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PATHWAYS FOR THE ENERGY TRANSFORMATION: COST-EFFECTIVE AND CLIMATE-FRIENDLY TRANSFORMATION STRATEGIES FOR THE GERMAN ENERGY SYSTEM BY 2050 AND THE ROLE OF HYDROGEN

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ABSTRACT

In line with the global climate goals of the 2015 Paris Agreement, Germany is pursuing an ambitious national greenhouse gas reduction strategy with national climate goals of 80-95% CO_2 emission reduction (compared to 1990). The central part of the investigation is based on a highly temporal resolved national energy system model for Germany, called FINE-NESTOR, which has been developed precisely for this purpose. This model was designed to minimize the total system costs of the entire German energy system while considering the energy sector and all end-use sectors are part of the optimization. This is implemented on the basis of a quadratic programming approach with a focus on cost uncertainties, and therefore provides robust solutions over a variety of future cost scenarios. Moreover, the model makes use of time series aggregation techniques, includes seasonal storages, and implements a wide range of cross-sectoral technologies totaling to 50 pathways. In order to face the upcoming challenges of the energy transition, the results are further improved by the iterative coupling of other energy system related models. This involves a highly-resolved geospatial renewable energy potential model, hourly simulation of wind and PV generators, a European power flow model, and a global infrastructure model for the sustainable supply of synthetic fuels such as hydrogen and methane. Moreover, many of these models have been published open-source. Based on these aspects, different strategies for the reduction of CO_2 emissions as well as their impact on the energy system are investigated with focus on the role of hydrogen within these strategies.

Keywords: Energy System, Hydrogen, Energy Scenarios

INTRODUCTION

The most recent IPCC Special Report states that the current climate reduction activities worldwide are not sufficient to limit global warming to 1.5 °C. The IPCC therefore calls for more drastic measures to be taken and implemented quickly. Against the background of the Paris Convention on Climate Change, which was ratified by the European Union in 2016, the reduction commitments became binding under international law. With its energy concept, the Federal Government of Germany initiated the energy system transformation in 2010 and set objectives that have been continuously updated and modified over the last years. The range of the objectives is broad and encompasses the reduction of electricity consumption to the expansion of wind power and photovoltaics. The overarching goal of all of these efforts is to ensure compliance with the greenhouse gas reduction targets. Against the baseline year of 1990, German greenhouse gas emissions need to be reduced by 80-95% by 2050. Germany has detailed greenhouse gas reduction targets for the years 2020, 2030 and 2040. It is already apparent today that the target for 2020 might not be met. The overarching greenhouse gas reduction targets and the energy systems transformation targets are not aligned with each other, since the latter have been evolving historically, whereas the overarching goals have been broken down from climate considerations. In addition, it is largely unclear which interactions exist between the individual fields of action that could have a negative impact on the exploitation of reduction potentials. The central question addressed in this study is therefore: "How would a consistent and cost-effective CO_2 reduction strategy for the German greenhouse gas reduction targets look like and what is the role of hydrogen in this cost-effective strategy?"

MODELING

The Institute for Energy and Climate Research – Techno-economic Systems Analysis (IEK-3) at the Forschungszentrum Jülich has developed a model suite which enables the calculation of cost-optimal greenhouse gas reduction strategies for Germany. The core of this model suite is an overall model that maps the national energy supply across all sectors, hosts an algorithm for cost minimization and draws the specific information of the different sectors from comprehensive subroutines. This allows calculating cost-optimal transformation strategies. The special feature is that across all sectors (households, energy sector, heavy industry and transport) a wide variety of reduction measures are competing with one another. The underlying model algorithm makes it possible to select the most cost-effective reduction measures, which are aligned to form a consistent national greenhouse gas reduction strategy.

