Centre for Climate
and Energy Analyses

THE MODEL FOR EUROPEAN ENERGY SYSTEM ANALYSIS
MEESA

TECHNICAL DOCUMENTATION FOR THE MODEL
VERSION 2.0

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KOBiZE

VIIEW
2050

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List of abbreviations

AMPL	A Mathematical Programming Language
ARE SA	Energy Market Agency SA
CAKE	Centre for Climate and Energy Analyses
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)
EC	European Commission
E^{3}MLab	Energy-Economy-Environment Modelling Laboratory
ENTSO-E	European Network of Transmission System Operators for Electricity
EPICA model	Evaluation of Policy Impacts on Climate and Agriculture Model
EU	European Union
EU ETS	European Union Emissions Trading System
EU27	European Union of 27 Member States
GAMS	General Algebraic Modelling System
GHG	Greenhouse Gases
HP	Heat only Plant
IAEA	the International Atomic Energy Agency
IBM CPLEX	International Business Machines Corporation CPLEX solver
IEA	International Energy Agency
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	The National Centre for Emissions Management
KTH	Royal Institute of Technology
MEESA	Model for European Energy System Analysis
MIP	Mixed Integer Programming
NC SU	North Carolina State University
NECP(s)	National Energy and Climate Plan(s)
OSeMOSYS	Open Source energy MOdelling SYStem
PP	Power Plant
PRIMES	PRice-Induced Market Equilibrium System

PSI	Paul Scherrer Institute
PV	Photovoltaics
PWR	Pressurized Water Reactor
RES	Renewable Energy Sources
TR^{3}E model	Transport European Emission Economic Model
TSO	Transmission System Operator
SEI	Stockholm Environment Institute
SU	Stanford University
UCL	University College London
UCT	University of Cape Town
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	the United Nations Industrial Development Organisation
WEO	World Energy Outlook

Keywords: climate policy, district heating, energy balance, energy modelling, energy policy, energy sources, electricity, EU ETS, long term energy analyses.

1. Introduction

1. 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 crucial to adequately and precisely model the energy sector. Economic impact assessments are generally done by using Computable General Equilibrium models (CGE) Typically in the CGE models, the energy sector is addressed in a simplified manner – through nested functions of production in which energy can be substituted for by a combination of capital and labour and at a lower level, by fuel substitution. At this level of generality, it is not possible to accurately represent the operation of the energy sector. In consequence, it is necessary to create a tool which would enable more detailed analyses of the energy sector, taking into account its specificity, and to link it to the CGE model. Furthermore, to deal with analyses about the entire economy, containing specific reliance between sectors the CAKE project is developing an analytical workshop consisting of a global general equilibrium model d-PLACE[1] and cooperative sectoral energy MEESA, agriculture EPICA[2] and transport TR^{3}E[3] models.

2. The energy model implemented in the GAMS linear programming language and based on OSeMOSYS modelling platform covers the supply and demand sides of the energy sector, enabling detailed analyses of the effects of the climate and energy policies pursued. The necessity for Poland to prepare long-term sector analyses arises from both national legislation, EU legislation, as well as UNFCCC commitments in line with the Paris Agreement. The model addresses the issues of power security and sufficiency, its transmission and storage, the operation of unstable renewable sources, conventional and nuclear generators, cross-border electricity exchange, district heating generation (including cogeneration), green hydrogen generation, the capabilities and directions of fuel imports. The model has a European range, with greater focus on Poland's energy system. The OSeMOSYS[4] model was chosen due to open access to the source code enabling its modification in order to better reflect the specifics of the analysed scenarios for Energy sector development as well as to facilitate its connection with other CAKE models.

3. The combination of sectoral models, with detailed description of a given sector, and general equilibrium model, significantly extends the opportunity to examine the economic

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[1] Gąska, J., Pyrka, M., Rabiega, W., Jeszke, R.(2022). The CGE model d-PLACE, Institute of Environmental Protection - National Research Institute / National Centre for Emissions Management (KOBiZE), Warsaw.

[2] Wąs, A., Witajewski-Baltvilks, J., Krupin, V., Kobus, P. (2022). The EPICA model, Institute of Environmental Protection - National Research Institute / National Centre for Emissions Management (KOBiZE), Warsaw.

[3] Gąska, J., Rabiega, W., Sikora, P. (2022). The TR3E Model, Institute of Environmental Protection - National Research Institute / National Centre for Emissions Management (KOBiZE), Warsaw.

[4] 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.

effects of particular scenarios. In that approach CGE model provides data concerning economy development and final energy demand in particular regions and sectors for a given policy scenario, while the energy model is used for finding optimal solution to fulfill this demands, taking into account technical and environmental restrictions, cost of technologies and energy sources etc. The energy model also provides more detailed information about GHG emissions in the energy sector and costs of energy generation which is used in next iteration of CGE calculation in order to achieve convergence between the models. Although modelling linkage is being done mainly through the CGE model it is also possible to exchange some data directly between energy and transport model – especially data concerning electricity consumption in transport and different scenarios for electric vehicles charging.

2. The MEESA model

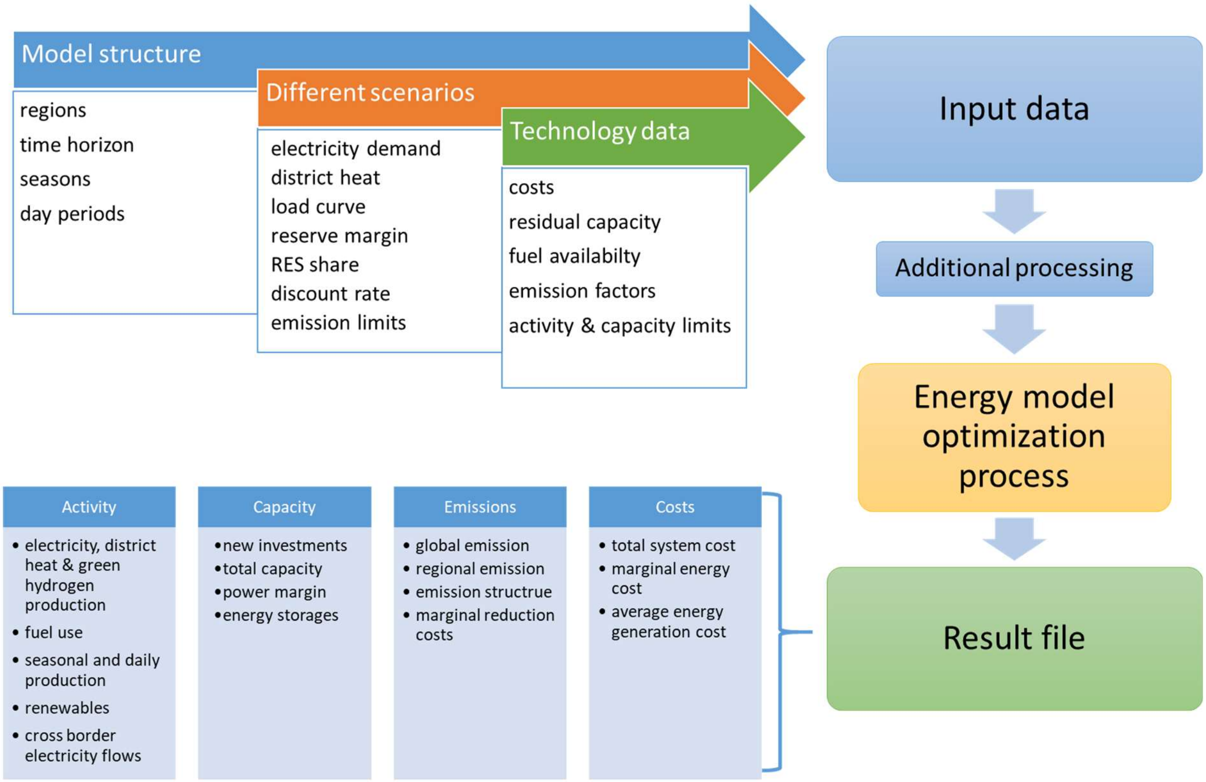
2.1. General description

4. Model for European Energy System Analysis optimises the energy supply mix (electricity, district heat and green hydrogen generated in the process of hydrolysis) meeting the set of constraints and minimising the total discounted cost. Computed energy mix is saved into csv file in order to enable further data processing and facilitate results' analysis. Results are basically divided into four categories:

   - activity,
   - capacity,
   - emissions,
   - costs.

5. Multiplicity of data needed to feed the MEESA database, lack of possibilities to collect them from one source and size of output information which must be analysed after the calculations, require building few additional tools to transform calculation output into a useful form. Figure 1 below presents a diagram of the overall process of calculation along with general types of the input data and range of obtained results. Input data are entered into a “data tables” - specially prepared spreadsheet file with additional tools for data standardization and processing. These data are directly (automatically) uploaded into the optimization model in the calculation process. The data preparation process consists of determining their scope, sources of statistical data, quality control and unification of units to be used as well as ways of aggregation of individual data categories. This process is necessary to ensure the consistency of the input data entered into the model for different countries, often from different sources and based on different methodologies (e.g. in relation to different ways of aggregating power, production, fuel consumption).

Figure 1. General scheme of operation in MEESA



Source: CAKE/KOBiZE own study

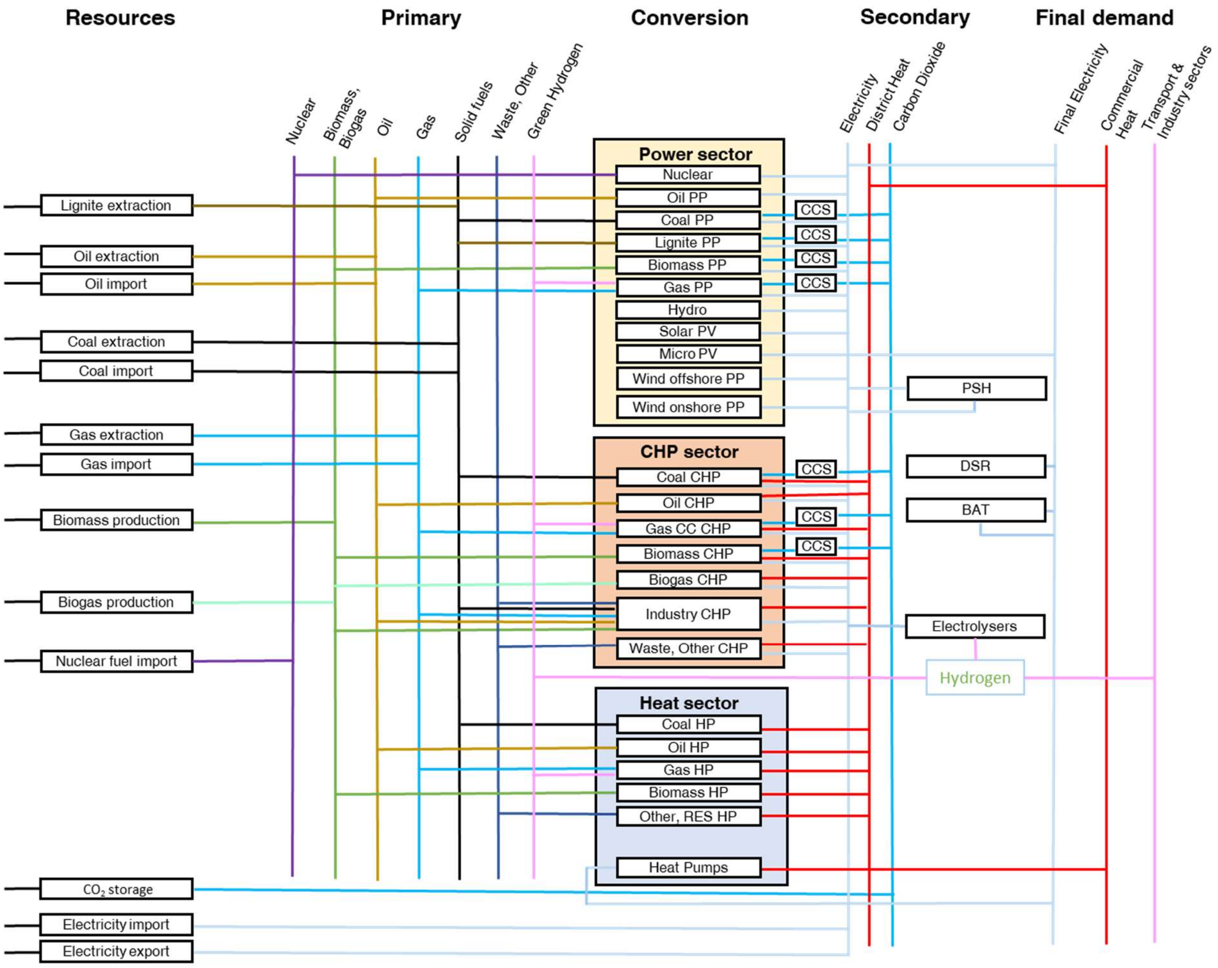
2.2. Main features

6. MEESA is a model of energy system of 27 EU Member States including also United Kingdom, Switzerland and Norway, designed for long-term integrated assessment and energy planning in this region. The main purpose of the proposed software 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 and 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 and green hydrogen sectors.

7. MEESA allows to prepare a long term (currently with the time horizon till 2055) 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, 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 vector

of demands for electricity, district heat and green hydrogen, model assures sufficient supply to demand, utilizing the technologies and resources considered. Energy demand data, exogenous to the model, is given at the final level of energy chain. 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 to demand, which is generally referred to as energy chain and steps are called levels. Figure 2 shows the Schematic presentation of Reference Energy System applied in MEESA model.

