Centre for Climate and Energy Analyses

SCENARIOS OF LOW-EMISSION ENERGY SECTOR FOR POLAND AND THE EU UNTIL 2050

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\# LIFEClimateCAKEPL

KOBiZE

Warsaw, October 2019

IOŚ-PIB

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The authors would like to thank Paweł Mzyk, Robert Jeszke, Aneta Tylka, Maciej Cygler, Marta Rosłaniec, Izabela Tobiasz, Jan Witajewski-Baltvilks, Eugeniusz Smol, Przemysław Sikora for valuable contributions, inputs, and insightful feedback.

Upon quoting, please refer to the source, as follows:

Tatarewicz, I., Lewarski, M., Skwierz, S. (2019). *Scenarios of low-emission Energy sector for Poland and the EU until 2050*, Institute of Environmental Protection - National Research Institute / National Centre for Emissions Management (KOBiZE), Warsaw.

This document was prepared in the Centre for Climate and Energy Analyses (CAKE) set up in the National Centre for Emissions Management (KOBiZE), whereas KOBiZE is a part of the Institute of Environmental Protection - National Research institute (IOŚ-PIB).

This document was prepared within the scope of the project: "*The system of providing and exchanging information in order to strategically support implementation of the climate and energy policy (LIFE Climate CAKE PL)*" - LIFE16 GIC/PL/000031 – LIFE Climate CAKE PL

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The document was completed in October 2019.

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Project "The system of providing and exchanging information in order to strategically support implementation of the climate and energy policy (LIFE Climate CAKE PL)" is co-financed from the EU LIFE program and co-financed from the funds of the National Fund for Environmental Protection and Water Management.

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List of abbreviations

ARE SA	Energy Market Agency
ASSET	Advanced System Studies for Energy Transition
CAKE	Centre for Climate and Energy Analyses
CAPEX	CAPital EXpenditures
CCS	Carbon Capture and Storage
CGE model	Computable General Equilibrium model
CHP	Combined Heat and Power
d-PLACE model	Dynamic version of PLACE model (CGE model created in Polish Laboratory for the Analysis of Climate and Energy)
DSR	Demand Side Response
EC	European Commission
ENTSO-E	European Network of Transmission System Operators for Electricity
EPICA model	Evaluation of Policy Impacts on Climate and Agriculture Model
ESR	Effort Sharing Regulation
EU	European Union
EU ETS	European Union Emissions Trading System
EU28	European Union of 28 Member States
GDP	Gross Domestic Product
GHG	Greenhouse Gases
HP	Heat only Plant
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IOS-PIB	Institute of Environmental Protection – National Research Institute
IPCC	Intergovernmental Panel on Climate Change
JRC IDEES	Integrated Database of the European Energy Sector
JRC-EU-TIMES	model developed as an evolution of the Pan European TIMES (PET) model
KOBiZE	National Centre for Emissions Management
MEESA	Model for European Energy System Analysis
NECP(s)	National Energy and Climate Plan(s)
OSeMOSYS	Open Source energy MOdelling SYStem
PP	Power Plant
PRIMES	PRice-Induced Market Equilibrium System
PV	Photovoltaics
PWR	Pressurized Water Reactor
RES	Renewable Energy Sources
TR^{3}E model	Transport European Emission Economic Model
TSO	Transmission System Operator
UNFCCC	United Nations Framework Convention on Climate Change
WACC	Weighted Average Cost of Capital
WEO	World Energy Outlook
WNA	World Nuclear Association

Abstract

European Union puts significant effort in deep emission reduction to maintain the leadership position in the fight against global warming. The main goal is set as carbon neutrality of the whole economy, but limiting the cost of emission reduction is very important in terms of competitiveness, risk of carbon leakage and energy poverty. Power and heat generation are responsible for a substantial part of the emissions of greenhouse gases and other air pollutants. Therefore, in order to ensure a reliable assessment of the climate-related and environmental effects of the policies pursued, it is essential to adequately and precisely model the energy sector and alternative paths of its future development.

The main objective of this report is to present the assumptions currently used in the MEESA model, its functionalities and set of results that can be obtained as well as the most important conclusions. Model functionality will be explained based on 4 scenarios analysis presented in this report (described later). The MEESA model, as majority of energy system models, uses large data sets, requiring continuous improvement and updates to adapt to changing market conditions and technological progress. One of the motives for making this report public is to obtain constructive feedback aiming to improve the model's inputs, applied equations and technical solutions, as well as obtained outputs. The scenarios prepared in the study make it possible to verify the proposed model in terms of the logic of the obtained results.

MEESA is a model of energy system of EU Member States including also Switzerland and Norway, designed for the long-term integrated assessment and energy planning in this region. The main purpose of the proposed tool is to gain a clear and comprehensive understanding of the system-wide implications of energy strategies focused on transitions to a competitive low-carbon energy sector in EU. MEESA model is designed to formulate and evaluate alternative energy supply strategies consonant with the user-defined constraints such as limits on new investment, fuel availability and trade, environmental regulations, market regulations, cross-border energy flow, required levels of emission reduction, required share of RES in given period, etc. The model covers the most important dynamics and relations that reflect the functioning of the power & district heat sector.

In the first chapter a brief summary of European Union climate policy is presented. Second and third chapters are short description of the model and data sources. Fourth chapter present analysed scenarios. Fifth chapter focuses on the scenarios results while sixth presents the most important conclusions regarding possible pathways to the future low-emission EU energy mix.

Keywords: climate policy, electricity supply, district heat supply, energy balance, energy modelling, energy policy, energy sources, EU ETS, long term energy analyses, long term energy strategy, net-zero emissions, climate neutrality

Key policy insights:

- Total emission reduction in electricity and district heat production over the period 2015-2050 reaches ca. **60%** in no forced emission reduction scenario (REF), **80%** in moderate reduction scenario (BAU), **95%** in deep emission reduction scenario (DEEP), and **95%** in deep emission reduction scenario without possibility of building new nuclear power plants in the EU (DEEPNN).
- **Emission reduction until 2030 (almost by 50%) are mainly driven by domestic policies concerning coal withdrawal and to some extent by RES development.** But further changes requires setting new goals – otherwise pace of emission reduction will drop after 2030.
- **Reducing CO_2 emissions from electricity generation is easier to achieve than in district heat generation.** This will result in a shift in energy production within the EU ETS, if district heat production is replaced by electricity used for heating purposes or "leak" of emission from the EU ETS, if consumers switch to individual heating installations based on fossil fuels.
- **The power sector moves towards renewable electricity practically in all considered scenarios.** This is caused not only by the growing cost of EUA, but also by the cost-effectiveness of certain RES electricity technologies. Especially, in deep reduction scenarios RES are developing very dynamically.
- For all the countries average electricity generation cost increases in scenarios of more challenging emission reduction targets, but what is important - **without new nuclear investments the energy costs are much higher, with the same emission reduction goals achieved.** The generation cost increase is more significant in the countries with lower potential of zero emission energy sources.
- The results show an increasing role of gas in the energy mix in REF scenario, while in scenarios with assumed deep CO_2 emission reduction, after 2040, gas (without CCS) is gradually replaced by emission-free generation units. Nevertheless gas power remains important as a backup technology. In the DEEPNN scenario, **without new nuclear capacities, the role of renewable sources and gas units equipped with CCS is growing**.
- **The decrease in the share of coal in the production structure takes place at the expense of the rising role of RES**, which due to rising prices of CO_2 emission allowances and dedicated subsidizing programs at an early stage, become an economically viable option.
- Energy exchange in 2050 is about **60%** larger in DEEP scenario than in REF scenario – which shows how important the development of electricity connection will be to achieve reduction goals.

1. Introduction

1. The EU aspires to be at the forefront of addressing the climate change tackling and strengthening the coordinated global response under the Paris Agreement. The Paris Agreement, ratified by 187 parties, requires strong action to reduce greenhouse gas emissions, with the objective to hold global temperature increase to well below 2°C and to pursue efforts to limit it to 1.5°C. It also has the goal to achieve a balance between emissions by sources and removals by sinks of greenhouse gases on a global scale in the second half of this century. The EU, responsible for 10% of global greenhouse gas emissions, is a global leader in the transition towards a net-zero-greenhouse gas emissions economy. The long-term strategy aims to confirm Europe's commitment to lead in global climate action and to present a vision that can lead to achieving net-zero greenhouse gas emissions by 2050 through a socially-fair transition in a cost-efficient manner. Only combined efforts of all members in gaining RES share, growing interconnectivity and energy efficiency, development of new technologies and consumer awareness of undertaken choices can lead EU to the ambitious goal.
2. At the European Council of October 2014, the EU set a domestic GHGs reduction target of at least 40% below 1990 levels by 2030. EU adopted a large number of legislative actions that will enable it to deliver on the commitment. In the Effort Sharing Regulation (ESR), adopted in May 2018, the reduction of emissions in effort sharing sectors has been set on 30% by 2030. Negotiations between the European Parliament and the Council set the level of the EU targets for renewable energy sources and energy efficiency on 32% and 32.5% respectively (for renewable energy sources previous proposal was 27%). Together, if fully implemented, it is estimated that these measures will result in a cut in EU emissions of around 45% by 2030. In its Resolution of 25 October 2018 on the 2018 Katowice UNFCCC Conference (COP24), the European Parliament supported updating the EU's target to reduce GHG emissions to 55% below 1990 levels by 2030. In November 2017, the European Parliament and the Council reached an agreement on the revision of the EU ETS for the post-2020 period, which was adopted in March 2018. Among other things, it reduces the emissions cap further by raising the linear reduction factor to 2.2% a year (compared to 1.74% currently), as of 2021.
3. In June 2018, the European Parliament and the Council reached an agreement on the Regulation on the governance of the Energy Union. The new governance system will help to ensure that the EU and the Member States achieve their 2030 goals as regards GHG emissions reductions, renewables and energy efficiency. Member States will prepare national energy and climate plans for 2021-2030 and report on their progress in implementing the plans, mostly every two years, while the Commission will monitor the progress of the EU as a whole. The EU and Member States will also prepare long-term strategies, covering a period of at least 30 years from 2020 onwards. The

Regulation will incorporate the existing EU climate monitoring and reporting mechanism and update it in line with the Paris Agreement's transparency requirements[1]. The EU's energy and climate policy will lead to far-reaching changes in the functioning of Europe's fuel and energy supply systems. There will be a change in the structure of generation towards carbon-free and low-carbon solutions, decentralisation of generation sources, integration of markets, which will imply a number of economic, social and environmental impacts. The analytical toolkit proposed under the CAKE project aims to analyse these and many other impacts of the European climate and energy policy. These changes have been underway for at least a dozen years and the entire fuel and energy supply system is likely to be completely transformed in the coming decades. The aim of the analysis, the results of which are presented in this chapter, is to test the model in terms of logic and consistency of obtained projections. In this way, the usefulness of the model for analysing the effects of various energy and climate policy solutions will be confirmed.

2. Short description of the energy model MEESA

4. The Model for European Energy System Analysis (MEESA)[2] is one of the models currently used and developed within the LIFE Climate CAKE PL project in the National Centre for Emissions Management (KOBiZE), which is a part of the Institute of Environmental Protection – National Research Institute (IOS-PIB). The main objective of this project is to build a sustainable and comprehensive system of creating and exchanging information and knowledge, supporting the development of cross-sectional analyses of the effects of various solutions in the field of climate and energy policy. The project's objectives are consistent with supporting the implementation of the EU climate change policy, support the implementation of the energy and climate package 2020 and the EU climate policy framework until 2030, also in the perspective of the long-term strategy until 2055. The project is developing an analytical workshop consisting of a global general equilibrium model (CGE) d-PLACE[3] and cooperative sectoral energy MEESA, agriculture EPICA and transport TR[3]E[4] models (Figure 1).

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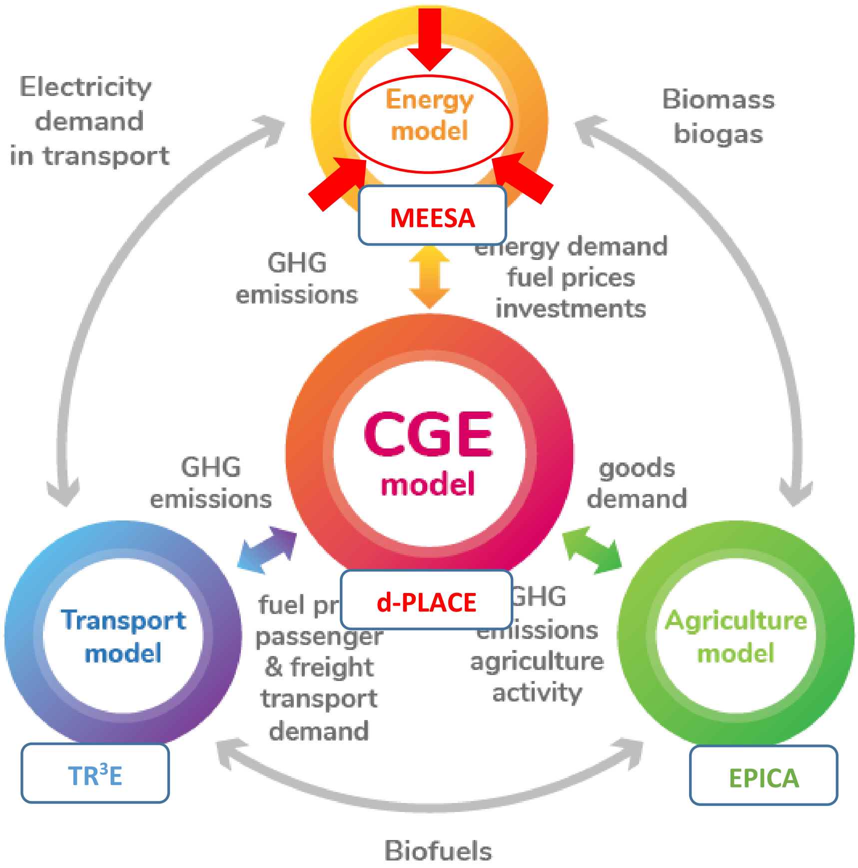
[1] European Parliament, Policy Department for economic, Scientific and Quality of Life Policies. Directorate General for Internal Policies (2019). European policies on climate and energy towards 2020, 2030 and 2040. Brussels, January 2019.

[2] Tatarewicz, I., Lewarski, M., Skwierz, S. (2019). The MEESA model documentation, Institute of Environmental Protection - National Research Institute / National Centre for Emissions Management (KOBiZE), Warsaw.

[3] Gąska, J., Pyrka, M., Rabiega, W., Jeszke, R.(2019). The CGE model d-PLACE, Institute of Environmental Protection - National Research Institute / National Centre for Emissions Management (KOBiZE), Warsaw.

[4] Gąska, J., Rabiega, W., Sikora, P. (2019). The TR3E Model, Institute of Environmental Protection - National Research Institute / National Centre for Emissions Management (KOBiZE), Warsaw.

Figure 1. General scheme of operation of models in the LIFE Climate CAKE PL project

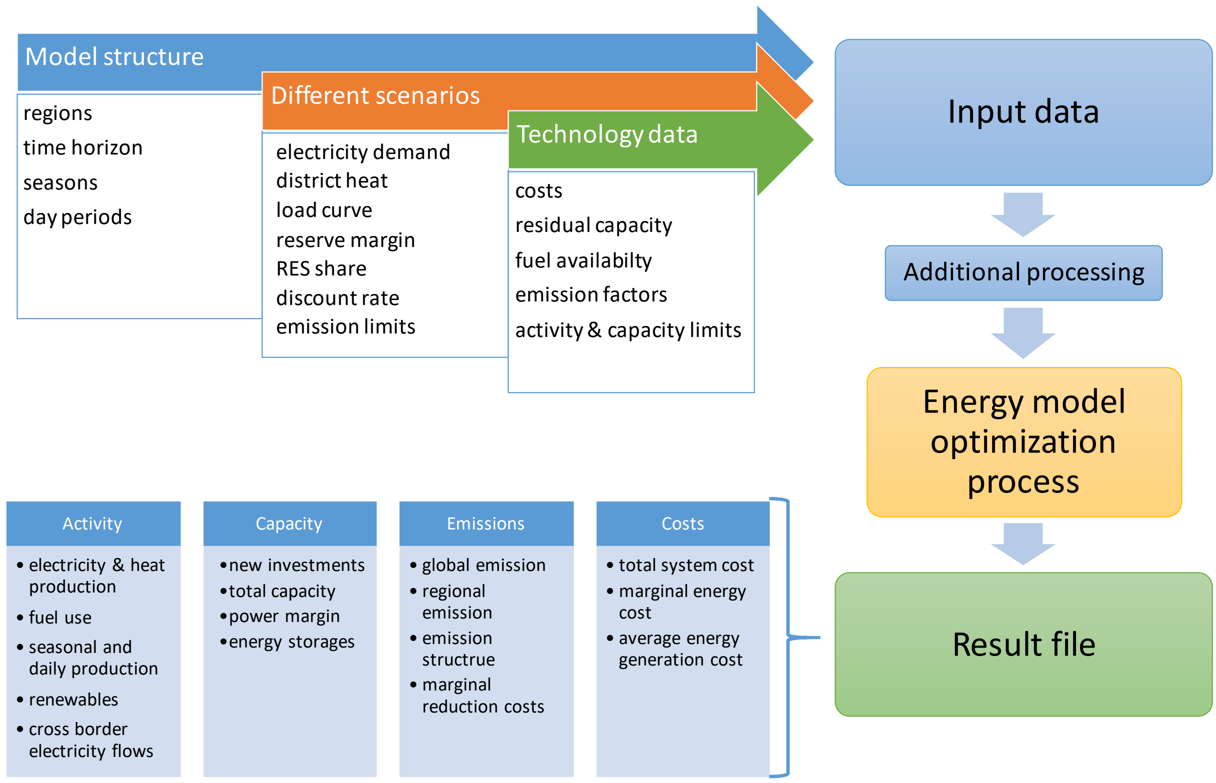


Source: CAKE/KOBiZE

5. The MEESA model (marked with red arrows on the figure above) allows modelling the supply of electricity and district heat. It has been designed to analyse the role of energy technologies and innovation in achieving European policy objectives related to energy and climate change in the power sector. It is a tool supporting energy policy impact assessment analyses that require quantitative modelling at the level of the energy system with a high level of technological detail. In general, the model allows us to formulate and evaluate alternative electricity and district heat supply strategies consonant with the user-defined constraints.

6. The MEESA model optimises the energy supply mix (electricity and district heat) meeting the given demand under a set of constraints. Minimization of the total discounted system costs is the criterion used for optimisation. Computed energy mix is saved into csv file in order to enable further data processing and facilitate results' analysis. Results are divided into four categories:
   - activity,
   - capacity,
   - emissions,
   - costs.