Future projections are naturally associated with considerable uncertainties. Here, a newly developed methodology capacitates the authors to include data uncertainties in the decision-making process. This leads to robust and consistent greenhouse gas reduction strategies that can provide a solid and well-founded basis for political and economic decision-making. In addition, models with high temporal and spatial resolution are used, for example for the consideration of wind and PV potentials or the hydrogen infrastructure. These aspects are implemented in great detail and enable in-depth infrastructure analyses.

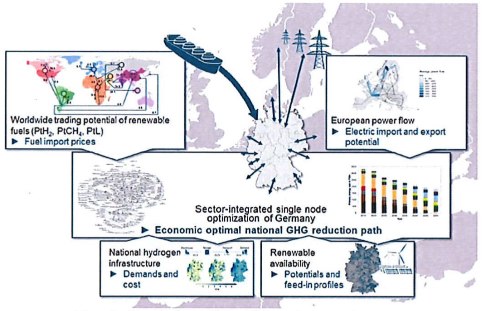

Fig. 1. Applied model suite and procedures

Using the newly developed model family, various greenhouse gas reduction scenarios were generated and analyzed. The analyses shall include reduction strategies for achieving the 80 and 95% greenhouse gas reduction targets by 2050. The model suite (Figure 1) is largely based on the open accessible model generator FINE [1]. With this model, it is feasible to simulate energy flows at high temporal and spatial resolutions and to create cost-optimal solutions for the respective greenhouse gas reduction targets. The developed models are coupled to each other and used iteratively, so that their respective strengths are brought to bear. Compared to other existing model approaches [2], the following advantages are to be emphasized, which overall constitute a unique selling proposition:

- Detailed design and optimization of PtX pathways from primary energy to end-use
- Consideration of sectoral interactions ensuring consistent cross-sectoral optimization
- High temporal and spatial resolution of renewable power generation (hourly resolved generation profiles over multiple years, exact and replicable siting of RE power units) and infrastructures
- Mapping of future energy infrastructures (electricity, gas, H_2) and storage facilities with cutting edge spatial resolution
- Location-specific presentation of renewable potentials (wind, PV) and potential electrolysis locations
- Illustration of future global energy markets (e.g., hydrogen, synthetic fuels)
- Application of custom designed novel methods for identifying robust greenhouse gas reduction strategies under consideration of data uncertainties

RESULTS AND DISCUSSION

<u>CO_2 Emissions and Energy Consumption</u>

A comparison of the two proposed reduction strategies (80% vs. 95%) reveals significant differences – especially from 2040 onwards. Compared to 1990, the SCENARIO 80 still allows to emit 210 million t_{CO2eq} in 2050. The main emitters in 2050 will be the heavy industry and the energy sector, according to the scenario. Together these sectors are responsible for almost three quarters of the remaining emissions. On the other hand, the shares for transportation and buildings are significantly lower, at 16% and 10%, respectively. With a CO_2 abatement of 95% (SCENARIO 95), the permissible emissions in 2050 are limited to 52 million t_{CO2eq}. Approximately 70% of these emissions will be generated by the industry sector. With this strategy, the transport, building and energy sectors are almost climate-neutral. How these developments look like in detail and which technical combinations they will consist of are explained in detail in the following. It should also be noted that from 2040 onwards, the scope for action will be relatively limited to 10 years, which requires a high degree of dynamic change. Our analyses show that the interim target set by the Federal

Government for 2040 is only compatible with the 80% scenario. To achieve the 95% reduction target, efforts to attain this interim target need to be intensified.

The main elements of mitigation strategies are renewable energy technologies and the accelerated application of energy efficiency technologies.