Figure 2. Schematic presentation of Reference Energy System



Source: CAKE/KOBiZE own study

8. MEESA allows accounting of existing capacities of different technologies. In the optimization process, the model computes the new capacity requirement taking into account the existing capacities and their decommissioning time. Modelling of the existing capacities enhances the amount and quality of obtainable information. By gaining

knowledge on the investment requirement for additional capacity building, one can assess the effects of the energy sector's development on the economy.

9. The user can put limitations on an resource or technology – such as minimum or maximum capacity, or minimum and maximum levels of output from a technology. There are various limits and bounds that can be defined on capacity building of technologies and resources. Furthermore, there is a set of limits that can be defined on activities of a technology i.e. its input/output.
10. An important advantage of the MEESA model is the possibility to differentiate the level of demand for a given energy carrier according to the seasons, day types and time of day. This information is the basis for defining the technological mix and mode of operation of the installed units (base, peak and off-peak load). The equivalent load curve used in the MEESA model is based on data from TSO's regarding the load level for historical periods (modelling future changes in these curves is also possible). ENTSO-E data are the main source of this information. Including specific load curves improves the representation of power demand and the requirements for different types of generation units. Additionally, more detailed representation of load opens the opportunity to model energy storage.
11. Environmental aspects can be analysed by accounting, and if it is necessary limiting, the amounts of pollutants emitted by various technologies at various steps in energy supplies. This helps to evaluate the impact of environmental regulations on energy system development.
12. Another important functionality of the model is the possibility to estimate marginal energy costs for given region and electricity exchange between regions defined in the model within multilateral trade system. To model a marketplace the user must identify regions that participates both in the production and consumption of the traded commodity. Then an exchange process is used to link all regions with the marketplace region (this is described in more detail in the section 5 of the document).
13. Thanks to vide range of energy technologies, using different energy carriers and producing electricity, district heat, both electricity and district heat (in cogeneration) or green hydrogen (in electrolysis) - with its specific parameters and restrictions, possible application of the model in creating long term European Union energy and climate strategies is feasible.
14. While all the constraints and limits imposed by computed scenario are being met, it is possible to analyse contribution of each country energy sector in accordance with present and future EU climate policy targets. It is possible to study future energy cost changes, import dependency, RES share, CO_2 emissions and energy mix in any individual country analysed or for entire EU.

3. Model description and source code

15. MEESA is based on OSeMOSYS model developed by: the International Atomic Energy Agency (IAEA), the United Nations Industrial Development Organisation (UNIDO), KTH Royal Institute of Technology, Stanford University, University College London (UCL), University of Cape Town (UCT), Paul Scherrer Institute (PSI), Stockholm Environment Institute (SEI), and North Carolina State University (NC SU). Original source code written in AMPL programming language has been translated into GAMS programming language for compatibility with other CAKE models and to allow possible use of wider spectrum of sophisticated solvers (currently IBM CPLEX solver is used). Apart from translation, additional changes to original code have been made to achieve additional functionality, as well as for optimization reasons – all such changes are more precisely explained below. In MEESA the same names of parameters, variables and equations as in original OSeMOSYS model have been used (apart from new parameters and equations implemented in MEESA – but then similar naming convention is used). Accordingly, it is relatively easy to compare both models code as well as to implement any future upgrades and changes from OSeMOSYS into MEESA (however such changes must be made carefully, because of differences between the models).

16. MEESA source code consists of four parts:

    - main file - includes model definition of parameters, variables and equations,
    - data file - stores model input data,
    - results file - code for processing several results files (loaded into Excel application for analysing model results),
    - additional two files containing additional solver parameters.

3.1. Key parameters and terms used in model

17. Meaning of main parameters and terms used within model were explained below:

A. General parameters:

- **Year** – set defined to establish time horizon of calculation - in MEESA calculations are carried out annually with additional shorter time periods within the year (so called time-slices - explained below).
- **Technology** – is in fact the core of the model, represents real world energy technology and it's parameters. All costs, technical parameters and energy flows in model are defined in terms of technology. In MEESA technology typically doesn't represent certain unit – like specific power plant – but rather aggregation of the same kind power plants. Besides technology are defined for each region separately, since similar

technologies could have different parameters in different local conditions (availability factors, efficiency, cogeneration factor etc.).

- **Fuel** – set of defined energy carriers. This includes input fuels as well as energy product like electricity and heat.
- **Time-slices** - fractions of year which describe different levels of energy demand and define how year is divided into seasons, days and shorter time period within a model. Theoretically it is possible to divide year into hours, but such approach isn't feasible for large models because of limited computing capacity. Therefore typical approach is to divide year into several time-slices – to represent typical periods of demand level.

  For defining time-slices additional parameters are used:

  - ✓ Day type – are used for defining different types of day - in MEESA for example working days and holidays are defined.
  - ✓ Daily time bracket – defines shorter time periods within a day – in basic version of the MEESA model every day is divided into three periods – night period, day average and day peak load period which differ mainly in the level of energy demand. In more advanced version, day is divided into twelve 2-hour periods. User can easily switch between both versions of time-periods.
  - ✓ Season - currently in MEESA there are two type of seasons implemented – Winter and Summer but within each season there are days with different demand and different weather conditions defined, to reflect also demand level during intermediate seasons, to some extent.
  - ✓ YearSplit – parameter used to set length of each defined time period.

  This eventually gives 18 timeslices in the basic version of the model and 72 timeslices in the advanced version, defined within a modelling year. The extended version allows to model some technologies more accurately – this is particularly important in research focused on photovoltaics and energy storage. However, it also causes a significant increase in computation time.

- **Demand** – There are two types of energy demand definition within the model:
  - ✓ Specified Annual Demand along with Specified Demand Profile allows to establish demand for particular energy carrier for every time period (time-slice). Typically these parameters are used for defining electricity, and district heat demand and how this demand changes over the year (in specific time periods). In other words this is the way to define load curve for a given region.
  - ✓ Accumulated Annual Demand defines required energy amount during the whole year, but doesn't specify the annual distribution of this demand. In MEESA this kind of demand is used to establish certain amount of electricity produced from renewable sources and also green hydrogen production. In those cases it's not

important when this production occurs but only that required amount of green energy was generated throughout the year.

- ✓ *Reserve margin* – margin of power over maximal demand which should be ensured for safe operation of energy system (typically about 15-20%) defined for every region. Different technologies have different ability to provide such service – therefore parameter *Reserve Margin Tag Technology* allows to define for every technology share of its installed capacity used for margin power reserve. Large ability to take part in margin reserve characterise technologies like gas fired open-cycle turbines or hydro-pumped storages. In case of unstable renewable technologies only small share of their installed capacity could be accounted for margin reserve.
- ✓ *Trade route* – enables energy transfer between different regions. In MEESA this feature is used mainly to model electricity cross-border exchange.
- ✓ *Discount rate* - the rate used in the model to discount all costs and revenues to the beginning of model time horizon. Currently MEESA uses one rate of return – the same for all technologies.

B. Technology parameters:

- **Costs -** There are several types of costs assigned to technology in the model:
  - ✓ *Capital cost* – represents investment cost of technology per capacity unit (in M€/GW) (see also Interest during construction (IDC) in section 3.3.1)
  - ✓ *Fixed cost* – operational fixed cost per unit of capacity (M€/GW)
  - ✓ *Variable cost* – operational cost of technology per unit of activity (M€/PJ or €/GJ)
  - ✓ *Subvention* – this parameter could be used for modelling subsidies for renewable sources (although there are other ways to promote renewables in the model).

In MEESA a common convention is used that in case of cogeneration power plants capital and fixed costs are related to electric power only. This is done by proper change in *Capacity To Activity Unit* parameter what is explained further.

Variable costs are related to overall activity of technology in M€/PJ. However in many cases it's more convenient to express this costs per electrical output in MWh. Therefore there are additional tools for preparing and storing data for MEESA model. Technology parameters could be inputted directly into data tables or through special data form. In case of variable cost for electricity producers user can input data through the data form in € per MWh of electricity, instead of € per GJ of overall activity. Then it is converted into €/GJ overall activity during process of exporting data to final tables.

- **Input activity ratio and output activity ratio -** Input activity is the share of particular energy carrier use in relation to technology activity rate. Output activity is the share of energy carrier production to activity rate. As proposed in original OSeMOSYS in

MEESA sum of different energy carriers (for example heat and electricity in CHP) produced by technology is equal to 1, while sum of fuel used by technology is 1 divided by technology efficiency. However in the MEESA model additional dummy energy carrier are used to account “green” electricity produced by renewable sources – in that case sum of energy produced by technology could be greater than 1.

In case of multi-fuel technologies each output activity must be calculated taking into account a given fuel share and overall efficiency.

- **Mode of operation -** Some technologies may have several different ways of working depending on circumstances. To simulate that user can define different modes of operation. There is no restriction to number of modes of operation, however from performance reason it is good to use lowest possible number of modes. In different modes of operation technology could have been characterised by different set of parameters related to activity – efficiency, fuel shares, energy outputs, variable cost and emission factors.

  In MEESA two modes of operation are used – mainly to model condensing mode in cogeneration power plants (in which only electricity is produced in CHP), biomass co-firing in some coal fuelled power plants (one mode for coal only, second for co-firing), charging and discharging (two different modes) hydro-pumped storages or batteries, cross-border electricity exchange (one mode for import, second for export).

- **Capacity to activity unit -** This parameter provides relation between activity and capacity. Typically for most of technologies activity is measured in PJ and capacity in GW. The proper value of potential quantity of energy generation per GW per year is calculated as follows:

  $$0.0036\ [\mathrm{PJ/GWh}] * 8\,760\ \mathrm{h} = 31.536\ [\mathrm{PJ/GW}]$$

  Cogeneration power plants however are modelled slightly differently than other technologies and in that case this parameter must be modified (31.536 value must be divided by share of electricity production by CHP). This approach doesn’t affect technology ability to produce heat, but has some advantages - in case of CHP user defines only electrical part of capacity – which means that all input data and results – residual capacity, new capacities, power constraints – are related to electric power. In similar manner capital and fixed cost are defined per electric capacity only. This way it’s more convenient to prepare input data as well as to interpret the results.

- **Operational life -** Specifies technical lifetime of technology and is important to calculate pace of technology replacement as well as salvage value (in case technology lifetime exceeds model time horizon).
- **Construction time -** Specifies construction time for technology, used for calculation of capital cost during construction.

- **Availability and Capacity Factors -** In general this parameters define how long technology works during a year. The difference is that availability factor defines what share of the year technology is available but doesn't specify when precisely, while capacity factor specifies technology availability in particular time-slices. Therefore availability factor is used rather to restrict maximum annual activity in case of stable and conventional technologies. On the other hand capacity factor is used mainly for renewable sources to specify technologies seasonal and daily variability (e.g. in case of PV maximum availability during a summer day, lower during winter day and no energy production at nights).
- **Residual Capacity -** Defines currently installed capacity as well as assumptions regarding the rate of decommissioning of existing capacities.
- **Emission factor -** Specifies technology emissions per activity rate for every defined pollutants.
- **Emission penalty -** Defines additional cost related to GHG emissions. This parameter is crucial for different scenarios of climate policy and European Union Emissions Trading System (EU ETS).
- **Constraints -** Problem of establishing proper restrictions for technology development rate are especially important in case of linear models, because without it model tends to develop optimal technologies rapidly and often beyond technical or economical feasibility. In real life there are many additional factors that limit rate of technology development but it could be very hard or even impossible to reflect that in the model. These factors can be of technical, economic, behavioural or even political origin. Therefore it is very important to establish some reasonable limitations for technology development rate based on assumptions about technology potential, observed trends, new policies and regulations, business activities. Such limitations could be set on capacity as well as activity levels.
- **Capacity constraints -** There are four types of capacity constraints in the model. *Total annual maximum capacity* and *total annual minimum capacity* are for setting maximal and minimal total capacity level of technology in every year. This way limit for total amount of particular technology capacity installed in the given region could be entered.

  The other two types of capacity constraints - *total annual maximum capacity investment* and *total annual minimum capacity investment* sets maximum and minimum level of new capacity investment of specific technology within one year. The first one is used to limit annual rate of technology growth. The second one is typically used if there are some units already under construction or planned and it should be reflected in model (in that case the investment is not an effect of optimisation process but the model is forced to do it).

- **Activity constraints -** There are four types of activity constraints. *Total technology annual activity upper limit* and *total technology annual activity lower limit* sets limits for annual technology activity, and are useful if there is a need to establish limits on technology by means of activity rather than capacity. It is also convenient way to set technology energy production for base year.

  Total technology model period activity upper limit and *total technology model period activity lower limit* are the other two activity constraints which restrict technology overall activity within whole modelling period. This could be useful for modelling some very limited resources or in case of analysis with very long time horizon (for example for depletion of some fossil fuels).

- **Emission limits -** There are two levels of emission limits in MEESA. The regional limit could be set as annual maximum emission (parameter *annual emission limit*) or as total emission level during the whole modelling period (parameter *model period emission limit*). Except that global (for all regions) annual emission level could be set. This kind of limit is useful to model climate policy related regulations implemented on European level.
- **Storage parameters -** There are several parameters specific only for storages to define storage capabilities and its state.
  - ✓ *Technology to storage and technology from storage* – parameters to define which technologies can work together with particular type of storage.
  - ✓ *Storage max charge rate and storage max discharge rate* – determines maximum rate of energy accumulation (and discharging) in storage.
  - ✓ *Storage level start* – level of storage charge at the beginning of the modelling period.
  - ✓ *Minimal storage charge* – threshold that storage can't be discharge beyond.