Figure 2. General scheme of operation in MEESA

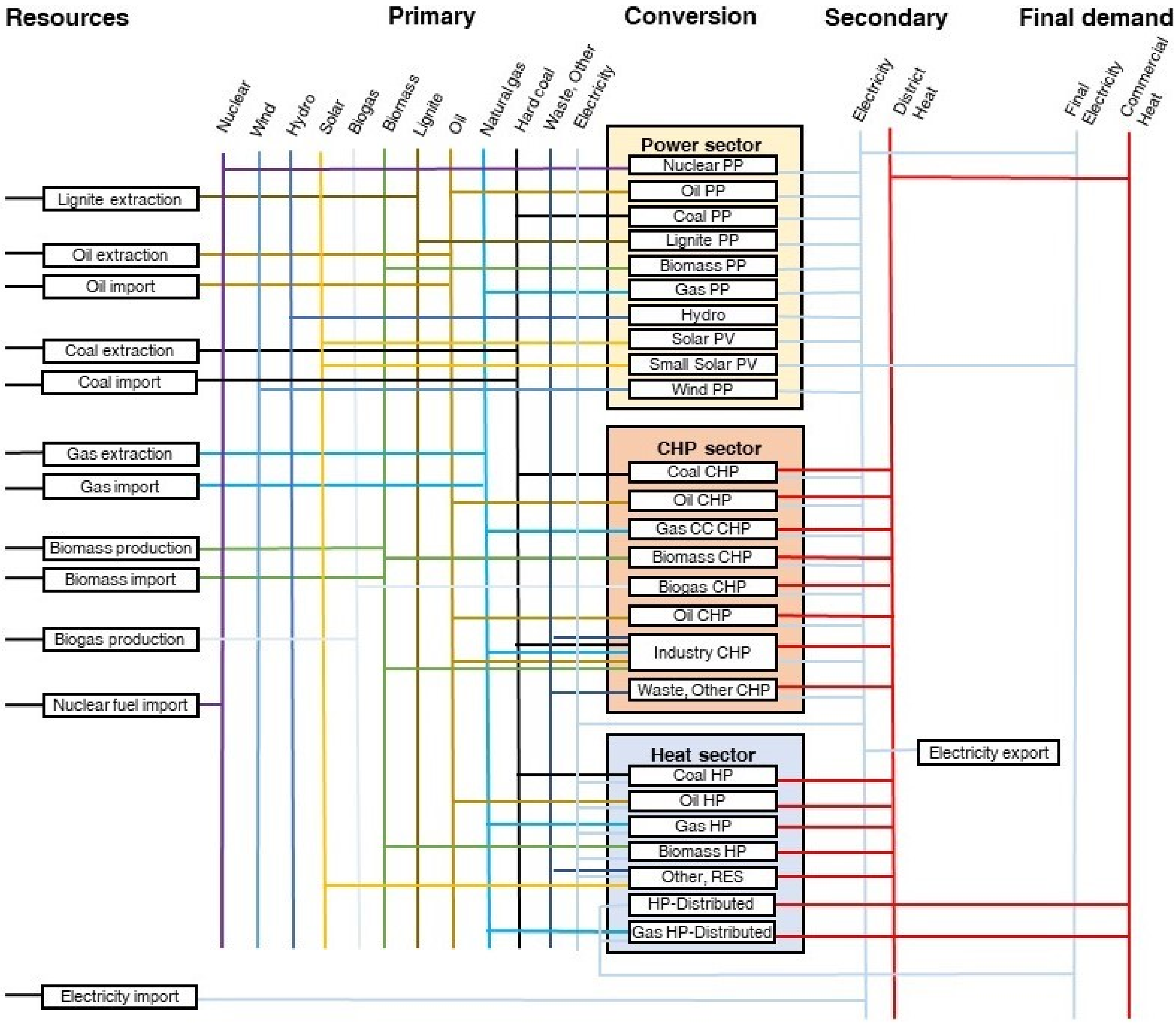


Source: CAKE/KOBiZE own study

7. MEESA allows to prepare a long term (currently with the 2055 time horizon) optimization of future energy mix for connected EU countries based on specific technical, economic and political conditions. The underlying principle of a model, built on the basis of the OSeMOSYS[5], is optimization of an objective function under a set of constraints that define the feasible region containing all possible solutions of the problem. Given a data of demands for electricity and district heat, model assures sufficient supply to demand, utilizing the technologies and resources considered. Energy demand data, exogenous to the model, is given at the first level of energy chain and the model computes demands at following levels of the chain up to energy resource level. The value of the objective function helps to choose the solution considered best according to the criteria specified. MEESA allows modelling of all steps in the energy flows from supply sources to demand, which is generally referred to as energy chain and steps are called levels. Figure 3 shows the schematic representation of energy chain applied in MEESA model.

[5] Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazilian, M., Roehrl, A. (2011). OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development. *Energy Policy*, 39 (10), pp. 5850-5870.

Figure 3. Schematic presentation of energy chain



Source: CAKE/KOBiZE own study

3. Modelling assumptions

8. In its conclusions of 23 and 24 October 2014, the European Council endorsed a 2030 Framework for Energy and Climate for the Union based on four key Union-level targets: a reduction of at least 40% in economy-wide greenhouse gas (GHG) emissions, an indicative target of at least 27% improvement in energy efficiency, at least a 27% share of renewable energy consumed in the Union, and electricity interconnection of at least 15%. A recast of Directive 2009/28/EC of the European Parliament and of the Council has introduced a new, binding, renewable energy target for the Union for 2030 of at least 32%, including a provision for a review with a view to increasing the Union-level target by 2023. Amendments to Directive 2012/27/EU of the European Parliament and of the Council have set the Union-level target for improvements in energy efficiency in 2030 to at least 32.5%, including a provision for a review with a view to increasing the

Union-level targets. The EU has agreed a comprehensive update of its energy policy framework to facilitate the transition away from fossil fuels towards cleaner energy and to deliver on the EU's Paris Agreement commitments for reducing greenhouse gas emissions. The new objectives are presented in a set of documents called the Clean energy for all Europeans package. It consists of eight legislative acts.

9. These EU energy policy elements are intended to contribute together to the achievement of the objectives and targets of the Energy Union and in the long term to the commitments stemming from the EU ratified on 5 October 2016 Paris Agreement. In pursuit of the temperature goals in the Paris Agreement, the Union should aim to achieve a balance between anthropogenic GHG emissions by sources and removals by sinks as early as possible and, as appropriate, achieve negative emissions thereafter.

10. The most important acts of legislation in force in the EU aimed at achieving ambitious climate and energy policy objectives, which have a key impact on the modelling process, are as follows:

- Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources. The original renewable energy directive (2009/28/EC) establishes an overall policy for the production and promotion of energy from renewable sources in the EU. It requires the EU to fulfil at least 20% of its total energy needs with renewables by 2020 – to be achieved through the attainment of individual national targets. All EU countries must also ensure that at least 10% of their transport fuels come from renewable sources by 2020.

- Revised Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources entered into force, as part of the Clean energy for all Europeans package. The Directive sets a common target for the EU to achieve 32% of energy from renewable sources in gross final energy consumption, with a clause for a possible upward revision by 2023. The overall target for bioenergy in the transport sector has been set on 14%.

- Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC is a document establishing a common framework for energy efficiency measures in the Union to ensure the achievement of the Union headline target of 20% energy efficiency improvement by 2020 and to create the conditions for further improvement of energy efficiency after that target date. Therefore, it requires annual savings in the period from 1 January 2014 to 31 December 2020 of 1.5% of the annual volume of sales of energy to final customers in the most recent three-year period before 1 January 2013.

- Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency updates the Union's headline target to at least 32.5% in 2030. Member States are therefore required to achieve savings of 0.8% of their annual final energy consumption averaged over the last three years before 1 January 2019.
- Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity establishes common rules for the generation, transmission, distribution, storage and supply of electricity, together with consumer protection rules, as well as rules on the independence of regulatory authorities in the Member States. It also lays down the modalities for cooperation between Member States, regulatory authorities and transmission system operators in order to create a fully interconnected internal market for electricity. The Union's efforts in this area shall also be guided by the development of interconnection. The objective for Member States is to achieve cross-border interconnection capacity of at least 10% of peak demand by 2020 and 15% by 2030.
- Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity lays down basic rules for the functioning of integrated electricity markets within the framework of the current climate and energy objectives of the European Union for 2030. Additionally, it lays down rules for cross-border exchanges in electricity to facilitate integration, thereby enhancing security of electricity supply. The regulation introduces provisions concerning restrictions on aid within the power market for new generation sources with unitary emissions exceeding 550 g CO_2 per 1 kWh or 350 kg CO_2 per 1 kW/year, for which the final investment decision will be taken after the entry into force of the new regulations. On the other hand, existing power plants (i.e. those which started operating before the entry into force of the Regulation) emitting more than 550 g CO_2 per 1 kWh and more than 350 kg CO_2 per year on average for each installed power 1 kW will be able to participate in these mechanisms only until 1 July 2025. Contracts signed within the power market until the end of 2019 are excluded from the regulatory restrictions.
- Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action Regulation. The document will ensure coherence and better cooperation of Member States' long term energy and climate policy planning and foresee reporting, review and close monitoring of progress. As a result of the Governance Regulation, Member States are expected to establish and to submit their ten year integrated National Energy and Climate Plans (NECPs) by the end of 2019 covering all five dimensions of the Energy Union. These plans will define and explore synergies between Member

States' objectives and contributions to the Energy Union goals and, in particular, national targets for the non-ETS sector as set in the Effort Sharing Regulation, national contributions to the EU renewable energy and energy efficiency targets with a view to their achievement by 2030. This will put the EU in a good position to reduce greenhouse gas emissions beyond the 40% target by 2030 and on the carbon neutral trajectory. National energy and climate plans are required to be consistent with both the EU long-term strategy and the national Long Term Strategies to be submitted by January 2020.

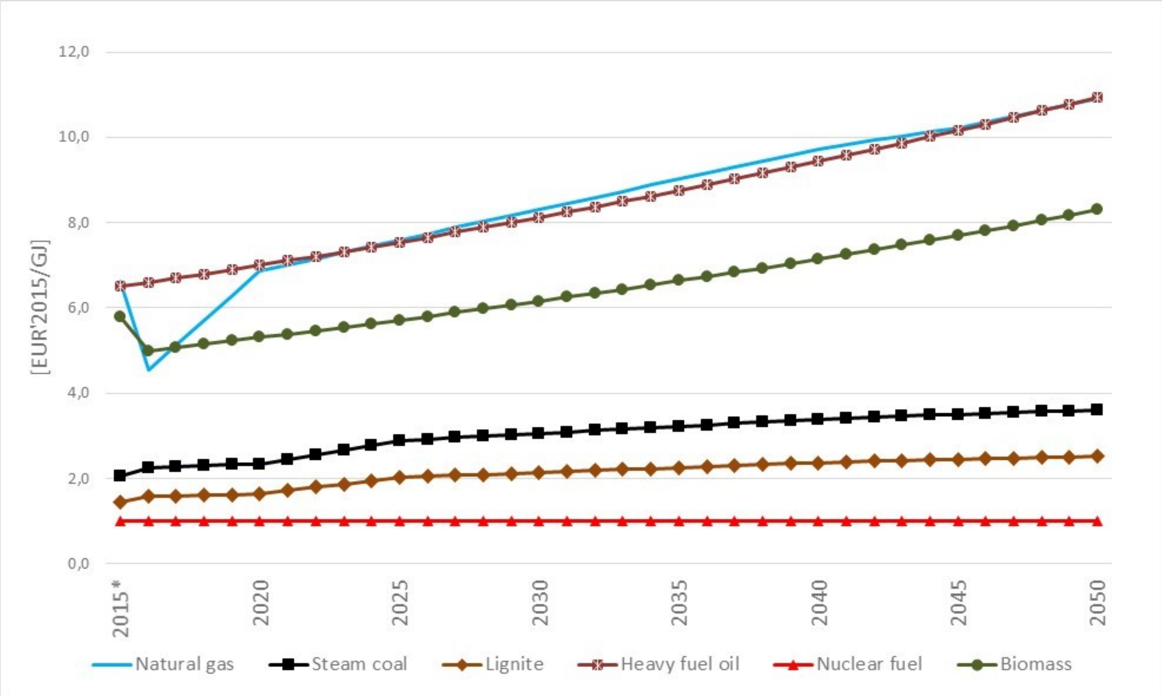
11. After 2030 further increase of RES target is very probable - especially in electricity generation. Level of that target is expected to be raising along with the lowering costs of electricity production from renewable sources. Support programs worldwide have kick-started a dramatic decrease in the cost of renewable energy technologies and this trend is expected to be sustained. The increasing share of renewable energy investments will be also the result of a slump in the commissioning of new fossil fuel capacity and ageing of existing power plants.

3.1. World fuel prices and CO_2 emission allowance prices

12. Model takes the evolution of prices of fossil fuel imported to EU as exogenous assumptions. For all four scenarios described in the report, prices were taken from the Current Policies Scenario of the World Energy Outlook 2017 (IEA)[6]. Model used by IEA (World Energy Model) endogenously derives consistent price trajectories for oil, natural gas and coal based on the evolution of global energy demand, resources and reserves, extraction costs and bilateral trade between regions. The price trajectories are smooth trend lines, and do not attempt to anticipate the cycles and short-term fluctuations that characterise all commodity markets in practice. Values beyond 2040 are the result of extrapolation (Figure 4).

[6] IEA (2017a). World Energy Outlook, annual. Paris, https://webstore.iea.org/world-energy-outlook-2017. Current Policies Scenario

Figure 4. Fuel prices assumed in all scenarios

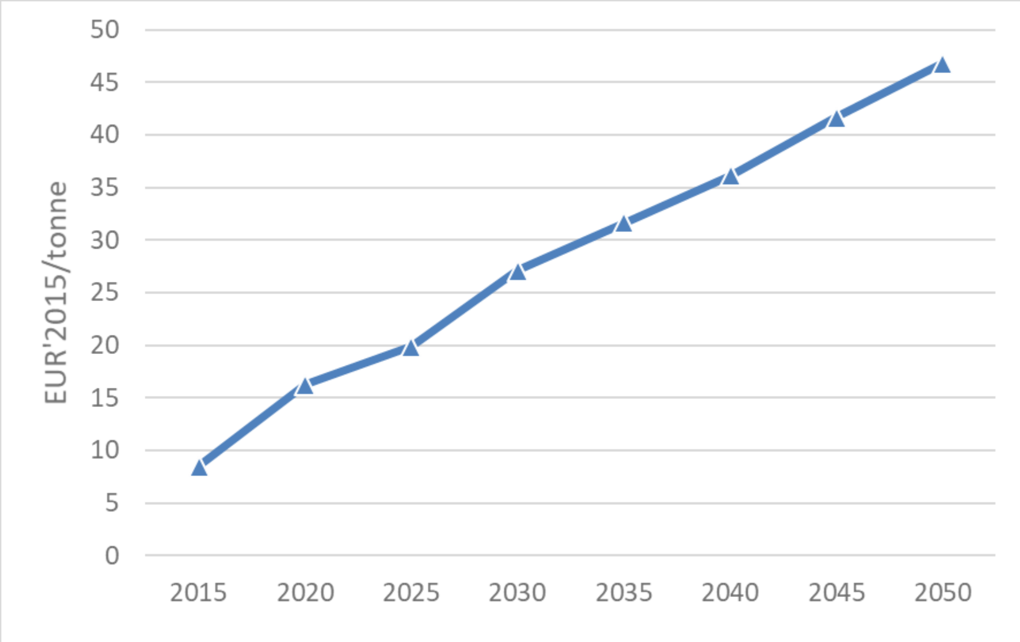


Source: CAKE/KOBiZE own study, based on International Energy Agency. World Energy Outlook 2017, Current Policies Scenario. Paris, 2018.

13. The model also enables adding the transportation cost to the wholesale fuel price. Due to lack of respective data for the purpose of the analysis it has been done in a simplified way, namely based on assumption that fuel price imported to EU is the same as the price of purchase by power plant.

14. The projection of CO_2 emission allowance prices in the EU ETS is also an exogenous assumption to the model. It has been adopted on the basis of the forecast of the International Energy Agency (WEO 2017, Current Policies Scenario), similarly to fuel price projections. Values beyond 2040 has been extrapolated. Values of this category can be freely adopted to the model from various sources. In this way, the projections of capacity and production structure generated in the model can be differentiated. CO_2 price scenarios depends on the objective and variant of the analysis.

Figure 5. CO_2 emission allowance prices assumed in all examined scenarios



Source: CAKE/KOBiZE own assumptions based on International Energy Agency. World Energy Outlook 2017, Current Policies Scenario. Paris, 2018.

3.2. Electricity and district heat demand

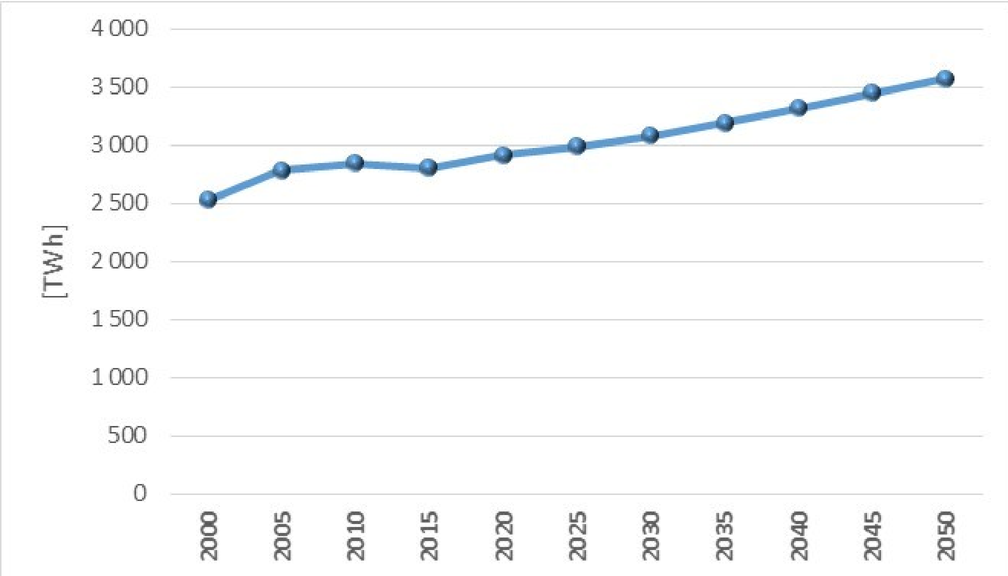
15. MEESA model is driven by the energy demand given to the model exogenously as the model finds out the least-cost expansion in the energy system to meet these projected demand in each period. According to scheme presented on Figure 1 there are some soft linkages between energy, transport and CGE models to better present all economy branches. In such a way after sectoral analyses where new data is generated as an output of one model, it can be used as an input data in other models. Eventually energy demand for countries will be generated in d-PLACE model and, after calculation in MEESA model new results covering changes of electricity costs, energy mix, GHG emissions and new investment in energy sector will be taken into d-PLACE model as input for next calculation.

16. Similar iterative process will be performed with transport model - the electricity price increase for each scenario will be used as an input into TR^3E^4 model which in result will generate new electricity demand for transportation for next iteration of calculation in MEESA model.

17. However, since mechanism of data exchange with other models is still under development, for the purposes of this study, projections of electricity and district heat

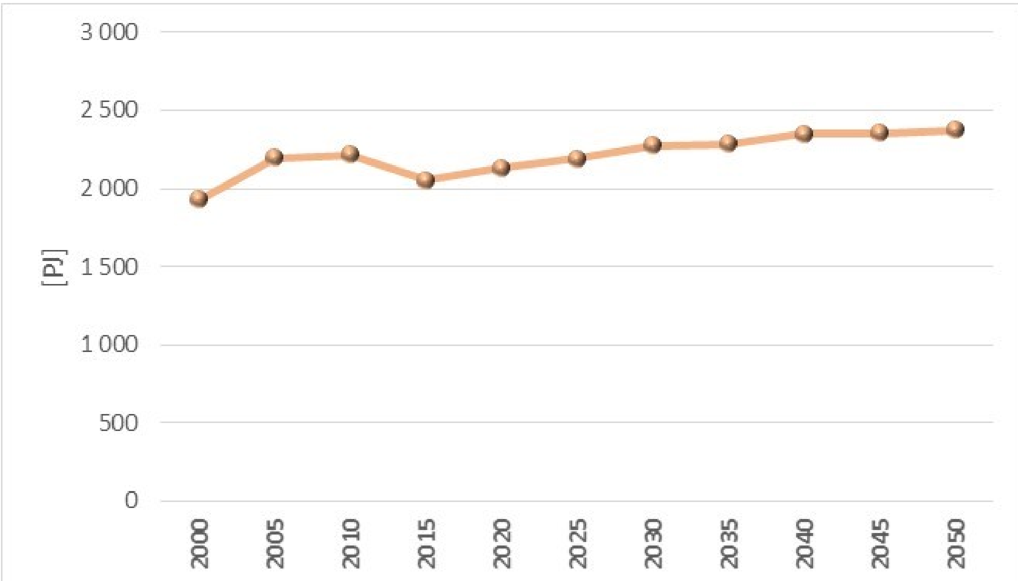
demand for a given country have been adopted from PRIMES 2016 Reference scenario[7]. The PRIMES model is the EU energy system model which simulates energy consumption and the energy supply system. It is a partial equilibrium modelling tool that simulates an energy market equilibrium in the European Union and each of its Member States. Electricity demand and district heat for all EU countries has been shown respectively on Figure 6 and Figure 7.

Figure 6. Electricity demand in EU-28



Source: PRIMES 2016 Reference scenario.

Figure 7. District heat demand in EU-28



Source: PRIMES 2016 Reference scenario.

[7] European Commission, Directorate-General for Energy, Directorate-General for Climate Action and Directorate-General for Mobility and Transport (2016). EU Reference Scenario 2016. Energy, transport and GHG emissions. Trends to 2050. Brussels.

