped storages, only the existing capacity is used permanently. The demand for heat storages (Fig. 15) also increases over time. In the

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[3] Large-scale heat pumps supply district heating networks. Residential heat pumps are widely used and not subject to optimisation. Their electricity demand is part of total electricity demand.

innovative scenario A, it can be seen that the heat demand in 2050 decreases compared to 2040, due to the higher renovation rate than in the conservative scenario B. However, in order to achieve the goal of climate neutrality, more heat storage capacity is needed again than without. The need for gas storage (Fig. 16) increases, as already mentioned, and can be seen here again for both scenarios. Hydrogen storages (Fig. 17) are needed in innovative scenario A in 2050, in connection with electrolysis, because innovative scenario A assumes hydrogen-based mobility.

Finally, costs and emissions can be compared. Fig. 18 shows the total costs. 100 % represent the costs of the conservative baseline scenario B in 2030. The other costs are shown in relation to this. It can be seen that the costs decrease because the energy demand to be covered also decreases. If Thuringia is to become climate-neutral, the total costs are again somewhat higher than if only 95 % CO_2 is to be saved. The innovative scenario A is more beneficial than the conservative one because, on the one hand, a lower energy demand has to be met and, on the other hand, a different composition of PtX technologies is assumed to generate the useful energy demand.

The emissions shown in Fig. 19 also decrease. Again, 100 % are the emissions of the conservative baseline scenario B, the other emissions are shown in proportion. The potential limits are the climate policy restrictions, i.e. the CO_2 budgets calculated on the basis of the savings potentials. Again, this shows that emissions are falling and do not even reach the CO_2 limit, except in Scenario B 2050 with the 95% savings target. The emissions of the innovative scenario A are always lower than those of the base scenario B. The last entry stands for climate neutrality, so that 0 emissions are emitted.

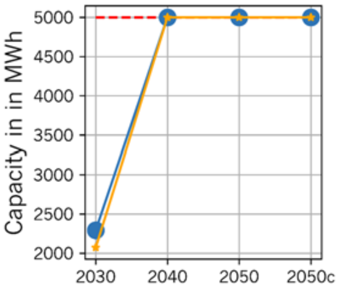

Fig. 14: Sodium storage

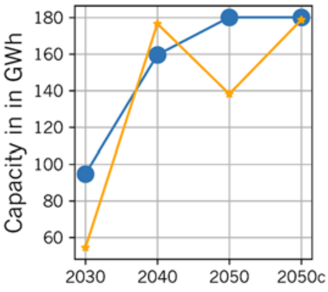

Fig. 15: Heat storage

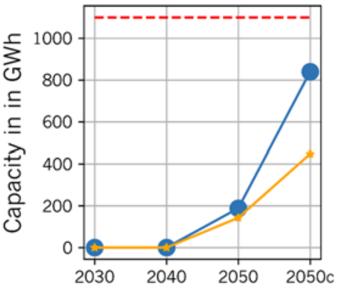

Fig. 16: Gas storage

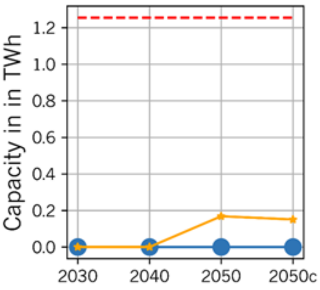

Fig. 17: Hydrogen storage

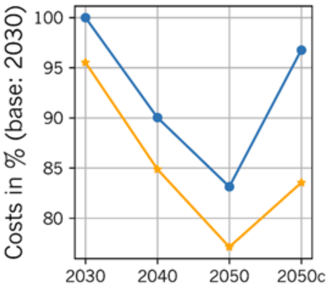

Fig. 18: Costs developement

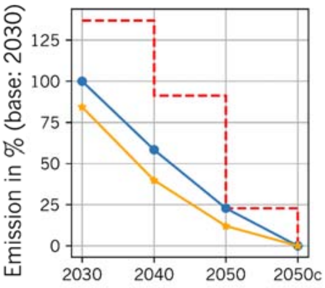

Fig. 19: Emissions developpement

6. Summary

Some technologies are needed immediately and with high output, such as wind power, photovoltaics and electricity storages. Other technologies need to be continuously expanded, including electrod heating elements, heat and hydrogen storages including electrolysis, but also gas storages. The last mentioned are also undergoing a change of use, with biomethane being stored in them instead of natural gas. The change of use is biogas, which is no longer used for electricity and heat production, but is processed for injection into the natural gas grid. Some technologies are less used, including large-scale heat pumps, assuming that there are more electrode heating elements, and the CCGT, which is made redundant by the other gas use. Unused technologies are solar thermal energy (whereby however existing plants were not taken into account) hydrogen injection into the natural gas grid, PtL from hydrogen, methanation from hydrogen, and stationary fuel cells.

The prices for the provision of final energy remain at a comparable level and the CO_2 price and energy efficiency measures ensure compliance with the climate policy boundary conditions in 2030 and 2040. If the innovative scenario comes into effect, both costs and emissions will decrease significantly.

Further scenarios were calculated, which illuminate the effects of a different CO_2 price, include a higher wind power potential, as well as studies on energy self-sufficiency, solar thermal energy and electricity storages. They are published together with all information about the anticipated development of demands, costs, efficiencies and other technological parameters (in.RET, 2021).

7. Acknowledgments

This paper is based on the research project on energy system modelling of Thuringia, for the development of state-specific detailed models, funded by the Thuringian Ministry for the Environment, Energy and Nature Conservation, as a sub-project within the project "ZO.RRO -Zero Carbon Cross Energy System", funded by the German Federal Ministry for Economic Affairs and Energy under the funding code: 03ET4080A. The authors are responsible for the content of this publication. The contents presented here are only a part of the overall project and are not to be understood as a project result.

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