  There are also storage parameters similar to parameters for typical energy technologies - *residual storage capacity, capital storage costs, operational life* - this parameters work the same way as those described earlier.

3.2. Overview of key model equations

18. The most important model equations in simplified notation are presented below with some remarks and explanations - mainly to focus on the model logic rather, not on the code itself. That's why for better clarity this section omits conditional expressions in equations, as these elements are not essential to understand how the model works. On the other hand these conditional expressions are crucial for optimization reasons and because of that have been fully explained in part dedicated to the model optimization.

The following aliases have been used in equations:

Year – y, yy	Fuel – f	Time slice – l	Daily time bracket – lh
Region – r, rr	Emission – e	Season – ls	Storage - s
Technology – t	Mode of operation – m	Day type – ld	

- **Objective function:**

```
cost.. z = sum((r, y), TotalDiscountedCost(r, y))
```

19. The aim of optimization process within the model is to find the lowest discounted total cost of energy system with given energy demands and constraints. This is widely used approach but has important consequence in model which covers many countries - the result represents least cost option for the whole system, but not necessarily best for every specific country considered alone. Optimal solution for isolated region could be very different. In real world such deep optimization is limited by political and technical means. In model such limitations are reflected by possibilities of electricity transfers between different regions (countries) and other user defined constraints. Model allows to create analyses for selected country, groups of countries or with and without possibility of electricity exchange between regions. These capabilities together with connection CGE model and Energy Sector model gives opportunity to create wide range of evaluation of optimal climate goals from the viewpoint of Member States or EU as a whole.

- **Demand:**

20. As stated before energy demand is defined by overall annual demand of particular fuel (*specified annual demand* parameter) and its distribution for shorter periods (*specified demand profile*). This two parameters along with *YearSplit* (which defines length of every time-slice) are used for calculation energy demand (*rate of demand* variable) in every specific time-slice.

```
EQ_SpecifiedDemand(r, l, f, y).. SpecifiedAnnualDemand(r,f,y) * SpecifiedDemandProfile(r,f,t,y) /
YearSplit(t,y) = RateOfDemand(r,t,f,y)
```

21. Apart from above which describes demand for every short time period there is another way of defining demand - annually only - in cases where particular energy demand for shorter period is not important (*accumulated annual demand* parameter). For example in MEESA model that feature is used for setting required annual amount of energy production from renewable sources and green hydrogen production. In that cases it is only important to meet the annual green energy generation target, but the model can decide how and when (within the year) this energy is produced - it depends mainly on renewable sources characteristics and their abilities to produce energy in particular time period.

```
EBb4_EnergyBalanceEachYear4(r,f,y).. ProductionAnnual(r,f,y) >= UseAnnual(r,f,y) + sum(rr,
TradeAnnual(r,rr,f,y) * TradeRoute(r,rr,f,y)) + AccumulatedAnnualDemand(r,f,y)
```

22. The equation (EBb4) containing *Accumulated annual demand* is part of wider equations system defining energy balances which is described below.

- **Energy balance:**

23. The aim of the model is to find least expensive way to satisfy energy demand. In order to do that model has to meet demand with energy production taking into account the whole chain of energy carriers, technologies efficiency, power and production constraints, and other factors. The main part of the model responsible for finding required energy production for given energy demand is a group of equations for energy balance.

24. Energy balances are divided into two parts (A and B). The first part (energy balance A) describes connection between demand in each time-slices and energy production and fuel use in particular technologies.

25. Energy production for given fuel and technology, for every time-slice, fuel and mode of operation is determined (in equation EBa1) out of the technology parameters (*output activity ratio*) and rate of activity (which is a model variable describing how intensively technology operates in specific time-slice for particular *mode of operation*). Then values for all modes of operation are summed up for every technology (equation EBa2) and finally production of all technologies are summed up for every region (EBa3).

```
EBa1_RateOfFuelProduction1(r, l, f, t, m, y).. RateOfActivity(r,l,t,m,y) * OutputActivityRatio(r,t,f,m,y) =
RateOfProductionByTechnologyByMode(r,l,t,m,f,y)

EBa2_RateOfFuelProduction2(r,l,f,t,y).. sum(m, RateOfProductionByTechnologyByMode(r,l,t,m,f,y)) =
RateOfProductionByTechnology(r,l,t,f,y)

EBa3_RateOfFuelProduction3(r,l,f,y).. sum(t, RateOfProductionByTechnology(r,l,t,f,y)) =
RateOfProduction(r,l,f,y)
```

26. It's important to distinguish between activity rate and production. Production refers to particular fuel (energy) generation while activity could be interpreted as a sum of all fuels production from the technology.

27. In similar manner to production, fuel use is determined in equations EBa4 - EBa6.

```
EBa4_RateOfFuelUse1(r,l,f,t,m,y).. RateOfActivity(r,l,t,m,y) * InputActivityRatio(r,t,f,m,y) =
RateOfUseByTechnologyByMode(r,l,t,m,f,y)

EBa5_RateOfFuelUse2(r,l,f,t,y).. sum(m, RateOfUseByTechnologyByMode(r,l,t,m,f,y)) =
RateOfUseByTechnology(r,l,t,f,y)

EBa6_RateOfFuelUse3(r,l,f,y).. sum(t, RateOfUseByTechnology(r,l,t,f,y)) = RateOfUse(r,l,f,y)
```

28. Equations EBa7 and EBa8 determine total annual production and fuel consumption for particular region in any time-slice.

EBa7_EnergyBalanceEachTS1(r,l,f,y).. RateOfProduction(r,l,f,y) * YearSplit(l,y) = Production(r,l,f,y)

EBa8_EnergyBalanceEachTS2(r,l,f,y).. RateOfUse(r,l,f,y) * YearSplit(l,y) = Use(r,l,f,y)

29. Equations EBa9 – EBa11 combine demand for specific fuel in particular region with its production, domestic consumption (by technologies) and trade with other regions.

EBa9_EnergyBalanceEachTS3(r,l,f,y).. RateOfDemand(r,l,f,y) * YearSplit(l,y) = Demand(r,l,f,y)

EBa10_EnergyBalanceEachTS4(r,rr,l,f,y).. Trade(r,rr,l,f,y) = -Trade(rr,r,l,f,y)

EBa11_EnergyBalanceEachTS5(r,l,f,y).. Production(r,l,f,y) >= Demand(r,l,f,y) + Use(r,l,f,y) + sum(rr, Trade(r,rr,l,f,y) * TradeRoute(r,rr,f,y))

30. Next group of equations (EBb1-EBb4) is used to compute annual fuel production, fuel use and exchange with other regions. The EBb4 equation implements total annual demand (*accumulated annual demand*) in addition to demand specified for every time-slice (*specified annual demand*) - the difference between the two has been explained above in demand section.

EBb1_EnergyBalanceEachYear1(r,f,y).. sum(l, Production(r,l,f,y)) = ProductionAnnual(r,f,y)

EBb2_EnergyBalanceEachYear2(r,f,y).. sum(l, Use(r,l,f,y)) = UseAnnual(r,f,y)

EBb3_EnergyBalanceEachYear3(r,rr,f,y).. sum(l, Trade(r,rr,l,f,y)) = TradeAnnual(r,rr,f,y)

EBb4_EnergyBalanceEachYear4(r,f,y).. ProductionAnnual(r,f,y) >= UseAnnual(r,f,y) + sum(rr, TradeAnnual(r,rr,f,y) * TradeRoute(r,rr,f,y)) + AccumulatedAnnualDemand(r,f,y)

- **Auxiliary energy equations:**

31. This set of equations is important to implement additional variables necessary to establish constraints for annual activity of specific technology in specific region. While energy balances explained above evaluate overall fuel production and use for whole region, here this values are calculated for particular technology.

Acc1_FuelProductionByTechnology(r,l,t,f,y).. RateOfProductionByTechnology(r,l,t,f,y) * YearSplit(l,y) = ProductionByTechnology(r,l,t,f,y)

Acc2_FuelUseByTechnology(r,l,t,f,y).. RateOfUseByTechnology(r,l,t,f,y) * YearSplit(l,y) = UseByTechnology(r,l,t,f,y)

Acc3_AverageAnnualRateOfActivity(r,t,m,y).. sum(l, RateOfActivity(r,l,t,m,y)* YearSplit(l,y)) = TotalAnnualTechnologyActivityByMode(r,t,m,y)

- **Activity constraints:**

32. User can establish activity constraints for any technology in particular year by setting maximum or minimum activity level (*total technology annual activity upper limit* and *total technology annual activity lower limit* respectively). This feature is implemented by the following equations.

```
AAC1_TotalAnnualTechnologyActivity(r,t,y).. sum(l, RateOfTotalActivity(r,l,t,y) * YearSplit(l,y)) =
TotalTechnologyAnnualActivity(r,t,y)

AAC2_TotalAnnualTechnologyActivityUpperLimit(r,t,y).. TotalTechnologyAnnualActivity(r,t,y) <=
TotalTechnologyAnnualActivityUpperLimit(r,t,y)

AAC3_TotalAnnualTechnologyActivityLowerLimit(r,t,y).. TotalTechnologyAnnualActivity(r,t,y) >=
TotalTechnologyAnnualActivityLowerLimit(r,t,y)
```

- **Capacity equations:**

33. Main role of capacity equations is to calculate capacity level necessary for required energy generation in every time-slice. The model takes into account existing capacities (*residual capacity*) as well as new investments and ensures that sum of residual and new capacity will be sufficient for meeting the energy demand.

34. Equations CAa1 summarizes new capacity introduced in each year into total installed new capacity (except capacity already decommissioned because of exceeding their technical life time). Equation CAa2 adds total installed new capacity and residual capacity while equations CAa3 and CAa4 connects activity rate of particular technology with total capacity.

```
CAa1_TotalNewCapacity(r,t,y).. AccumulatedNewCapacity(r,t,y) = sum(yy$((YearVal(y) - YearVal(yy))
< OperationalLife(r,t) and (YearVal(y) - YearVal(yy))>=0), NewCapacity(r,t,yy))

CAa2_TotalAnnualCapacity(r,t,y).. AccumulatedNewCapacity(r,t,y) + ResidualCapacity(r,t,y) =
TotalCapacityAnnual(r,t,y)

CAa3_TotalActivityOfEachTechnology(r,l,t,y).. sum(m, RateOfActivity(r,l,t,m,y)) =
RateOfTotalActivity(r,l,t,y)
```

35. Equation CAa4 and CAb1 implement additional parameters related to technology capacity - *capacity factor*, *availability factor* and *capacity to activity unit.*

```
CAa4_Constraint_Capacity(r,l,t,y).. RateOfTotalActivity(r,l,t,y) <= (sum(yy$((YearVal(y) - YearVal(yy))
< OperationalLife(r,t) AND (YearVal(y) - YearVal(yy)>=0)), NewCapacity(r,t,yy) *
CapacityFactor(r,t,l,yy)) + ResidualCapacity(r,t,y) * smin(y0, CapacityFactor(r,t,l,y0))) *
CapacityToActivityUnit(r,t)

CAb1_PlannedMaintenance(r,t,y).. sum(l,RateOfTotalActivity(r,l,t,y) * YearSplit(l,y)) <=
sum(l,(sum(yy$((YearVal(y) -YearVal(yy)) < OperationalLife(r,t) AND (YearVal(y) - YearVal(yy)>=0)),
NewCapacity(r,t,yy) * CapacityFactor(r,t,l,yy)) + ResidualCapacity(r,t,y) * smin(y0,
CapacityFactor(r,t,l,y0))) * YearSplit(l,y)) * AvailabilityFactor(r,t,y) * CapacityToActivityUnit(r,t)
```

36. It should be mentioned here that the original OSeMOSYS equations CAa4 and CAb1 are slightly modified in MEESA model to change role of capacity factor – what has been explained in detail in part related to differences between OSeMOSYS and MEESA models.