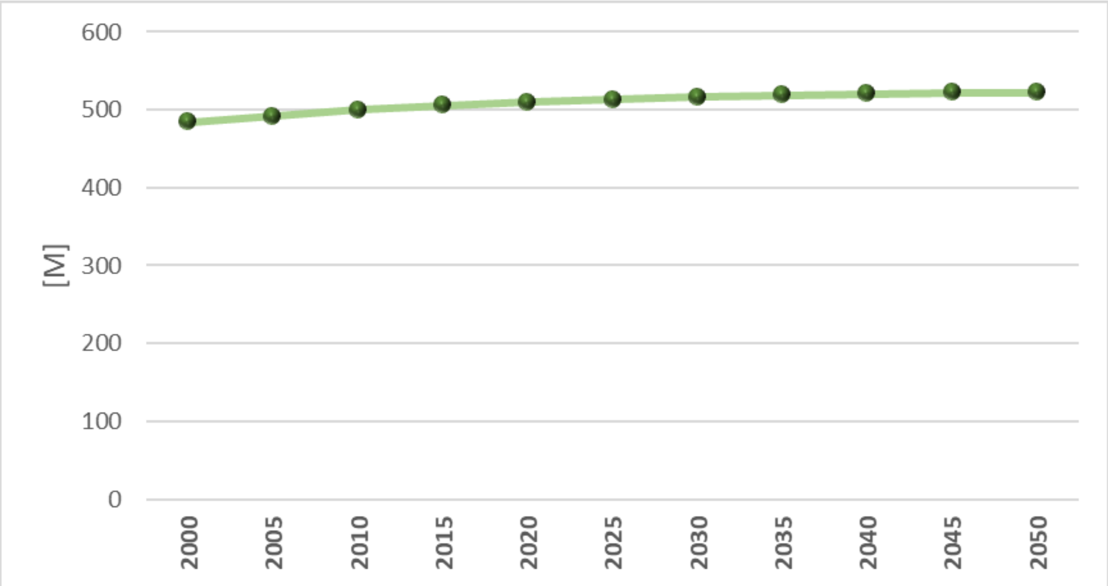
18. The PRIMES Reference 2016 scenario is based on the following demographic and macroeconomic assumptions:

- **Demographic assumptions**

19. The EU population is projected to increase over coming decades up to 2050, however with declining growth rates. Following fertility, life expectancy and migration dynamics age structure in the EU is projected to change strongly in the following decades. Elderly people, aged 65 or more, would account for 24% of the total population by 2030 and 28% by 2050 as opposed to 18% today. Demographic assumptions strongly affects on the results for energy demand.

20. The European Union (EU28) is one of the largest economies in the world, with a gross domestic product (GDP) of 14,635 EUR billion in 2015. It has 508 million inhabitants, or 7% of the world´s population.

Figure 8. Population in the EU-28



Source: PRIMES 2016 Reference scenario.

- **Macroeconomic assumptions**

21. The GDP and value added assumptions underlying the energy services demand are presented in Table 1 and following figures. PRIMES 2016 Reference scenario considers an average annual EU GDP growth rate of 1.5 until 2050. The annual average potential GDP growth rate in the EU is projected to remain quite stable over the long-term and much lower than in previous decades.

Table 1. Annual growth rate of the EU-28 GDP considered in the energy models

2015-2020	2020-2025	2025-2030	2030-2035	2035-2040	2040-2045	2045-2050	2015-2050
1.6%	1.4%	1.4%	1.5%	1.6%	1.5%	1.5%	1.5%

Source: PRIMES 2016 Reference scenario.

22. According to these projections, tertiary sector is projected to generate 79% of gross value added by 2050, continuously increasing its share in the analyzed period of time. Energy intensive industries maintain their shares in gross value added close to present levels. Relatively slow growth is projected in the energy sector.

3.3. Schedule for the decommissioning of generating units

23. Schedule for decommissioning of generating unit was based on 2015 mix of existing units and assumed lifetime of particular technologies. Because of lack of complete database including age of existing units some own assumptions concerning rate of decommission was necessary - especially in case of heat plants. Information about current structure of installed capacity for particular states was based on EUROSTAT[8], ENTSO-E[9], IEA[10] data. Other assumptions concerning coal phase out and decommissioning of nuclear power plants were based on information provided by WNA[11] and on NCEPs[12] declaration (Table 2).

Table 2. Phase out dates for technology in analysed countries

No.	Country	Coal PP phase out	Nuclear PP phase out
1.	Belgium	2017	2025
2.	Denmark	2030	-
3.	Estonia	2030*	-
4.	France	2022	-
5.	Finland	2029	-
6.	Germany	2038	2022
7.	Ireland	2025	-
8.	Italy	2025	-
9.	Netherlands	2029	2033
10.	Portugal	2030	-
11.	Spain	-	2048
12.	Switzerland	-	2034

*Oil shale

Source: CAKE/KOBiZE own study based on WNA and NCEPs

[8] European Commission. EUROSTAT Database. Luxembourg, https://ec.europa.eu/eurostat/data/database
[9] ENTSO-E (2018). Ten Year Network Development Plan 2018. Brussels.
[10] IEA. OECD.Stat. Paris, https://stats.oecd.org
[11] World Nuclear Association. London, https://www.world-nuclear.org/information-library/country-profiles.aspx
[12] European Commission. Brussels, https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/governance-energy-union/national-energy-climate-plans

3.4. Techno-economic assumptions of new generating units

24. Currently, techno-economic assumptions in MEESA model are based on EU funded project named ASSET (Advanced System Studies for Energy Transition)[13]. This study covers most of the technologies currently implemented in the MEESA model as well as some that will be implemented in the future version of MEESA model. At this stage model includes about 50 energy generation technologies.

25. The MEESA model is based on a single discount rate used for annualizing capital or investment expenditures (CAPEX). In the calculation of the investment costs, the discount rate assumed was equal to the weighted average cost of capital at 7.5%. WACC was calculated on the assumption that the interest rate on borrowed capital is 7% per annum and the cost of equity is 8.5% (the share of equity in the structure of investment financing at the level of 30% was assumed).

3.5. Potential of individual resources, technologies, load curves and interconnectors

- **Bioenergy**

26. Regarding bioenergy, the MEESA considers the following different types of primary energy sources: wood from forestry, agricultural energy crops, biodegradable fraction of municipal solid waste (which are grouped in the model as a biomass), agricultural biogas, landfill gas and sewage sludge (which are grouped in the model as a biogas). The existing and expected potential for the use of these resources has been determined on the basis of the studies: see Berien Elbersen, et. all (2012)[14], Ruiz P. et. all (2015)[15]. This publications contains mapped and quantified overview of different biomass feedstocks and import potentials. This information has been further combined with cost information to derive cost-supply curves at national and EU wide scale.

- **Conventional units**

27. The development of the potential conventional generation sources has been determined on the basis of publicly available projections published by recognized research centers. The basic source of information are the projections of the European Commission carried out by the Technical University of Athens under the leadership of prof. A. Capros[7,16] and

[13] Tractebel, E3Modelling, Ecofys (2018). Technology pathways in decarbonisation scenarios. July 2018.
[14] Elbersen, B., Startisky, I., Hengeveld, G., Schelhaas, M.J, Naeff, H., Böttcher, H. (2012). Atlas of EU biomass potentials. Spatially detailed and quantified overview of EU biomass potential taking into account the main criteria determining biomass availability from different sources. February 2012.
[15] Ruiz, P., Sgobbi, A., Nijs, W., Thiel, C., Longa, F.D., Kober, T., Elbersen, B., Hengeveld G. (2015). The JRC-EU-TIMES model. Bioenergy potentials for EU and neighbouring countries. Luxembourg.
[16] E3MLab & IIASA (2016). Technical report on Member State results of the EUCO policy scenarios. December 2016 with further modifications.

ENTSO-E[9]. Following these projections, minimum and maximum of the total capacity installed and annual power increments in particular technologies are determined. These figures constitute very important constraints in the optimisation process. In next steps, the list of sources on which these estimates are based will be gradually extended. Projections presented by individual countries as part of their National Energy and Climate Plans (NECPs) will undoubtedly be a valuable source of information in this respect.

- **RES technical potential**

28. Another relevant exogenous inputs in the MEESA model is the renewable energy technical potentials per technology and per country. The total and annual capacity development potential of individual RES technologies is estimated based on various literature sources and most recent projections, published by recognized research centers (ENTSO-E, PRIMES, JRC-EU-TIMES). Inputs to the model are minimum or maximum limits on annual or total power (in given period) increase. The pace and scope of development of RES generation units is determined by the technical and resource capabilities which are characteristic for a given country or region.

- **Interconnections and load curves**

29. The main source of data about cross-border interconnections for period 2015-2019 was ENTSO-E Transparency Platform[17]. Period from 2020 onwards were taken from ENTSO-E analyses[9,18,19].

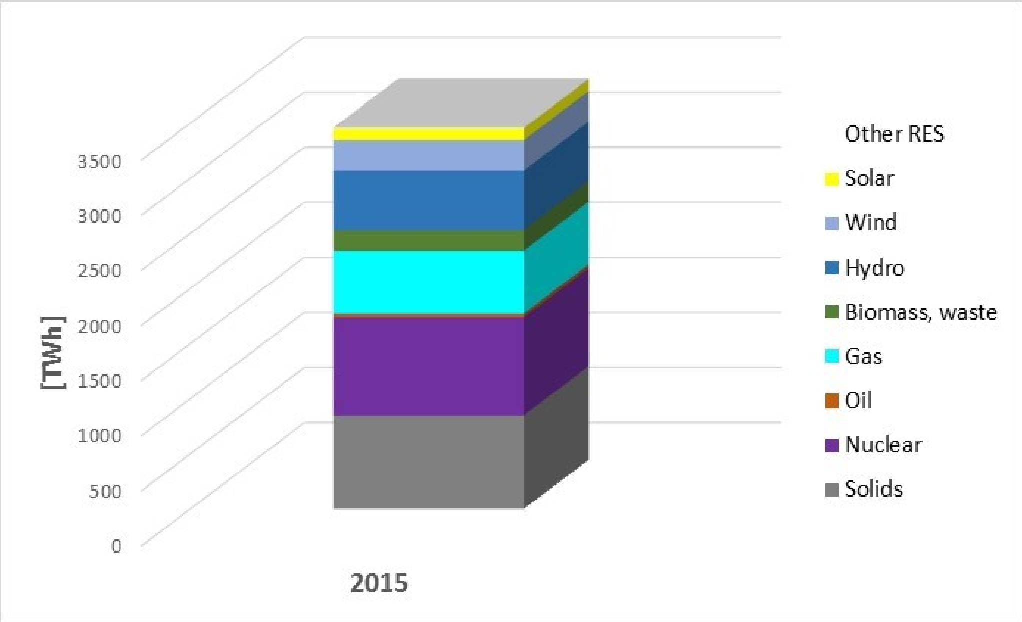
30. Data used for building demand curves were taken from ENTSO-E Transparency Platform[17] (more information about load curves and interconnections in the MEESA model documentation[2]).

3.6. Electricity generating capacity structure

31. The main sources of statistical data for the base year (2015) are: EUROSTAT[8], ENTSO-E[9], IEA[10], TSO homepages and domestic literature sources. Technical parameters, including efficiency, input/output ratio, fuel share, operational time, capacity factor, are calculated based on the gathered data. Model considers also the option of biomass co-firing in coal plants. Figures 9 and 10 present the structure of electricity production and generation capacity broken down by fuel in the base year (2015). These data are based on EUROSTAT and constitute the starting point for the prepared analysis.

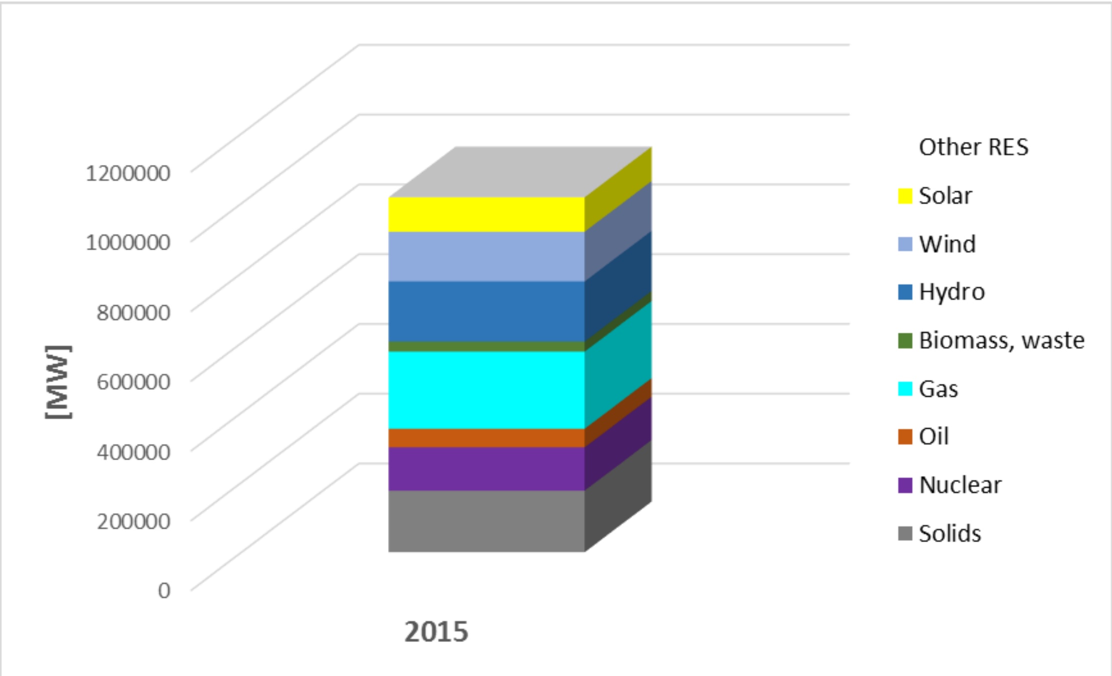
[17] ENTSO-E. Transparency Platform. Brussels. https://transparency.entsoe.eu
[18] ENTSO-E (2018). Mid Term Adequacy Forecast 2018. Brussels.
[19] ENTSO-E (2018). Europe Power System 2040: Completing the map Technical Appendix. Brussels.

Figure 9. Net electricity generation structure in EU-28 + CHE + NOR



Source: EUROSTAT

Figure 10. Net electricity generation capacity structure in EU-28 + CHE + NOR



Source: EUROSTAT

32. The type of about 50 installations defined in the model are grouped according to fuel input, technology type and whether the plant is electricity only (PP), Combined Heat and Power (CHP) or heat only (HP).

Table 3. Group of units considered in the model

No.	Type of unit	Fuel input	Output
1.	Hard coal old power plant	Hard coal, Biomass	Electricity, heat*
2.	Hard coal new power plant	Hard coal, Biomass	Electricity
3.	Lignite old power plant	Lignite, Biomass	Electricity, heat*
4.	Lignite new power plant	Lignite, Biomass	Electricity
5.	Gas old power plant combined cycle	Natural gas, Oil	Electricity
6.	Gas power plant combined cycle	Natural gas	Electricity
7.	Oil power plant combined cycle	Oil, Biomass	Electricity
8.	Nuclear gen 3 PWR power plant	Nuclear fuel	Electricity, heat*
9.	Biomass power plant old	Biomass, Biogas	Electricity
10.	Biomass power plant	Biomass	Electricity
11.	Hard coal new power plant + CCS	Hard coal	Electricity
12.	Lignite new power plant + CCS	Lignite	Electricity
13.	Gas new power plant + CCS	Natural gas	Electricity
14.	Peak gas turbine (open cycle)	Natural gas	Electricity
15.	Pumped storage hydroelectricity plant	Electricity	Electricity
16.	Hard coal old chp	Hard coal, lignite,	Electricity, heat
17.	Hard coal chp	Hard coal, lignite,	Electricity, heat
18.	Gas chp old	Natural gas	Electricity, heat
19.	Gas chp	Natural gas	Electricity, heat
20.	Oil chp	Oil	Electricity, heat
21.	Waste chp	Non-renewable waste	Electricity, heat
22.	Bio waste chp	Renewable waste	Electricity, heat
23.	Onshore wind turbine	Wind onshore energy	Electricity
24.	Offshore wind turbine	Wind offshore energy	Electricity
25.	Large hydro power plant (HYD)	Hydro energy	Electricity
26.	Small hydro power plant (HYDs)	Hydro energy	Electricity
27.	Biomass old chp	Biomass	Electricity, heat
28.	Biomass new chp	Biomass	Electricity, heat
29.	Biogas chp	Biogas	Electricity, heat
30.	Photovoltaic	Sun energy	Electricity
31.	Small photovoltaic**	Sun energy	Electricity
32.	Industrial old chp (mixed fuels)	Hard coal, lignite, oil,	Electricity
33.	Hard coal heat plant	Hard coal, lignite,	Heat
34.	Gas heat plant	Natural gas, electricity	Heat
35.	Oil heat plant	Oil, electricity	Heat
36.	Biomass heat plant	Biomass, biogas, electricity	Heat
37.	Geothermal heat plant	Geothermal energy, electricity	Heat, electricity*
38.	Heat waste	Renewable and non-renewable waste	Heat
39.	Heat pump – distributed***	Electricity	Heat
40.	Electric boiler – distributed***	Electricity	Heat
41.	Gas heat plant – distributed***	Natural gas, electricity	Heat
42.	Hard coal import	-	Hard coal

43.	Hard coal mine	-	Hard coal
44.	Lignite mine	-	Lignite
45.	Natural gas import	-	Natural gas
46.	Natural gas extraction	-	Natural gas
47.	Oil import	-	Oil
48.	Uranium import	-	Nuclear fuel
49.	Biomass production	-	Biomass
50.	Biogas production	-	Biogas
51.	Waste production	-	Non-renewable
52.	Waste bio production	-	Renewable
53.	Other fuels production	-	Other
54.	Electricity transmission	Electricity	Electricity
55.	Electricity distribution	Electricity	Electricity
56.	Heat distribution	Heat	Heat
57.	Sun energy production****	-	Sun energy
58.	Wind onshore energy****	-	Wind onshore
59.	Wind offshore energy****	-	Wind offshore
60.	Hydro energy****	-	Hydro energy
61.	Geothermal energy****	-	Geothermal

**Only in existing plant in four countries (namely Poland – lignite and hard coal, Slovakia - nuclear, Czech Republic – lignite, Italy – electricity from geothermal) for calibrating base year.*

***Small photovoltaic produces electricity for final demand.*

****In order to model leakage in district heat from ETS to non-ETS two technology are implemented to show a possible change in heat consumption. Taking into account current and future restrictions on emissions and the fact that buildings connected to district heat network are in cities and solid fuels will not be possible to economically use. Electricity, gas and heat are in these technologies connected at the final stage of production and consumption (different prices and losses are taking into account).*

*****Artificial technology for modeling production of renewable energy carrier.*

Source: CAKE/KOBiZE own study

33. The model includes 27 regions connected by electricity transmission grid as follows: EU countries (Austria, Belgium plus Luxembourg, Bulgaria, Croatia, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, Greece plus Cyprus, Hungary, Ireland, Italy plus Malta, Lithuania, Latvia, the Netherlands, Poland, Portugal, Romania, Sweden, Slovenia, Slovakia, the United Kingdom) and Non-EU countries (Switzerland, Norway).

Table 4. Regions considered in MEESA model and respective codes

Country	Code	Country	Code
Austria	**AUT**	Ireland	**IRL**
Belgium + Luxembourg	**BEL**	Italy + Malta	**ITA**
Bulgaria	**BGR**	Lithuania	**LTU**
Switzerland	**CHE**	Latvia	**LVA**
Czech Republic	**CZE**	the Netherlands	**NLD**
Germany	**DEU**	Norway	**NOR**
Denmark	**DNK**	Poland	**POL**
Estonia	**EST**	Portugal	**PRT**
Spain	**ESP**	Romania	**ROM**
Finland	**FIN**	Sweden	**SWE**
France	**FRA**	Slovenia	**SVN**
Greece + Cyprus	**GRC**	Slovakia	**SVK**
Croatia	**HRV**	United Kingdom	**GBR**
Hungary	**HUN**		

Source: CAKE/KOBiZE own study

4. Scenarios considered in the analysis

34. The study considers four scenarios of future European energy mix based on different assumptions regarding CO_2 emission reduction goals for 2050. All main assumptions – fuel prices, coal phase out plans, rate of decommissioning nuclear power, minimal share of renewable generation remain the same in each scenario:

- **REF – Reference** - No emission reduction goal is set. In this case, the emission reduction is the result of improved technology efficiency, the assumed minimum level of renewable and domestic polices of coal phase-out. It results in an emission reduction level being around 60%.
- **BAU - Business As Usual** - 80% reduction in CO_2 emissions in 2050 compared to 2015. Other assumptions identical to the REF scenario.
- **DEEP - Deep Energy Emission Programme** - 95% reduction in CO_2 emissions in 2050 compared to 2015 (over 96% of reduction of 1990 levels - the same level as

in Energy Roadmap 2050[20] for power generation sector). Other assumptions are the same as in the REF scenario.

- **DEEPNN - Deep Energy Emission Reduction Programme with no New Nuclear reactors** - in this scenario all assumptions from DEEP are in force except that nuclear energy is no longer an acceptable option. Only reactors currently operated or under construction can reach its lifetime. This scenario analyses the consequences of giving up nuclear power in low carbon future economy of EU countries.

