

# Bridging the Gap between Energy- and Grid Models

Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

Thesis

University of Flensburg

June 2015

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### **Bridging the Gap Between Energy- and Grid Models:**

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Sven Teske, Hamburg June 2015

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*Climate change, air pollution and water stress are direct or indirect impacts from mining and burning fossil fuels to provide energy services around the world.*

*Therefore “a fundamental shift in the way energy is consumed and generated must begin immediately and be well underway within the next ten years in order to avert the worst impacts of climate change” (IPCC-SRREN, Chapter 1, May 2011).*



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## Acknowledgements

During preparation and writing of this thesis I was privileged to receive support in many ways. I would like to thank first and foremost my wife Kerstin Teske and my son Travis Teske for giving me the time and support throughout the whole process. I also thank my mother Brigitte Teske and my father Peter Teske.

Special thanks go to Dr. Christoph Schlenzig from seven2one GmbH Karlsruhe for providing the license and technical support around MESAP/PlaNet. Furthermore I am grateful for ongoing technical support from Sebastian Siegmund from seven2one and for his patience. Rocco Balnus and Fiona Baumhögger from seven2one also helped a lot with technical support especially during the database exchange from Access to SQL.

I would like to thank Dr. Stuart White and Dr. Jay Rutovitz, Dr. Ed Langham and Barbara Courtille from the Institute for Sustainable Futures (IFS) at the University of Technology (UTS) Sydney/Australia for hosting me early 2013 and providing all support to enable me to work on this thesis.

Thank you very much to Dr. Thomas Ackermann, Dr. Eckehard Tröster and Dr. Tom Brown from ENERGYNAUTICS for providing data and insights around their grid model.

Dr. Thomas Pregger and Dr. Tobias Nägler from DLR also supported this thesis with data and fruitful discussions.

I also would like to thank Greenpeace in Hamburg, Amsterdam Sydney and , Auckland for giving me the chance to step out of my daily work for a period of time to do programming, research and writing of this thesis.

Also a special thanks for supporting me in the initial phase of this thesis to Prof. Dr. Ing. Uwe Andres and Prof. Dr. Dietmar Windisch of Jade Hochschule Wilhelmshaven.

Finally I would like to thank my supervisor Prof. Dr. Olav Hohmeyer especially with regard to the helpful discussions through-out the entire time of my thesis. Furthermore, thanks to Prof. Dr. Manfred Fishedick for co-refereeing this thesis and providing very helpful research support.

Last but certainly not least a special thanks to Alexandra Dawe for proof reading this thesis.

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## **Bridging the Gap Between Energy- and Grid Models:**

Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

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### **Executive Summary**

*Climate change, air pollution and water stress are direct or indirect impacts from mining and burning fossil fuels to provide energy services around the world. Therefore “a fundamental shift in the way energy is consumed and generated must begin immediately and be well underway within the next ten years in order to avert the worst impacts of climate change” (IPCC-SRREN, Chapter 1, May 2011).*

The transformation of existing energy systems as well as the implementation of new energy systems in developing countries requires in depth planning and system analysis tools to use locally available renewable energy resources as efficiently and economically as possible.

### ***Aim of the Thesis***

This thesis aims to develop a specific bottom-up modelling algorithm which can be adapted to different countries, regions or cities in order to link energy scenario models with annual resolution to grid simulation models with resolution of an hour or less. The growing market penetration of flexible solar and wind power plants make it increasingly important to bridge the gap between energy planning tools at different temporal resolution. National or regional energy planning using scenario analysis will be inherently flawed if it disregards temporal and seasonal fluctuations, as well as the requirements and costs of maintaining constant supply.

The aim of this thesis therefore is to bridge the gap between energy models and grid simulation tools in order to move from rather static national energy scenarios, which do not reflect regional renewable resource differences within a modelled country, towards 100% renewable energy (RE) models which also takes infrastructural requirements into account.

Moving from conventional energy to renewable energy resources – especially for 100% renewable energy scenarios – requires a fundamental change in the modelling approach due to large shares of fluctuating wind and solar generation. The need for dispatching and wheeling of large amounts of wind and solar electricity within a specific region or country leads to very different infrastructural requirements of future energy systems and must be reflected in new energy models.

### ***The methodical approach of this thesis:***

1. Research the status quo of existing energy and grid models
2. Research suitable methodologies to combine energy and grid modelling
3. Research to find suitable software to calculate a new model
4. Develop and implement user friendly and standardized data implementation methods
5. Develop a standard concept to report on output

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6. Compromise between realistic data and low data volumes to save calculation times and to make it operational for personal computers
  7. Verify mathematical correctness of the new developed model
  8. Present and discuss initial model results
  9. Identify the strength and weakness of the developed program

It is not the aim of the thesis to find the best power supply and grid concept for a specific region, but to develop a tool to enable this.

### *Scope of Necessary Programming Work for this Thesis*

The model was programmed on the basis of commercial available software which is used by energy traders, emission control agencies and utilities for documentation and reporting of energy and CO<sub>2</sub> flows. The software was selected due to its flexibility and its extensive ability to model processes and (energy) flows in three dimensions, detailed cost allocations and due to its ability to interface with different database systems such as Microsoft SQL and Oracle.

However, the software only provides the toolbox as a basis for the programming work – equal to e.g. the GAMS software is used for the development of new models.

The model developed for this thesis has been built up from a “blank screen” bottom-up from the household demand side level to the 400kV supply side across all four voltage levels over more than two years. All commodities, processes and their interaction via mathematical functions which defines the logical flow of the model have been developed for this thesis.

Infrastructure for 100% RE systems will not only require changed power grids, but also multiple electric and thermal storage technologies as well as interconnected (district) heating and gas networks. Thus the model to be developed for this thesis needs to be able to add various different technologies into the calculation process if required. This model flexibility would be beneficial to find the best possible renewable energy integration concept with a large range of different and perhaps unknown technologies. The model should provide technical information about the required renewable energy capacities for a secure power supply in response to the location and the voltage level. It should also identify possible limits for the integration of flexible renewables for each grid level and enable the modeller to calculate associated costs for each involved process.

The integrated bottom-up modelling concept is developed with an existing and commercially available database program for energy planning and/or energy trading in order to make it relevant for energy models currently in use. The model developed for this thesis has been named [R]E 24/7 which stands for “Renewable Energy 24 hours a day, seven days a week”.

### **Bridging the Gap Between Energy- and Grid Models:**

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### ***Suitable Energy Models***

The first step of this thesis was to search for existing energy models in order to find a suitable energy modeling methodology. Chapter 2 provides a comprehensive overview of existing energy models on the basis of three Meta-studies of the Energy Modeling Forum<sup>28</sup> (EMF<sup>28</sup>), the International Panel on Climate Change Special Report Renewables (IPCC-SRREN) and the University of Limerick (Connolly et. al.). For the development of [R]E 24/7, specific methodological energy model characteristics - according to (Knopf et. al. 2013) - are required:

- **Economic coverage:** Full equilibrium macro-economic models which describe the nexus between economic and energy systems. A detailed calculation of overall economic parameters leads in most macro-economic models to aggregation of technology parameters, especially in the field of renewable energy technology. However, a high resolution of technical parameters for the power sector, imperative for further analysis of the necessary infrastructure, is too detailed on the economic side but not detailed enough on the energy technology side. Partial equilibrium and energy-engineering (or scenario models) focus on energy systems with higher technology resolutions both for the supply and demand side compared to macro-economic-models (IPCC-SRREN 2011<sup>1</sup>) and therefore are preferred for an interconnection with infrastructural planning tools.
- **Geographic coverage:** A high regional resolution within the calculated area is required in order to transfer the data into a computer model which simulates national or regional power grid systems. The higher the geographic resolution of the energy model, the better the possibilities for connecting grid models which require high regional resolution to be able to identify bottlenecks in the grid system.
- **Inter-temporal solution methodology:** The energy model must have the possibility for a high time series resolution of one hour or less for an entire year (8760h) in order to model seasonal and daily changes of the demand and supply nexus.
- **International trade:** Interregional exchange / trade of electricity functions of energy models could serve as a possible interface to infrastructural planning tools. However this function is not a prerequisite for connecting energy and grid model methodologies.

To conclude: Balancing demand and supply and introducing dispatch orders across several voltage levels with a high regional resolution require a model that allows the integration of these additional functions, besides the ability to reflect a high degree of technical details. Schröder et.al. 2013<sup>2</sup> developed the applied model *EMELIE-ESY* under the Energy Modeling Forum 28 (EMF) which computes a partial equilibrium of the electricity and combines hourly operation of power plants ("dispatch") with a long-term horizon up to 2050 on the basis of electricity and emission prices. Based on the research for this thesis, *EMELIE-ESY* was the only energy model found in the literature, which has a high technical resolution on the supply side and an innovative

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mix of annual and hourly time series. However *EMELIE-ESY* still lacks the technical details on the demand side as well as on the power grid infrastructure itself. The aim of the model is to find the most economic combination of generation capacities; the investigation of required infrastructure and costs to transport the electricity is not possible. Thus bottle necks in the grid cannot be identified. Therefore it is assumed that the [R]E 24/7 represents a new approach to bridging the gap between energy- and grid models.

### *Suitable Grid Models*

In a second step, seven different grid models were analyzed. All analyzed models serve different purposes thus various methodologies are used. However the methodologies can be categorized in line with their characteristics:

- Transmission Grid models for infrastructural planning (RWTH11-2012); (van Hulle 2009); (Tröster et.al. 2011)
- GIS Cluster models for the optimal distribution of power generation (Scholz 2012)
- Economic models to calculate trade-off between network expansion and non-network expansion related measures (Langham 2011)
- Distribution Grid models for infrastructural planning (DENA 2012); (Gwisdorf et.al. 2010)

[R]E 24/7 has specific requirements in relation to methodological model characteristics:

- Transmission and distribution grid levels must be covered
- Regional clusters for the distribution of decentralized power generation are needed, especially when it comes to locally available renewable energy resources
- Economic calculation module required

While several models combined energy and power grid models (RWTH 11-12), (van Hulle 2009) none of the analysed models reflected all voltage levels and included a voltage specific economic calculation component. The [R]E 24/7 model should cover a whole range of different tasks, while it should also be user friendly, data requirements with regards to data availability and volume should not present a major barrier in using the model and to allow short calculation times. Thus simplifications are required.

### *Development of the Methodology*

The [R]E 24/7 aims to combine energy and grid models which require the methodologies from both models to be compatible. Therefore the output parameter of the energy model needs to match the input parameter requirements of the grid model. While most energy models presented in chapter 2 cover all energy sectors (power, heating/cooling and transport), the grid model only focuses on the power sector. The level of technical detail with which the power sector is calculated in the energy model – both in terms of demand and supply – is of great importance. Table

## Bridging the Gap Between Energy- and Grid Models:

Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

1 provides an overview of different energy- and grid model methodologies, the requirements for the interface parameters and the chosen [R]E 24/7 methodology.

Energy Model	Requirement for Interface	Grid Model	[R]E 24/7 - Methodology
Economic Coverage			
a Full Economic Coverage b Partial Equilibrium Model overall energy sector c Partial Equilibrium Model power sector only d Energy Engineering Simulation Tools	High Resolution required > Power Generation Technologies > Demand Structure	a High Voltage Level (DC) b High + Medium Voltage Level (DC) c All Voltage Levels (DC) d All Voltage Levels (AC)	All Voltage level (DC)
Geographic Coverage			
a Global b National c Regional d Side Specific	High Resolution preferred > National Level > regional energy parameter available	a GIS Cluster b Multiple Region c Grid Node d Distribution Grid Analysis	Grid Node - Cluster Combination with simplified Distribution Grid Analysis
Time Resolution			
a Year b Year > Days c Year > Hours	High Resolution preferred > Installed Capacity in MW for one specific year > Energy Parameter in MWh/a	a Representative days - 24h/day b Representative weeks - 24h/day c 8760 hour per year	Representative weeks - 24/day

Table 1: Suitable Methodology for the [R]E24/7 Model

The left column of Table 1 lists model specific characteristics in terms of their economic / technical and geographical resolution as well as the calculated time steps and classifies them. As such “a” marks the lowest resolution; “c” and “d” respectively the highest resolution. The [R]E 24/7 methodology seeks to find the best possible combination between high resolution input and output, data availability and data volume on one hand and largest possible scope and transferability to various world regions and network conditions on the other hand.