37. The next equation is newly implemented one, not present in original OSeMOSYS. Its purpose is to provide possibility to establish minimal capacity factor for particular

technology. This feature is used to ensure that some technologies will be used at least at some minimal level in every time-slice. It was introduced to reflect fact that there is a share of power units which must generate energy all the time due to voltage stability and grid safety.

```
CAb2_PlannedMaintenance(r,t,l,y).. sum(m, RateOfActivity(r,l,t,m,y) * YearSplit(l,y)) >=
((sum(yy$((YearVal(y) - YearVal(yy) < OperationalLife(r,t)) AND (YearVal(y) - YearVal(yy) >=0)),
NewCapacity(r,t,yy)) + ResidualCapacity(r,t,y)) * CapacityFactorMIN(r,t,y) * YearSplit(l,y)) *
AvailabilityFactor(r,t,y) * CapacityToActivityUnit(r,t)
```

- **Capacity constraints:**

38. Like in case of activity user can set constraints for capacity level for particular technology. There are four types of capacity constraints possible – *maximum total installed capacity* of technology, *minimum total installed capacity*, *maximum annual capacity investment* and *minimum annual capacity investment* (typical function of every kind of constraint has been explained earlier). Equations TCC1, TCC2, NCC1 and NCC2 implements capacity constraints.

```
TCC1_TotalAnnualMaxCapacityConstraint(r,t,y).. TotalCapacityAnnual(r,t,y) <=
TotalAnnualMaxCapacity(r,t,y)

TCC2_TotalAnnualMinCapacityConstraint(r,t,y).. TotalCapacityAnnual(r,t,y) >=
TotalAnnualMinCapacity(r,t,y)

NCC1_TotalAnnualMaxNewCapacityConstraint(r,t,y).. NewCapacity(r,t,y) <=
TotalAnnualMaxCapacityInvestment(r,t,y)

NCC2_TotalAnnualMinNewCapacityConstraint(r,t,y).. NewCapacity(r,t,y) >=
TotalAnnualMinCapacityInvestment(r,t,y)
```

- **Reserve margin:**

39. The model provides possibility to define amount of necessary power excess over maximum energy demand, called reserve margin (the amount depends on specific national regulations but typically it is about 15-20% of additional reserve capacity over maximum demand). User have to define which technologies could provide such reserve and to what extent (share of its installed capacity). There are technologies particularly suitable for this role like gas fired turbines or hydro pumped storages, other stable energy sources also have large ability to take part in margin reserve, but unstable sources like wind farms or photovoltaics have very limited abilities in this area. Reserve margin is a type of constraint concerning the entire energy system. It is implemented in RM1 – RM3 equations.

```
RM1_ReserveMargin_TechologiesIncluded_In_Activity_Units(r,l,y).. sum(t, TotalCapacityAnnual(r,t,y) *
ReserveMarginTagTechnology(r,t,y) * 31.536) = TotalCapacityInReserveMargin(r,y)
```

```
RM2_ReserveMargin_FuelsIncluded(r,l,y).. sum(f, RateOfProduction(r,l,f,y) *
ReserveMarginTagFuel(r,f,y)) = DemandNeedingReserveMargin(r,l,y)

RM3_ReserveMargin_Constraint(r,l,y).. DemandNeedingReserveMargin(r,l,y) * ReserveMargin(r,y) <=
TotalCapacityInReserveMargin(r,y)
```

40. Note the 31.536 number used in RM1 equation - in original OSeMOSYS code in this place the *capacity to activity unit* factor has been used. The change is the result of convention adopted to modelling CHP technologies - that in case of CHP capacity and fixed cost are related electric power only. If the original form of RM1 equation was left, the user would have to make additional calculations to define technology ability for reserve margin, taking into account different than 31.536 *capacity to activity unit* factor – otherwise electric capacity provided by cogeneration power plants would be overestimated. This approach should be less confusing.

- **Costs:**

41. There are several groups of equations related to technology costs. In most cases this equations are quite obvious and do not require additional explanation.

42. For every group of costs there are additional discounting equations. The approaches to discount calculation are very similar for each type of costs, therefore in this overview discounting equation is included as an example only for capital costs.

43. Capital Cost (CC1 and CC2 equations)

```
CC1_UndiscountedCapitalInvestment(r,t,y).. CapitalCost(r,t,y) * NewCapacity(r,t,y) =
CapitalInvestment(r,t,y)

CC2_DiscountingCapitalInvestment(r,t,y).. CapitalCost(r,t,y) *
NewCapacity(r,t,y)/((1+DiscountRate(r))**(YearVal(y) -smin(yy, YearVal(yy)))) =
DiscountedCapitalInvestment(r,t,y)
```

44. Salvage value equations (SV1-SV3) are used to calculate value of investment that goes beyond modelling time horizon. Without applying them, the model would prefer to invest in technology with low investment cost or short operational time.

```
SV1_SalvageValueAtEndOfPeriod1(r,t,y)$((YearVal(y) + OperationalLife(r,t)-1) > (smax(yy,
YearVal(yy))) AND DiscountRate(r)>0).. SalvageValue(r,t,y) = CapitalCost(r,t,y) * NewCapacity(r,t,y) *
(1-(((1+DiscountRate(r))**(smax(yy, YearVal(yy)) - YearVal(y) + 1) - 1) / ((1 +
DiscountRate(r))**OperationalLife(r,t) - 1)))

SV2_SalvageValueAtEndOfPeriod2(r,t,y)$((YearVal(y) + OperationalLife(r,t) - 1) > (smax(yy,
YearVal(yy))) AND DiscountRate(r)=0).. SalvageValue(r,t,y) = CapitalCost(r,t,y) * NewCapacity(r,t,y) *
(1 - (smax(yy, YearVal(yy)) - YearVal(y) + 1) / OperationalLife(r,t))

SV3_SalvageValueAtEndOfPeriod3(r,t,y)$((YearVal(y) + OperationalLife(r,t) - 1) <= (smax(yy,
YearVal(yy)))).. SalvageValue(r,t,y) = 0
```

45. There are tree equations concerning operating cost. Equation OC1 and OC2 calculates respectively variable and fixed costs while equation OC3 determines total operational cost of technology.

```
OC1_OperatingCostsVariable(r,t,y).. sum(m, TotalAnnualTechnologyActivityByMode(r,t,m,y) *
(VariableCost(r,t,m,y) -VariableSubvention(r,t,m,y))) = AnnualVariableOperatingCost(r,t,y)

OC2_OperatingCostsFixedAnnual(r,t,y).. TotalCapacityAnnual(r,t,y) * FixedCost(r,t,y) =
AnnualFixedOperatingCost(r,t,y)

OC3_OperatingCostsTotalAnnual(r,t,y).. AnnualFixedOperatingCost(r,t,y) +
AnnualVariableOperatingCost(r,t,y) = OperatingCost(r,t,y)
```

46. Cost related to emissions are calculated in equations E3 and E4. It should be mentioned, there is an additional parameter in E3 equation, not included in original OSeMOSYS – *FreeAlloc* which is used to define share of free CO_2 allowances for particular type of technology. This was implemented in order to reflect some measures of EU ETS (CO_2 trading system).

```
E3_EmissionsPenaltyByTechAndEmission(r,t,e,y).. AnnualTechnologyEmission(r,t,e,y)
*EmissionsPenalty(r,e,y) * (1 -FreeAlloc(r,t,e,y)) =
AnnualTechnologyEmissionPenaltyByEmission(r,t,e,y)

E4_EmissionsPenaltyByTechnology(r,t,y).. sum(e,
AnnualTechnologyEmissionPenaltyByEmission(r,t,e,y)) = AnnualTechnologyEmissionsPenalty(r,t,y)
```

47. Total cost – combines all technology costs and then summarizes cost of all technologies into the whole region cost (total cost).

```
TDC1_TotalDiscountedCostByTechnology(r,t,y).. DiscountedOperatingCost(r,t,y) +
DiscountedCapitalInvestment(r,t,y) + DiscountedTechnologyEmissionsPenalty(r,t,y) -
DiscountedSalvageValue(r,t,y) =e= TotalDiscountedCostByTechnology(r,t,y)

TDC2_TotalDiscountedCost(r,y).. sum(t, TotalDiscountedCostByTechnology(r,t,y)) +
sum(s,TotalDiscountedStorageCost(r,s,y)) =e= TotalDiscountedCost(r,y)
```

48. Sum of regional total discounted cost is the total cost of entire system which minimization is an objective function (mentioned earlier).

- **Emissions:**

49. Environmental impact of technology is defined by emission factor and is related to activity level. Whether emission factor is connected to input fuels or to energy production depends on adopted convention to input and output activity ratio. In MEESA (same as in original OSeMOSYS) we assume that sum of output activity ratio is 1 and input activity ratio is higher than 1 (1 divided by technology efficiency) – thus emission factor of technology is related to energy production. However in case of CO_2 emissions it is more convenient to use emission factor related to fuel input – therefore Excel file containing MEESA data

tables have an option to convert emission factors related to fuel use, into form used by model (for output activity).

50. Amount of emission from given technology is calculated by multiplying emission factor (*emission activity ratio*) by technology activity in each mode and summarized for annual period (equations E1 and E2). Note that different activity mode could be characterized by different emission factors. In MEESA this functionality is used for example in modelling biomass co-firing in coal power plants.

```
E1_AnnualEmissionProductionByMode(r,t,e,m,y).. EmissionActivityRatio(r,t,e,m,y) *
TotalAnnualTechnologyActivityByMode(r,t,m,y) = AnnualTechnologyEmissionByMode(r,t,e,m,y)

E2_AnnualEmissionProduction(r,t,e,y).. sum(m, AnnualTechnologyEmissionByMode(r,t,e,m,y)) =
AnnualTechnologyEmission(r,t,e,y)
```

51. Equations E3-E5 are used for emission cost calculations and were described above. Equation E6 and E7 calculates the sum of annual emission for particular year for specific region and then for entire modelling period. Equations E8 and E9 provides possibility of establishing maximum emission levels.

```
E6_EmissionsAccounting1(r,e,y).. sum(t, AnnualTechnologyEmission(r,t,e,y)) = AnnualEmissions(r,e,y)

E7_EmissionsAccounting2(r,e).. sum(y, AnnualEmissions(r,e,y)) = ModelPeriodEmissions(r,e) -
ModelPeriodExogenousEmission(r,e)

E8_AnnualEmissionsLimit(r,e,y).. AnnualEmissions(r,e,y) + AnnualExogenousEmission(r,e,y) <=
AnnualEmissionLimit(r,e,y)

E9_ModelPeriodEmissionsLimit(r,e).. ModelPeriodEmissions(r,e) <= ModelPeriodEmissionLimit(r,e)
```

52. Because MEESA is a European scale model, there was a need to calculate sum of emissions for all regions as well as for establishing emission limits on global level (in order to examine different options of European climate policies). Therefore additional equations E10 and E11 have been implemented in MEESA.

```
E10_ModelGlobalEmissionsLimit(e,y).. GlobalEmissions(e,y) = sum(r, AnnualEmissions(r,e,y) +
AnnualExogenousEmission(r,e,y))

E11_ModelGlobalEmissionsLimit(e,y).. GlobalEmissions(e,y) <= GlobalEmissionLimit(e,y)
```

- **Storages:**

53. Storages are model elements that differ from typical technology. With ability to store certain amount of energy, storages could represent different types of energy accumulators. Storages are connected to the rest of energy system through special technologies which are used to charge and discharge storage. In MEESA storages are used mainly to model hydro-pumped storages, and large batteries which role probably will be growing in the future following the fast development of renewable sources. Storage

equation system is large and one of the most complicated part of the model, but not essential to understand general model behaviour and logic. Therefore only brief description of storage system is given here.

54. Storages have some features similar to other technologies like capital cost, operational life, residual capacity while other – like connection to charging technology or charge and discharge rates are specific for storages. Nevertheless the main difference is that for other technologies energy balances are calculated for defined time-slices, while for storages energy balances are calculated in a more complicated way – in order to reflect its daily and day to day activity, taking into account the order of successive periods of the day and different days of the week. That way energy could be stored on nights or weekend days (because of lower demand level) and then used during peak demand on working days.

55. Typically in linear optimisation model of energy sector, particular technology defined within model represent sum of all energy sources of that kind. Generally it is justified simplification, but in some cases this could rise a serious problem. One of such examples would be modelling small household energy storage. The problem is model treats the sum of individual devices like one big unit with a very large storage capacity, which could be charged within a season and discharged gradually in next season or even next year. In some cases model gradually increases storage capacity, slowly charge them and keep energy stored for years. This of course doesn't reflect how small energy storages work.

56. Therefore new equation connecting maximum storage capacity with charging technology was implemented. The equation introduces new parameter StorageHours – which defines storage capacity in terms of available hours of discharge with maximum power. This prevents too fast development of storage capacity and ensures more realistic behaviour of short term energy storages. It is especially useful for modelling house batteries and electric cars.

3.3. Main differences between MEESA and original OSeMOSYS Platform

57. As it was mentioned before, MEESA is based on OSeMOSYS energy model. Apart from obvious differences concerning programming language and scope of the model data structure there are other important differences. Some changes refer to model features, while other to performance issues.

3.3.1. Functionality changes

- **Mixed integer programing**

58. Original OSeMOSYS allows to solve classic linear problems as well as mixed integer problems (MIP). Unfortunately MIP problems are very demanding in terms of computing time. MEESA has been constructed from the beginning to cover a large energy system – that is why decision has been made to skip MIP functionality and remove relevant equations for better clarity (equation CAa5 *Total new capacity* has been removed along with *capacity of one technology unit* parameter and *number of new technology units* variable).

- **Renewables generation target**

59. One of the original OSeMOSYS features is the possibility of forcing the model to achieve certain share of energy generation from renewable sources. The user defines which technologies are considered renewable sources, then sets required share of renewables production and determines which energy carrier will be used as a reference point.

60. Unfortunately such approach has some limitations – it is not possible to define technology that produce energy from renewable sources in one mode of operation and from fossil fuels in another – this means that in case of multi-fuel installations only fixed share of fuels would be possible. This is a significant limitation, because in fossil fuels and biomass co-firing power plants amount of renewable fuel may change in wide range depending on fuel prices, subsidies and other incentives (in some countries biomass co-firing has an important role in renewable energy production).

61. Therefore MEESA uses different approach to accounting energy from renewable sources. In MEESA model each renewable technology apart from normal electricity production, generates also additional artificial commodity (which could be also recognized as a form of certificate for renewable energy). Required level of electricity production from renewable is defined as share of final electricity consumption (this share is deducted by amount of energy used for green hydrogen generation).

62. This approach is slightly different to original way of defining renewable share in OSeMOSYS, using additional green energy carrier rather than technology activity for

defining share of renewable production. With this method model can decide what share of biomass (up to specific level) would be used in co-firing power plants, based on emission restrictions, energy and CO_2 allowances prices, renewable share etc. while in original approach share of co-firing would be fixed. In fact dynamic change in biomass co-firing depending on CO_2 prices and required share of renewable energy was observed in Poland.