35. The general indicative targets for electricity production by renewable sources were set at 35% in 2020 and 50% in 2030 of final electricity consumption. These minimal levels roughly correspond to respectively 20% and 32% of total RES target in final energy consumption. However, more detailed assumption were necessary for particular countries concerning pace of RES development, taking into account current RES level, available potential and other factors. Eventually, almost all countries reach at least RES targets of 50% by 2050.

5. Results

36. The results of analyses carried out using the MEESA model, presented in this chapter, are selected for their illustrative value and serve primarily to assess and verify the performance of the proposed model. They are based on the assumptions described in the previous chapters and should be interpreted in close connection with them. This research work aims to identify the essential features of the MEESA model, which determine its usefulness as a tool supporting decision-making processes in the field of energy strategy, in particular in the context of the energy and climate policy in the EU. The wide field of application of the model and its high efficiency as a research tool have been achieved through the flexibility of the software and the practical usability of the developed software for collecting, visualizing data and calculation results. The aim of the analysis is to demonstrate the key features of the model that determine its usefulness in EU energy sector development research.

5.1. Electricity generation

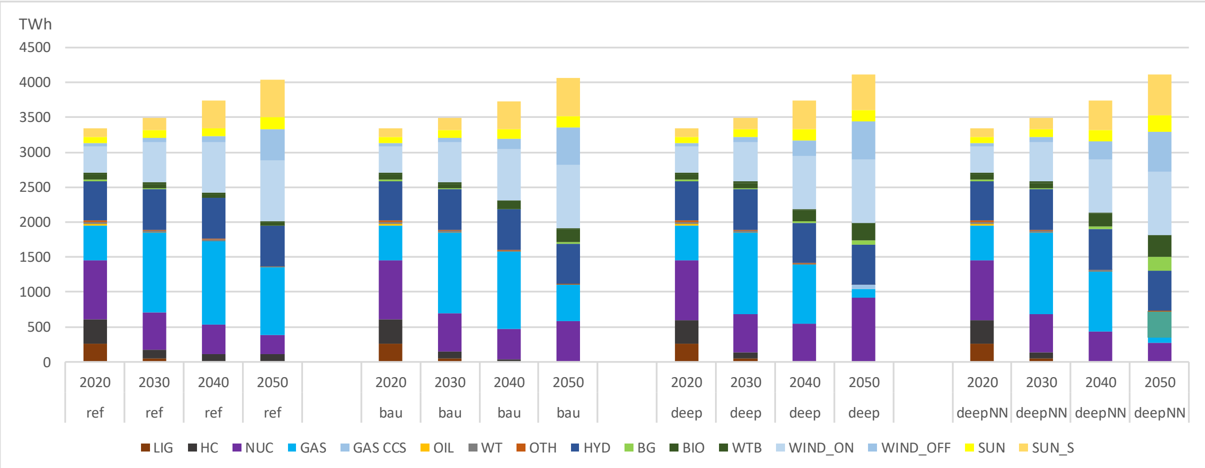
37. The basic functionality of the MEESA model is to optimise the power structure and electricity and district heat generation. As mentioned in the model documentation, MEESA is formulated as a linear programming task. In this case, the optimal solution is determined on the basis of the criterion of minimising the sum of discounted annual costs related to the coverage of a given demand for energy over the whole investigated

[20] European Commission, Energy Roadmap 2050. COM(2011) 885 final., Brussels, 15.12.2011

time horizon. The optimisation process takes into account a number of technical, economic, political and social constraints creating equations and linear inequalities.

38. The determination of the energy mix is the basis for further calculation of the usage of primary fuels, the expected level of emissions from the sector, the costs associated with the implementation of a given scenario and costs of electricity generation. Figure 11 presents the aggregate results of the projection of electricity production in the EU28 + NOR + CHE by fuel, obtained using the MEESA model for all considered scenarios. It should be stressed here that all these scenarios are based on the same projection of final electricity and district heat demand.

Figure 11. Electricity production (in TWh) by energy source for EU-28 + CHE + NOR. [Scenarios REF, BAU, DEEP, DEEPNN]



Source: MEESA model

39. In the studied forecast horizon (2050) one can observe far-reaching changes in the structure of electricity production. This applies to all four scenarios under consideration, the common feature of which is the assumption of deep CO_2 emission reduction in the energy sector and relatively high EUA prices.

40. In each of the considered scenarios, the role of coal is significantly reduced in the perspective of the next ten years. This is the result of the assumption concerning coal phase-out plans in many countries as well as pressure exerted by rising EUA prices and, to a lesser extent, emission reduction assumed in the model. Even in the REF scenario, CO_2 prices are at a level that makes old coal technologies no longer competitive with other generation units, including expensive but emission-free RES or nuclear units. Gas and nuclear units, supported by modern energy storage systems, take over the stabilization role in the system.

41. The decrease in the share of coal in the production structure takes place at the expense of the growing role of RES, which due to rising prices of CO_2 emission allowances and dedicated subsidizing programmes at an early stage, become an economically viable

option. This applies in particular to wind and roof photovoltaics - however, it should be noted that for most countries the RES level achieved are higher than the assumed minimum, resulting from the RES development policy (even in the REF scenario, where it is a consequence of, high EUA prices). In the DEEP scenario RES share exceeds the level of 75% in total electricity generation in the EU.

42. The results show an increase in the role of gas in the energy mix, while in scenarios with assumed deep CO_2 emission reduction, a clear decrease in the importance of this technology is visible after 2040. In scenarios: BAU, DEEP, DEEPNN gas (without CCS) is only a temporary solution. In the initial period of the forecast gas play an important role in the deep emission reduction policy, then it is replaced with emission-free generation units, but remains important as a backup technology.

43. In scenarios with assumed deeper emission reductions – BAU and DEEP - the role of nuclear power is growing. Unless it is possible to significantly reduce the costs of energy storage technology, nuclear power seems to be a promising solution in the context of an ambitious deep emission reduction policy. At the same time, a very important feature that these units must have is high flexibility in terms of electrical load. An increase in the share of combined heat and power plants for biogas and biomass is also visible. Besides, combined heat and power plants for biogas and biomass supply "green" heat to district heating networks.

44. In the DEEPNN scenario, if no new nuclear capacity is built, the use of renewable sources is increasing and gas units equipped with CCS are beginning to play an important role. CCS technology, despite high investment cost and a few percent reduction in the efficiency of power units, becomes an option in the DEEP reduction scenario.

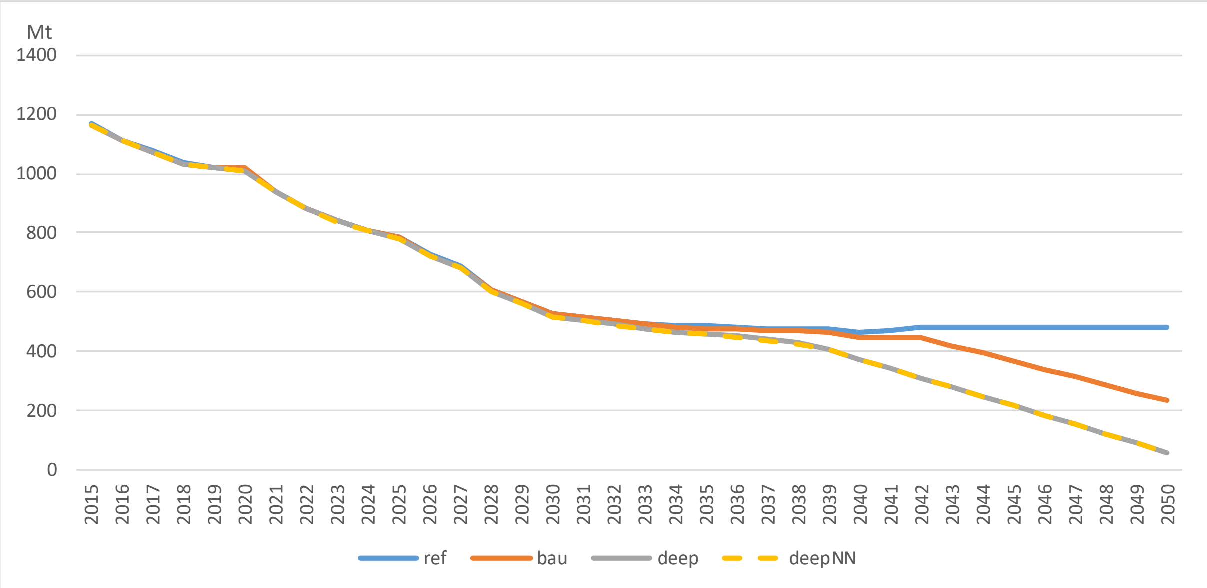
45. Wind and photovoltaic power plants with unstable operation play a key role in all scenarios, so it is important to improve the flexibility of the system to ensure a sustainable ability to balance electricity supply and demand over different time scales. Cost-effective and technically reliable integration of RES becomes an urgent need and strategic challenge. The implementation of these scenarios entails increased flexibility for power plants, transmission and distribution, consumers and storage.

5.2. CO_2 emissions

46. A very important element of the scenarios constructed using the MEESA model are carbon dioxide emission projections. They enable quantification and graphical presentation of the emission values corresponding to the structure of electricity and heat production determined through optimisation. Such result data are crucial in the analysis of the effects of implementing the energy and climate policy, especially in the context of the analysis of the balance of allowances in the EU ETS. The amount of reduction in the

BAU, DEEP and DEEPNN scenarios was defined from above in the case under consideration, hence the obtained results are a consequence of this assumption. Figure 12 shows cumulative emissions from the EU28 + CHE + NOR.

Figure 12. CO_2 emissions from electricity and district heat production in EU-28 + CHE + NOR [Mt]



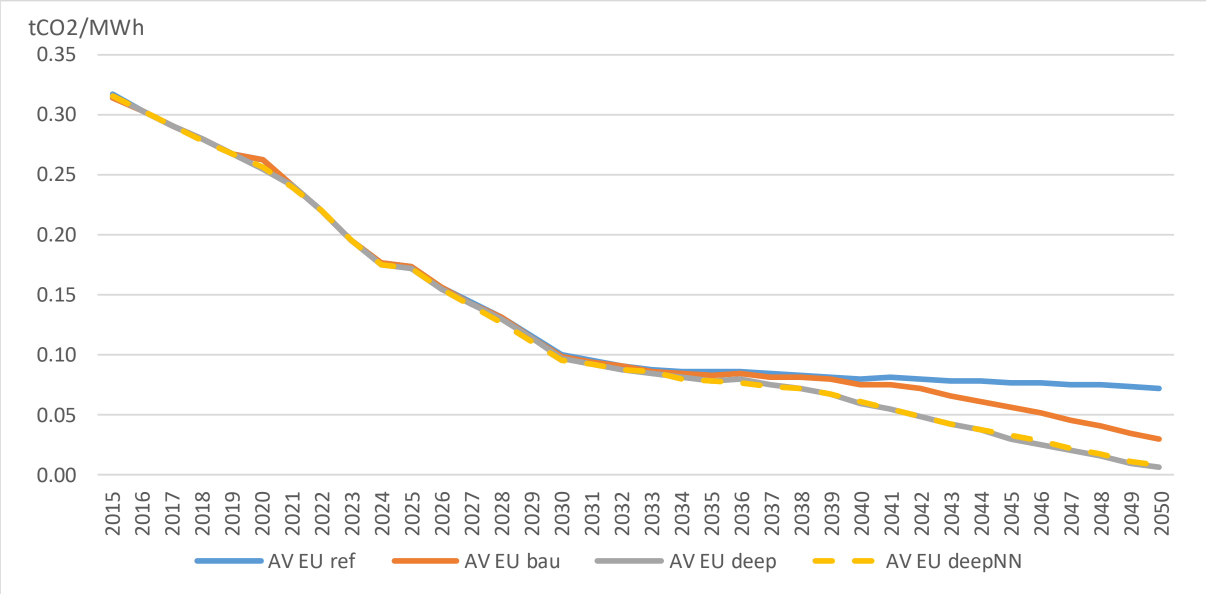
Source: MEESA model

47. CO_2 reduction levels for each scenario are as follows:

- **REF** - a decrease in emissions by ca. 60% as compared to 2015. It is worth to notice that this scenario does not force any reduction, but the EUA prices, RES development policy and the schedule for decommissioning coal-fired units result in a significant reduction in CO_2 emissions
- **BAU** - an 80% reduction by 2050 in the energy sector's carbon dioxide emissions compared to 2015, which is based on the initial assumption of the reduction
- **DEEP and DEEPNN** – forced reductions in the power generation sector by 95% as compared to 2015.

48. The initial fast pace of reduction is mainly due to national policies related to coal withdrawal and RES development. The impact of EUA prices in this period is smaller, what can be clearly seen from the decrease of pace of emission reduction between 2030 and 2040 (and in the Reference scenario till the 2050 r.). Forcing further reductions in BAU, DEEP, DEEPNN scenarios results in a resumption of the pace of emission reductions after 2040.

Figure 13. CO_2 average electricity production emission factor in EU-28 + CHE + NOR [t CO_2/MWh]



Source: MEESA model

49. The changes in the average CO_2 emission benchmark for electricity generation are strongly correlated with the changes in emissions in the whole sector:

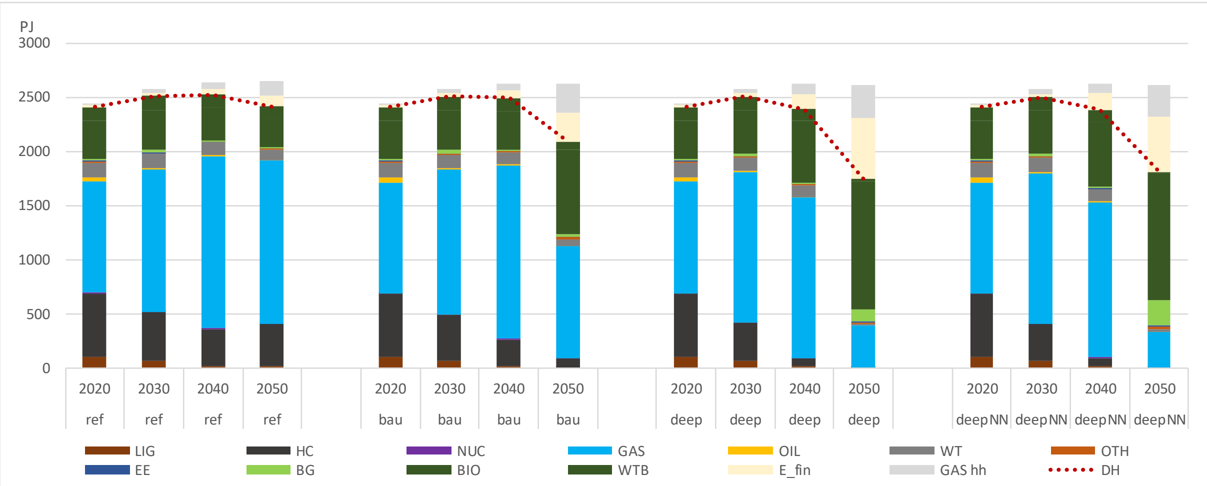
- The evolution of changes in the emissivity index for DEEP and DEEPNN scenarios is similar, but the final value of this index for the DEEPNN scenario is slightly higher (higher emissivity of production). This means that it is possible to achieve a 95% reduction in CO_2 emissions in the power sector without nuclear power, but this may involve higher costs. It becomes necessary to use carbon dioxide capture technology to obtain such reduction.
- In all scenarios there is a noticeable decrease of share of CO_2 emissions from electricity production, while the share of emissions from district heat production is growing (especially if district heating can't be replaced by individual heating systems – heat pumps or electric heaters). This suggests that reduction potential is higher in the electricity generation sector than in the district heating sector.
- The marginal costs of CO_2 emission increase significantly in all scenarios with forced emission reduction – it reaches about 100 EUR/t CO_2 in BAU scenario, more than 300 EUR/t CO_2 in DEEP and over 500 EUR/t CO_2 in DEEPNN scenario. That marginal costs cannot be considered reliable forecasts of EU ETS prices since there are technical and financial solutions in real life not taken into account in the model. Nevertheless, these results show the importance of nuclear power in emission reduction effort, as well as fact that reduction potential in conventional technologies are limited and availability of new technologies as battery energy storage, power-

to-x and demand response might be crucial in achieving reduction goals. Such technologies will be implemented in the next version of MEESA model to further investigate the problem. The other reason for observed high marginal emission costs may be related to the fact that the model covers only the energy sector without industry, which could limit technical and structural capabilities for shifting toward low emission options.

5.3. District heat generation

50. The MEESA model also optimizes commercial heat generation units. These units include commercial and industrial CHP plants as well as district heating plants. The model makes it possible to analyse the development of these units and their impact on the power sector. It also allows the estimation of emissions from this sub-sector. The results obtained for commercial heat production in all investigated scenarios are presented below in a graphical form.

Figure 14. District heat production (in PJ) by energy source for EU-28 + CHE + NOR. Scenarios REF, BAU, DEEP, DEEPNN



Source: MEESA model

51. The graphs presented above show that gas and biomass-based technologies will play a decisive role in the reduction of CO_2 emissions in district heat production in the future. The use of electricity for space heating (heat pumps and electric heaters) and biogas can also play an important role. As biomass resources are limited and European countries do not have sufficient natural gas resources (therefore they are largely dependent on imports from third countries), solutions to reduce heat consumption in buildings and the use of individual emission-free heating systems (heat pumps, solar panels, geothermal energy) are becoming increasingly important. On the other hand, these are currently one

of the most expensive heating options and cannot always be successfully applied in all countries. Reducing CO_2 emissions from district heating is probably to be one of the biggest challenges, especially in the colder countries of northern and central-eastern Europe.

52. In the REF and BAU scenarios, natural gas plays a dominant role in heat generation, while in the deep reduction scenarios (DEEP and DEEPNN), the role of gas after 2040 is clearly diminishing. The role of biomass fuels and biogas is growing.

53. While in electricity generation, even in the REF scenario, coal fuels are quickly reduced, in the heating sector without additional reduction pressure, hard coal remains an important fuel. In other scenarios, coal is gradually replaced by sources with lower emissions.

54. In the analysis, individual heating technologies were modelled to capture the potential effect of a reduction in the demand for district heat due to customers switching to heat coming from individual sources - heat pumps, electric heaters and small gas boilers (in Figure 14 the total demand for district heat is shown by red dotted line). It is clearly noticeable that the deeper the scenario of emission reduction is, the greater the shift of heat generation from the heating sector to individual sources.

55. In deep emission reduction scenarios, the use of electricity for heating (heat pumps and electric heaters) becomes one of the preferred options. This results in a shift in energy production within the EU ETS - a reduction in district heat production while at the same time increasing electricity production for heating purposes.

56. The second effect that may occur is the possibility of consumers switching to individual heating installations based on fossil fuels (this analysis assumes that it will be mainly natural gas, as coal sources will be covered by national programs to reduce other pollutants and will be gradually phased out). In such case, emissions related to heat production will "leak" from the EU ETS and will have to be covered by reduction schemes outside the EU ETS (this analysis does not assume any additional charges related to emissions outside the EU ETS).

57. The two effects of reducing the demand for district heating described above by switching to individual heating systems require further analysis. Due to the efficiency limitations of the model, it was not possible to estimate the scale of this effect in detail in the current analyses. In the considered case, it was only about the qualitative assessment of the possibility of occurrence of such effects (the analysis assumed simplistic assumptions that the maximum level of district heat substitution for individual

countries may amount to 30%[21] for heat pumps and 15% for gas sources, respectively). However, this analysis has shown that with deep reductions, such effects are very likely to occur in many countries, but the estimation of their scale requires a detailed analysis of individual district heating systems at the city level (the national level is insufficient).