The combination of the grid node and cluster methodology allows electricity flow simulation throughout a network with different voltage levels, but has the disadvantage that relatively large amounts of data for a region are required. The grid node methodology was chosen for the simulation of the upper voltage levels, while the cluster methodology is intended to reflect the distribution network level.

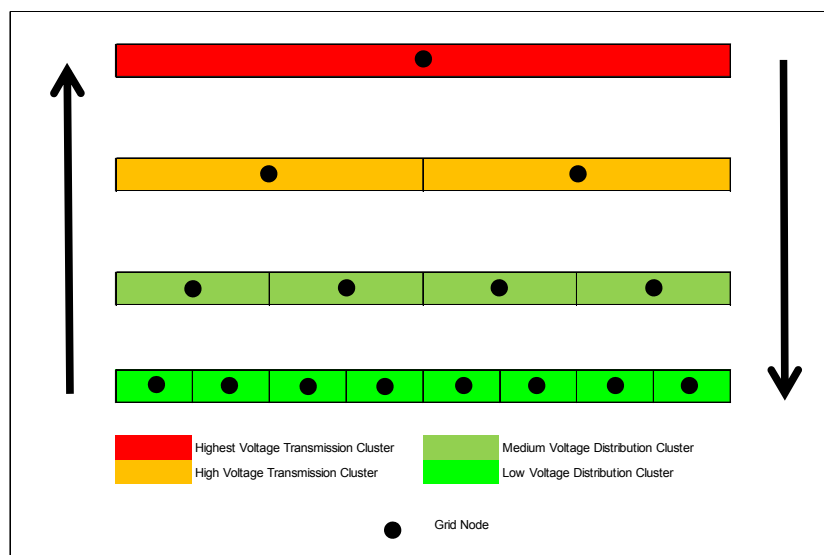


Figure 1: Schematic Representation of the RE 24/7 Methodology

One grid node has been assigned in the center of each cluster. The clusters were placed one above the other. Each layer represents a voltage level. The size of the clusters decreases from top to bottom, which is intended to represent the average



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transfer length for each voltage level. In this manner, each cluster can be separately optimized from the bottom upwards. This approach is intended to relieve the use of the transport network and at the same time use regional resources as effectively as possible.

The [R]E 24/7 model calculates the physical flow between clusters for specific geographical positions and for each grid level. Figure 1 shows the schematic [R]E 24/7 methodology. The [R]E 24/7 methodology combines energy models with high geographical, technical and inter-temporal resolution and inter-regional (trade) functions which are based on user friendly software platforms with power grid simulation tools. A combination of the grid node methodology with a cascade of clusters of sub-grid nodes seems the optimal solution.

The model prioritizes renewable generation and power generation capacities on the level of the demand. The dispatch order can be changed in each cluster, however decentralized solar and wind capacities will be dispatched ahead of capacities from higher voltage levels. This is due to the model architecture and cannot be changed, which is a weakness of the methodology.

Each process throughout the entire simulation is connected to an individual economic calculation module. The [R]E 24/7 methodology deliberately assigned an individual cost calculation algorithm for each process and commodity throughout all levels, in order to allow cluster specific cost calculation for both centralized and decentralized power generation strategies. Different grid costs and external and / or political costs such as a CO<sub>2</sub> price calculation scenarios should be possible as well as the evaluation of e.g. business models for storage or generation technologies. While the physical flow can be calculated separately without costs calculation, it is not possible to do cost calculation only (see 5.13) which leads to high data volumes and long calculation times which is a disadvantage of the model.

Finally the [R]E 24/7 methodology focused on technical resolution in great detail, in order to carry out economic calculations of very detailed supply and demand strategies.

### *Development of the [R]E 24/7 Model*

Chapter 5 documents the entire technical development process for the infrastructural planning tool [R]E 24/7. The selection of software for the programming significantly determines the model architecture. Therefore a detailed description of all components of the model is required in order to make the development process of [R]E 24/7 as transparent as possible. While the selected software MESAP/PlaNet is user friendly and very flexible, there are also certain limitations. Detailed models go hand in hand with high data volumes and long calculation times. The original software was unable to handle calculation processes with data volumes over 500 MB. In order to develop the [R]E 24/7 methodology idea further, the software needed to be extended to adapt to the necessary greater computing capacity.

### **Bridging the Gap Between Energy- and Grid Models:**

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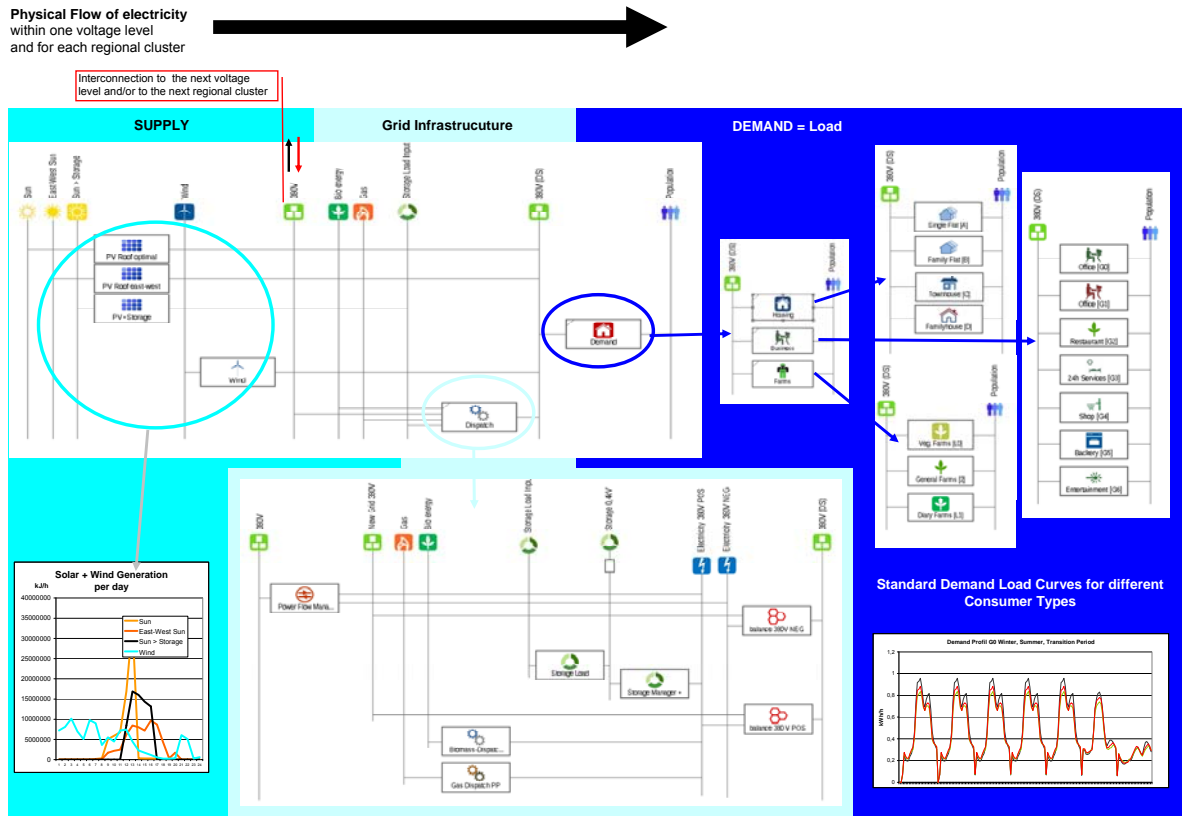
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The [R]E 24/7 model has been programmed to reflect a great level of technical details across all voltage levels. The large number of data points – 18.000 parameters for the entire [R]E 24/7 model – leads to a very high number of variables which made an optimization process impractical. The lack of an optimization function therefore represents a weakness of the model.

Programming the model required the progression of various new processes, sub-processes, external- and internal commodities needed to simulated power grids. The software has never been used to model electricity grids and the high time resolution of one hour in combination with load flow calculation with a high possibility of reverse flows made it necessary to develop new mathematical functions and use multi-level sub-processes such as the *Dispatch* process and the *Power Flow Manager* process.

All parts of the model, especially those required for grid simulations with all necessary parameters have been constantly accompanied with test runs to verify the mathematical correctness of the model results.

Figure 2 visualizes the electricity flow, within one voltage level and one geographical cluster, from the generation side via the grid infrastructure to the demand side (= load), from left to right. The sub process *dispatch*, marked with a light blue circle, hosts the grid relevant processes (5.6), storage facilities as well as dispatch power plants (= “can-run”). The sub process demand, marked with a dark blue circle, hosts all demand and consumer categories and the following sub process includes all load profiles used in a specific region.



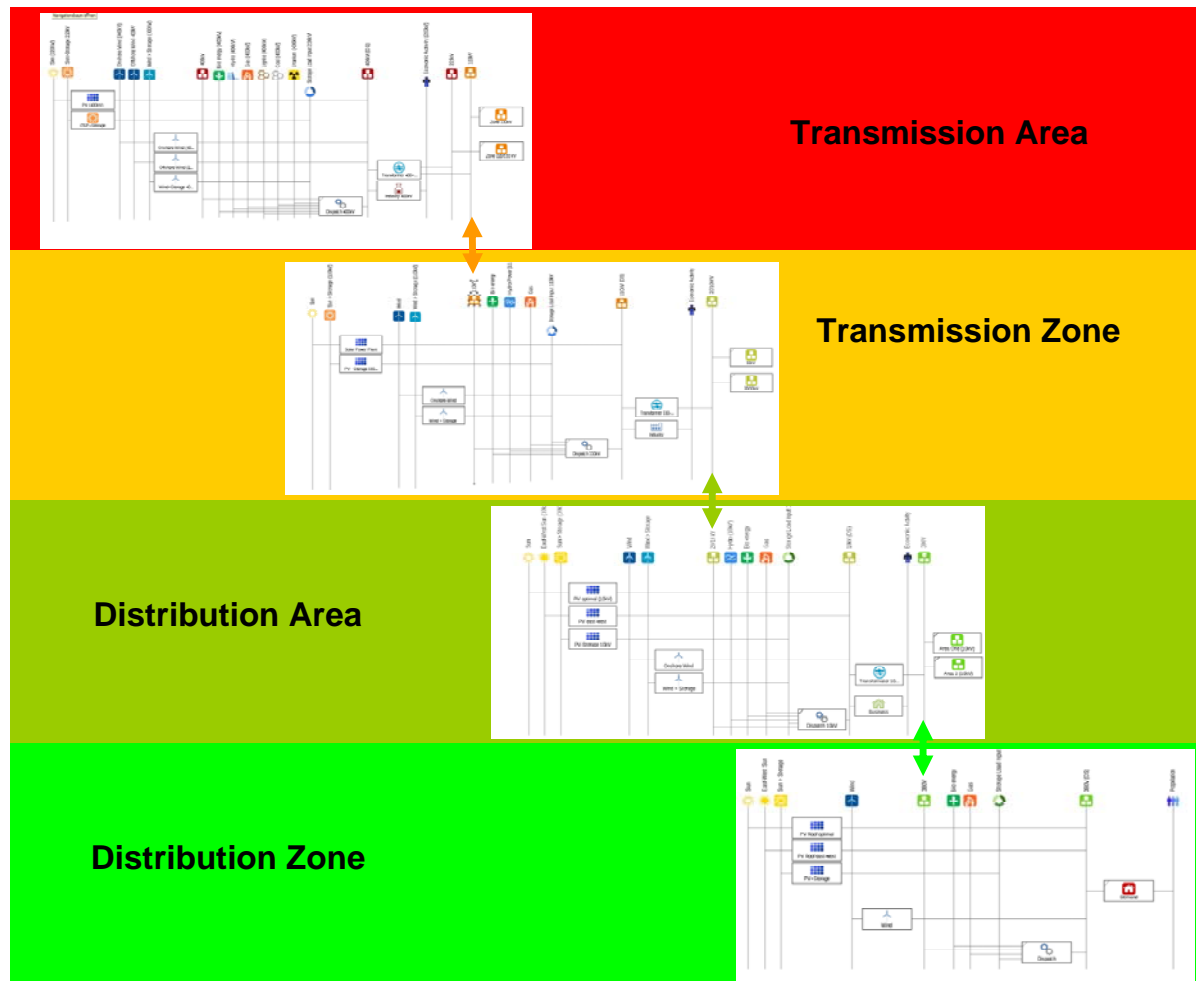
**Figure 2:** Physical Flow of Electricity within one Voltage Level and Regional Cluster

A series of identical clusters for all geographical regions across all voltage levels - from the transmission to the distribution level – form the [R]E 27/4 model. The electricity can flow via transformer both from the high voltage level to the lower voltage level and vice versa. The transformer is a process connected with the “*demand side*” (DS) of the higher voltage level and the “*supply side*” (SS) of the lower voltage level. There are no other interconnections between different voltage levels. So the transformer process is the gatekeeper for each voltage level.