63. In order to implement that equations *RE2 Tech included*, *RE3 Fuel included*, *RE4 Energy constraints* where redefined to calculate defined green energy carrier production instead of technology activity. This also changes meaning of some model variables used in these equations.

64. In case of equation modification or removal general rule is adopted that original OSeMOSYS names and numbers stay unchanged in order to keep MEESA as comparable to OSeMOSYS as possible (that's why in MEESA equation RE1 and RE5 are next to each other).

- **Capacity factor**

65. In MEESA model the way capacity factor works has been slightly modified in comparison to OSeMOSYS. In general, capacity factor could be used to model changes of technology effectiveness over time. It could simulate deterioration of old units or improvements of new investments. In practice it is used mainly for the latter, because in area of energy technologies (especially some renewable sources) there is a fast technological progress observed. In OSeMOSYS capacity factor affects every instance of given technology – new as well as old ones the same way. In theory this effect could be avoided by defining different technology for every year (or at least some time periods) but in practice this would hugely affect model performance.

66. Therefore that behaviour has been changed in MEESA by connecting capacity factor of particular technology to its construction year. This way new investments have improved capacity factor while existing ones use capacity factor related to construction year (in case of residual capacity – the first modelling year). In order to implement this feature, equations *CAa4 Constraint Capacity* and *CAb1 Planned Maintenance* are modified in MEESA model.

67. Modified equations are slightly more complicated than original ones, but are more convenient for modelling renewable sources. However, it must be kept in mind, that capacity factor no longer can be used for simulating technology efficiency drop over time – instead *availability factor* or *input activity ratio* (in other words efficiency) should be used.

- **Capacity factor min**

68. The minimal capacity factor forces model to use certain kind of technology to be active at least at some defined level in every time-slices. It was implemented to model situations when some technologies are used at least at some minimal level all the time in order to

maintain voltage stability, grid safety or because of some industrial processes needs. This functionality has been implemented in equation CAb2.

- **Global emission limit**

69. In original OSeMOSYS model emission limits are set for individual regions, which of course still could be done in MEESA. But in case of modelling CO_2 emissions it is useful to have possibility for setting one common limit for all the regions – and find out optimal reduction path for entire system. With this additional feature it is also possible to estimate global marginal reduction costs.

70. This is implemented in MEESA by adding E10 and E11 equations (described above in source code section).

- **Subsidies for renewable sources**

71. There are several different mechanisms to consider renewable sources support in the model. The first method defines minimal level of energy from renewables production as constraint to be met. The second method is similar, but obligations could be fulfilled not only by real electricity generation but also by paying a fee for not meeting the required amount of energy production. This is similar to green certificate systems introduced in some countries. This way also transfer of obligations between different countries could be modelled.

72. The other methods involve direct financial support for investment or energy generation and can be done by changes in the technology costs. However, it is important to understand, that such direct financial support for renewables can be useful for testing effectiveness of subsidies from the perspective of individual investor - but at the same time it can lead to misunderstandings when compared to scenarios without subsidies. Especially in terms of total cost and optimal solutions for the entire system. The problem is that such subsidies in a model are not perceived as costs – on the contrary – it seems as financial aid out of the system, while in real life subsidies are the costs paid by state or final energy consumers. The user has to be aware of this limitations.

- **Cost curve for renewable sources**

73. In MEESA an additional cost raising mechanism for renewable sources was implemented. This feature (made as parallel part of source code) can be enabled during the model execution. It splits the overall potential of given renewable source into several parts with different cost, modelled by assumed exponential growth curve. In case of photovoltaics, wind turbines and heat pumps investment costs are increased, while in case of biomass and biogas – fuel costs. This approach better reflects the situation of limited renewable resources and seems particularly useful when analysing very ambitious climate goals.

- **Interest during construction (IDC)**

74. In OSeMOSYS capital cost are overnight costs, without taking into account interest incurred during construction. If one want to take into account IDC cost it must be calculated outside of the model and input directly as capital cost. The problem arise when user want to make calculations for different discount rate, because IDC cost must be recalculated and manually changed for each technology. In MEESA IDC cost are calculated within the model from capital cost, discount rate and construction time – defined for every technology. This calculation take place after importing data into the model, before the optimisation process start. There is however an simplifying assumption that capital cost are spread evenly during the construction time.

```
CapitalCost(r, t, y) = CapitalCost(r, t, y) * (-1/ConstructionTime(r, t)*(1-(1/(1+DiscountRate(r))**(-
ConstructionTime(r, t))))/(1-1/(1+DiscountRate(r))));
```

75. Similar equation is used for calculating IDC cost for storages.

- **Changes to energy storage**

76. In order to implement short term energy storage new equation *SC8_SeasonalBalance* was introduced along with new parameter *StorageLongPercent*.

```
SC8_SeasonalBalance(r, s, ls, y).. sum((ld, lh), NetChargeWithinYear(r, s, ls, ld, lh, y)) <=
StorageLongPercent(s)*StorageUpperLimit(r, s, y);
```

77. Although it looks like parameter *StorageLongPercent* limits the amount of energy which could be transferred between seasons, in practice, due to the way the whole system of equations for modelling storages works (a specific season consists of identical weeks), it limits the energy transferred between two weeks.

78. Therefore when parameter *StorageLongPercent(s)* is defined as 1, particular storage works like in OSeMOSYS – energy could be stored indefinitely. If parameter is defined as 0 – storage must be charged and discharged within a week. This allows to model small household's batteries or electric cars.

79. There were implemented two new equations into the storage modelling system. First equation connects maximum storage capacity with charging technology which prevents too fast development of storage capacity in relation to charging power. Without this model could, in some situations, increase storage capacity, slowly charge them and keep energy stored for years.

```
SI1b_StorageUpperLimit_hour(r,s,yd).. StorageUpperLimit(r,s,yd) <=
sum((t,m)$(TechnologyToStorage(r,t,s,m)>0),
StorageHours(r,s)*TechnologyToStorage(r,t,s,m)*TotalCapacityAnnual(r, t, yd)/1000*3.6)
```

80. This equation introduces new parameter StorageHours – which defines storage capacity in terms available hours of discharge with maximum power. For example we assume that house battery storages will be able to work for 4 hours with given power.

81. Second equation implements limits on new investment in storage capacity. This way we could reflect some barriers and prevent unrealistically rapid development of storage potential.

```
SI4b_MaxNewStorageCapacity(r, s, yd).. NewStorageCapacity(r,s,yd) <=
MaxNewStorageCapacity(r,s)
```

- **Parameter “Existing”**

82. MEESA uses this new parameter to establish whether particular technology is defined within specific region. This parameter was introduced in order to reduce computing performance issues (see next chapter).

- **Technology cost increase as the potential is depleted**

83. This option allows to model increasing cost for particular technologies in case of limited resources. It is used mainly for renewable sources to reflect the fact that the best sites are used first, but eventually also not optimal locations will be used, which will result in an increased generation costs. To use this mechanism user has to define (in dedicated text file) cost increase as a function of maximal potential used for particular technology. Technically this option doesn’t change model itself, because this operation is performed dynamically during data reading phase and before solver starts. From solver perspective this option defines set of additional technologies with new parameters, but it doesn’t change the original input data or results files structure.

3.3.2. Performance related changes

84. Perhaps, the most important were the changes made to increase model computational performance. In case of very large data files OSeMOSYS model is very computationally demanding – especially in terms of memory usage. Even using fast IBM CPLEX solver, model for all EU countries with about 50 technologies in each country is practically impossible to solve on personal computer because of very large amount of memory needed and very long calculation time. In the first step of calculation process large matrix is created from the model definition. This is sparse matrix which is then optimized and reduced during the presolving process and before actual calculations. Unfortunately, in case of very large model, input matrix could be too big to be dealt with by presolver, because of insufficient computer memory – in that case actual calculations couldn’t even start.

85. Therefore it’s critical to reduce the size of the matrix from the beginning, by removal of unnecessary elements at the stage of equation formulation. To do this the most memory consuming equations have been identified and modified by additional conditions that filter out unused elements in the equations.

86. Below the full list of equations changed in order to increase model performance have been presented. The modifications have been marked in red.

```
EQ_SpecifiedDemand(r, l, f, y)$(SpecifiedAnnualDemand(r,f,y)<>0)..
SpecifiedAnnualDemand(r,f,y)*SpecifiedDemandProfile(r,f,l,y) /
YearSplit(l,y)=e=RateOfDemand(r,l,f,y);

CAa1_TotalNewCapacity(r,t,y)$(Existing(r,t)<>0).. AccumulatedNewCapacity(r,t,y) =e=
sum(yy$((YearVal(y)-YearVal(yy)) < Existing(r,t) and (YearVal(y)-YearVal(yy))>=0),
NewCapacity(r,t,yy));

CAa2_TotalAnnualCapacity(r,t,y)$(Existing(r,t)<>0).. AccumulatedNewCapacity(r,t,y)+
ResidualCapacity(r,t,y) =e= TotalCapacityAnnual(r,t,y);

CAa3_TotalActivityOfEachTechnology(r,l,t,y)$(Existing(r,t)<>0).. sum(m, RateOfActivity(r,l,t,m,y)) =e=
RateOfTotalActivity(r,l,t,y);

CAa4_Constraint_Capacity(r,l,t,y)$(Existing(r,t)<>0).. RateOfTotalActivity(r,l,t,y) =l=
(sum(yy$((YearVal(y)-YearVal(yy)) < Existing(r,t) AND (YearVal(y)-YearVal(yy)>=0)),
NewCapacity(r,t,yy)*CapacityFactor(r,t,l,yy))+ResidualCapacity(r,t,y)* smin(y0,
CapacityFactor(r,t,l,y0)))*CapacityToActivityUnit(r,t)

CAb1_PlannedMaintenance(r,t,y)$(Existing(r,t)<>0).. sum(l,RateOfTotalActivity(r,l,t,y)*YearSplit(l,y))
=l= sum(l,(sum(yy$((YearVal(y)-YearVal(yy)) < Existing(r,t) AND (YearVal(y)-YearVal(yy)>=0)),
NewCapacity(r,t,yy)*CapacityFactor(r,t,l,yy))+ResidualCapacity(r,t,y)* smin(y0,
CapacityFactor(r,t,l,y0)))* YearSplit(l,y))*AvailabilityFactor(r,t,y)*CapacityToActivityUnit(r,t)

CAb2_PlannedMaintenance(r,t,l,y)$(Existing(r,t)<>0).. sum(m, RateOfActivity(r,l,t,m,y)*YearSplit(l,y))
=g= ((sum(yy$((YearVal(y)-YearVal(yy) < Existing(r,t)) AND (YearVal(y)-YearVal(yy) >=0)),
NewCapacity(r,t,yy))+ ResidualCapacity(r,t,y))*CapacityFactorMIN(r,t,y)*YearSplit(l,y))*
AvailabilityFactor(r,t,y)*CapacityToActivityUnit(r,t);

EBa2_RateOfFuelProduction2(r,l,f,t,y)$(sum(m,OutputActivityRatio(r,t,f,m,y)<>0))..
sum(m$(OutputActivityRatio(r,t,f,m,y) <>0), RateOfProductionByTechnologyByMode(r,l,t,m,f,y)) =e=
RateOfProductionByTechnology(r,l,t,f,y)

EBa3_RateOfFuelProduction3(r,l,f,y).. sum(t$(sum(m,OutputActivityRatio(r,t,f,m,y)<>0)),
RateOfProductionByTechnology(r,l,t,f,y)) =e= RateOfProduction(r,l,f,y);

EBa5_RateOfFuelUse2(r,l,f,t,y)$(sum(m,InputActivityRatio(r,t,f,m,y)<>0))..
sum(m$(InputActivityRatio(r,t,f,m,y)<>0), RateOfUseByTechnologyByMode(r,l,t,m,f,y)) =e=
RateOfUseByTechnology(r,l,t,f,y);

EBa6_RateOfFuelUse3(r,l,f,y).. sum(t$(sum(m,InputActivityRatio(r,t,f,m,y)<>0)),
RateOfUseByTechnology(r,l,t,f,y)) =e= RateOfUse(r,l,f,y);

Acc1_FuelProductionByTechnology(r,l,t,f,y)$(sum(m,OutputActivityRatio(r,t,f,m,y))<>0)..
RateOfProductionByTechnology(r,l,t,f,y) * YearSplit(l,y) =e= ProductionByTechnology(r,l,t,f,y);

Acc2_FuelUseByTechnology(r,l,t,f,y)$(sum(m,InputActivityRatio(r,t,f,m,y))<>0)..
RateOfUseByTechnology(r,l,t,f,y) * YearSplit(l,y) =e= UseByTechnology(r,l,t,f,y);
```

```
RE1_FuelProductionByTechnologyAnnual(r,t,f,y)$(sum(m,OutputActivityRatio(r,t,f,m,y))<>0).. sum(l,
ProductionByTechnology(r,l,t,f,y)) =e= ProductionByTechnologyAnnual(r,t,f,y);

RE5_FuelUseByTechnologyAnnual(r,t,f,y)$(sum(m,InputActivityRatio(r,t,f,m,y))<>0).. sum(l,
RateOfUseByTechnology(r,l,t,f,y)*YearSplit(l,y)) =e= UseByTechnologyAnnual(r,t,f,y);

EBa10_EnergyBalanceEachTS4(r,rr,l,f,y)$(TradeRoute(r,rr,f,y)<>0).. Trade(r,rr,l,f,y) =e= -
Trade(rr,r,l,f,y);

EBb3_EnergyBalanceEachYear3(r,rr,f,y)$(TradeRoute(r,rr,f,y)<>0).. sum(l, Trade(r,rr,l,f,y)) =e=
TradeAnnual(r,rr,f,y);
```

87. Region aggregations – current version of the MEESA model enables dynamic aggregation of individual regions into larger structures that define a new set of regions. This option was introduced for performance issues as well as for compatibility with other modelling tools – especially CGE model which can be used in connection with MEESA. In order to create aggregated regions user has to define data set which maps every original region with new set of regions. Then each parameter for every technology is automatically recalculated for the new regions – depending on specific parameter it could be simple summation, weighed average but in case of some parameters more complex calculation is required (e.g. interconnection capabilities which are deducted by interconnection capacity between aggregated countries).