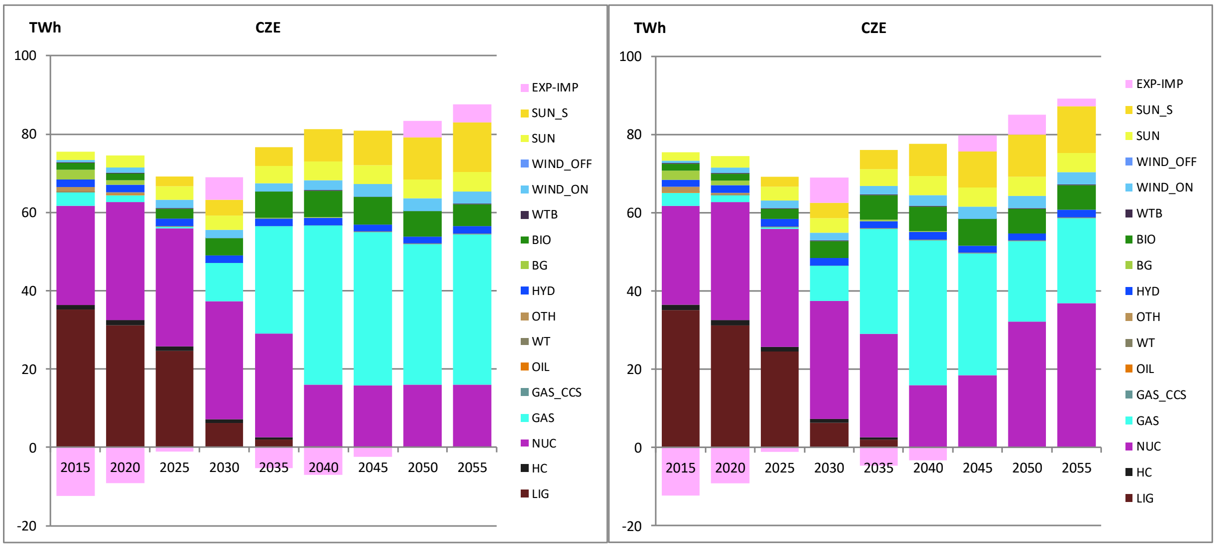
58. It is worth to notice that the possibility of shifting generation from the heating system to electricity generation (or individual sources) may have a significant impact on the marginal costs of CO_2 emission reduction.

5.4. Results for selected countries

59. This section presents the results of the projection for selected countries, including Poland. Among them there are three countries with whom Poland may conduct cross-border trade (Czech Republic, Germany, Sweden). Other countries for which more detailed analysis results have been presented are Denmark, Spain and France.

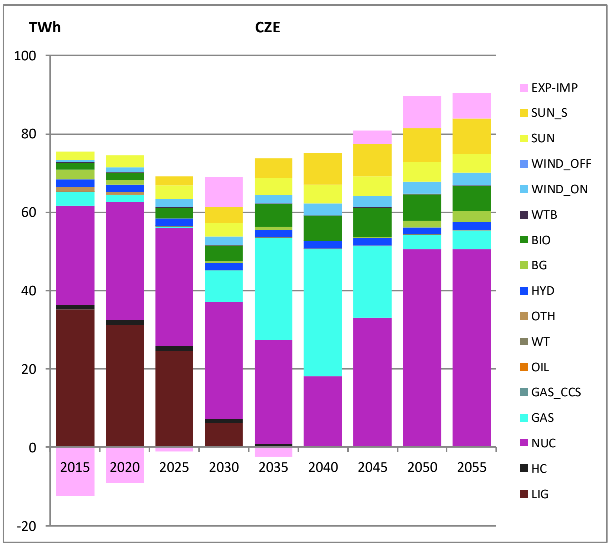
Figure 15. Electricity production (in TWh) by energy source for Czech Republic [Scenarios]:

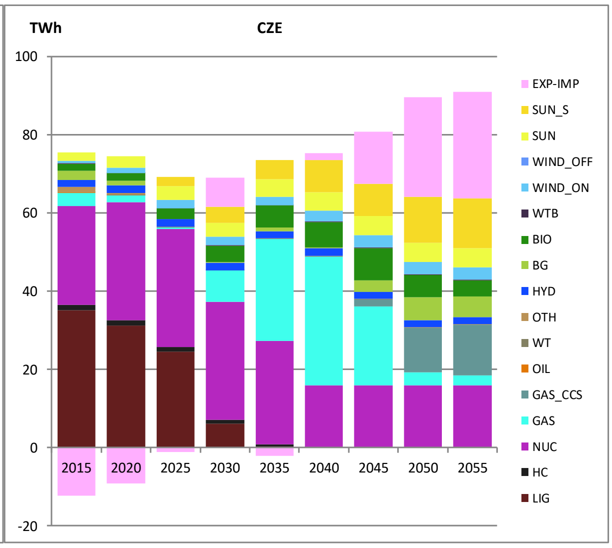
REF **BAU**



[21] Paardekooper, S., Lund, R. S., Mathiesen, B. V., Chang, M., Petersen, U. R., Grundahl, L., . Persson, U. (2018). Heat Roadmap Europe 4: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. Aalborg Universitetsforlag.

DEEP **DEEPNN**





Source: MEESA model

60. The structure of electricity generation in Czech Republic is characterized by a high share of lignite, therefore the biggest challenge for this country in the context of energy and climate policy will be a gradual reduction of this high-emission fuel use. The scenarios considered in this analysis show different options of deep emission reduction of the power sector in this country.

61. In the REF and BAU scenarios, natural gas will play a key role in the deep emission reduction process, while in the latter scenario, the share of gas increases significantly in the perspective of 2040, and then begins to decline, as a result of further CO_2 emission reductions assumed in the forecast. The key issue for this country is to ensure an adequate level of gas supplies and adequate development of the gas transmission infrastructure.

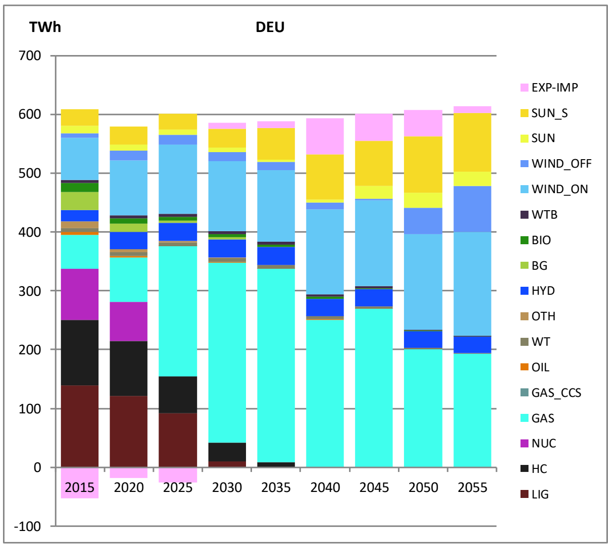
62. In scenarios assuming deep emission reduction of the electricity sector (DEEP and DEEPNN), gas is only a temporary solution. Nuclear power plays an important role in the DEEP scenario. The limited RES potential in the DEEPNN scenario results in significant imports of electricity, which indicates that the development of nuclear power in Czech Republic is a deeply justified option in the view of deep reductions, enabling the provision of secure and cost-effective energy supplies without the need to expand the gas infrastructure.

63. In the DEEPNN scenario gas-fired power plants with CCS installations appear in the electricity production structure, but high costs and potential difficulties in transporting and storing captured CO_2 can in fact be a serious obstacle and should not be the preferred option.

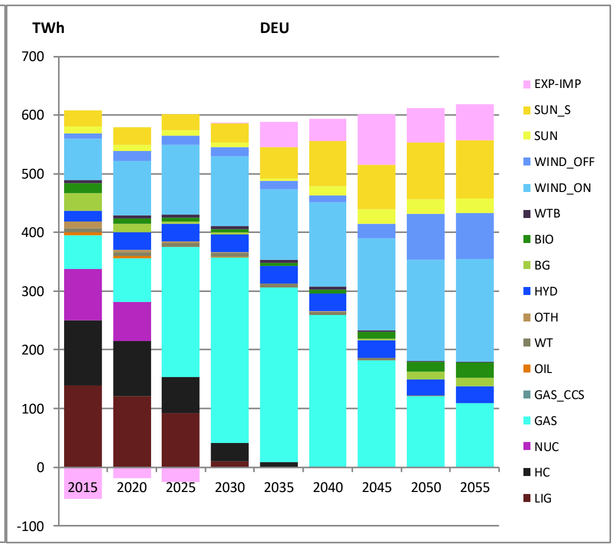
64. Due to difficulties in reducing emissions from heat, the consumption of electricity is increasing, as a result of customers switching to electric heating and the increasing use of heat pumps.

Figure 16. Electricity production (in TWh) by energy source for Germany [Scenarios]:

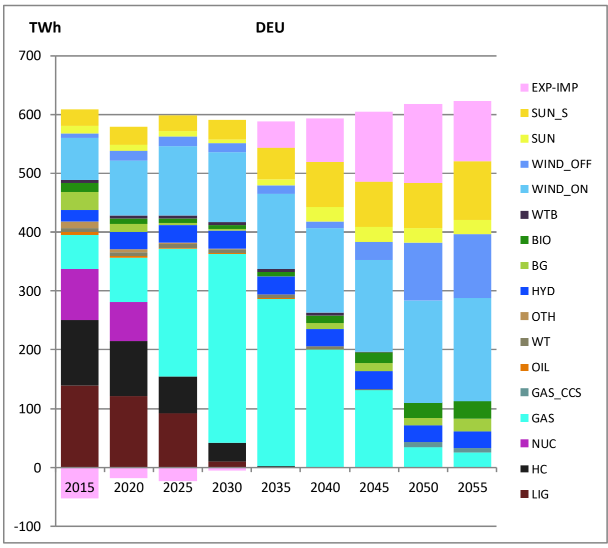
REF



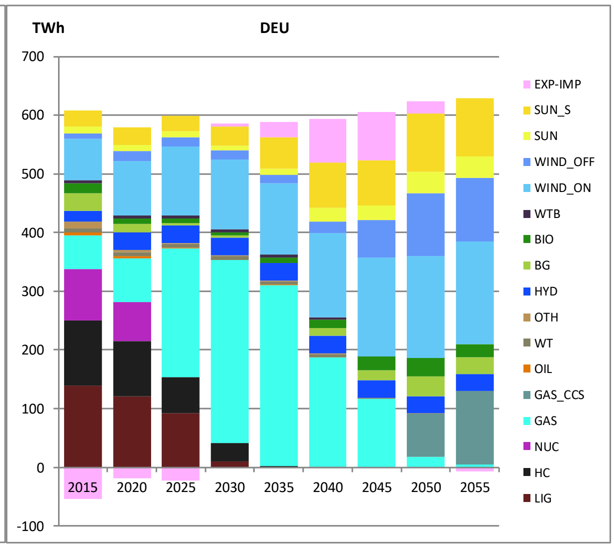
BAU



DEEP



DEEPNN



Source: MEESA model

65. Germany is another country with a relatively high share of coal in the structure of electricity generation, despite the declared a few years ago departure from this fuel. Despite dynamic development of RES in this country (mainly in onshore wind power plants, and in recent years also in photovoltaics), it has not been possible to significantly

reduce emissions from the power sector, although it is to be expected that the directions set in this respect will continue in the future. Renewable energy sources are heavily subsidized in Germany and there is still a strong public support for such measures. Therefore, the continuation of the policy in this area will result in a gradual increase in the share of renewable energy sources.

66. All scenarios considered in the analysis assume further development of wind energy and photovoltaics. The use of biomass and biogas is also increasing.

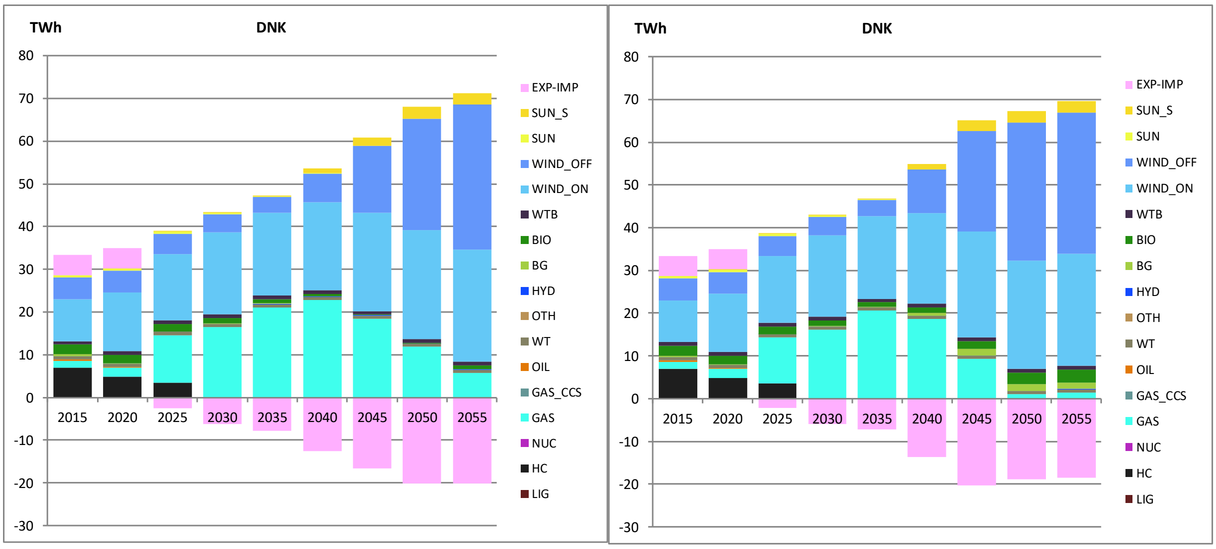
67. Gas is a fuel that will replace hard coal and lignite especially in the initial period. Measures to expand the transmission infrastructure and ensure safe supplies of this energy resource have been taken for some time now.

68. The declared exit from the atom in 2022 and coal by 2038 is likely to result in Germany becoming a net importer of electricity from its current position as a net exporter. From the perspective of energy balance, deep emission reduction and related costs, the phasing out of nuclear power seems unreasonable.

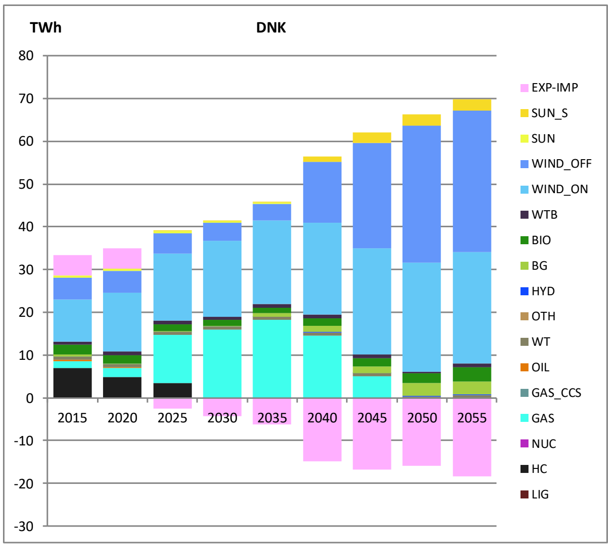
69. Although Germany plans to phase out nuclear capacity, the availability of nuclear power in other countries has a significant impact on the structure of production in Germany. In the scenario with the possibility to build new nuclear capacity, Germany imports significant amounts of energy (mainly from France), whereas in the no-nuclear scenario import energy is more difficult to access and more expensive and CCS gas production is starting to play a significant role.

Figure 17. Electricity production (in TWh) by energy source for Denmark [Scenarios]:

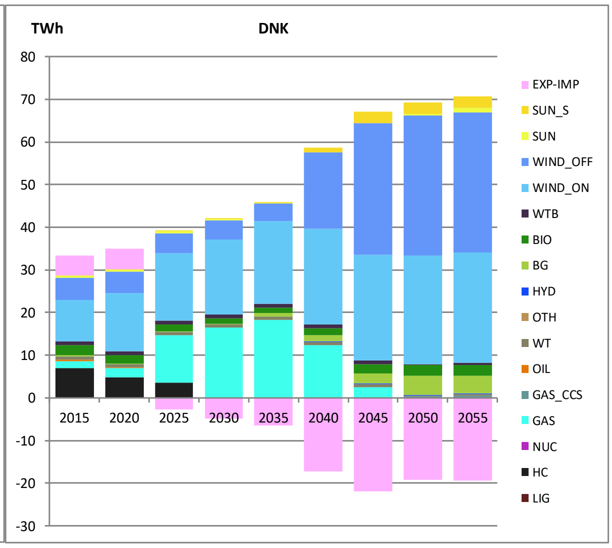
REF **BAU**



DEEP



DEEPNN

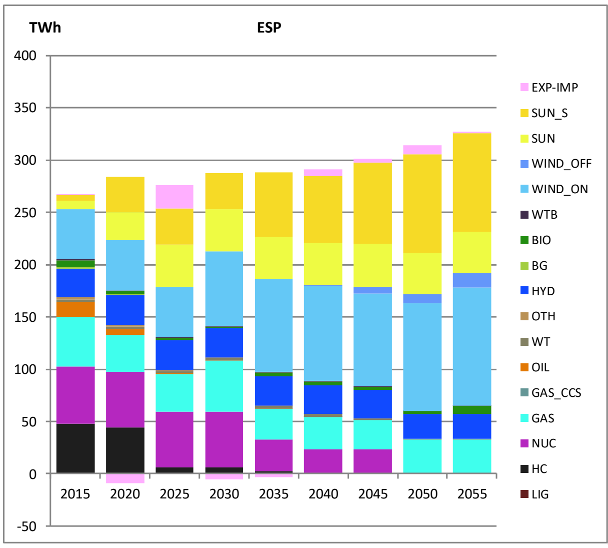


Source: MEESA model

70. Denmark is the country where renewable energy sources dominate in the generation structure, including mainly onshore and offshore wind power. Denmark has very good conditions to develop wind power technologies, so it is somewhat natural direction.
71. A significant increase in electricity production in this country is expected in the time horizon under consideration, resulting from growing demand as well as the level of energy exports.
72. Regardless of the scenario, the country becomes a major exporter of electricity due to the developed potential in the wind. In the DEEPNN scenario, energy exports are much larger - indicating difficulties in generating electricity in other countries' systems.

Figure 18. Electricity production (in TWh) by energy source for Spain [Scenarios]:

REF



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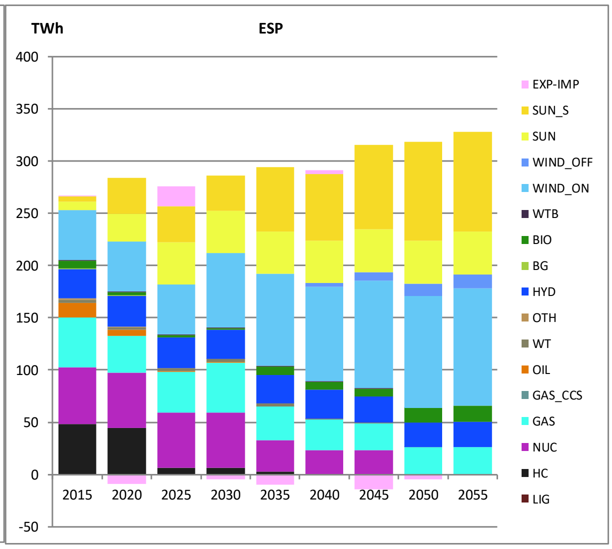
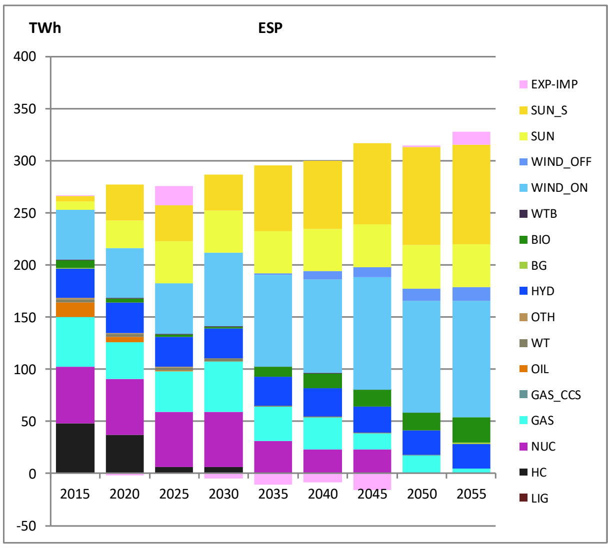
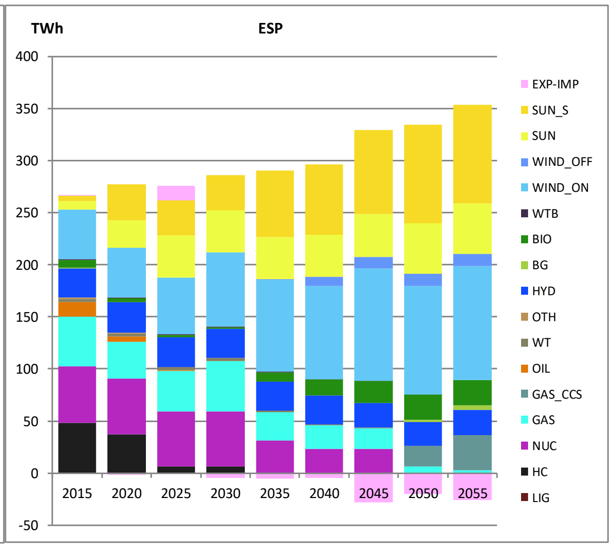


DEEP



DEEPNN



Source: MEESA model

73. Spain is a country with a largely diversified electricity generation structure. It has an almost model energy mix, but the deep emission reduction policy will require the decommissioning of units based on coal and oil in the forthcoming future. The results of analyses show that it is possible to achieve this within the next 10 years. In each of the scenarios considered, these units disappear completely after 2030.