[R]E 24/7 allows flows from the high voltage level towards the lower voltage level, which is currently the usual flow in electricity grids, and has a positive arithmetic sign. In case the generation capacity is higher than the demand within a grid level, the flow turns around from the lower to the higher voltage level – the arithmetic sign gets negative. Thus the model identifies the load flow within a certain cluster (Figure 3).

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**Figure 3:** Physical Flow between Different Voltage Levels

To facilitate the overview of all input and output data, a colour code was introduced which was maintained throughout the thesis (Figure 4):

Transmission Area	
Transmission Zone	
Distribution Area	
Distribution Zone	
Power Generation	
Grid Operator (TSO)	
Distribution + Demand	

**Figure 4:** Colour-Code for [R]E 24/7

Once the physical flow has been verified the cost calculation module can be implemented. PlaNet is a macro-economic cost model which calculates the costs of flows, commodities and processes. In the energy sector, costs are mainly driven by installed capacities e.g. from power plants or from capacities of cables, the technical lifetime and the investment costs needed to install the required equipment and fuel costs, if fuel is required. Besides that, all technical equipment requires service and maintenance which are considered as fixed costs in the model. PlaNet allows defining “other fixed costs” as well, so carbon tax or other external driven costs can be added to each process. Fuel costs from commodities such as coal or gas are an input for each process. However, each commodity and all processes require the same set of input parameters.

Figure 5 shows four cost categories which are calculated within each cluster: (a) Power generation costs, (b) Distribution and grid management costs (c) Costs for storage facilities and (d) Costs for electricity generated and transmission for “imported” from other cluster. Costs (a) to (d) add up to the real hourly supply costs (e) both specific costs per kWh and total costs per time resolution of one hour.

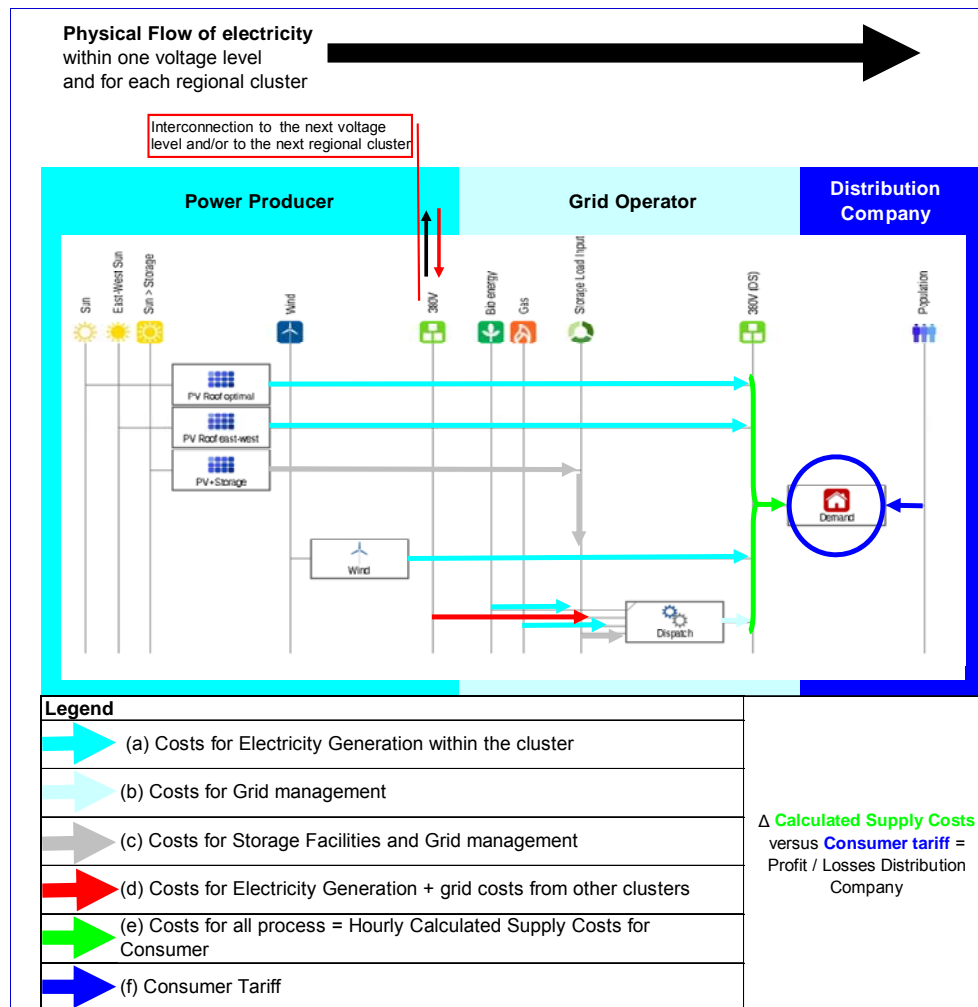


Figure 5: Overview Cost Flow within one Cluster

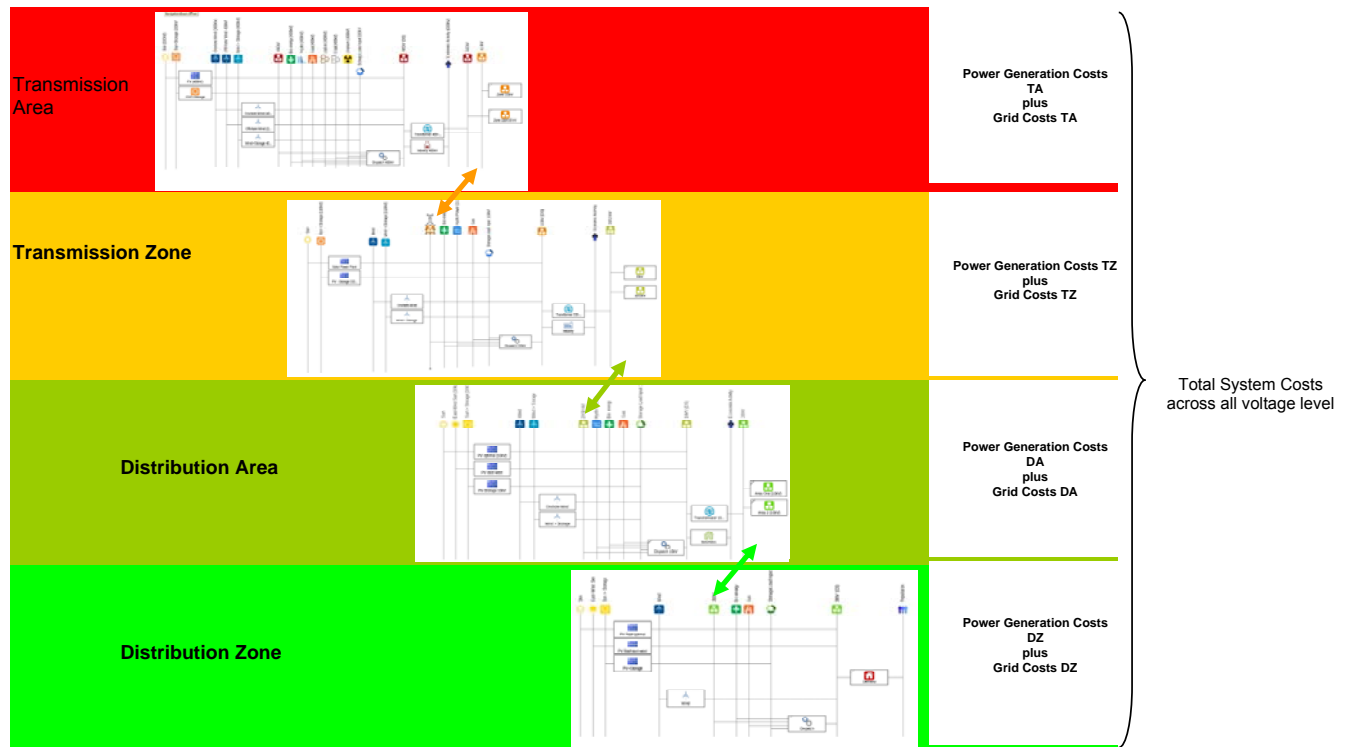
The cost module allows detailed simulations of the financial flow across all voltage levels and enables the modeler to include external and / or political costs as well. However the resulting large data volumes limit the length of model period to one month or less, depending on the capacity of the computer. Therefore instead of calculating a full year, some extreme days, weeks or months should be analyzed. Finding the optimal energy solution is an iterative process and requires multiple model runs. The lack of an optimization module represents a weakness of the model.

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### *Cost Flow Across all Grid Levels*

Figure 6 shows the cost flow across all grid levels. For customers connected to the distribution level, grid costs from each level will be added to the generation costs. In general, the calculation of supply costs will take all voltage levels between the power plant connection and consumer outlet into account.



**Figure 6:** Costs Across all Voltage Levels

In a next step, the model developed for this thesis is transferred to a specific region and compared with the calculation results of another model.

### *Three-Dimensional Topographical Concept*

The topographical concept of the model (Chapter 6) is key for the methodology. One cluster represents one specific voltage level in a specific region. The objective for the [R]E 24/7 model is to develop a software tool which can simulate electricity flows for all countries. Therefore the model uses a modular system of clusters. The individual combinations and the number of those basic model clusters depend on the geographical and technical conditions of the grid. The constant developments of electricity grid technologies of the past decades lead to very different technology combinations depending on where and when the grid has been built. Therefore electricity grids around the world use a combination of different voltage levels for long distance transmission and distribution. In order to reflect this, four different grid categories have been developed specifically for the [R]E 24/7 model (Table 2).