88. 5-year calculation period – this feature was introduced, similarly to region aggregation, both for performance and compatibility reasons. It makes possible to solve the model for 5-year periods instead of for each year. Of course with this approach results are somewhat simplified, but the difference in the final results between the full and simplified version are relatively small, so unless it is necessary to obtain results for every year it is justified to use this simplified version, as it significantly reduces the calculation time and it is easy to switch between both options.

4. Data files, data reading procedure, result files

89. The data entry method has been changed in the MEESA model compared to the original OSeMOSYS, where data for all parameters are stored in large tables. MEESA uses more flexible approach to setting model parameters, based on raw data inputting raw data mixed with using formulas and macros written in the gams programming language. For example – this way it is not necessary to define repeatedly same parameter for many regions – it could be done by one line of code instead of large multidimensional table. Similar way any technological changes (like e.g. efficiency improvement in the following years) could be implemented by programming code rather than inserting direct numbers for every year. This makes the input data easier to read and maintain.

90. Data file includes also several additional macros and functions written in gams programming language to facilitate data entry, processing and validation. Before starting the actual calculation process, the data is pre-processed. This includes checking the data for conflicting constraints and other possible data integrity issues. This phase also includes a data rounding procedure to avoid possible problems with numerical instability during the calculation.

91. In an additional file user can choose several options with which the model will be launched: regional aggregation, 5-year time calculation, extended version of time-slices, reading data from the CGE model (used in iterations with other models) and cost increase option. Then the optimization process begins. The number of iterations depends extensively on model size, therefore it is very important to use the available options for regions aggregation and calculating over 5-year periods whenever possible. Once calculations are over raw results are saved into several csv files – this are very large text files not very convenient for direct analysing. Therefore an additional Excel file was made to import model results and to review it in more convenient way. There are several tables for different result aspects (for every region and technology), e.g.:

- Capacity and investments: total capacity of every technology, new investments, reserve margin, short-term power generation (in time-slices),
- Activity of technology: global fuel structure of electricity generation, annual electricity and district heat production per technology and country, activity in particular time-slice, fuel use, electricity cross-border exchange, renewable energy production, green hydrogen production and consumption for electricity and district heat generation,
- Emissions: global and country level emissions, emissions of particular technology,
- Costs: total cost, technology specific cost, country specific electricity generation costs, marginal energy cost,

- Other (depends on): effective constraints, marginal cost of electricity per region in every timeslice, marginal cost of emission reduction.

5. Data collecting and model calibrating process

5.1. Main data sources

92. The main objective of this chapter is to provide an overview of the major data inputs and their sources in order to better understand what type of information the model is based on. It also would facilitate future information exchange with other modelling teams and stakeholders. The proposed energy model required preparation of an extensive set of input data to reflect characteristic features of energy systems in the considered region. These data are as follows:

    - demand curves,
    - net installed capacity, net electricity and district heat production, fuel use,
    - CO_2 emissions from the power & district heat sector,
    - world fuel prices and CO_2 emission allowance prices,
    - cross-border interconnections and planned development,
    - potential of individual resources/technologies in different countries,
    - electricity prices (for model calibration – in general electricity cost are endogenous in MEESA).

93. Data mentioned above are prepared for the all 27 UE member countries (plus United Kingdom, Switzerland and Norway). 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) and Non-EU countries (United Kingdom, Switzerland, Norway). Considering electricity flows in MEESA model three options based on ENTSO-E data - described in 5.1.5. - are possible. First, country by country with specific information from which to which country electricity flows - the most demanding but also the most profitable. Second, node by node - less demanding with import and export information only in aggregated regions. Third, each country has its own capacity import and export constrains but there is no information from which to which country or region electricity flows. Because of computation limits now the last option is considered in the model.

94. There is an artificial node for balancing fuels import to EU named YYY. This node can be used also in balancing import and export of electricity - now in the less computationally

intensive option based on 2015 data electricity flows between modelled countries and YYY is equal to zero.

Table 1. 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

As it was mentioned before current MEESA version implements option for dynamic region aggregation. This is especially useful when MEESA is used in iterative manner with CGE model and sectoral models. Current region aggregation is shown in table 2 but as the aggregation is performed dynamically on original data it can be easily changed if necessary.

Table 2. Aggregated regions considered in MEESA model and respective codes

Aggregated region code	Country code
BEN	BEL + LUX, NLD
CEU	AUT, CHE, CZE, HUN, SVK, SVN
IBI	ESP, ITA + MLT, PRT
NTH	DNK, EST, FIN, LTU, LVA, NOR, SWE
STH	BGR, GRC + CYP, HRV, ROM
UKI	GBR, IRL
DEU	DEU
FRA	FRA
POL	POL

Source: CAKE/KOBiZE own study

5.1.1. Demand curves

95. Data used for building demand curves are taken from ENTSO-E Transparency Platform.[5] These curves are based on:

- Actual Total Load - for all countries (except Cyprus and Malta),
- Day-ahead Total Load Forecast - for Cyprus (because of lack of Actual Total Load data)
- the Cyprus curve corrected using the relation of yearly gross electricity consumption in these countries - for Malta (because of lack of any load data).

96. In cases there was observed a lack of data or data was far from desirable level the data was changed base on:

- Day-ahead Total Load Forecast - for big countries,
- Similar time period - for small countries.

97. These assumptions are based on the observed better fit to real electricity production curve. High consumption is very well predicted by TSOs, while small is not. That's why for small countries the principle of using previous/next day or the same day from previous/next week works better.

98. TSOs report load the data in 1 hour, 30 minutes or in 15 minutes slices. All data are recalculated to 1 hour slices.

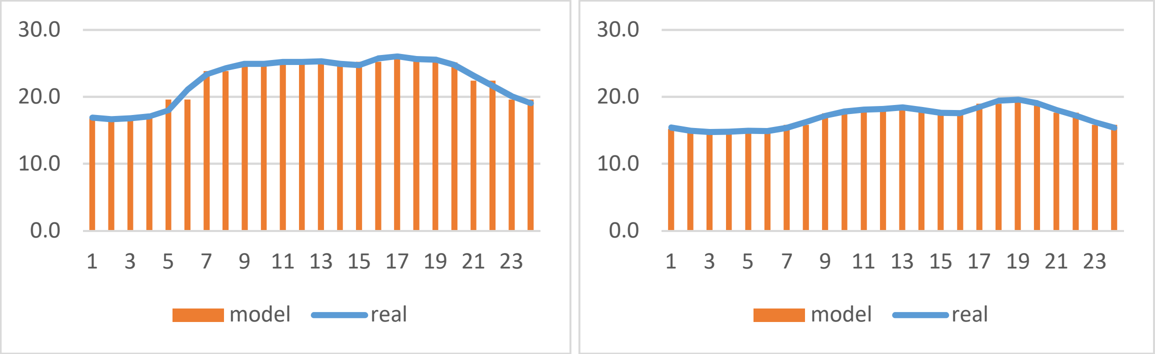
---

[5] ENTSO-E. Transparency Platform. Brussels. https://transparency.entsoe.eu

99. This data has been processed, and converted into demands for model time periods (time-slices). It is important to understand that in case of long-term energy system modelling, setting an actual hourly demand based on historical data is not feasible because of extensive performance burden. In MEESA year is divided into 18 or 72 periods consisting of two seasons (Winter, Summer), three day types (working days with different demand and weather conditions and weekends) and three daily periods (night, day, peak) in case of 18 time-slices demand curve or twelve 2-hour daily periods for 72 time-slices demand curve (see also time-slices in section 3.1.A.). The real demand curves are approximated into mentioned modelling periods. Specific daily load curve for workdays and weekends for each country are selected for every season as, respectively, days in which maximum and minimum demand occurred. In case of electricity sector extreme states of the system are most problematic and it is equally important to reflect maximum and minimum demand properly as to meet the average energy consumption. Following the approximation process additional small adjustment has been made (mainly for night periods) to avoid inconsistencies between real annual energy demand and demand calculated from integration of modelling short periods demand. The same procedure has been applied for each country.

100. Exemplary load curve for winter days with its modelling approximation is presented below.

Figure 3. Real and model demand curve for winter - workdays (left) and weekends (right) in Poland [GW]



Source: CAKE/KOBiZE own study

5.1.2. Installed capacity, net electricity and district heat production, fuel use

101. The type of 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, hydrogen	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, biomass	Electricity, heat
17.	Hard coal chp	Hard coal, lignite, biomass	Electricity, heat
18.	Gas chp old	Natural gas	Electricity, heat
19.	Gas chp	Natural gas, hydrogen	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.	Biomass power plant + CCS	Biomass	Electricity
30.	Biomass chp + CCS	Biomass	Electricity, heat
31.	Biogas chp	Biogas	Electricity, heat
32.	Photovoltaic	Sun energy	Electricity
33.	Small photovoltaic**	Sun energy	Electricity
34.	Industrial old chp (mixed fuels)	Hard coal, lignite, oil, natural gas, renewable waste, non-renewable waste, other, biogas, biomass	Electricity, heat
35.	Hard coal heat plant	Hard coal, lignite, electricity	Heat
36.	Gas heat plant	Natural gas, hydrogen, electricity	Heat
37.	Oil heat plant	Oil, electricity	Heat
38.	Biomass heat plant	Biomass, biogas, electricity	Heat
39.	Geothermal heat plant	Geothermal energy, electricity	Heat, electricity*
40.	Heat waste	Renewable and non-renewable waste	Heat
41.	Large district heating heat pump	Electricity	Heat
42.	Heat pump – distributed***	Electricity	Heat
43.	Electric boiler – distributed***	Electricity	Heat

44.	Gas heat plant – distributed***	Natural gas, electricity	Heat
45.	Hydrogen production	Electricity	Hydrogen
46.	Hydrogen storage	Hydrogen	Hydrogen
47.	Household electric storage (batteries)	Electricity	Electricity
48.	Electric cars (electricity storage)	Electricity (storage)	Electricity (final consumption)
49.	Hard coal import	-	Hard coal
50.	Hard coal mine	-	Hard coal
51.	Lignite mine	-	Lignite
52.	Natural gas import	-	Natural gas
53.	Natural gas extraction	-	Natural gas
54.	Oil import	-	Oil
55.	Uranium import	-	Nuclear fuel
56.	Biomass production	-	Biomass
57.	Biogas production	-	Biogas
58.	Waste production	-	Non-renewable waste
59.	Waste bio production	-	Renewable waste
60.	Other fuels production	-	Other
61.	Electricity transmission	Electricity	Electricity
62.	Electricity distribution	Electricity	Electricity
63.	Heat distribution	Heat	Heat
64.	Sun energy production****	-	Sun energy
65.	Wind onshore energy****	-	Wind onshore energy
66.	Wind offshore energy****	-	Wind offshore energy

67.	Hydro energy****	-	Hydro energy
68.	Geothermal energy****	-	Geothermal energy

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 possible change in heat consumption. Taking into account current and future restrictions on emissions and 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 this technologies connected at final stage of production and consumption (different prices and losses are taking into account).*

****Artificial technology used for modelling production of renewable energy carrier.*

Source: CAKE/KOBiZE own study

102. The main sources of statistical data for the base year (2020) are: EUROSTAT[6], ENTSO-E[7,8], IEA[9], 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 the option of biomass co-firing in coal plants. Table 4 presents the source of statistical information used in calibration of the base year.

Table 4. Source of statistical information used in base year calibration process

Type of data	Type of unit (existing)	Source
Net installed capacity	Hard coal PP	EUROSTAT, ENTSO-E
	Lignite PP	EUROSTAT, ENTSO-E
	Gas PP	EUROSTAT, ENTSO-E
	Nuclear PP	EUROSTAT, ENTSO-E
	Biomass PP	EUROSTAT, ENTSO-E, IEA
	Oil PP	EUROSTAT, ENTSO-E
	Peak gas turbine	EUROSTAT, ENTSO-E
	Pumped storage hydro plant	EUROSTAT, ENTSO-E

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[6] European Commission. EUROSTAT Database. Luxembourg, https://ec.europa.eu/eurostat/data/database

[7] ENTSO-E (2018). Ten Year Network Development Plan 2018. Brussels.

[8] ENTSO-E (2020). Ten Year Network Development Plan 2020. Brussels.