74. However, a rapid phase-out of hard coal may make the country an electricity importer for a decade or so in the period around 2020. After this period, thanks to the development of both PV and onshore wind after 2040, it has a chance to become an

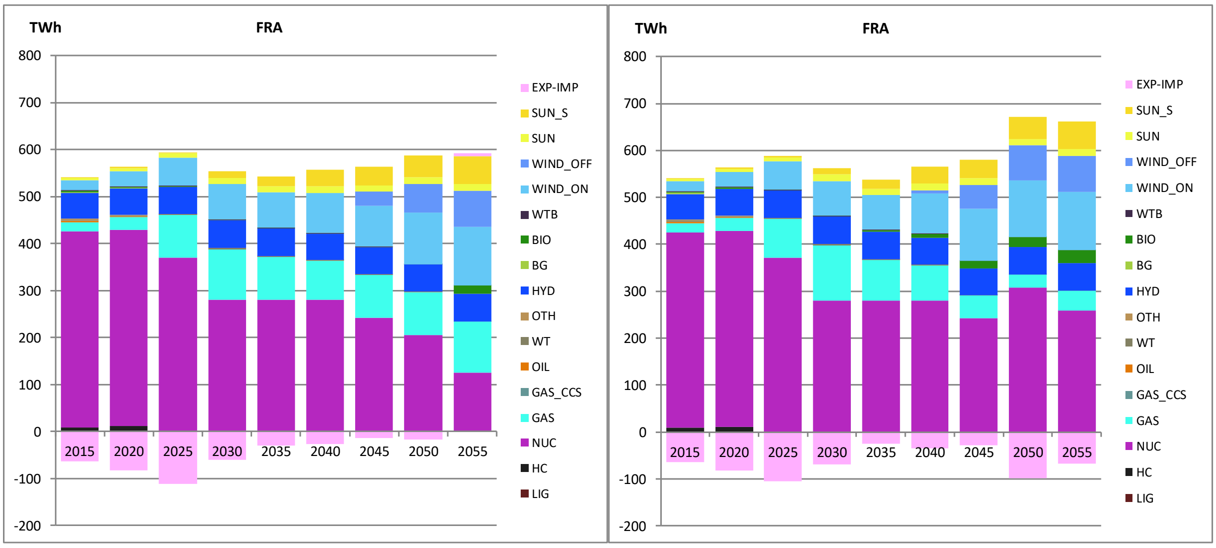
exporter of energy until nuclear power is completely abandoned (if a decision is made in this respect).

75. The departure from coal and in the long term even from nuclear power is possible because Spain has very good conditions for the development of photovoltaics and wind energy. In this context, the issues of system flexibility will be of great importance. These changes will require system operators to adopt a new approach to ensure the security and reliability of energy supply. In particular, the demand for highly flexible resources (gas units, energy storage, DSR services) will increase. One of the main elements of flexibility is also the transmission and distribution networks, which enable spatial sharing of flexibility resources. Energy transmission compensates for temporary or structural shortages of electricity at the local level.

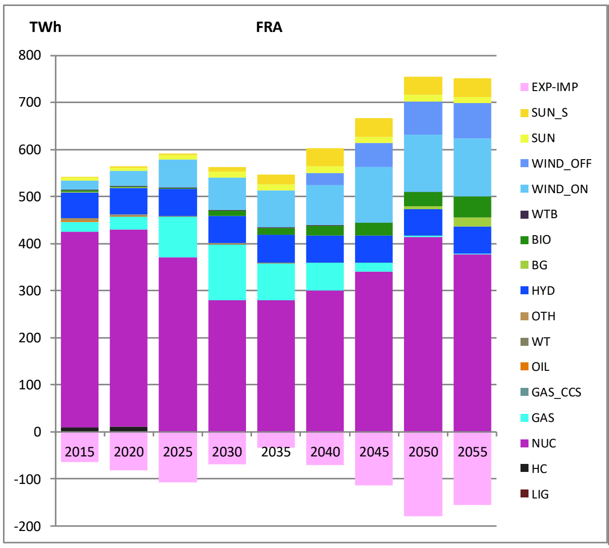
76. In the DEEPNN scenario, high electricity prices on the neighboring markets increase the profitability of exports. In this scenario, significant amounts of energy are generated from biomass and biogas power plants as well as from gas-fired, CCS-equipped power plants.

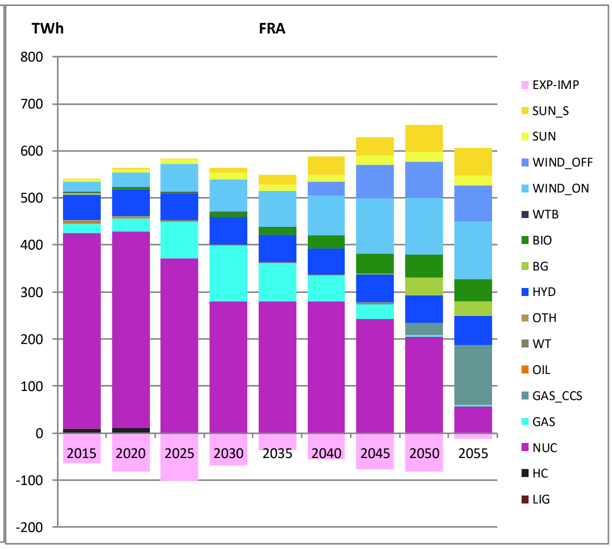
Figure 19. Electricity production (in TWh) by energy source for France [Scenarios]:

REF **BAU**



DEEP **DEEPNN**





Source: MEESA model

77. France is a country with a very significant share of nuclear power in electricity generation (almost 75%). The nuclear power plants operating in France, most of which are long-depreciated, supply consumers with electricity at one of the lowest costs in Europe. Therefore, France has been the largest exporter of energy in Europe for many years. The main export direction is, of course, Germany. The challenge for France is to modernise these units (most of them were designed for 40 years and were built in the 1970's and 1980's) and diversify generation sources towards greater use of renewable sources.

78. The basic RES technology that can be successfully developed in France is wind energy (both onshore and offshore). It is also possible to introduce to the energy balance large amounts of electricity coming from photovoltaics and in a lesser degree from biomass.

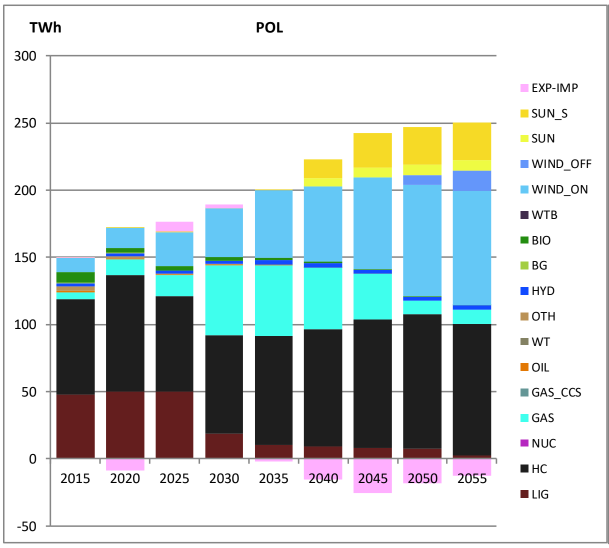
79. As in other countries, an increase in energy from unstable RES sources will make it necessary to make the system more flexible, which may not be an easy task given the flexibility of most existing nuclear power plants.

80. The results of the analyses indicate that further reliance on nuclear power will help France to maintain its position as the largest exporter of electricity in Europe. In the scenarios under consideration, the more energy is produced in these units, the higher is the export.

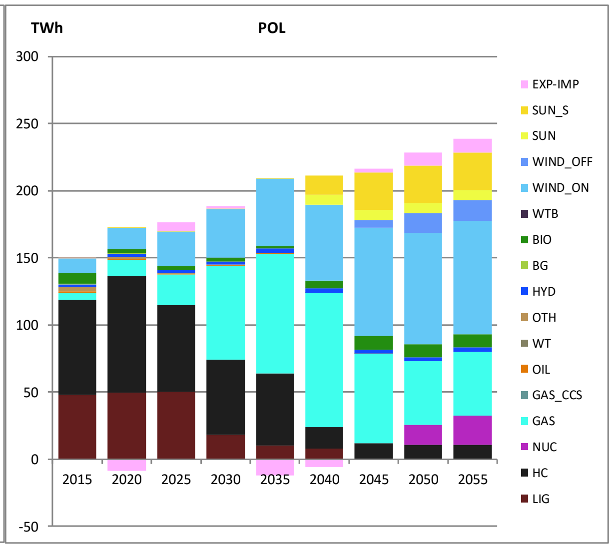
81. Without new investments in nuclear power plants electricity export is significantly lower than in scenarios with dynamic growth of nuclear power (especially DEEP scenario). This effect alone shows the importance of nuclear energy in achieving climate goals.

Figure 20. Electricity production (in TWh) by energy source for Poland [Scenarios]:

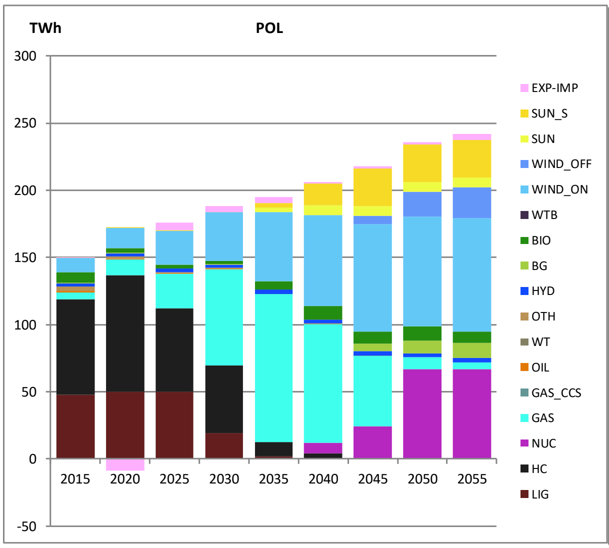
REF



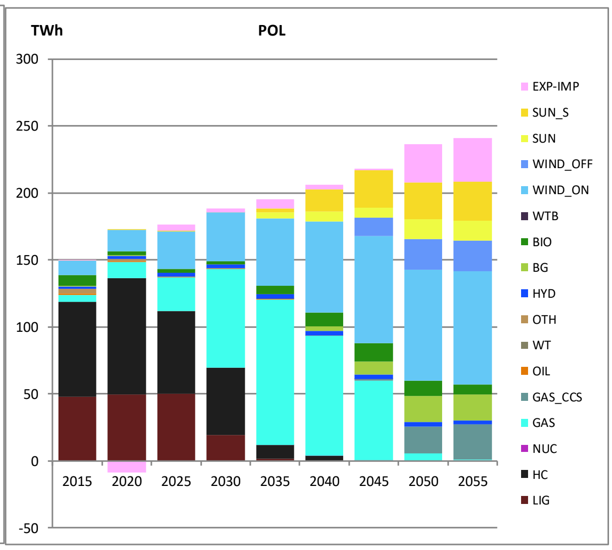
BAU



DEEP



DEEPNN



Source: MEESA model

82. Results of the electricity generation structure for Poland differ significantly from scenario to scenario, showing the possible directions of development of the electricity sector in the long term, in the light of the deep emission reduction paths under consideration. Due to the high share of coal fuels, Poland is one of the European countries in which the energy and climate policy will significantly influence the shape of the energy mix. Reduction of carbon dioxide emissions by 80-95% in the perspective of 2050 means a huge and costly challenge for this country. Today, almost 80% of electricity production comes from coal. Moreover, a further increase in demand for electricity is expected, as

Poland has one of the lowest electricity consumption indices per capita in Europe and is a country that is still developing economically.

83. The results of the analysis of Poland’s power sector indicate gradual and far-reaching changes that will take place in the structure of electricity production, resulting from the conditions determined by the EU climate and energy policy. The administratively enforced development of renewable energy sources and growing prices of CO_2 emission allowances in the EU ETS system will cause a gradual decrease in the share of power plants based on solid fuels in the structure of electricity production.

84. Only in the REF scenario, the share of coal remains quite significant, although it concerns mainly new hard coal-fired power plants and cogeneration. This is a result of relatively mild assumptions regarding the cost of CO_2 emission for power sector. In the other scenarios, there is a significant decrease in electricity production in coal-fired units (in DEEP and DEEPNN scenarios, coal disappear almost utterly after 2040).

85. In all scenarios, after 2030, lignite production is very low (in DEEP and DEEPNN even disappears completely after 2040) due to high CO_2 emission charges and to a lesser extent due to depletion of previously exploited resources.

86. The first nuclear power plant in Poland appears in the BAU scenario only after 2045. In the DEEP scenario, the pace and scale of nuclear power development is significantly higher. Energy exports are also higher. As mentioned earlier in the deep reduction scenarios, coal-fired power generation is uncompetitive and therefore disappears completely from the structure.

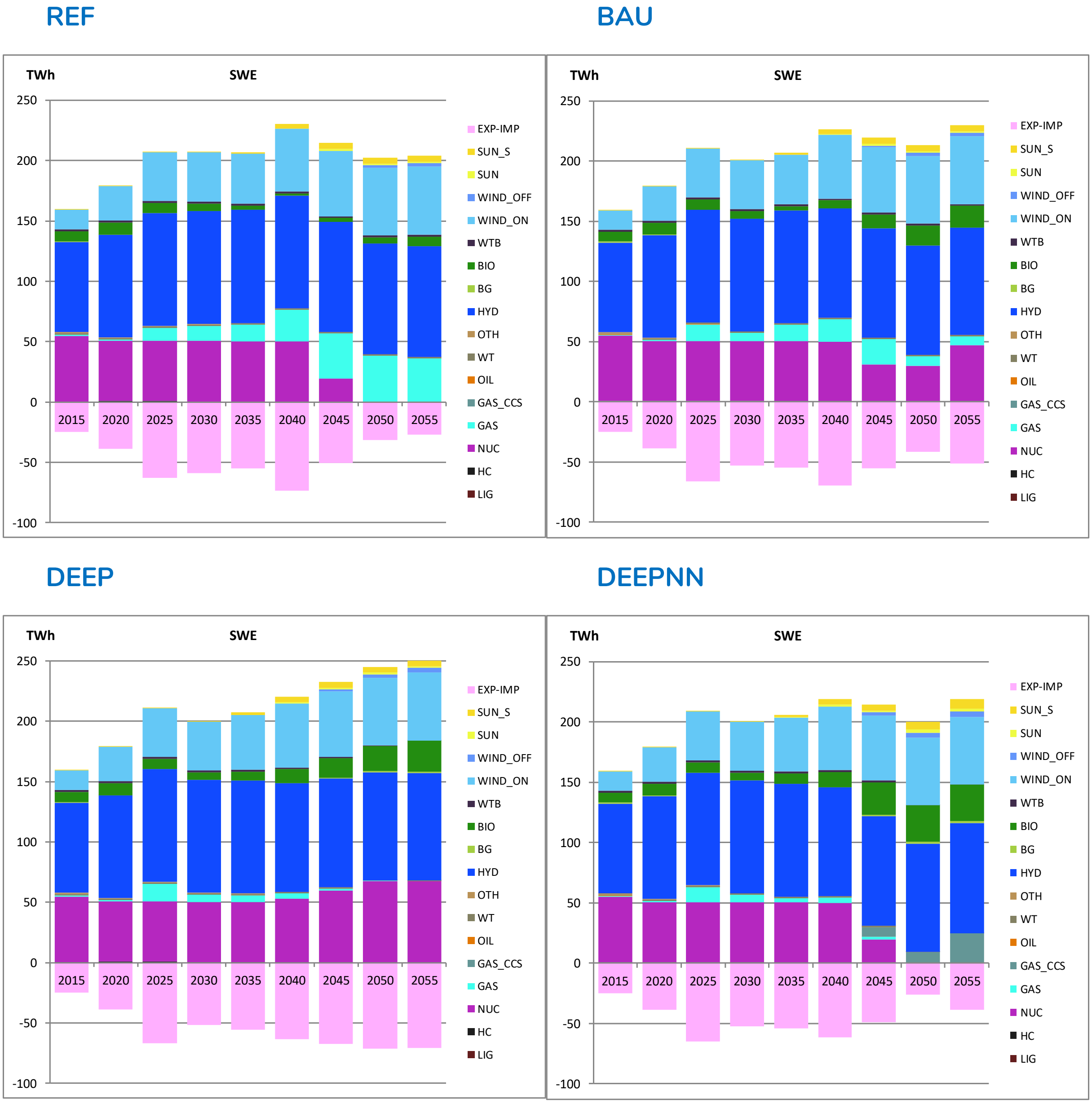
87. In the deep reduction scenarios, the share of renewable energy - especially wind, photovoltaics and biogas - is significantly higher. This effect is even more clear in the DEEPNN scenario. The relatively low use of biomass for electricity generation in these scenarios occurs because to a large extent it’s potential is used for district heat generation.

88. In the DEEPNN scenario, the lack of nuclear power in the generation structure is compensated by the production from the units based on natural gas (with all new large gas-fired power plants after 2048 being CCS units) and with increased energy imports.

89. All scenarios considered indicate that natural gas will be a transitional fuel. It will play a key role in the first phase of deep emission reduction and will be progressively replaced by carbon-free technologies thereafter.

90. Increasing the share of gas has a negative impact on the rate of energy self-sufficiency, increasing the country's dependence on expensive imports of this carrier. This is one of the most unequivocal negative effects of energy and climate policy.

Figure 21. Electricity production (in TWh) by energy source for Sweden [Scenarios]:



Source: MEESA model

91. Sweden is a country with a high share of hydro and nuclear power in electricity generation. Thanks to this, the cost of electricity generation is one of the lowest in Europe. Sweden also has very good conditions for wind energy development.

92. Due to hydrological and wind conditions, regardless of the scenario, the country remains an exporter of electricity throughout the analysis period.

93. The results of the analyses indicate that the phasing out of nuclear power will entail the need to introduce gas into the energy mix. This process will increase the costs of electricity generation and consequently prices on the wholesale market, which may

reduce the competitiveness of this product and partially reduce exports (as can be seen in the REF and DEEPNN scenarios).

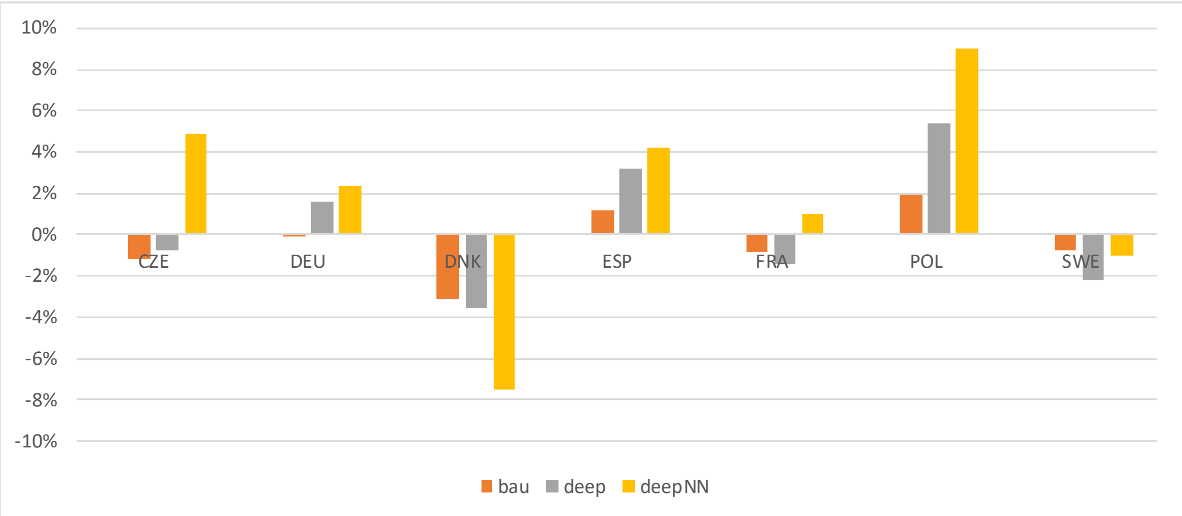
94. In scenarios with a higher share of nuclear power, Sweden is increasing its export volumes to neighboring countries.