Grid category	Voltage Level	Abbreviation	Name in the literature
Transmission Area:	$\geq 300$ kV	TA	Highest Voltage
Transmission Zone:	$\geq 100$ kV	TZ	High Voltage
Distribution Area:	$\geq 10$ kV	DA	Medium Voltage
Distribution Zone:	$\leq 10$ kV	DZ	Low Voltage

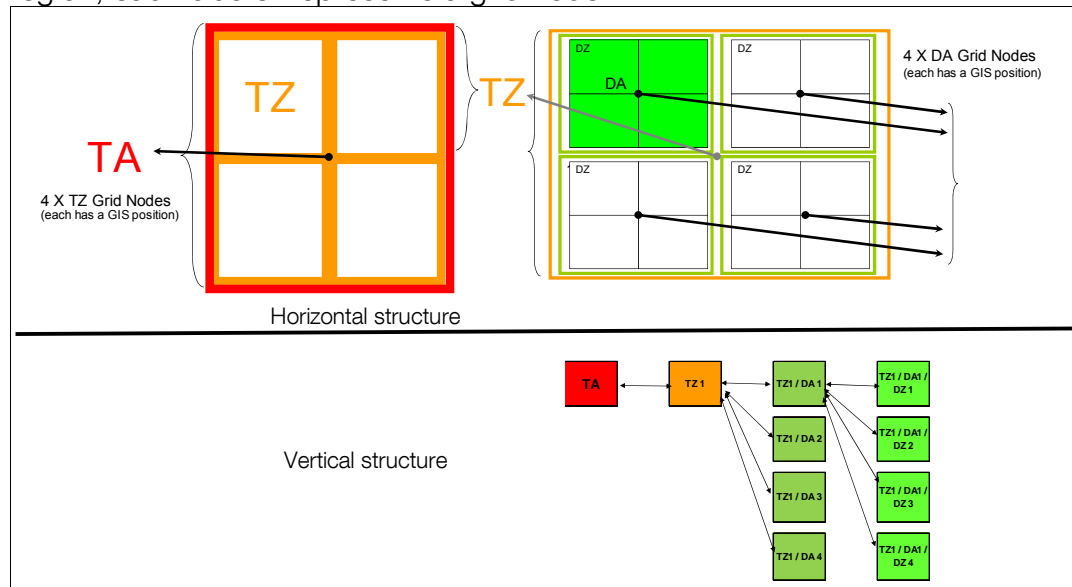
**Table 2:** Grid Categories for the [R]E 24/7 Model

While high voltage lines transmit electricity over several hundred kilometres, low voltage lines in distribution zones transport electricity only across short distances. The cluster size for each voltage level is therefore different. Transmission Areas (TA) with several hundred kilometres can cover areas of 400 km by 400 km and more, the [R]E 24/7 therefore defines this area as the average TA cluster size. For lower voltage levels, the model needs to simplify and reduce the number of clusters. Table 3 shows the assumptions made for the [R]E 24/7 cluster sizes and number of clusters within each grid level. However, cluster sizes can vary due to geographical or technical conditions in the research region.

Grid category	Real transmission distance	[R]E 24/7 Average Cluster Size	Average number of clusters per grid category	Total No. clusters
TA	400 km – 500 km	400 km X 400 km	2 X TZ	2
TZ	100 km – 200 km	200 km X 200 km	4 x DA	8
DA	10 km – 20 km	100 km X 100 km	4 X DZ	32
DZ	1 km – 2 km	50 km X 50 km		
<b>Total</b>				<b>43</b>

**Table 3:** Cluster Sizes in the [R]E 24/7 Model

The numbers of clusters for each grid level has been reduced in the model developed for this thesis in order to keep calculation times for each simulation short and to limit the required amount of input data. If necessary more than four clusters e.g. for the DZ level can be implemented in the model. In order to identify specific geographical areas for each cluster and to assign the actual grid topology in this region, each cluster represents a grid node.



**Figure 7:** Three-Dimensional Topographical Concept

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### ***Data Input Concept***

The energy model developed for this thesis uses a complex data set of 6872 different parameters therefore a user friendly interface between datasheets and the actual model is indispensable. Consequently an input concept to make [R]E 24/7 as user friendly as possible was developed. There are four different kinds of input sheets:

- Manual input of data which remains the same over the entire model period such as the installed capacity of power plants
- Data about technical assumptions such as efficiencies or commodity costs
- Specific Excel sheets which summarize data of all clusters and voltage levels to help keeping the overview across all assumptions
- Original data such as load profiles, actual production data from wind farms or meteorological data

Input sheets of all categories are finally connected to a data sheet which serves as an interface to MESAP. Each input value is assigned a unique ID and carries all model relevant informations about the grid level, attributes etc. The “Converter function” of MESAP is assigned for data transfer from Excel or other formats. By activating “Input Technology” only technology relevant parameters will be uploaded.

The categorized data transfer prevents unmodified data being uploaded again, reduces model run times and allows quick corrections of individual parameters. The [R]E24/7 model uses just over 18.000 program ID's thus each commodity and attribute in each cluster has a unique code to avoid possible data errors.

### ***Verification and Comparison of Model Results***

#### ***Step1: Mathematical Comparison of Calculated Results***

In order to mathematically verify the [R]E 24/7 model, original input data from ENERGYNAUTICS has been used and outputs of both models have been compared with each other. The following parameters have been analyzed:

- Demand in MW per hour for each voltage level
- Supply in MW per hour for each generation technology and voltage level
- Overall generation in MWh
- Overall supply shares by technology in percent

The comparison has been done with input data for two different ENERGYNAUTICS (EN) scenarios: *before* and *after curtailment* of wind and solar capacities. Besides that, the scenario After Curtailment has been compared with [R]E 24/7 calculation results achieved with different dispatch order settings:

- Top-down: priority for Offshore wind (TA) over dispatch capacity (TZ)
- Bottom-up: priority of (TZ) generation capacity over (TA) offshore wind



- Distributed generation: Supply + demand distributed across all voltage levels

*Comparison of Model Results at time with extreme wind and solar conditions*

After the mathematical verification process scenario results of both models under specific extreme wind and solar conditions are compared with each other. The bottom-up dispatch order of the [R]E 24/7 model remained in all cases to evaluate deviations of grid node and cluster methodologies. In order to limit the amount of presented data and to focus on the main differences, four time series with the highest curtailment rates and changes in the load flow for the transmission line between TZ1 (DK02) and TZ2 (DE03) have been selected:

Time series	Event	Exact time of the event
3.Feb. - 10. Feb.	High Wind Generation	5.Feb. 4am - 5 am; 7.Feb. 2pm
7.May - 8.May	High Solar Generation	7. May and 8.May around noon
25. Nov. - 30.Nov.	High Wind Generation	26. and 27. November (at night)
1.Dec. - 31. Dec.	High Wind Generation	3, 9, 13, 28, 2 December several times a day

Table 4: Selected Time Series at Special Events

The original input and output data from the EN has been re-calculated with two different scenarios:

- **Centralized-generation:** all power plant capacities are connected to one voltage level
- **Distributed generation :** distributed power plant capacities across voltage levels

The different topographical concepts of the [R]E 24/7 and the EN model requires tests with diverse power supply assumptions as distributed power generation leads to different calculation results even when all other parameters – including equal installed capacities for e.g. wind – are the same.

Besides the scenario based assumptions, there are different model specific methodologies which potentially lead to different results. Table 5 provides an overview about the key assumptions of the EN grid node model and the [R]E 24/7 cluster model.

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Technology type	Technologies	Scenario Assumption		Model specific methodology	
		Dispatch order	Operation mode	ENERGYNAUTICS	[R]E 24/7
Variable	Solar Photovoltaic, Onshore Wind, Offshore Wind	0	Fixed availability profiles, can be curtailed	Model Input: Maximum Curtailment rate [%/a] per grid node	Curtailment for each cluster only via different model runs
Renewable controllables	Biomass, Hydro, Gas	1	Full flexibility	Dispatch order for each grid node depending on individual costs per technology	Dispatch order for each cluster and voltage level, depending on model settings (see 5.8)
Conventional controllable	Coal, Lignite, Nuclear	2	Limited shutdown and ramping	Model Input: Minimum capacity factor	Dispatch order for each cluster and voltage level, depending on model settings (see 5.8)
Storage	Pumped hydro	3	Stores, dispatches, efficiency losses	Exoginus input during optimization process	Exoginus input during optimization process

Table 5 Scenario and Model Specific Assumptions

### Results – Model Verification

Chapter 8 documents the verification and calibration process of the [R]E 24/7 model. Original input data from the ENERGYNAUTICS grid node model has been used and simulation results have been compared with each other. When assumptions and dispatch settings are similar, [R]E 24/7 can re-calculate results of the EN model. Both the consumption and the **MUST-RUN** solar and wind generation profiles are calculated with an error of less than +/- 5%.

The results for **can-run** dispatch power plants however deviate from each other. In the case of priority dispatch for offshore wind - which represents a change to top-down dispatch priority from RE 24/7 typical bottom-up dispatch approach - the calculated supply shares of the EN model can be reconstructed with a deviation of less than +/- 5%.

However if [R]E 24/7 uses bottom-up dispatch setting, results vary significantly depending on the distribution of supply capacity and demand by voltage level. In the case of large shares of distributed generation and scattered demand over several clusters and voltage levels; the deviation from EN results was up to 30%. Thus a direct comparison of both model results is no longer possible.

In addition, the demarcation problem leads to different simulation results as well. While the EN model simulates a meshed system in which power can flow over neighboring grid nodes back into the analyzed region (Loop-flows) the [R]E 24/7 model defines clear boundaries. The load flows in clear defined cascades from top-down or vice versa and therefore possible loop flows are not recognized, which represents a clear disadvantage of the [R]E 24/7 model.

Furthermore, the EN model introduces specific capacity factors and a minimum power output for dispatch power plants, which is not possible for [R]E24/7 and might lead to very low operational hours or power production in a partial load range,

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which has strong effects on the economy of these power stations (see 9.1 Specific Generation Costs of Dispatch Power Plants).

To conclude: The [R]E 24/7 model can re-calculate EN results mathematically correct within an error of +/-5%. However, both model architectures lead to very different scenario results. In the case of a power grid analysis for multiple grid nodes and entire countries, the results will almost certainly deviate to an extent that direct comparisons of both simulations are not possible.

The [R]E 24/7 model can simulate clear defined areas like distribution networks or small-scale power grid systems of e.g. island power systems as well as overlay DC network systems which connect only two grid nodes detailed and across all voltage levels. This represents the strength of the model. However the EN model reflects a meshed transmission network in more detail as opposed to [R]E 24/7 and therefore has significant advantages for the modeling of transmission networks.

### *Sample Results of the [R]E 24/7 Economic Module*

Once the physical flow of scenarios has been verified, the economic evaluation takes place. A comparison with the EN model is not possible, as the methodologies significantly differ. While the [R]E 24/7 model calculates all involved costs parallel with the physical flow simulation, the EN model provides no hourly generation costs but optimizes with exogenous cost values provided for processes and commodities.

The economic calculation module of the [R]E 24/7 model is connected to the physical flow simulation and cannot be separated. Thus the data volume of the economic calculation is very large and leads to high calculation times. However specific generation costs for all technologies and each grid level can be calculated to analyze supply costs for various cases.

The analysis of average supply costs by voltage level has been tested and model results of various simulations indicate reliable functioning. However the calculation of negative electricity flows – from low voltage levels towards high voltage levels - is not possible as negative costs occur and the software does not allow individual changes of formulas of the economic calculation module. This represents an additional weakness of the program.

Supply costs for each voltage level add up from TA to DZ which allows calculation of overall up-stream supply costs for customers of each voltage level. The overall supply costs for a customer connected to the distribution area (DA) for example are a composition of average power generation costs of level TA, TZ and DA. Additional costs like assumed grid costs are taken into account with specific costs for each *transformer* process. However first simulations have been done without assumed grid costs in order to better control the accuracy of all power generation cost calculations.

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To calculate costs for required grid expansion parallel to the system cost analysis is not effective as the decision to expand the power transport capacity would be a result of this analysis. Therefore the calculation for required investments in new power lines must take place after the overall system costs analysis is completed.

To conclude: The economic module of the [R]E 24/7 model allows the calculation of hourly supply costs for each cluster and across all grid levels. Detailed analysis for clusters under various supply compositions are possible and can be utilized for bottom-up cost calculations. However the high data volume which does not allow an annual cost analysis with a single model run and the lack of an optimization function represent a weakness of the program.