[9] IEA. OECD.Stat. Paris, https://stats.oecd.org

	Hard coal CHP	Own assumptions, EUROSTAT, EC Country datasheets
	Gas CHP	Own assumptions, EUROSTAT, EC Country datasheets
	Oil CHP	Own assumptions, EUROSTAT, EC Country datasheets
	Geothermal	ENTSO-E
	Onshore wind turbine	ENTSO-E
	Offshore wind turbine	ENTSO-E
	Large hydro power plant	EUROSTAT
	Small hydro power plant	EUROSTAT
	Biomass CHP	Own assumptions, EUROSTAT
	Biogas CHP	Own assumptions, EUROSTAT
	Large photovoltaic	EUROSTAT, ENTSO-E
	Small photovoltaic	ENTSO-E
	Autoproducer oil CHP	Own assumptions
	Autoproducer coal CHP	Own assumptions
	Autoproducer biomass CHP	Own assumptions
	Autoproducer gas CHP	Own assumptions
	Autoproducer other CHP	Own assumptions, EUROSTAT
	Waste CHP (non-renewable)	Own assumptions, EUROSTAT, ENTSO-E
	Waste CHP (renewable)	Own assumptions, EUROSTAT, ENTSO-E
	Hard coal heat plant	Own assumptions, IEA
	Gas heat plant	Own assumptions, IEA
	Oil heat plant	Own assumptions, IEA
	Biomass heat plant	Own assumptions, IEA
	Other fuel heat plant	Own assumptions, IEA
Net electricity production	Hard coal PP	ENTSO-E, EUROSTAT, Own assumptions
	Lignite PP	ENTSO-E, EUROSTAT

	Gas PP	ENTSO-E, EUROSTAT, Own assumptions
	Nuclear PP	ENTSO-E, EUROSTAT
	Biomass PP	EUROSTAT, ENTSO-E, ARE SA, Own assumptions
	Oil PP	ENTSO-E, EUROSTAT, Own assumptions
	Peak gas turbine	Own assumptions
	Pumped storage hydro plant	EUROSTAT, ENTSO-E
	Hard coal CHP	Own assumptions, EUROSTAT
	Gas CHP	Own assumptions, EUROSTAT
	Oil CHP	Own assumptions, EUROSTAT
	Geothermal	ENTSO-E, EUROSTAT
	Onshore wind turbine	ENTSO-E, EUROSTAT
	Offshore wind turbine	ENTSO-E, EUROSTAT
	Large hydro power plant	EUROSTAT
	Small hydro power plant	EUROSTAT
	Biomass CHP	Own assumptions, EUROSTAT
	Biogas CHP	Own assumptions, EUROSTAT
	Large photovoltaic	EUROSTAT, ENTSO-E
	Small photovoltaic	EUROSTAT, ENTSO-E
	Autoproducer oil CHP	Own assumptions, EUROSTAT
	Autoproducer coal CHP	Own assumptions, EUROSTAT
	Autoproducer biomass CHP	Own assumptions, EUROSTAT
	Autoproducer gas CHP	Own assumptions, EUROSTAT
	Autoproducer other CHP	Own assumptions, EUROSTAT
	Waste CHP (non-renewable)	Own assumptions, EUROSTAT, ENTSO-E
	Waste CHP (renewable)	Own assumptions, EUROSTAT, ENTSO-E
	Hard coal heat plant	Own assumptions, IEA

	Gas heat plant	Own assumptions, IEA
	Oil heat plant	Own assumptions, IEA
	Biomass heat plant	Own assumptions, IEA
	Other fuel heat plant	Own assumptions, IEA
Derived heat production	All relevant technologies	EUROSTAT
Fuel use	Power plants	EUROSTAT, IEA (Energy balances)
	CHP Plants	Own assumptions, based on EUROSTAT and IEA data

Source: CAKE/KOBiZE own study

5.1.3. CO_2 emissions from the power & district heat sector

103. The CO_2 emission factors for individual power and heat generation technologies are an important element of the model. Individual data for each fuel was taken from 2006 IPCC[10] and KOBiZE database. The emission coefficients considered in the given database are the ones used in several national emission inventories. In case of the electricity and heat generation emissions, the CO_2 emission coefficients are technology dependent and vary according to technologies performance. Model emission values should be in line with statistical emission data for base year. Unfortunately modelling results compared to EUROSTAT data – CO_2 emission from Public Electricity and Heat Production were slightly different – mainly due to inconsistencies in accounting industrial CHP emissions in some countries in EUROSTAT database. Problem was solved by using JRC IDEES emission database[11] instead - MEESA results are very similar to CO_2 emission level reported by this database for all electricity and district heat production (sum of CHP, PP and HP emissions). Description of the calibration of the CO_2 emission balance for the base year is given in the section 6.6. CO_2 emission country balance.

5.1.4. World fuel prices and CO_2 emission allowance prices

104. Model takes the evolution of fossil fuel prices imported to UE as exogenous assumptions. Ultimately, these data will come from the d-PLACE model. For the Reference scenario calibration purposes, fuel prices for the main primary energy carriers were taken from the Current Policies Scenario of the World Energy Outlook 2017 (IEA).[12] Model used

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[10] IPCC (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

[11] JRC C6 (2018). JRC-IDEES - Integrated Database of the European Energy System (2000-2015). CO_2 Emission balances. Spain, July 2018.

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

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.

105. The model also enables adding the transportation cost to the wholesale fuel price. This can be done in two ways: first - simplified, assume the adoption of average transport fee for all defined countries (different for coal, lignite and gas). The second method allows for the adoption of differentiated transport fees, but this requires the collection of detailed and unfortunately not always available data. For Poland, the transport fee was determined on the basis of historical data as the difference between the total cost of supply of a given fuel and its purchase price, is reported in the Energy Market Agency's publications[13].

106. Another question is biomass which is of various types, and its supply and prices highly depends on domestic conditions. That's why additional efforts are made to estimate the prices of the following biomass types: firewood, wood pellets, wood chips and straw bales what is based on EUROSTAT data. There are many gaps in an official European statistics (a large number of reporting countries still do not provide any data), although the identified gaps are likely to be filled in the near future. Missing data can also be completed on the basis of resources available in branch institutes and scientific centres operating in particular country. Therefore at the moment model rely on average biomass prices, but it is planned to differentiate the types of biomass used for electricity and heat production and consequently their supply prices when reliable statistical data is available.

107. The projection of CO_2 emission allowance prices in the EU ETS is also an exogenous assumption to the model. Initially, it has been adopted on the basis of the long-term forecast of the International Energy Agency (WEO 2017, New Policies Scenario), similarly to fuel price projections. Of course, it is not the only possible source of data. Values of this category can be freely adopted to the model. 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.

108. Prices of the CO_2 emission allowances in Europe depend on the level of CO_2 emission reduction set by the European Commission and on the functioning of the European emissions trading system (EU ETS), which after the implementation of the Directive 2018/410 of the European Parliament and of the Council (EU) in April 2018 still remains one of the main tools for the implementation of the EU Climate and Energy Package until 2030.

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[13] Energy Market Agency (ARE SA) (2016-2021). Polish Power Sector Statistics. Warsaw.

5.1.5. Cross-border interconnections and planned development

109. The main source of data about cross-border interconnections was ENTSO-E[14]. For the time period 2015-2020 assumed interconnection capacity in model based mostly on Forecast Transfer Capacities - Month Ahead or Forecast Transfer Capacities - Year Ahead data (maximum value for each year are taken into account). If there was no such data – maximum Cross-Border Physical Flow in a specific year were taken into account. Period from 2020 onwards were taken from ENTSO-E analyses[15,16,17,18]. If there was no capacity in ENTSO-E data and it was some energy flow in EUROSTAT database, capacity of cross-border interconnector were assumed based on historical, physical energy exchanged and probably available power capacity for period 2015-2040 (for Finland and Norway interconnector).

110. All this data allow to define state and future development of cross-border capacities from 2015 to 2040.

5.1.6. Potential of individual resources/technologies

5.1.6.1. Energy resources

- **Supply sector**

111. The MEESA considers the following primary resources: natural gas, hard coal, lignite, uranium and oil. These can be mined and processed within the modelled countries or imported from outside the modelled countries. There are also three categories of fossil fuels which can be produced only in a country which consumes it, namely other fuels, lignite and non-renewable waste. The model allows for at least two alternative approaches to domestic fuel extraction constraints. The first solution consists in introducing upper restrictions on the level of extraction of given energy resources (either on the basis of external studies, expert assumptions, as well as on the basis of analysis of historical trends). The mining activities can also be modelled by a supply curve with several cost steps for the following three types of sources: identified reserves (or producing pools), reserves growth (or enhanced recovery), and new discoveries. The choice of the solution depends on the purpose of the analysis and data availability.

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[14] Transparency Platform, op.cit.

[15] ENTSO-E (2018). Mid Term Adequacy Forecast 2018. Brussels.

[16] ENTSO-E (2018). Europe Power System 2040: Completing the map Technical Appendix. Brussels.

[17] Ten Year Network Development Plan 2018, op.cit.

[18] Ten Year Network Development Plan 2020, op.cit.

- **Bioenergy**

112. 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)[19], Ruiz P. et. all (2015)[20]. 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.

5.1.6.2. Technologies

- **Conventional units**

113. 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[21,22,23] and ENTSO-E[24,25]. 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.

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[19] 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.

[20] 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.

[21] 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.

[22] E3MLab & IIASA (2016). Technical report on Member State results of the EUCO policy scenarios. December 2016 with further modifications.

[23] European Commission, Directorate-General for Energy, Directorate-General for Climate Action and Directorate-General for Mobility and Transport (2021). EU Reference Scenario 2020. Energy, transport and GHG emissions. Trends to 2050. Brussels.

[24] Ten Year Network Development Plan 2018, op.cit.

[25] Ten Year Network Development Plan 2020, op.cit.

- **RES**

114. Another relevant exogenous inputs in the MEESA model is the renewable energy technical potentials per technology and per country. The total and annual capacity additions potential of individual RES technologies is estimated based on various literature sources and most recent projections, published by recognized research centers (ENTSO-E, E^{3}MLab, JRC-EU-TIMES). Inputs to the model are minimum or maximum limits on annual capacity additions 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.

6. Calibration of the base year and data matching procedure

6.1. Calibration of the CHP main activity plants

115. In the EUROSTAT statistics for the energy sector, combined heat and power (CHP) plants are treated in a way that is significantly different from what is assumed in the model. Namely, EUROSTAT statistics includes in this group all sorts of units that produce even the smallest heat volumes. As a result, a significant group of units, which are in fact condensing power plants, are qualified to the group of CHP plants. For this reason, the following methodological approach is used for preparing model data, which makes it possible to roughly estimate total installed power capacity and production in public thermal power, broken down by fuel.

116. On the basis of heat production (broken down by technology and by fuels) derived from EUROSTAT database, the electricity production from CHP's was determined by applying cogeneration coefficients expressed in GWh/TJ, typical for the technology used (assumed on available statistical data and by expert methods). In the next step, based on the volume of electricity production and the assumed coefficient of utilisation of installed capacity, the power capacity for the various groups of main activity CHP's, is determined.

117. Then, on the basis of the assumed efficiency of the conversion process, typical for the technologies in question, the amount of fuel input is calculated for particular cogeneration units. The results obtained in terms of available capacity, electricity and heat production were verified by comparison with the results obtained with those presented by the European Commission[26], in total for the whole group of cogeneration units, after deduction of industrial CHP's. Estimates of the fuel input used were verified by checking the total consumption in main activity units and checking the efficiency indicators in all types of units considered. The selection of indicators is the user's

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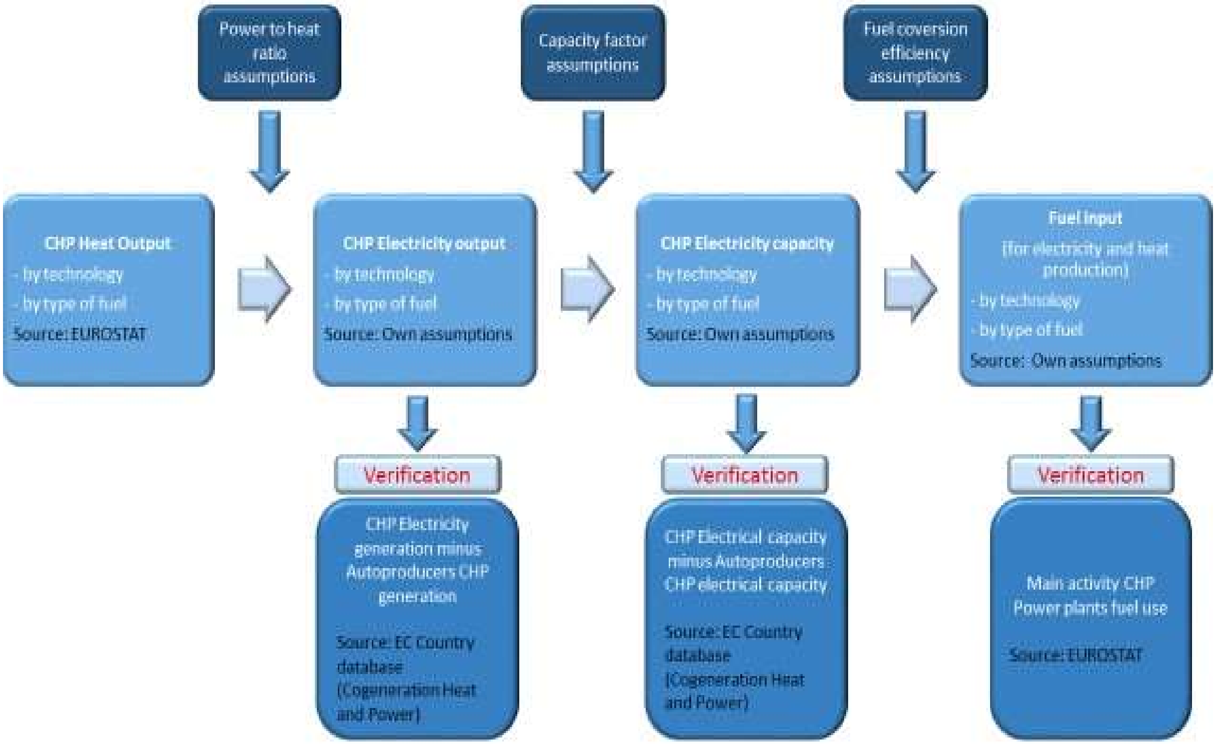
[26] European Commission, Directorate-General for Energy (2021). Energy datasheets: EU27 countries. Brussels.

responsibility and is usually done using the iterative method, i.e. these indicators are initially assumed in an expert manner, and then it is examined how that selection affects the final results (whether the production volume obtained for individual cogeneration units corresponds to the sum of electricity production reported in the European Commission report "Country Data Sheets", whether the amount of fuel consumption agrees and whether other indicators such as conversion efficiency, operational time, capacity factor are logical for all generating units). Figure 4 illustrates, in the form of a diagram, the method used and the range of statistical data used to calibrate CHP plants in the base year.