5.5. Costs of the energy system

95. The total discounted system costs covering all regions included in the model are higher the deeper the assumed reduction targets are. The increase in these costs compared to the REF scenario is about 0.10% in BAU, 0.45% in DEEP scenario and 0.70% in DEEPNN scenario. It seems that it is not much, but one must consider that the REF scenario already takes into account a significant part of the policies that have an important impact on emission reductions – coal phase-out and RES requirements. Besides, the current model does not take into account the costs of the capacity of cross-border interconnection expansion and all scenarios have the same assumptions about the increase of cross-border exchange capacity.

96. Moreover, the results are quite similar for all scenarios until 2035, what makes any differences between scenarios less obvious when considered in the entire time horizon. Therefore, it is more useful to compare the increase of costs between scenarios in the period 2035-2055. Within this period, the total cost in relation to the REF scenario is similar in the BAU scenario, but in the DEEP scenario is by about 1% higher and in the DEEPNN scenario is by more than 3% higher. The differences between scenarios are far more significant when analyzed per country.

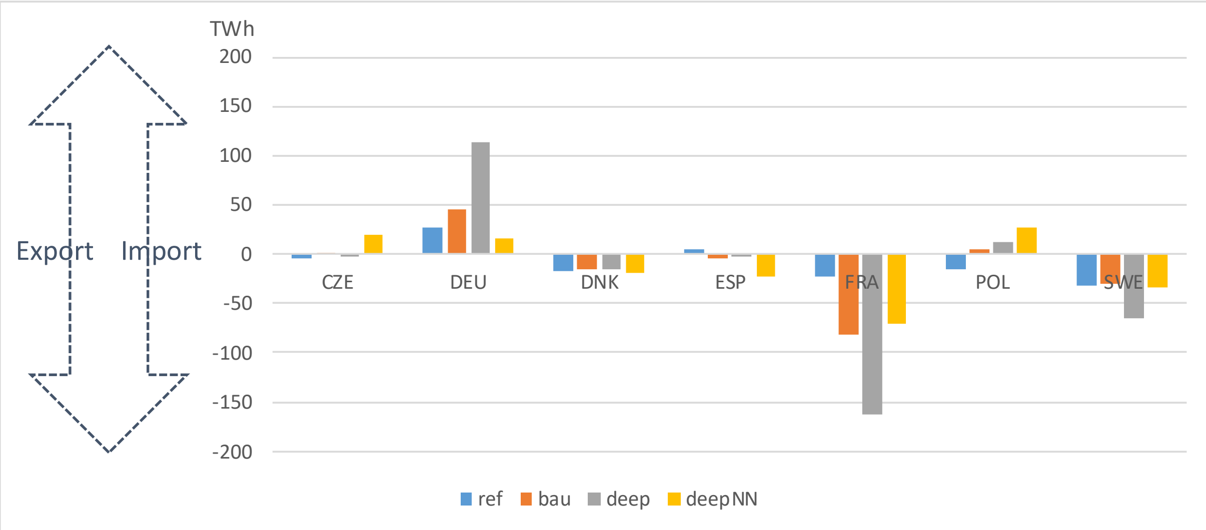
Figure 22. % change in the total cost for BAU, DEEP and DEEPNN scenarios in a relation to REF scenario in selected countries between 2035 to 2055



Source: MEESA model

97. Significantly, the percentage changes in total cost vary from country to country, partly due to the balance of revenues and costs associated with cross-border energy exchanges. Countries with lower RES potential and higher energy import needs are affected by higher cost increases, while countries with excess energy and export capacity may even benefit from these changes (Denmark, France - especially the scenario with new nuclear capacity).

Figure 23. Balance of cross-border exchange in the years 2048-2052 for selected countries in scenarios REF, BAU, DEEP, DEEPNN



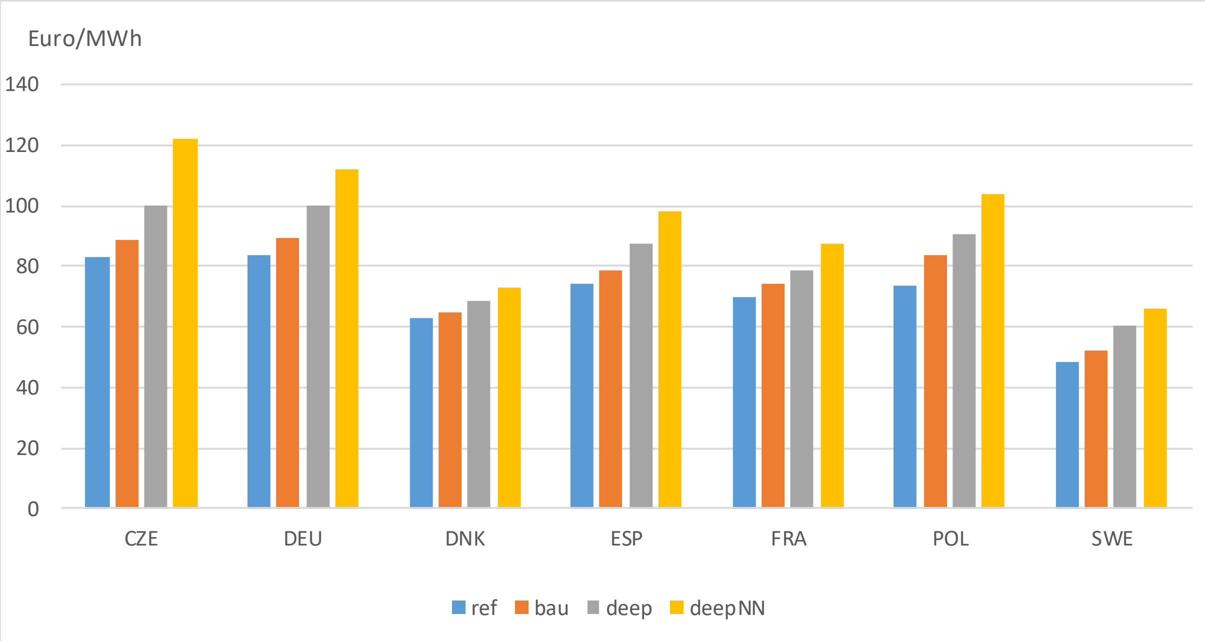
Source: MEESA model

98. The role of electricity cross-border exchange is more important in scenarios with high reduction goals and the availability of new nuclear power. Uneven distribution of nuclear power plants among Europe causes large energy flows from countries with nuclear power to the rest (the best example is energy flow between France and Germany). In scenario without new nuclear power plants (DEEPNN) amount of energy exchange is much smaller.

99. There is also significant energy exchange between countries with large renewable potential (like Sweden or Denmark) to countries with lower capabilities in renewable sources (Czech Republic, Poland).

100. In general, energy exchange in 2050 is about 60% larger in DEEP scenario than in REF scenario – which shows how important the development of electricity connection will be to achieve reduction goals.

Figure 24. Electricity generation costs (cost of import energy included) in 2048-2052 for selected countries in REF, BAU, DEEP, DEEPNN scenarios



Source: CAKE/KOBiZE own calculations based on MEESA model

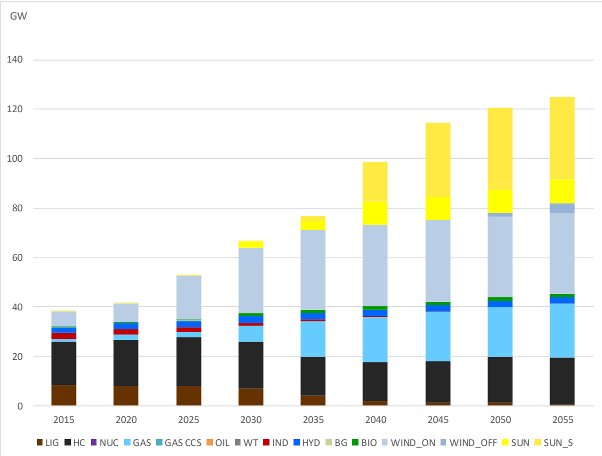
101. For all the countries average electricity generation cost increases in scenarios of more challenging emission reduction targets. The generation cost increase is more significant in the countries with lower potential of zero emission energy sources.

5.6. More detailed results for Poland

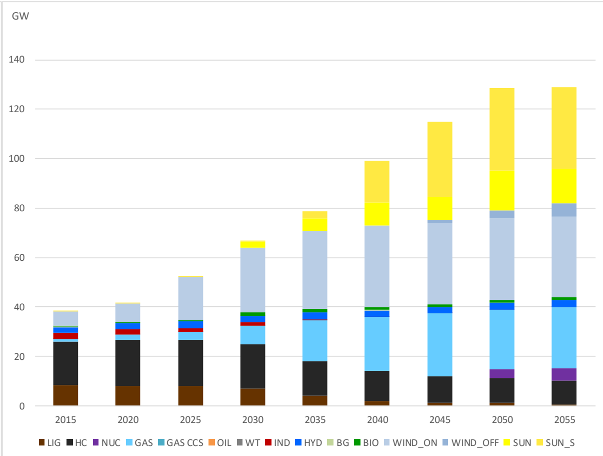
102. This subchapter contains an extension of the scope of information and data with respect to the analyzed paths of development of the power system in Poland. Below the structure of generating capacity for every scenario, related capital expenditures and exemplary daily production diagrams for selected cases were presented.

Figure 25. Generating capacity in Poland [Scenarios]:

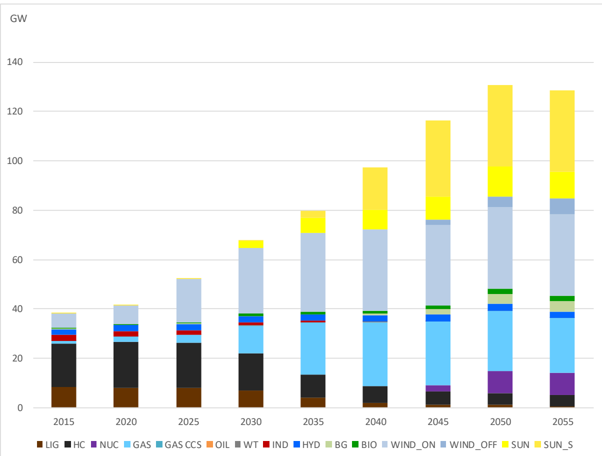
REF



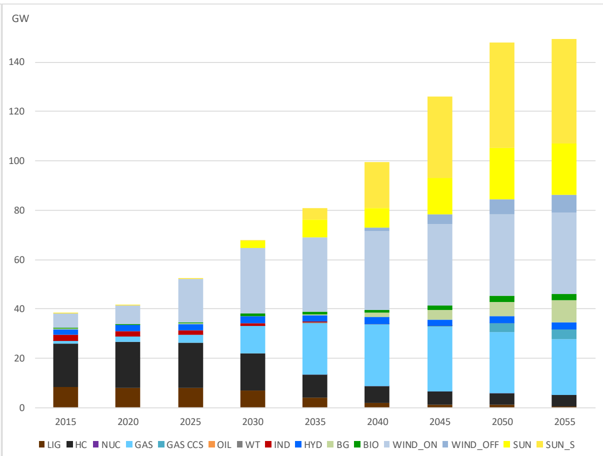
BAU



DEEP



DEEPNN



Source: MEESA model

103. The most important conclusion from the analyses carried out with regard to generation capacity is the pace and scope of the envisaged changes for coal-fired units. The age of these units, the assumed level of CO_2 emission reduction and EUA purchase costs, as well as environmental requirements articulated in the BAT conclusions, will result in a

relatively fast decommissioning of coal-fired power plants and their replacement with emission-free and low-emission sources.

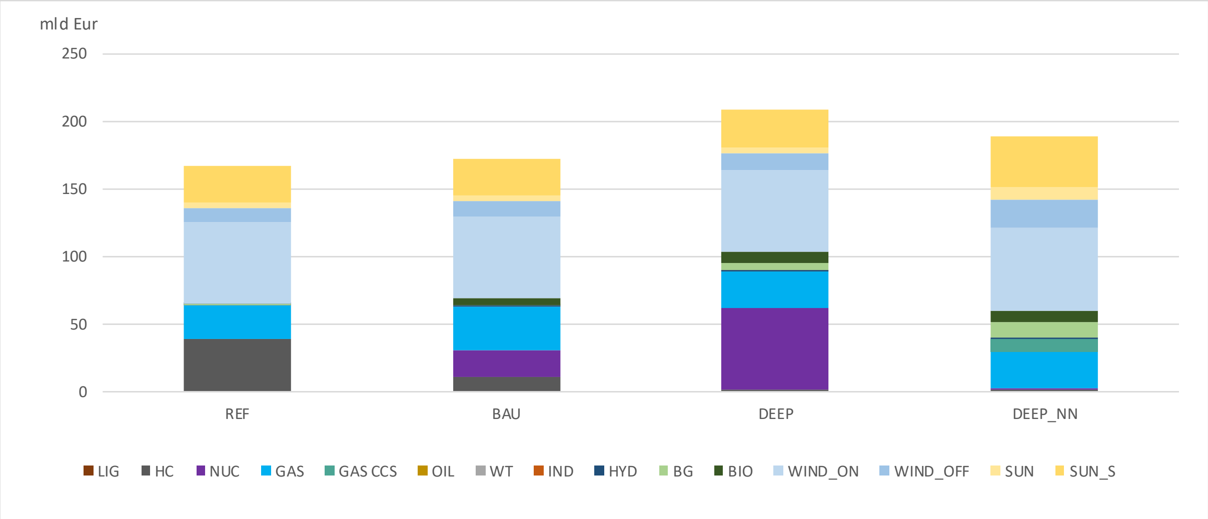
104. In all scenarios, the dynamic development of RES generation capacity (wind and photovoltaic) is a characteristic feature.

105. The rapid increase in capacity in all scenarios is primarily related to renewable sources, both directly (significant capacity with relatively low annual energy production - especially in the case of photovoltaics, but also partially in the case of wind farms) and indirectly - due to the need to reserve wind power - mainly by elastic gas units.

106. Natural gas will play an important role in the process of energy transformation in Poland. It is expected to develop dynamically in combined heat and power plants as well as in units whose main task will be to reserve the capacity of unstable renewable sources. The implementation of nuclear energy may be partly an alternative to gas but in terms of backup capacity gas remains important.

107. The level of installed capacity in the DEEPNN scenario is clearly higher than in the other scenarios due to the need for a higher share of renewables in the generation mix.

Figure 26. Total investment costs for Poland in 2021-2055 for different kind of technology in REF, BAU, DEEP, DEEPNN scenarios in electricity generation sector

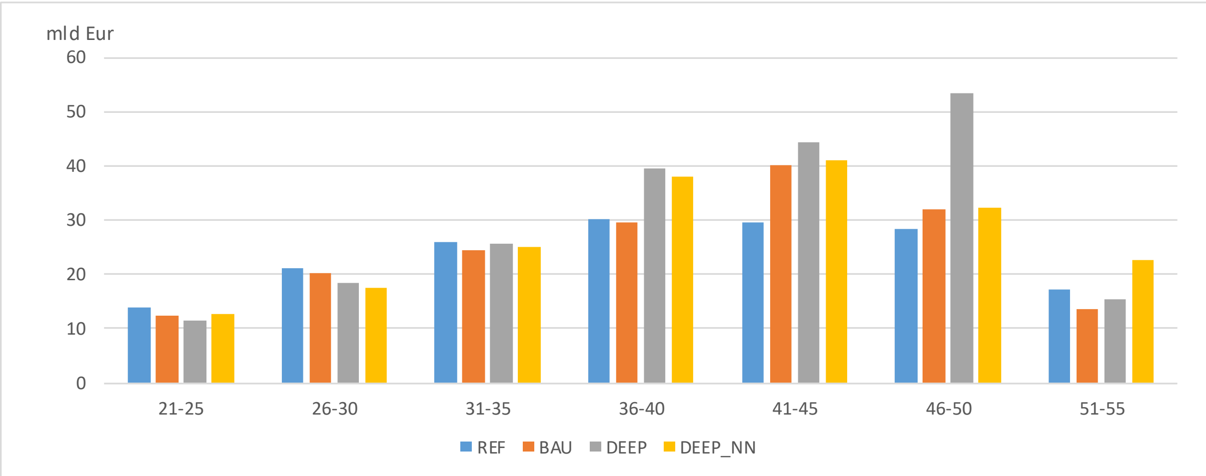


Source: CAKE/KOBiZE own calculations based on MEESA model

108. The total investment cost for Poland in 2021-2055 are highest in DEEP scenario because of the intensive development of a nuclear energy program. Nevertheless, the average cost of electricity generation is lower in DEEP than in DEEPNN scenario, because of long technical life time of nuclear units and moderate levelised costs.

109. In REF, BAU and DEEP scenarios about 60-64% of total investments is related to renewable sources while in DEEPNN scenario it's almost 80% of investments. In DEEP scenario nuclear power plants account for around 29% of investments. The share of conventional investments (coal and gas fired plants) differs from 38% in REF scenario to 14% in DEEP scenario.

Figure 27. Investment costs for Poland in 2021-2055 in REF, BAU, DEEP, DEEPNN scenarios in electricity generation sector

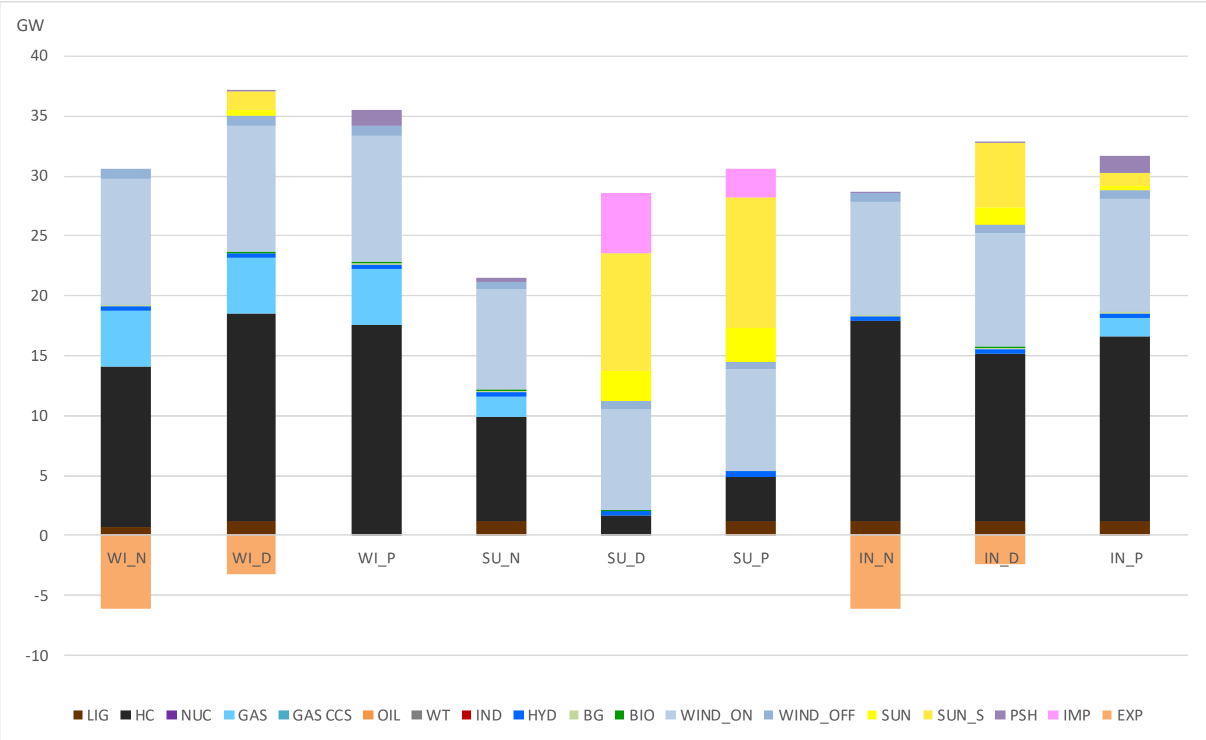


Source: CAKE/KOBiZE own calculations based on MEESA model

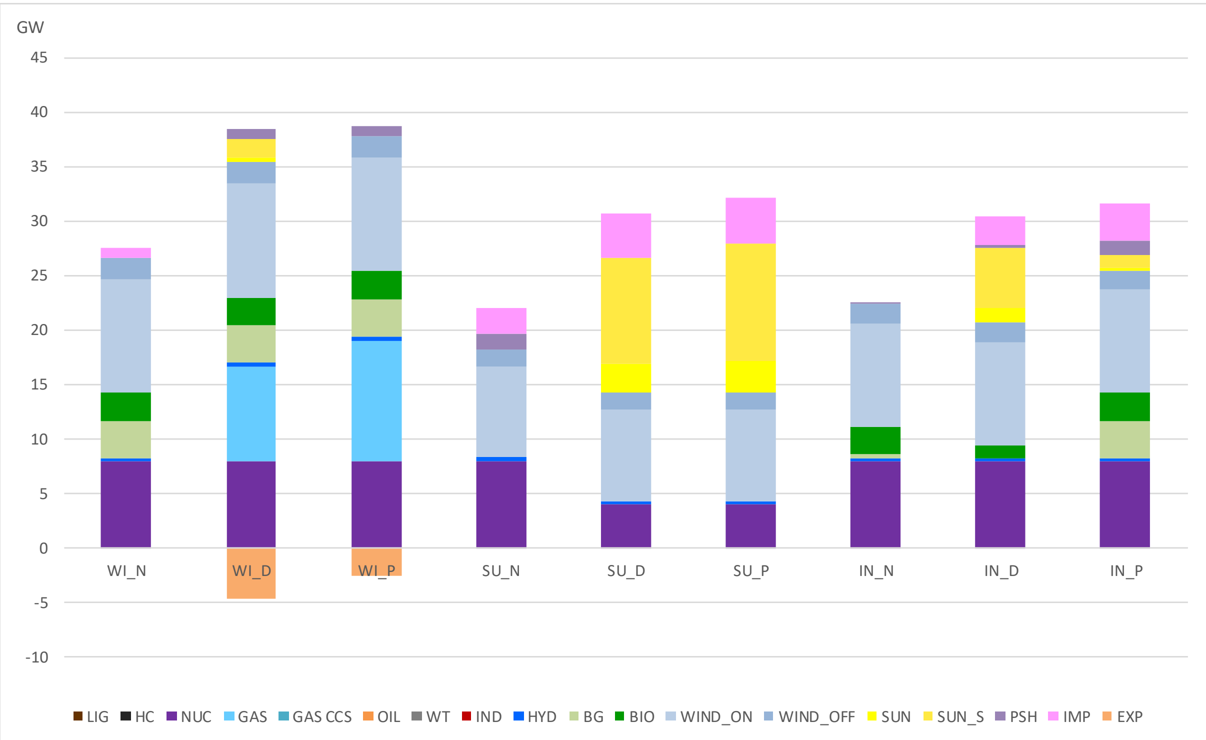
110. The distribution of expenditure over time is very uneven. The largest investments occur in 2035-2050 period. The amount of investment in 2051-2055, with reduction goals already achieved, is significantly lower than in previous years.