### **Conclusion**

Due to the sharp increase of solar and wind power generation numerous scientific institutions are currently developing new grid modeling tools. Countries that have reached a high share of fluctuating renewable electricity in the power grid are already investing in research programs including: the US Department of Energy (DoE) in cooperation with Pacific North west Laboratories<sup>3</sup>, the *Smart-Grid Initiative* from the Danish Ministry of Climate, Energy and Buildings<sup>4</sup>, the German Ministry of Economics and Energy (BMWi) in cooperation with the German Energy Agency (DENA)<sup>5</sup> or the “10 Year Development Plan” (TNYDP) for the European Union coordinated by European Network of Transmission System Operators for Electricity (ENTSO-E)<sup>6</sup>.

Thus numerous grid models are currently in use or under development worldwide. The two main tasks are transmission grid planning in order to transport large quantities of medium and large scale renewable power generation mainly onshore and offshore wind and the integration of distributed generation – predominantly solar photovoltaic – in distribution networks.

#### *Has Bottom-Up Grid Modeling Advantages over Top-Down Modeling?*

The assumption of this thesis was that bottom-up models for 100% RE grids have advantages over top-down models, because possible bottlenecks in power grid systems can be allocated to the voltage level in which they appear. While increasing shares of solar photovoltaic system are mainly connected to distribution grids and therefore possible measures for a better integration can be simulated close to the generation capacity, onshore and offshore wind capacities connected to medium and high voltage transmission are also rapidly increasing.

Thus a bottom-up optimization might not necessarily lead to the best use of all renewable power capacities. Calculations with different settings of bottom-up and top-down priorities are documented in Chapter 8. Results indicate that when high shares of solar pv are connected to the distribution grid and high shares of onshore and offshore wind connected to the transmission grid, a strict bottom-up optimization would lead to a greater utilization of dispatch or storage capacities from lower voltage levels. Thus available wind capacities will not be sufficiently used.

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An advantage of bottom-up modeling, however, is the analysis of individual clusters. These can be calculated with a great level of technical detail with different supply concepts and/or changing load profiles both in terms of the load flow and required grid capacities as well as different economic assumptions. The [R]E 24/7 allows the separate calculation of individual clusters.

The chosen software MESAP/PlaNet has never been used to model electricity grids. The time resolution of one hour combined with load flow calculation with a high possibility of reverse flows made it necessary to develop new mathematical functions and use multi-level sub-processes such as the Dispatch process and the Power Flow Manager process. Programming the model required the progression of various new processes, sub-processes, external and internal commodities needed to simulated power grids. All parts of the model, especially those required for grid simulations with all necessary parameters have been constantly accompanied with test runs to verify the mathematical correctness of the model results.

To conclude: The model has been successfully programed as outlined in the thesis with commercially available software. A new three-dimensional methodology has been developed on the basis of a combination of two existing grid analysis methodologies and model results have been verified.

### *Strength*

The [R]E 24/7 model can be applied for different regions. The three-dimensional topographical concept documented in chapter 6 allows calculating different regions and adopting other voltages for power lines without changing the model architecture. The great level of technical details and the possibility to add new technology processes represents an advantage of the model. In combination with the standardized data input concept documented in chapter 7 parameters can both be collected and uploaded quickly.

Especially clear defined regions such as cities, communities or islands can be simulated with the model developed for this thesis. The economic calculation module delivers specific hourly average supply costs which allow detailed cost calculations for specific clusters or specific voltage levels. In addition the cost module allows detailed simulations of the financial flow across all voltage levels and enables the modeler to include external and / or political costs as well.

The implemented standard reports – an interface between the SQL database and Excel – allows a quick evaluation and visualization of all modeling results. All figures of [R]E 24/7 model outputs in chapter 8 and 9 are based on these standard reports and a reliable and fast reproduction of this visualization with changed assumptions is possible.

### *Weaknesses*

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The [R]E 24/7 model was programmed to reflect a great level of technical details across all voltage levels. The advantage of a detailed technology simulation in three dimensions – across all voltage levels – turns out to be a disadvantage as well. The large number of data points – 18,000 parameters for the entire [R]E 24/7 model leads to a very high number of variables which makes an optimization process impractical. However the lack of an optimization function represents one of the main weaknesses of the model.

The economic calculation module is based on the physical flow calculation and cannot be separated. This leads to very large data volumes and therefore extensive calculation times. This is a weakness of the program as economic calculation of a whole year is not possible without mainframes. Time series longer than 2 months are not possible because data volumes would exceed the data limit of SQL as well as average personal computers.

Furthermore pure grid node models which simulate meshed power systems reflect load flows in large scale interconnected transmission systems better than combined grid node and cluster models. The high data volume of the [R]E 24/7 does not allow the simulation of large regions with multiple grid nodes.

Finally the economic calculation of negative electricity flows – from low voltage level towards high voltage levels is not possible as negative costs would occur which represents an additional weakness of the program.

### **Further Research Needs**

In order to calibrate and verify the model further, comparisons with other model outputs which use different methodologies as well as the re-calculation of specific documented events in distribution and transmission grids are required. Especially simulation of load flows across several voltage levels and grid nodes with real power grid data is needed to further evaluate the three-dimensional grid-node cluster methodology developed for this thesis. Empirical comparison of grid simulation programs categorized in grid-node, cluster and hybrid models is required in order to further evaluate strength and weaknesses of various grid simulation methodologies.

The influence of cluster sizes and chosen grid node positions on calculation results requires further research. Especially the interaction of neighboring low voltage clusters which are connected to a wider network within a meshed grid node system should be further explored in order to adopt simulation algorithm of the new developed methodology accordingly.

MESAP/PlaNet allows creating interfaces between measured data from smart meters, distributed generation and wind turbines and the programmed [R]E 24/7 model. Uploading measured data further supports additional calibration work to verify and expand the model. By transferring [R]E 24/7 from a laptop to a mainframe

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a further expansion from a single TA to multiple TA would enable the calculation of large regions e.g. Germany.

Development of an optimization algorithm connected to the model while keeping the three-dimensional grid simulation methodology eliminates the main weakness and expands application areas for [R]E 24/7. Furthermore a Geographic-Information System (GIS) based mapping tool in combination with the standard report tool can improve visualization and evaluation options.

## 1. Introduction and Thesis

*“Climate change is one of the great challenges of the 21st century. Its most severe impacts may still be avoided if efforts are made to transform current energy systems. Renewable energy sources have a large potential to displace emissions of greenhouse gases from the combustion of fossil fuels and thereby to mitigate climate change. If implemented properly, renewable energy sources can contribute to social and economic development, to energy access, to a secure and sustainable energy supply, and to a reduction of negative impacts of energy provision on the environment and human health.” IPCC-SRREN, May 2011*

Climate change, air pollution and water stress are direct or indirect impacts from mining and burning fossil fuels to provide energy services around the world. Therefore we need “a fundamental shift in the way energy is consumed and generated must begin immediately and be well underway within the next ten years in order to avert the worst impacts of climate change” (IPCC-SRREN, Chapter 1, May 2011<sup>7</sup>). The transformation of existing energy systems as well as the implementation of new energy systems in developing countries require planning and system analysis tools to use the locally available renewable energy resources as efficient and economical as possible.

This thesis aims to develop a specific bottom-up modelling algorithm which can be adapted to different countries, regions or cities in order to link energy scenario models with annual resolution to grid simulation models with resolution of an hour or less. The growing market penetration of flexible solar and wind power plants make it increasingly important to develop a connection between energy planning tools at different temporal resolutions. National or regional energy planning using scenario analysis will be inherently flawed at if it disregards temporal and seasonal fluctuations as well as the requirements and costs of maintaining constant supply.

The aim of this thesis therefore is to bridge the gap between energy models and grid simulation tools in order to move from rather static national energy scenarios, which do not reflect regional renewable resource differences within the modelled country towards 100% renewable energy (RE) models, which take infrastructural requirements into account.

The integrated bottom-up modelling concept is to be developed with existing and commercially available database programs for energy planning and/or energy trading in order to make it relevant for energy models currently in use. The model developed for this thesis has been named [R]E 24/7 which stands for “Renewable Energy 24 hours a day, seven days a week”.



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## 1.1 Thesis

A bottom-up energy model which reflects multiple voltage levels of power systems and a time resolution adequate for dispatch analysis can be used as an infrastructural planning tool, bridging the gap between detailed grid simulation tools and energy scenarios. This model may be used to assess approximate indications of required grid capacities and to carry out economic calculations for alternative measures to grid expansion such as storage or demand side management. The exogenous optimization process takes place bottom-up – from the lowest voltage level to the highest in order to reduce electricity transport and to use local resources as efficiently as possible. The assumption of this thesis is that bottom-up models for 100% RE grids have advantages over top-down models, because possible bottlenecks in power grid systems can be allocated to the voltage level in which they appear. Increasing shares of solar photovoltaic systems are mainly connected to distribution grids and possible measures for a better integration can be calculated at all different voltages levels to find the most economical solution.

Moving from conventional energy to renewable energies – especially for 100% renewable energy scenarios – requires a fundamental change in the modelling approach due to large shares of fluctuating wind and solar generation. The need for dispatching and wheeling of large amounts of wind and solar electricity within a specific region or country leads to very different infrastructural requirements of future energy systems and must be reflected in new energy models.

Infrastructure for 100% RE systems might not only require changed power grids, but also multiple electric and thermal storage technologies as well as interconnected (district) heating and gas networks as well (IEA 2014<sup>8</sup>). Thus the model to be developed for this thesis should have the possibility to add various different technologies into the calculation process if required. This model flexibility would be beneficial to find the best possible renewable energy integration concept with a large range of different – maybe currently not known – technologies.

The first step of this thesis was to search for existing models and research projects which aim to model 100% renewable energy systems across all voltage levels. A selection of these existing models is presented in chapter 2 and 3. While several models combined energy and power grid models (RWTH 11-12<sup>9</sup>), (van Hulle 2009<sup>10</sup>) none of the analysed models reflected all voltage levels and included a voltage specific economic calculation component. While (Langham 2011<sup>11</sup>) allows a detailed and even transformer specific economic calculation possibility, higher voltage levels have not been included in the model. Also the transformer specific modelling approach limits the scope of the model due to data availability.

### The Methodical Approach of this Thesis:

- Research status quo of existing energy and grid models
- Research for suitable methodologies to combine energy and grid models
- Research to find suitable software to create a new model

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- Develop and implement a user friendly and standardized data input
- Develop a standard report concept to progress output
- Compromise between realistic data and low data volumes to save calculation time and in order to make it operational for personal computers
- Verify mathematical correctness of the new developed model
- Present and discuss initial model results
- Identify strength and weakness of the developed program

It is not aim of the thesis to find the best power supply and grid concept for a specific region, but to develop an enabling tool for this.

### **Scope of Necessary Programming Work for this Thesis**

The model has been programmed on the basis of commercial available software which is used by energy traders, emission control agencies and utilities for documentation and reporting of energy and CO<sub>2</sub> flows. The software has been selected due to its flexibility and its extensive opportunities to model processes and (energy) flows in three dimensions and with detailed cost allocations and due to its interfaces to different database systems such as MICROSOFT SQL and Oracle. However, the software only provides the toolbox as a basis for the programming work – equal to e.g. GAMS is used for the development of new models.

The model developed for this thesis has been build up from a “blank screen” bottom-up from the household demand side level to the 400kV supply side across all four voltage levels over more than two years. All commodities, processes and their interaction via mathematical functions which defines the logical flow of the model have been developed for this thesis.

### **Use and Application of the Model**

The model should provide technical information about the required renewable energy capacities for a secure power supply in response to the location and the voltage level. It should identify possible limits for the integration of flexible renewables for each grid level and enable the modeller to calculate associated costs for each involved process. The aim is to develop a tool which allows cost calculations for different energy supply concepts on an hourly basis and for regional clusters e.g. for communities, regional utilities, green power supplier and islands.