Figure 4. Diagram showing the method used to calibrate CHP's installed capacity, production and fuel input in the base year



Source: CAKE/KOBiZE own study

118. Below an example of calculations carried out for each type of unit in each country to determine the amount of electricity generation as well as the installed capacity of commercial gas-fired CHP's in Poland is presented. The data obtained are verified on the basis of available national statistics. The differences found are acceptable. It is assumed that a much more far-reaching simplification would be to rely on data directly from EUROSTAT, which could lead to a significant overestimation of power and production of electricity and heat in cogeneration units. In some countries, such as

Poland, but also Finland, Denmark and Lithuania, cogeneration is an important source of electricity and heat generation.

119. According to EUROSTAT data, the total heat production in Poland's CHP plants in 2015 amounted to 10 988 TJ. Following an expert estimation, the average cogeneration ratio [GWh/TJ] is assumed to be about 0.365 (taking into account technology and climatic conditions) and on this basis an approximate amount of electricity produced in cogeneration was calculated:

$$10\ 988\ [TJ] * 0.365\ [GWh/TJ] = 4\ 011\ GWh$$

120. Then the average efficiency of electricity generation is assumed at the level of 0.45. On the basis of these two values the estimated natural gas use in these units has been calculated:

$$4\ 011\ [GWh] *3.6\ [TJ/GWh]/0.45 = 32\ 088\ [TJ]$$

121. In order to determine the net installed capacity of main activity gas CHP's, a capacity utilisation factor of 0.44 was assumed and calculated as follows:

$$4\ 011\ [GWh]/(8760\ [h] * 0.44) = 1.04\ [GWel]$$

122. Similarly, the remaining cogeneration units have been treated and the expertly adopted parameters have been calibrated in such a way as to maintain, on the one hand, a certain logical consistency and, on the other hand, to ensure that the results obtained in terms of capacity, production and consumption form constitute an integral whole.

6.2. Calibration of the CHP autoproduction units

123. The available information from EUROSTAT, allows to calculate the energy balance for the autoproducers. However, EUROSTAT does not provide information related to the capacity of the separate groups of autoproducers CHP and electricity only. It only provides aggregated information of electrical capacity for the total of Autoproducers and the Main Activity Sector.

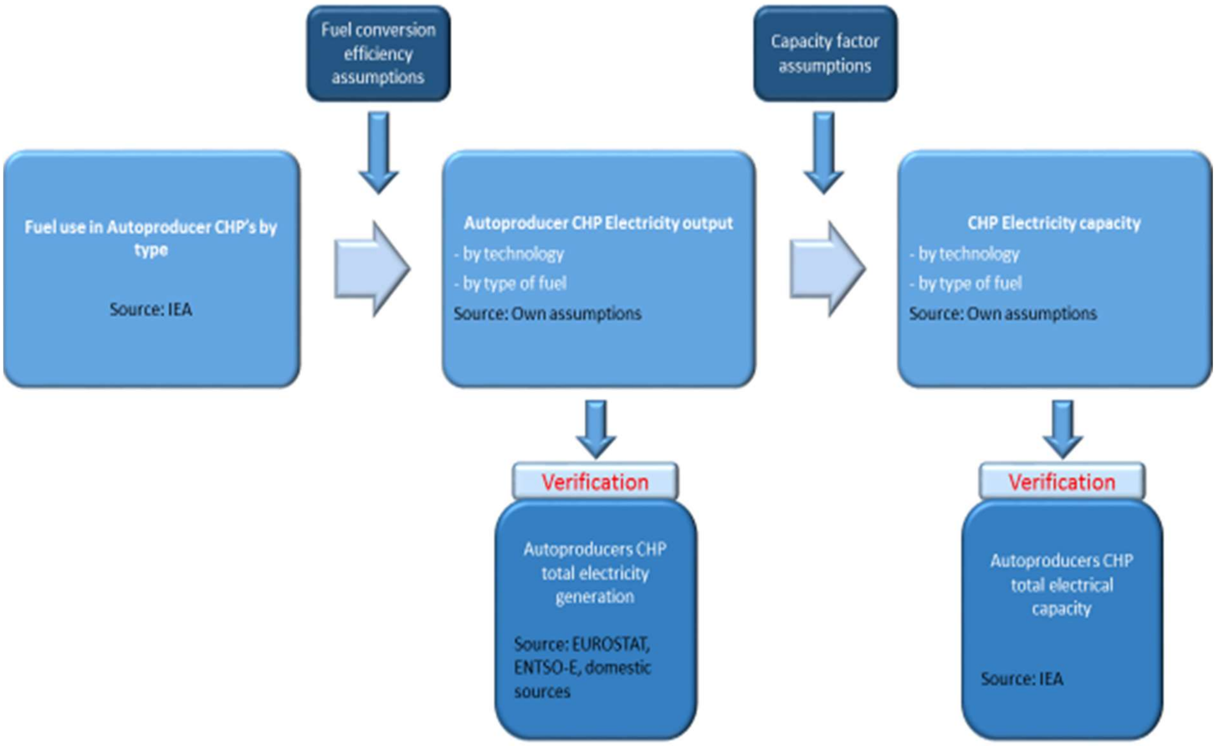
124. For this reason, the following methodological approach is used to calibrate the model in the base year. On the basis of data on the fuel use in the given groups of autoproducers, originating from the IEA (used for the production of heat sold to district heating networks), the amount of electricity produced by them is estimated assuming typical energy conversion efficiency. Then, on the basis of estimated electricity production, the approximate capacity power is determined after assuming appropriate indicators of the utilisation of the installed power. Heat production from given type of technology and fuel is taken from EUROSTAT. In the last phase of preparation of input data for autoproducers CHP plants, the results obtained have been verified by checking

compliance with the total values reported by EUROSTAT and IEA. The consistency of assumed and typical factors (efficiency, capacity factors, operational time, cogeneration factors) resulting from calculation are checked. The following actions are carried out to check the consistency of statistical data:

- Verification of compliance of total capacity and production in autoproducers CHP plants with the data reported by the IEA.
- Verification of compliance of total capacity and production in industrial and commercial biogas plants with the data reported by EUROSTAT.
- Verification of compliance of total capacity and production in industrial and commercial combined heat and power plants using municipal and industrial waste with the data reported by EUROSTAT.

125. Figure 5 illustrates, in the form of a diagram, the method used and the range of statistical data used to calibrate CHP plants in the base year.

Figure 5. Diagram showing the method used to calibrate autoproducers CHP's electricity output and installed capacity by fuel and technology in the base year



Source: CAKE/KOBiZE own study

6.3. Calibration of the main activity PP

126. As a consequence of applying the above two solutions for the determination of technical parameters of public and industrial CHP plants, the capacity, production and fuel consumption in public power plants are estimated for the base year on the basis of the following algorithm:

Power plants = Main activity power plants (EUROSTAT) + main activity CHP plants (EUROSTAT) – calculated main activity CHP plants

127. Industrial power plants in the model are fully included in the group of commercial power plants. Therefore, the following calculation algorithm was used in the base year calibration process:

Autoproducers PP = Autoproducers power plants (EUROSTAT) + Autoproducers CHP plants (EUROSTAT) – calculated Autoproducers CHP

128. Therefore, the total installed capacity, production and fuel consumption in main activity power plants is calculated as the sum of calculated Power plants and Autoproducers PP.

6.4. Calibration of the HP main activity plants

129. The method of the calibration of capacity output, production and fuel consumption in heat plants (divided into technologies and fuels) were prepared on the basis of statistical data on fuel consumption in heat plants (derived from the IEA database) and heat production is estimated assuming typical conversion efficiency. On the basis of the presented heat production calculation, the available capacity of the considered units is determined in an approximate manner, assuming typical capacity utilisation rates. Capacity Factor for new and old HP is assumed as 35 % - the same way as it is assumed in REFERENCE 2016[27] (mostly input data used for Primes REF 2016 - provided by the Commission) in order to be in step with NECPs.

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[27] EU Reference Scenario 2016. Energy, transport and GHG emissions. Trends to 2050, op.cit.

6.5. Share of electricity generation from RES

130. In the MEESA model, three approaches in setting the pace and scope of RES development in a given country/region can be chosen. Applying this approach depends on the purpose of the analysis that is going to be performed. One solution is to set national targets on the basis of external sources, e.g. based on the projections coming from the PRIMES model. PRIMES model has included detailed modelling of Member States policies representing a variety of economic support schemes, including feed-in-tariffs. The projected RES investments implied directly for the financial incentives and are considered as given by the market model which decides upon the remaining potentially necessary investments (among all power generation technologies) on the basis of pure economic considerations with a view to meeting the RES obligations.

131. Alternative approach involve modelling of the functioning and planned RES support systems in individual countries. In this case, the user have to control the amount of support necessary to achieve the target. At the same time, the solution enables estimation of the required amount of support for RES technologies to ensure given pace of growth. Another solution is to allow to fulfill RES targets by including green energy certificates transfers between countries. As a result model would optimize and generate the volumes of renewable energy produced in particular countries. Moreover, results would show which countries doesn't meet their obligations and would have to buy green certificates from countries with RES energy production greater than their target – which will make the overall EU target achievement feasible.

132. Shares of renewables in electricity for the years 2015–2020 are calibrated based on EUROSTAT statistics.

133. In order to avoid double counting, if electricity is consumed for green hydrogen generation appropriate amount of artificial commodity is deducted from RES generated in electricity sector (and it is added when green hydrogen if used for generation of electricity).

6.6. CO_2 emission country balance

134. Emission factors used in model technologies are based on KOBiZE database and 2006 IPCC Guidelines for National Greenhouse Gas Inventories[10]. In case of some fuels (especially some waste gases and derived fuels) emission factors could vary widely and it is not possible to assess proper emission factor value without detailed knowledge of a given industry installation. Therefore it is assumed that after calibration of electricity and heat generation as well as fuel use, some additional calibration of emission factors will be necessary. According to this procedure after calibration of production in base year for all 30 countries, CO_2 emission level in the model for every country are compared

with EUROSTAT database CO_2 emission from Public Electricity and Heat Production. Unfortunately observed discrepancy is too large to be explained by inaccuracy of some of the emission factors only.

135. On the other hand when compared to the European Commission's Joint Research Centre (JRC) data, MEESA base year results in terms of CO_2 emissions proved to be very similar.

136. Another challenge here is that MEESA includes electricity and heat production from public power and heat plants but also from industrial CHP (in case of heat only district heat is taken into account – process heat as well as related fuels and emissions are omitted because in statistics it is reported in industrial process section). Such approach is necessary to properly balance electricity and district heat production for each country. But in EUROSTAT data only emissions from public electricity and heat production are shown separately, while emissions from industrial CHP installation are under overall industry emission and it is very hard to extract electricity and district heat related emissions from industrial CHP in EUROSTAT data.

137. Therefore this additional emission factor calibrations are made based on JRC database, which covers the energy sector and industrial CHP in a similar way as MEESA model.

138. The main purpose of development new energy model 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, mainly for Poland, but taking into account whole European energy market and common emission reduction targets. 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 and green hydrogen sectors. Model allows to create analyses for selected country, groups of countries or with and without possibility of electricity exchange between regions. These capabilities together with connection CGE model and Energy Sector model (also between other sectoral models) gives opportunity to create wide range of evaluation of optimal climate goals from the viewpoint of Member States or EU as a whole.

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ANNEX

Main changes in the MEESA energy model between versions

Main changes in the MEESA energy model between current 2.0 version and previously published 1.0 version:

- Model data in new text file instead of an Excel file – this introduces more convenient way for maintain and update data with the use of gams language functions and dedicated macros.
- Implementation of a number of functions that verify consistency of the input data before running the solver.
- New option for dynamic aggregation of model regions – introduced for performance and compatibility with other models.
- New feature which allows for calculation in 5-years periods – introduced to improve performance and compatibility with other models.
- Implementation of the possibility of automatic data exchange and iterative calculations with the CGE model.
- New option to use more detailed time representation in the model – twelve two-hour periods instead of three periods available in base version. This allows for more accurate modelling of energy storage and photovoltaic sources.
- Changes in the modelling of energy storage to better reflect the functioning of small energy storage and electric cars.
- Implementation of green hydrogen production and possibility of hydrogen use in new gas fired power plant and CHP as well as in other sectors (when MEESA is used in connection with CGE model).
- Implementation of biomass power plants and CHP with CCS, which allows to achieve negative emission in the energy model.
- Implementation of large district heating heat pumps.
- Overall data update for 2020 as base year.