Figure 28. Example of average seasonal generation structure for time-slices the REF and DEEP scenario for 2050 for Poland (working days, WI – winter, SU-summer, IN – spring and fall, N – night, D – day, P – peak)

REF



DEEP



Source: MEESA model

111. The seasonal structure of electricity production from photovoltaic and wind farm is similar in REF and DEEP scenario (with a slightly larger share of offshore wind power in DEEP scenario), which means these technologies are competitive even in REF scenario. In DEEP scenario biomass and biogas energy sources are more important.

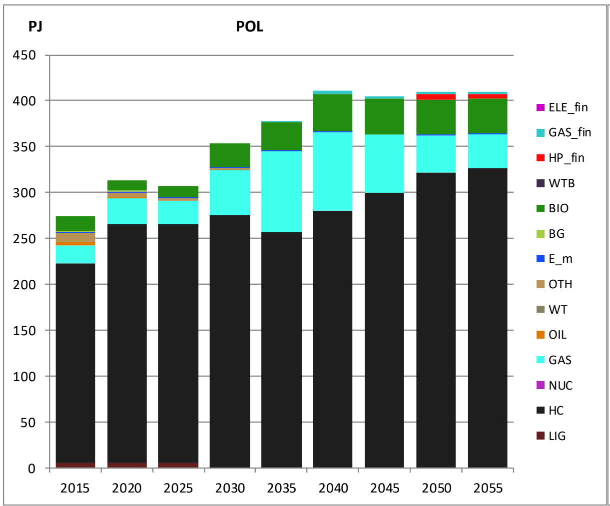
112. In REF scenario coal-fired power plants are used as base load units while in DEEP scenario base load generation is provided mainly by nuclear power plants. In both scenarios gas-fired power plants play an important role in stabilising the energy system, especially during the winter.

113. In DEEP scenario use of hydro-pumped storage is much greater than in REF scenario as well as import of electricity.

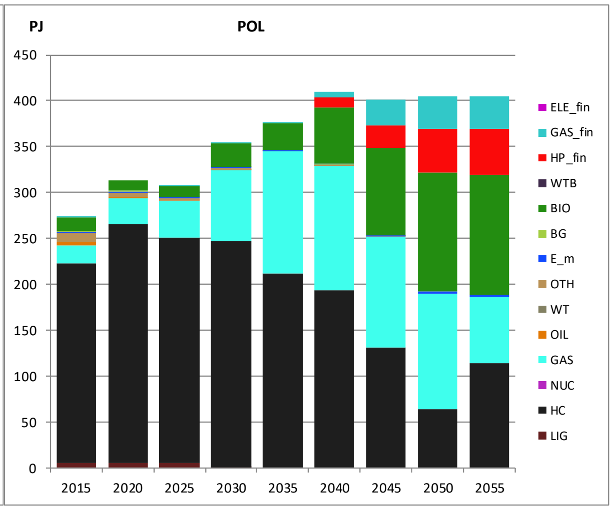
114. Below the results of the optimization of the district heat sector in Poland are presented. Figure 29 shows the production of district heat by fuel (and energy from domestic heating appliances which could replace district heating).

Figure 29. District heat production in Poland [Scenarios]:

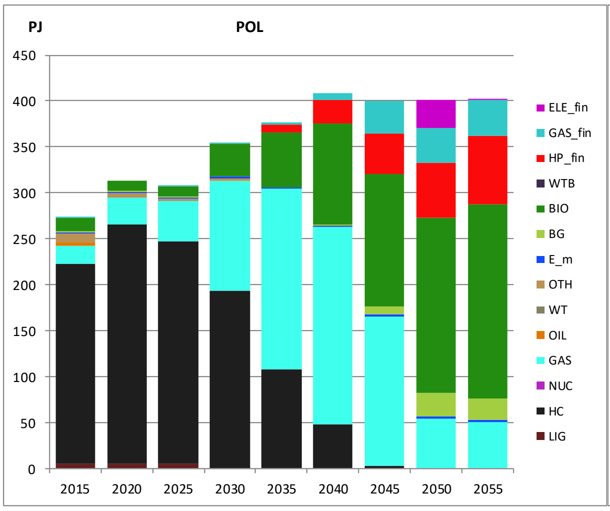
REF



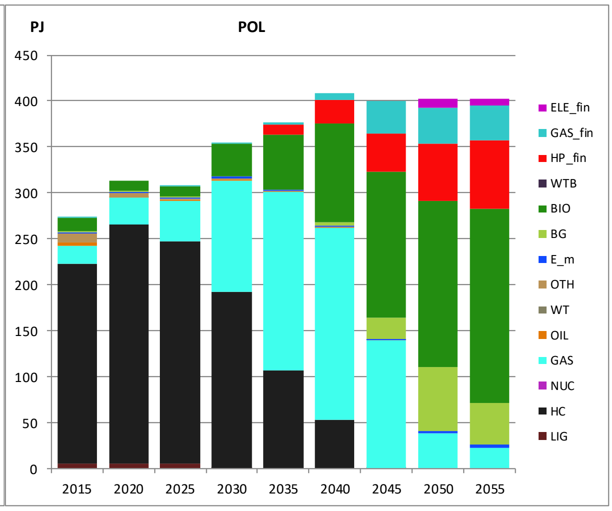
BAU



DEEP



DEEPNN



Source: MEESA model

115. In the REF scenario, despite high EUA prices, coal-fired units play an important role in district heat production - most of which are cogeneration power plants. In other scenarios, the role of coal decreases significantly over time.

116. The main fuels in the BAU, DEEP and DEEPNN scenarios are gas and biomass. It is expected that in the coming years old coal boilers in heat plants will be replaced by gas-fired and biomass-fired ones.

117. Due to limited resources, biomass should be used primarily in local district heating plants and CHP's, in order not to generate the need to import raw material from long distances.

118. In the BAU scenario, the decline in coal use in 2050 and the increase in gas production are the result of the need to meet very demanding European reduction target. In the following years however, coal-fired power generation increases because, assuming a fixed emission target after 2050, other emission reduction opportunities will arise. This particular effect should be interpreted as the result of some model limitations and it should be assumed that changes in fuel structure will be more gradual.

119. In scenarios with deep emission reduction, the share of heat from electricity and distributed gas is significantly increasing - which at the same time means a reduction in the demand for district heat. A significant amount of biomass is used to produce heat in order to meet the reduction of emissions, which in the heating sector turns out to be more difficult than in electricity.

5.7. Results for Poland according to MEESA model and NECP

120. Compared to the draft NECP submitted by Poland to the European Commission in January 2019, there are several significant differences that are a consequence of the adopted methodological assumptions. First of all – in MEESA there are four different scenarios, some with very ambitious long term emission reduction targets. Such EU wide emission restriction beyond 2040 was not implemented in NECP analysis. This is the most distinctive difference between approaches taken in both studies, because deep reduction targets for 2050 influence the direction of energy system development long before this date. Therefore most similar to NECP scenario is REF MEESA scenario, which does not impose any forced reduction targets, but the only gradual increase in CO_2 emissions costs. Nevertheless, it is interesting to compare this result and explain the main differences.

121. There is a lower share of coal (especially lignite) in the Energy mix in MEESA results. Electricity generation from lignite significantly declines already between 2026 and 2030, while in the NECP project the gradual decline is only taking place after 2031. There could be several reasons for that difference. Firstly, the MEESA model takes into account full wind potential, while NECP assume additional limitations in construction of new wind onshore farms due to the so-called Distance Act[22], which forbids to locate wind farms at a distance of less than 10 times the height of the tower from buildings. It is clearly visible that without such restrictions wind technology develops very quickly and puts pressure on the most emissive units. Secondly, the MEESA model assumes the possibility of covering the demand by electricity import, provided that there are favourable price relations in the connected markets. Part of the potential of coal-fired power plant production is therefore replaced by energy import. Thirdly, the share of coal in the NECP project is derived from the state's economic strategy, i.e. taking into account all the effects of the planned development of the electricity sector, including aspects such as the impact on employment, the social costs of mine and power plant closures, and energy self-sufficiency.

122. In all MEESA scenarios, the share of wind in electricity production is higher than in NECP. As was mentioned above the main reason was that in MEESA technically feasible potential was taken into account without additional limitations. Another reason is significantly lower investment cost assumptions for wind farm, according to newer studies, used in MEESA model.

123. In all scenarios, the share of electricity production from gas is higher (except for the REF scenario). The higher share of gas in the electricity generation structure than in the project of NECP, results from the less restrictive limits on the development of this

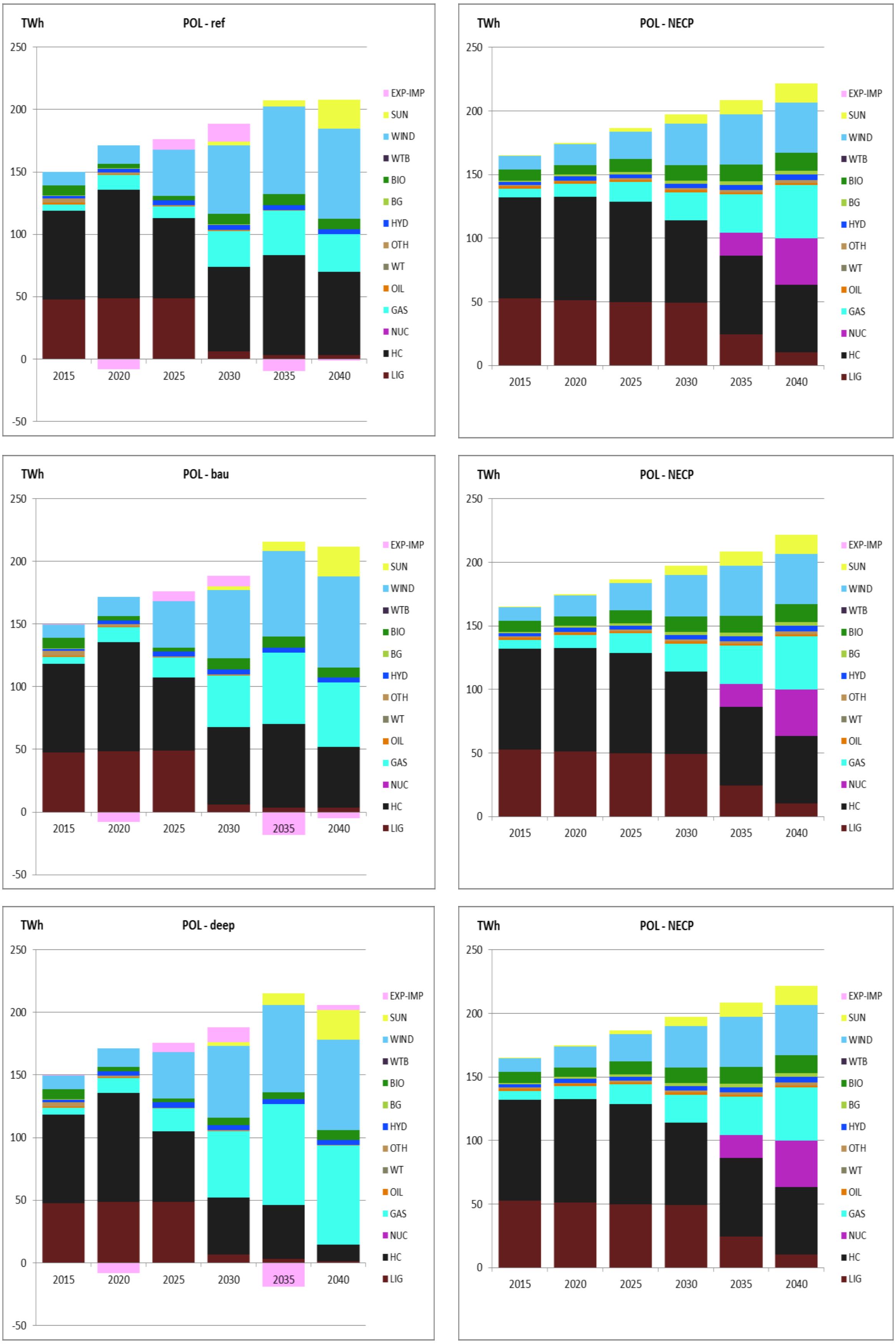
[22] Act of 20 May 2016 on Wind Energy Investments (Dz. U. z 2019. poz. 654, 1524)

technology. In conditions of high EUA prices, technologies based on gaseous fuels are competitive in relation to coal technologies. They also play an important role in the energy system regulation. Meanwhile, in the government's strategy, increasing the share of gas is considered to be a negative effect of the energy transformation, leading to increased dependence of the country on foreign supplies (Poland has limited resources of own gas). Therefore, in the NECP project, the share of gas in electricity generation is lower.

124. No nuclear power plant appears till 2040 in any of the considered MEESA scenarios, while the NECP scenario indicates the need to build two units by 2035 with a total capacity of 2.6 GW and production of 18.1 TWh. In the NECP project, the total installed nuclear capacity in 2040 is 5.2 GW along with the production of electricity equal to 36.2 TWh. The results obtained from the MEESA model indicate the need to build the first units of a nuclear power plant in Poland after 2040. One conclusion drawn from the conducted analyses is that a significant reduction of CO_2 emissions in the power sector can be achieved until 2040 alone by RES and natural gas technologies combined. Another explanation is that in MEESA, due to a higher interest rate used in calculations, nuclear power plants are less competitive than gas (until emission restriction became significant) - this also explains the larger use of natural gas in MEESA. However, a deeper reduction target after 2040 changes this picture and promotes fast development of nuclear energy. If climate neutrality is to be achieved by 2050, nuclear power plants are the most rational way to reduce electricity related emissions.

125. It should be noticed that the draft NECP submitted by Poland in January is currently in the consultation phase, so its final version may differ from the one taken for this comparisons.

Figure 30. Electricity generation. Comparisons with the NECP project



Source: MEESA model

6. Conclusions and further work

6.1. Most important conclusions

126. The MEESA model allows for analysis of the role of energy technologies for meeting EU energy and climate change related policy objectives. It can model the technologies deployment and their interaction with the energy infrastructure including storage options in an energy systems perspective. It can be used as a relevant tool to support impact assessment studies in the energy policy field that require quantitative modelling at an energy system level with a high technology detail.
127. The main objective of this report is to provide an overview of the major data inputs and assumptions of the MEESA model, in order to facilitate future information exchange with other modelling teams and stakeholders. The report also describes a number of model outputs obtained for exemplary scenarios. These results are preliminary and were made mainly to test the MEESA model response to different scenarios. Nevertheless many interesting conclusions can be drawn based on these results.
128. Emission reduction until 2030 are mainly driven by domestic policies concerning coal withdrawal and to some extent by renewable sources development – that is why results for all four scenarios are very similar for 2015-2030 period.
129. Nuclear power plays very important role in deep reduction scenarios in providing stable energy supply at moderate cost. Because of the uneven distribution of nuclear power plants and different RES potentials in particular countries, energy transmission capabilities will be an important factor in achieving reduction goals. In deep emission reduction scenarios natural gas is a transitional technology used mainly in 2020-2040 and then gradually replaced by low emission sources, but remains important as backup technology for providing system safety.
130. In the case of politically driven restrictions on new nuclear investments in EU accomplishment of reduction target is still possible but with significantly higher cost of energy supply. In that case mix of additional renewable sources and gas turbines with CCS fills the gap. It is worth to note that in MEESA results coal fired power plants with CCS were less competitive option.
131. Regarding the supply side of the energy system, the power sector moves towards renewable electricity practically in all considered scenarios. This is caused not only by the growing cost of EUA purchase, but also by the cost-effectiveness of certain RES electricity technologies. Especially in deep reduction scenarios RES development goes beyond assumed minimal level.

132. The higher the reduction requirements, the higher the costs of energy generation, which is obvious, but what more important - without new nuclear investments the costs are much higher but with the same emission reduction goals achieved.

133. It's important to understand that modelling results are deeply dependent on assumed future technology potentials and costs. Especially in case of renewable sources - still under development - in which many reports show a substantial decrease in investment cost. Also, all assumptions concerning strict polices of phasing out nuclear and coal power have a direct impact on results, limiting the scope of real optimization.

134. Another interesting observation is an interdependence between main political goals: renewable energy share and CO_2 reduction target. With high required a minimal share of renewables relatively low marginal emission costs persist longer, while without RES requirements emission costs increase faster.

135. In overall terms the most critical key assumptions and data inputs affecting the current MEESA results are the RES and nuclear power potentials and the costs.

136. The discount rate has a huge influence on optimization results. The higher the discount rate is the less competitive long life cycle and expensive, technologies like nuclear become, while short life cycle technologies become more competitive.

137. As noticed previously in deep emission reduction scenarios part of district heat could be replaced by individual heating systems. There are two different ways this could happen, with different consequences. The first one – district heating is replaced by electrical devices (mainly heat pumps but also in some cases less efficient but cheaper electric heaters). In that case demand for electricity increases, the emission is "transferred" from heat to electricity generation but remains under control of EU ETS system and in line with overall emission reduction targets. In the second mechanism district heating is replaced by heat from small gas-fired boilers - in that case the emission escapes from EU ETS system since small individual home heating devices are not covered by the system. Emission from large sources will be lower but overall emission could remain the same or even increase. This effect may be important and should be investigated further.

6.2. Comments on further work

138. The MEESA model due to its size and complexity has to be continuously improved, both regarding data inputs and modelling aspects.

139. The next steps will be made for further progress in linking all CAKE models in order to submit real relations between sectors of the economy. Sectoral models will need some extra technologies to deal with "net-zero" analyses. In the MEESA model the most important work to do is a further development of battery storages and power to X technologies.

140. Transport electrification will raise electricity consumption and change the demand curve, what could be an important element in future changes to electricity market. These issues will be addressed in the next version of MEESA model by additional technologies implemented in line with results from the transport model.

141. Depleting potential of RES with deep emission reduction and fast-growing demand for electricity is an important aspect of analyses. Calculations of this potential is made on the assumption of specific cost of resources, but with growing acceptable cost, the estimated potential of RES also can change. In the future, further work on the determination of potential at specific cost is needed.

142. Another area of MEESA model development will be an implementation of energy demand for households, especially in the area of individual heating systems, since this aspect is very important when particle emissions and population health is taken into account.

143. Described model development directions are needed to expand the scope of possible analyses in all important aspects of the 2050 horizon (and further) in the electricity and heat sector in the EU.

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