## **1.2 Thesis Outline**

Energy modelling tools are available for various different purposes and used methodologies depend on the areas of application. Chapter 2 describes frequently used energy simulation programs and puts them in the context of the model developed for this thesis. A detailed analysis of three Meta-studies of the Energy Modeling Forum 28 (EMF28), the International Panel on Climate Change Special Report Renewables (IPCC-SRREN) and the University of Limerick (Connolly et al

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2009)<sup>12</sup> provides an overview for the scientific development status from a whole range of over 50 energy models. Based on this survey, chapter 2 identifies a number of energy programs whose software provides the technical possibility and the required building blocks to develop an infrastructural planning tool.

The overall objective of Chapter 3 is to describe currently used methodologies for grid analysis and their strength and weaknesses. The selection of the presented grid models is based on their different methodologies to provide a synopsis for finding a suitable methodology for the for [R]E 24/7 program. Thus the overview only covers a limited amount of programs.

Chapter 4, concludes which methodology has been chosen to develop the model for this thesis and why. The development of the methodology for [R]E 24/7 is documented and explains why specific simplification and decisions during programming were made. Strength and weaknesses of the new model methodology are also presented.

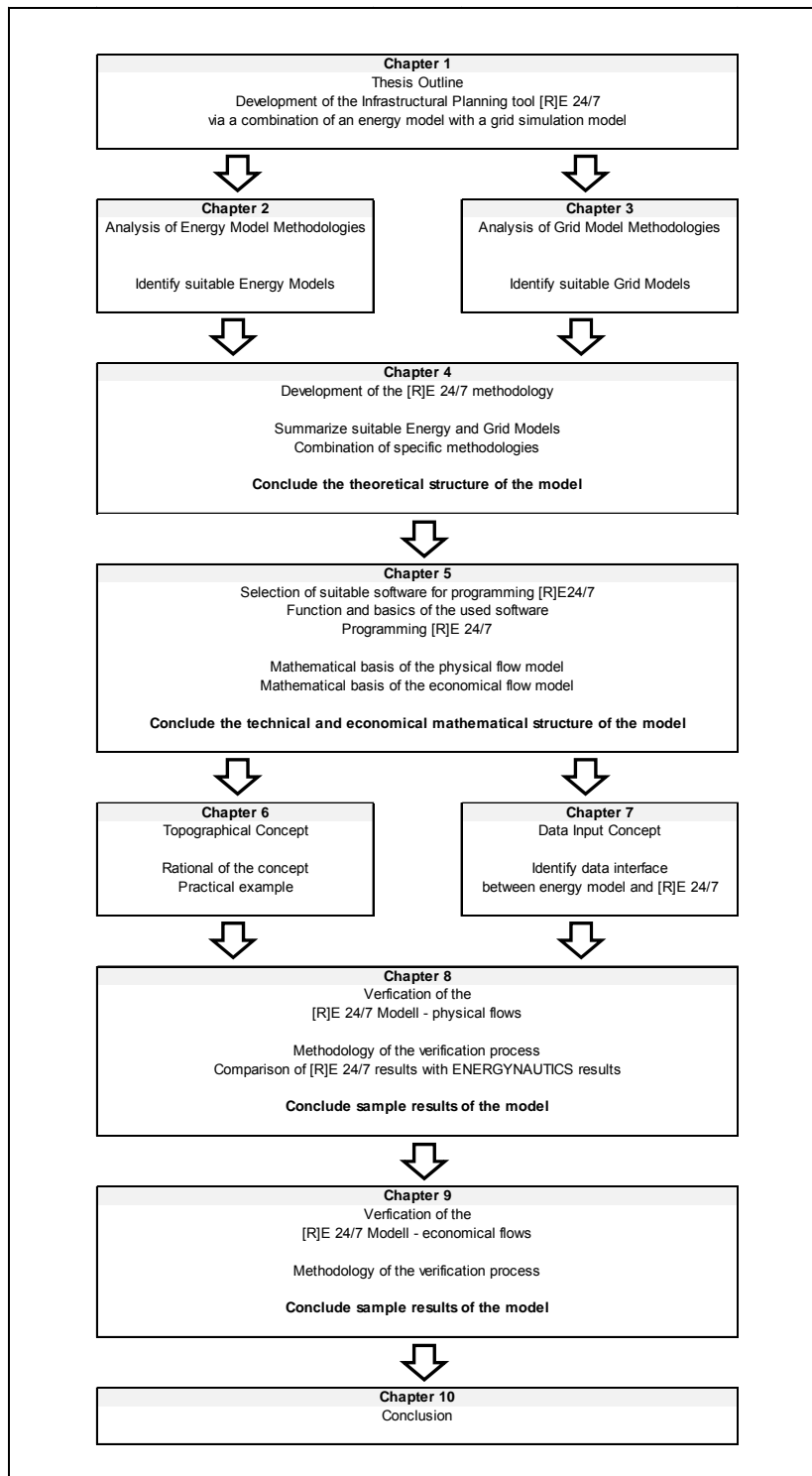
The actual development of the infrastructural planning model is documented in Chapter 5. The key building blocks of the used PlaNet network software – commodities, processes and attributes – are documented including all formulas to calculate physical flows. Once the physical flow of [R]E 24/7 has been verified, the cost module has been implemented. PlaNet is a macro-economic cost model which calculates the costs of flows, commodities and processes. The methodologies of the economic model including cost flows within one cluster and across the entire model are outlined.

The topographical concept of the program which is described in chapter 6 combines the “grid node approach” with the “copper plate approach” and is one of the key functions of the program development for this thesis. In connection to this, chapter 7 focuses on the data implementation concept and represents another key building block of the [R]E24/7 model. The objective was to achieve a high degree of standardization in order to create a user friendly interface between databases and the energy model itself. Both the data collection and required data input formats are key for coupling [R]E 24/7 with other energy scenario models.

In order to verify the function of [R]E 24/7 Chapter 8 focuses on the mathematical verification of the model developed for this thesis. Thus the input data from another grid analysis - carried out by EN (EN) - has been used and results of both models are compared. Chapter 8 compares results of a grid analysis from the chosen reference model with [R]E 24/7 in order to verify functions and results of the program and whether or not the results are comparable. Chapter 9 provides an overview about the cost calculation function of the program and sample results. Finally chapter 10 draws the conclusion, identifies strength and weaknesses and indicates further research needs.

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**Figure 8:** Structure of the Thesis

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## 2. Methodology for Energy System Analysis

Multiple stakeholders from governments, the financial sector, the energy industry as well as climate scientists and civil society groups use computer models for the analysis of energy systems. To optimize energy services according to their costs, emissions, fuel demands and physical flows leads to different methodologies. Available data and objectives of the analysis significantly influence the model architecture. It is of great importance to differentiate between an energy model and a scenario. The energy model is created in a particular programming language, which to some extent affects the model architecture, the methodology and functionality. An energy model is the technical basis for a scenario. Scenarios are results of the energy model which have been calculated with different input data and assumptions.

There are many energy modeling tools for different purposes and objective available. A coherent analysis of the renewable resource and technology potential is required to use renewable energy and to implement cost effective and secure energy systems. Identifying already available tools and choosing the most suitable tool for the planned investigation is of great importance. A detailed analysis of all existing and used energy models has not been the objective of this thesis. However to ascertain which energy model is most suitable to develop a bottom-up infrastructural planning tool, an analysis of energy models clustered by methodologies is required.

This chapter is based on meta-studies from the Energy Modeling Forum (EMF) and the IPCC Special Report Renewables which analyzed a wide range of different energy models. The aim is to provide an overview of the main energy models and their application areas. The focus of this thesis is on renewable energy scenario development.

### 2.1 Energy Model Overview of the Energy Modeling Forum (EMF)

The Energy Modeling Forum 28 (EMF28) conducted a comprehensive energy model comparison exercise, documented and published in several detailed scientific articles in December 2013 at Climate Change Economics, Vol. 4 ;World Scientific 2013. Knopf et. al 2013<sup>13</sup> listed 13 models of the EMF 28 comparison and identifies five main differences in relation to the methodological characteristics of the energy model:

- Economic coverage: Two major classes of models; full equilibrium macro-economic models which describe the nexus between economy and energy system and partial equilibrium models of the energy system. The EMF 28 macro-economic models include computable general equilibrium (CGE) (Knopf et. al. 2013<sup>14</sup>)
- Geographic coverage: Geographical coverage and regional resolution within calculated area

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- Inter-temporal solution methodology: Model horizon in years and time steps length
- General solution methodology: Market equilibrium or optimization
- International trade: If and what commodities are reflected within the model across regions

	Economic coverage	Geographic coverage (Number of EU regions)	Inter-temporal solution methodology	General solution methodology	International trade
EPPA [A]	Full economic coverage in CGE	Global (1)	Recursive dynamic	Market equilibrium	All commodities
FARM [B]	Full economic coverage in CGE	Global (5)	Recursive dynamic	Market equilibrium	All commodities
GEM-E3 [C]	Full economic coverage in CGE	Global (25)	Recursive dynamic model with static expectations	Market equilibrium	All commodities
PACE [D]	Full economic coverage in CGE	Global (1)	Recursive dynamic	Market equilibrium	All commodities
MERGE-CPB [E]	Full economic coverage in optimal growth model	Global (1)	Inter-temporal optimization	Optimization	Fossil Fuels
WITCH [F]	Full economic coverage in optimal growth model	Global (2)	Inter-temporal optimization	Optimization	Oil
POLES [G]	Partial equilibrium model of the energy sector	Global (27)	Recursive dynamic	Market equilibrium	Fossil Fuels
TIAM-UCL [H]	Partial equilibrium model of the energy sector	Global (3)	Inter-temporal optimization	Optimization	Fossil Fuels, uranium
TIMES-VTT [I]	Partial equilibrium model of the energy sector	Global (4)	Inter-temporal optimization	Optimization	Fossil Fuels, electricity, biofuels, CO2 storage
PRIMES [J]	Partial equilibrium model of the energy sector	EU (25)	Perfect foresight in power sector, 10 year foresight in	Market equilibrium	Electricity and gas in Europe
TIMES Pan EU [K]	Partial equilibrium model of the energy sector	EU (23)	Inter-temporal optimization	Optimization	Electricity, biomass, biofuels
PET [L]	Partial equilibrium model of the energy sector	EU (25)	Inter-temporal optimization	Optimization	Electricity
EMILIE-ESY [M]	Partial equilibrium model of the electricity sector	EU (27+2)	Inter-temporal optimization	Market equilibrium	Electricity, biomass, biofuels

Notes: [A] Paltsev et al. (2005), Paltsev et al. (2011) [B] Sands et al. (forthcoming); [C] Capros et al. (2010), Capros et al. (forthcoming); [D] Böhringer and Lange (2003), Böhringer et al. (2009), Böhringer and Löschel (2006); For this version of PACE7 calibrated to EU data up to 2050 Hübler and Löschel (2013); [E] Blanford et al. (2009), Aalbers and Bollen (2013); [F] Bosetti et al. (2006), De Cian et al. (2012); [G] Criqui and Mima (2012); [H] Anandarajah et al. (2011); [I] Koljonen and Lehtilä (2012); [J] Capros et al. (2012); [K] Blesl et al. (2012); [L] Kanudia and Gargiulo (2009); [M] Traber and Kemfert (2012), Schroeder (2012) **SOURCE: Knopf et. al. (2013)**

**Table 6:** Models of the EMF28 Comparison Exercise – Knopf et. al. 2013<sup>15</sup>.

E.DeCian et.al 2013<sup>16</sup> conducted a survey within the EMF 28 energy model analysis and characterized eight of the energy models (see Table 6) towards the international climate and energy mechanisms. He identifies three types of model:

- Computer General Equilibrium Model (CGE): EPPA, PACE, FARM-EU
- Energy system Model (ESM): POLES, TIAM-UCL, TIMES-VTT
- Optimal Growth Model (OGM): WITCH, CPB

In order to select a suitable energy model from within the EMF 28 analysis for the development of an infrastructural planning tool, the EMILIE-ESY model is the most interesting one as it includes a dispatch module. Therefore this model will be described more in depth.