The Role of Hydrogen

The substitution of fossil fuels leads to the increased direct use of electricity, as well as an increased use of new energy sources like hydrogen, synthetic fuels and other forms of energy such as heat, which in turn are produced using electricity. These developments, also known as Power-to-X (PtX), are particularly important in SCENARIO 95. The basic prerequisite for this is that the electricity used is produced by renewable energy technologies and is therefore free of CO_2 emissions. Compared to today's energy supply, the number of energy sources is thus decreasing. Hence, coupling of the energy sector and end-use sectors is increasing significantly. This effect, referred to as "sector coupling", plays a central role in achieving climate targets [3]. The hydrogen quantity for both routes in SCENARIO 80 is about 145 TWh (approximately 4 million t) in 2050. In SCENARIO 95, the required amount of hydrogen is 399 TWh (approximately 12 million t) and is thus significantly higher. While in SCENARIO 80 the hydrogen is based on natural gas reforming (plant capacity: 10 GW) and on 22 GW of installed electrolysis capacity, in SCENARIO 95 the natural gas reforming is replaced by hydrogen imports and the domestic electrolysis capacity is increased to 62 GW. The average full load hours of electrolyzers are 2600 (SCENARIO 80) and 2900 (SCENARIO 95). This underlines the need to install these at network nodes with considerable renewable power potential in Northern Germany, otherwise the high number of full load hours cannot be achieved and the overall costs increase. The analyses show that the input required for SCENARIO 95 on the total amount of hydrogen in 2050 cannot be produced exclusively by domestic production. The share of domestic hydrogen production is 45%, which means that more than half of the hydrogen will be imported. An important field of application for hydrogen is the production of pig iron. In SCENARIO 95, for example, the conventional blast furnace route will be almost completely replaced by the hydrogen direct reduction process of pig iron by 2050. This requires the use of an annual hydrogen quantity of 46 TWh. Hydrogen direct reduction and electric arc furnaces are the processes on which all future steel production will be based.

Due to its great storage properties, the re-electrification of hydrogen into the electricity grid, in SCENARIO 95, is an important option for maintaining a secure power supply.

In 2050, approximately 23% of the hydrogen input will be used for re-electrification. In addition to the direct use of hydrogen in the transport sector, another option for the use of hydrogen is the production of synthetic fuels (so-called power-to-fuel routes). Our analyses show that this only takes on a certain significance in SCENARIO 95 and involves the use of synthetic diesel fuels and jet engine fuels. However, these fuels are imported, as production at favorable locations abroad is significantly cheaper than domestic production; shipping considered.

CONCLUSIONS

One main research challenge to model energy transformation strategies is the wide variety of efficiency measures that are competing with each other and the necessary spatial and temporal resolution due to the renewable energies like wind and PV. Therefore we developed a model suite which we applied for an example case on Germany.

The core of the model suite is an overall model that maps the national energy supply across all sectors, hosts an algorithm for cost minimization and draws the specific information of the different sectors from comprehensive subroutines. Furthermore, spatial and temporal resolved models like a hydrogen infrastructure model are coupled to this overall model.

Parts of the 80% measures are not conducive for meeting a 95% target or may even be counterproductive. In concrete terms: measures in this target category planned today for the medium term would sooner or later end up as "stranded investments" if a 95% target was set. In order to use financial resources efficiently, industry and politics should consistently focus on medium-term reduction strategies and the associated investment measures for the 95% reduction target as early as in the beginning of the 2020s. The expansion of energy infrastructures requires considerable lead times for planning and implementation. The planning of the necessary infrastructure (e.g. hydrogen salt caverns, hydrogen-pipelines, etc.) should therefore start early.
Hydrogen plays a key role in cost-effective and climate-effective and climate-friendly transformation strategies for the German "Energy System". Especially for reduction pathways higher than 80% hydrogen needs to be integrated within the "Energy System" to achieve the reduction goals cost-effectively. For hydrogen amounts of 4 million t per year, the production with electrolysers in Germany is supplemented by natural gas reformers. For growing hydrogen demands the import of hydrogen gets more prominent. Sector coupling via hydrogen and PtX technologies for industrial

applications like steel production will lead to a significant demand for hydrogen in the future. The necessary prerequisite is a CO_2-free power generation. Both transformation strategies require the implementation of a hydrogen infrastructure for production, transportation and storage.

REFERENCES

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