The EMILIE-ESY is a partial equilibrium model for the power sector (Schröder et. al 2013)<sup>17</sup> and aims for profit maximization and identifies investment and dispatch decisions for conventional power plants. Other sectors which might influence the demand of electricity such as the heating and transport sector are not covered. The main outputs of the EMILIE-ESY model are electricity wholesale market prices,

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carbon prices, production and demand volumes and investments in conventional generation capacities (Schröder et. al 2013<sup>18</sup>). The regional resolution of EMELIE-ESY model application is equal to the number of EU member states (27) plus Norway and Switzerland. Therefore the energy model covers the average national electricity situation but does not cover a further regional break down.

However the temporal resolution is quite unique as it covers five 10-year periods (2010 to 2050) and each of these periods is represented by 24 consecutive hours. Hence, each decade is translated into one representative day with hourly time steps. Specific seasons with their different weather patterns cannot be reflected. The transmission grid structure in between countries (each one therefore represents one grid node) is taken from ENTSO-E 2012. The electricity consumption assumed in the EMELIE-EYS model is endogenous and dependent on the energy price calculated from the model and the basic demand projection.

The model covers two different nuclear reactor types, six coal power plants, four gas, two oil and one hydro power technologies with different investment, operation and maintenance and fuel cost, efficiencies fuel emissions and assumptions about the start-up depreciation. The EMELIE-EYS model can identify possible dispatch orders and their impact on the economics of power plants capacity factors, but cannot identify grid expansion needs.

## 2.2 Energy Model Overview of the IPCC Special Report Renewables

According to the IPCC Special Report Renewables, climate change mitigation scenarios are calculated with energy models which use two distinct approaches for the scenario development: quantitative modeling and qualitative narratives (IPCC-SRREN 2011<sup>19</sup>). Qualitative scenarios are not limited to energy related scenarios and take other GHG emissions from other sectors such as land-use change into account. Quantitative scenarios estimate RE deployment pathways in combination with other technical and political measures to analyze the role of RE in climate mitigation pathways. There are significant variations in the level of detail across all models especially concerning their sectorial breakdown and technology aggregations. The objective of climate change mitigation scenarios is to calculate possible Greenhouse Gas (GHG) emission pathways and technology choices are to a large extend cost driven, while the regional resolution is low.

The IPCC-SRREN energy model analysis (IPCC-SRREN 2011<sup>20</sup>) identifies five important methodological differences:

- Models which take an integrated view of the energy systems and therefore capture interactions between competing technologies
- Models are driven by economic criteria
- Global and long-term energy models with some regional details
- Models which include policy assumptions within the model architecture
- Models with sufficient detailed technology breakdown (both RE and conventional) and reflect regional details

### Bridging the Gap Between Energy- and Grid Models:

Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

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#### 2.2.1 Technology Clusters and Regional Distribution of RE

Some models cluster different technologies into one category and therefore cannot be used for further energy system analysis whether or not the existing energy infrastructure could cope with the proposed pathway. RE technologies, such as PV, geothermal and bio energy cogeneration plants are to a large extent decentralized energy production facilities, thus connected to distribution grids. Other renewable technologies involve industrial-scale energy production far away from demand centres such as offshore wind and concentrated solar power plants and therefore connected to high voltage transmission lines which requires different energy infrastructure than decentralized RE.

Furthermore, the locally available renewable energy resources like solar irradiation and wind speed have a significant economic impact, and therefore relevance for the deployment of RE in specific regions. However the grid infrastructure is one of the key factors whether or not RE deployment takes place (IEA 2014/8<sup>21</sup>). Obviously RE deployment is driven and hindered by various aspects; uncertainties about future developments are high and determined by specific assumptions.

The possible renewable energy market penetration for each sector, region and time horizon described in the scenarios depends on a number of assumptions. Especially the assumptions of current and future costs for different RE technologies are crucial for the scenario results. Feedback loops have to be considered as cost reduction potentials (learning curves) correlate with possible annual market growth. In that context data availability is problematic. Scenario results are not only determined by crucial assumptions alone, but might be dominated by the underlying modelling architecture and hidden as well as transparent restrictions (e.g. upper deployment bound for specific RE technologies).

For 100% RE scenarios the overall energy system analysis is from particular importance and needs to take required interaction between demand, supply and transport technologies into account.

There are numerous articles in the scientific literature discussing whether or not clustering methodologies for energy models as *top-down* or *bottom-up* is still adequate. According to IPCC-SRREN 2011<sup>22</sup> all IPCC assessment reports published before 2011 separated quantitative scenario modelling approaches broadly in the groups bottom-up and top-down.

The IPCC further states that “*this classification may have made sense in the past, recent developments make it decreasingly appropriate (...) as several models started to combine a top-down macro-economic model with a bottom-up energy-engineering model*”. Thus the transition between both categories continues, and “*many models, although rooted in one of the two traditions (...) incorporate important aspects of the other approach and thus belong to the class of so-called hybrid models*”. (IPCC-SRREN 2011<sup>13</sup>). The IPCC therefore classified *hybrid models* which combine elements of both the *top-down* and *bottom-up* methodology as integrated assessment tools.



However the combination of top-down models which typically use more aggregated data, and bottom-up models with greater technical details is challenging and can be traced back to competing paradigms (Böhringer et. al 2007<sup>23</sup>). Aggregated models are driven by economic parameters which often include non-energy parameters, while disaggregated models reflect the specific technologies of the overall energy system. The different levels of detail of both methodologies might lead to very complex models with high data volumes. Thus the modelling objective defines the parameters essential for the model, while not required results will lead to data aggregation.

The IPCC SRREN energy model analysis includes 16 different energy models all classified as energy-economic and integrated assessment models (see Table 7).

Model	Number of scenarios	Baseline scenarios	Policy Scenarios				Comparison project	Citation
			First best	Constrained technology	Second best policy	Constrained technology & second-best policy		
AIM/CGE	3	1	1	0	1	0	-	Masui et al (2010)
DNE21	7	1	3	3	0	0	-	Akimoto et al (2008)
GRAPE	2	1	1	0	0	0	-	Kurosawa (2006)
GTEM	7	1	4	0	2	0	EMF 22	Gurney et al (2009)
IEA-ETP	3	1	2	0	0	0	-	IEA (2008b)
IEA-WEM	1	1	0	0	0	0	-	IEA (2009); extension to 2050, Teske et al (2010)
IMACLIM	8	1	2	4	1	0	RECIPE	Luderer et al (2009)
IMAGE	17	3	5	6	0	3	EMF 22 / ADAM	van Vuuren et al (2007, 2010); van Vilet et al (2009)
MERGE-ETL	19	4	3	12	0	0	ADAM	Magne et al (2010)
MESAP/PlaNet	2	0	0	2	0	0	-	Krewitt et al (2009); Teske et al (2010)
MESSAGE	15	2	4	7	2	0	EMF 22	Riahi et al (2007), Krey and Riahi (2009)
MiniCam	15	1	5	4	3	2	EMF 22	Calvin et al (2009)
POLES	15	4	3	8	0	0	ADAM	Kitous et al (2010)
ReMIND	28	4	6	14	4	0	ADAM / RECIPE	Luderer et al (2009); Leimback et al (2010)
TIAM	10	1	5	0	4	0	EMF 22	Loulou et al (2009)
WITCH	12	1	4	4	3	0	EMF 22/RECIPE	Bosetti et al (2009); Luderer et al (2009)
<b>Total</b>	<b>164</b>	<b>27</b>	<b>48</b>	<b>64</b>	<b>20</b>	<b>5</b>		

**Table 7:** Energy-Economic and Integrated Assessment Models Considered in this Analysis – Source: IPCC-SRREN 2011<sup>24</sup>

## 2.3. Energy Models Overview – University of Limerick

The third meta-study presented in this chapter was conducted by the University of Limerick, published in Applied Science (Connolly et. al. 2009<sup>25</sup>). This survey has been chosen because it covers 37 energy models and technology simulation tools which are important for the development of an infrastructural planning tool. Connolly et. al. 2009<sup>26</sup> identified four different types of energy tools and categorized three methodologies which can either be used exclusively or in a combination:

1. Simulation tools: Simulates the operation of energy-systems including demand and supply interaction typically in hourly steps over one full year
2. Scenario tools: Simulates mid and long-term energy scenarios of entire regions or countries with a time resolution of annual steps or higher typically for 20 to 50 years
3. Equilibrium tools: Balance supply, demand, and prices in a whole economy or part of an economy and multiple markets. It is often assumed that agents are price takers and that equilibrium can be identified. Equilibrium tools are classified as *top-down* models
4. Macro-Economic Tools: Is a *top-down* tool typically using general macro-economic parameter to determine growth in energy prices and demands

### *Energy Scenario Methodologies:*

1. Bottom-up: A bottom-up tool identifies and analyses the specific energy technologies and thereby identifies investment options and alternatives (Connolly et al 2009<sup>25</sup>)
2. Top-down: Focuses on economic data and typically shows less technology details than bottom-up models
3. Optimization: Tools which optimizes either technical systems and their operation or investment via feed-back loops

According to Connolly et al. choosing an energy model also depends on the objective of the modeling. In order to simulate 100% RE systems, Connolly et. al 2009<sup>27</sup> identifies seven tools which have been used in the past for that purpose: EnergyPLAN, H2RES, Invert, DLR (MESAP/PlaNet), INFORSE, LEAP, and SimREN. Four of these, EnergyPLAN, DLR (MESAP/PlaNet), H2RES, and SimREN can use time-steps of 1 h or less, whereas the other three, Invert, INFORSE, and LEAP, used annual time-steps. As a result, if the objective is to optimize the energy-system to accommodate the fluctuations of renewable energy, EnergyPLAN, DLR (MESAP/PlaNet), H2RES, and SimREN would be more beneficial than Invert, INFORSE, and LEAP (Connolly et. al. 2009<sup>28</sup>).

Tool	Type						
	Simulation	Scenario	Equilibrium	Top-down	Bottom-up	Operation optimisation	Investment optimisation
AEOLIUS	Yes	–	–	–	Yes	–	–
BALMOREL	Yes	Yes	Partial	–	Yes	Yes	Yes
BCHP Screening Tool	Yes	–	–	–	Yes	Yes	–
COMPOSE	–	–	–	–	Yes	Yes	Yes
E4cast	–	Yes	Yes	–	Yes	–	Yes
EMCAS	Yes	Yes	–	–	Yes	–	Yes
EMINENT	–	Yes	–	–	Yes	–	–
EMPS	–	–	–	–	–	Yes	–
EnergyPLAN	Yes	Yes	–	–	Yes	Yes	Yes
energyPRO	Yes	Yes	–	–	–	Yes	Yes
ENPEP-BALANCE	–	Yes	Yes	Yes	–	–	–
GTMx	Yes	–	–	–	–	Yes	–
H2RES	Yes	Yes	–	–	Yes	Yes	–
HOMER	Yes	–	–	–	Yes	Yes	Yes
HYDROGEMS	–	Yes	–	–	–	–	–
IKARUS	–	Yes	–	–	Yes	–	Yes
INFORSE	–	Yes	–	–	–	–	–
Invert	Yes	Yes	–	–	Yes	–	Yes
LEAP	Yes	Yes	–	Yes	Yes	–	–
MARKAL/TIMES	–	Yes	Yes	Partly	Yes	–	Yes
Mesap PlaNet	–	Yes	–	–	Yes	–	–
MESSAGE	–	Yes	Partial	–	Yes	Yes	Yes
MiniCAM	Yes	Yes	Partial	Yes	Yes	–	–
NEMS	–	Yes	Yes	–	–	–	–
ORCED	Yes	Yes	Yes	–	Yes	Yes	Yes
PERSEUS	–	Yes	Yes	–	Yes	–	Yes
PRIMES	–	–	Yes	–	–	–	–
ProdRisk	Yes	–	–	–	–	Yes	Yes
RAMSES	Yes	–	–	–	Yes	Yes	–
RETScreen	–	Yes	–	–	Yes	–	Yes
SimREN	–	–	–	–	–	–	–
SIVAEI	–	–	–	–	–	–	–
STREAM	Yes	–	–	–	–	–	–
TRNSYS16	Yes	Yes	–	–	Yes	Yes	Yes
UniSyD3.0	–	Yes	Yes	–	Yes	–	–
WASP	Yes	–	–	–	–	–	Yes
WILMAR Planning Tool	Yes	–	–	–	–	Yes	–

**Table 8** Overview Methodologies of Energy Models (Source: Connolly et. al. 2009<sup>29</sup>)

Energy-sectors considered and renewable-energy penetrations simulated by each tool.

Tool	Energy-sectors considered			Renewable-energy penetrations simulated	
	Electricity sector	Heat sector	Transport sector	100% electricity simulated	100% renewable energy-system
<b>Reports available detailing these renewable-energy penetrations</b>					
EnergyPLAN	Yes	Yes	Yes	Yes	Yes
INFORSE	Yes	Yes	Yes	Yes	Yes
Mesap PlaNet	Yes	Yes	Yes	Yes	Yes
H2RES	Yes	Yes	Partly	Yes	Yes
SimREN	Yes	Yes	Partly	Yes	Yes
energyPRO	Yes	Partly	–	Yes	Partly <sup>a</sup>
HOMER	Yes	Yes	–	Yes	Partly <sup>a</sup>
TRNSYS16	Yes	Yes	–	Yes	Partly <sup>a</sup>
PERSEUS	Yes	Yes	Partly	Yes	–
MESSAGE	Yes	Yes	Yes	–	–
NEMS	Yes	Yes	Yes	–	–
<b>Reports NOT available detailing these renewable-energy penetrations</b>					
LEAP	Yes	Yes	Yes	Yes	Yes
Invert	Yes	Yes	Partly	Yes	Yes
EMPS	Yes	–	–	Yes	Partly <sup>a</sup>
ProdRisk	Yes	–	–	Yes	Partly <sup>a</sup>
RETScreen	Yes	Yes	–	Yes	Partly <sup>a</sup>
MiniCAM	Yes	Partly	Yes	Yes	–
SIVAEI	Yes	Partly	–	Yes	–
COMPOSE	Yes	Yes	Yes	–	–
ENPEP-BALANCE	Yes	Yes	Yes	–	–
IKARUS	Yes	Yes	Yes	–	–
MARKAL/TIMES	Yes	Yes	Yes	–	–
PRIMES	Yes	Yes	Yes	–	–
E4cast	Yes	Yes	Partly	–	–
STREAM	Yes	Yes	Partly	–	–
EMINENT	Yes	Yes	–	–	–
UniSyD3.0	Yes	Partly	Yes	–	–
WILMAR Planning Tool	Yes	Partly	Partly	–	–
BALMOREL	Yes	Partly	–	–	–
GTMx	Yes	Partly	–	–	–
RAMSES	Yes	Partly	–	–	–
HYDROGEMS	Yes	–	–	–	–
ORCED	Yes	–	Partly	–	–
EMCAS	Yes	–	Partly	–	–
WASP	Yes	–	–	–	–
AEOLIUS	Yes	–	–	–	–
BCHP Screening Tool	–	–	–	–	–

<sup>a</sup> Have simulated a 100% renewable-energy penetration in all the sectors they consider.

**Table 9:** Level of Details from Different Energy Models (Source: Connolly et. al. 2009<sup>30</sup>)

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## **2.4 Suitable Energy Modeling Methodology for the Development of an Infrastructural Planning Tool**

On the basis of the EMF, IPCC-SRREN and Connolly et. al. meta studies this subchapter seeks to draw a conclusion for the best suitable modeling methodology for the development of the infrastructural planning tool. The following specific requirements on the basis of the methodological energy model characteristics identified by Knopf et. al. 2013/2<sup>31</sup> for [R]E 24/7 are:

- Economic coverage: Full equilibrium macro-economic models describe the nexus between economic and energy systems. A detailed calculation of overall economic parameters leads in most macro-economic models to aggregation of technology parameters, especially in the field of renewable energy technology. However, a high resolution of technical parameters for the power sector is imperative for further analysis of the necessary infrastructure. Partial equilibrium and energy-engineering (or scenario models) focus on energy systems with higher technology resolutions; both for the supply and demand side compared to macro-economic-models (IPCC-SRREN 2011<sup>32</sup>), and therefore are preferred for an interconnection with infrastructural planning tools.
- Geographic coverage: A high regional resolution within the calculated area is required in order to transfer the data further into a computer model which simulates national or regional power grid systems. The higher the geographic resolution of the energy model, the better the possibilities to connect for grid models which require high regional resolution identify bottlenecks in the grid system.
- Inter-temporal solution methodology: The energy model must have the possibility for a high time series resolution of one hour or less for an entire year (8760h) in order to model seasonal and daily changes of the demand and supply nexus.
- International trade: Interregional exchange / trade of electricity functions of energy models could serve as a possible interface to infrastructural planning tools. However this function is not a prerequisite to connect energy and grid model methodologies.

This chapter documents three published Meta studies; EMF 28, (Knopf et. al.2013<sup>33</sup>) analyzed 13 models energy models for the EMF 28 survey, the IPCC (IPCC-SRREN 2011) 16 energy models and (Connolly et. al. 2009) provides an overview of 37 energy models. Some of the models have been covered in all three surveys. (Knopf et.al. 2013) and (IPCC-SREEN 2011) analyzed models which have been used to calculate long term energy transformation and Green House Gas (GGH) mitigation pathways. The EMF 28 analysis is based on a multi-model assessment, which includes six models with different economic coverage and solution models (Knopf et.at 2013<sup>34</sup>).

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The energy models presented in (IPCC-SRREN 2011<sup>35</sup>) “*are not power system models or engineering models, and they therefore employ stylized representations of many details that influence the performance and deployment of RE, for example, the challenges of incorporating variable electricity generation into the electric grid. The level of sophistication in representing these details varies substantially across models.*” Therefore it is assumed that these models do not include the analysis of the required infrastructure for 100% renewable electricity grids.

To conclude: Balancing demand and supply to introduce dispatch orders across several voltage levels with a high regional resolution requires a model which allows for the integration of these additional functions, as well as the ability to reflect a high degree of technical detail.

Schröder et.al. 2013<sup>36</sup> developed the applied model *EMELIE-ESY* under the Energy Modeling Forum 28 (EMF) which computes a partial equilibrium of the electricity in which: “*private investors optimize the fossil fuelled generation capacity investment and the hourly operation of these power plants (“dispatch”) over a long-term horizon up to 2050 on the basis of electricity and emission prices. Furthermore, the model includes the effect of power plant ramp-up restrictions on the hourly supply profile of an exemplary day and the consequent impact on price profiles in each country.*”

Based on the research for this thesis, *EMELIE-ESY* was the only energy model found in the literature, which has a high technical resolution on the supply side and an innovative mix of annual and hourly time series. However *EMELIE-ESY* still lacks the technical details on the demand side as well as on the power grid infrastructure itself. The aim of the model is to find the most economic combination of generation capacities; the investigation of required infrastructure and costs to transport the electricity is not possible. Thus bottle necks in the grid cannot be identified. Therefore it is assumed that the [R]E 24/7 represents a new approach to bridging the gap between energy and grid models.

### 3. Methodology for Grid Analysis

Methodologies currently used in grid analysis models - their basic function, areas of application as well as their level of technical and economical detail - are presented in this chapter. Due to the large amount of grid simulation programs, the selection of the described models is based on different characteristics to represent the full range of systematic approaches:

- Hybrids between energy and grid models (DLR-REMIX)
- Economic models (UTS DANCE)
- Models to integrate especially large amounts of wind power (EWEA-TradeWind)
- Multi-region models (RWTH)
- Grid node models (EN)

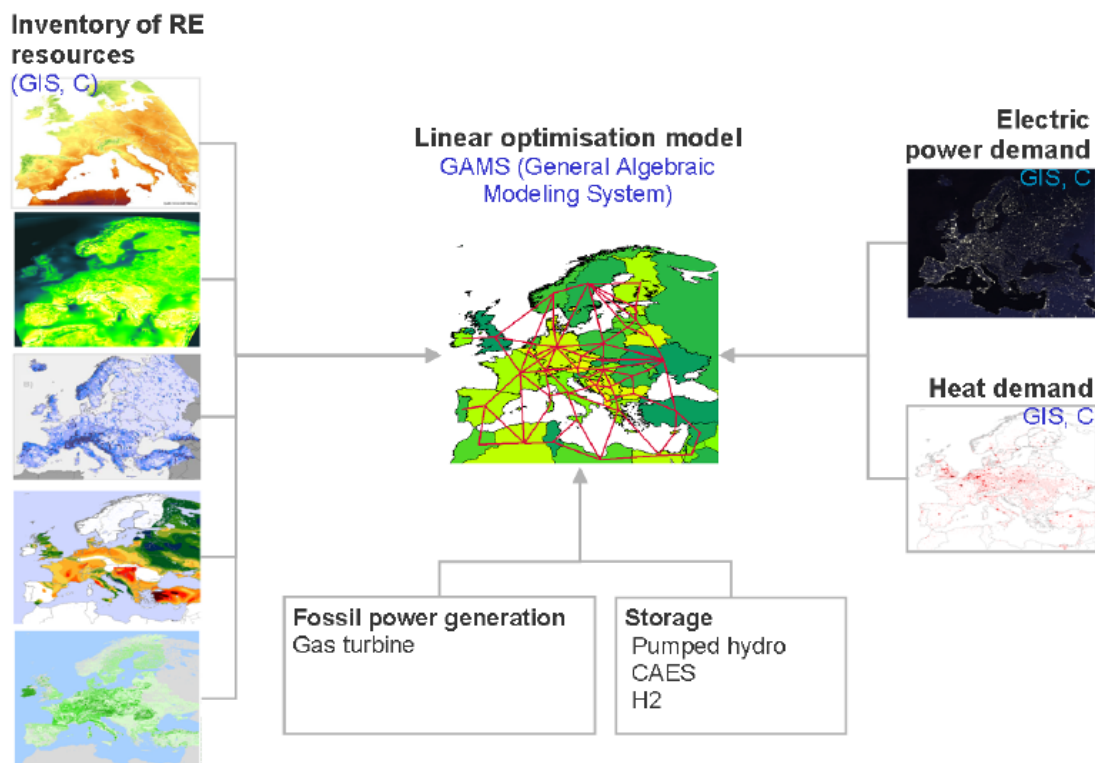
Additionally specific methodologies to simulate low voltage grids are presented in the chapter. Based on this analysis, the methodology of the [R]E 24/7 was developed.

#### 3.1 Power Grid Types – the Basics

Power grids are interconnected networks that transport electricity from power plants to consumers. The network has three main layers: High voltage lines for long distance transport of power, medium voltage lines for regional interconnections and low voltage lines to transport the electricity over “the last mile” to small scale consumers. While the exact voltage levels used varies significantly by region, the basic structure remains the same. All voltage levels are connected via transformers. The physical flow of the electricity can be *top-down* as well as *bottom-up*, while most transformers are currently not suitable for bottom-up power flows<sup>37</sup>. Centralized power generation is connected to medium or high voltage lines, while decentralized renewable energy sources are connected to low voltage lines.

### 3.2 GIS Cluster Model – Hybrid between Energy and Grid Model: DLR REMix

DLR's GIS Cluster model is a hybrid between an energy scenario model and a simplified grid model. The REMix Model (Renewable Energy Mix for sustainable energy supply in Europe) was developed with the objective to design technically feasible 100% RE electricity supply systems with intermittent availability (Scholz 2012<sup>38</sup>). The model is based to a large extent on Geographic Information Systems (GIS) coupled with the General Algebraic Modeling System (GAMS). The GIS based inventory assessment of RE resource defines the maximum available installed capacity; the demand curves – both for heat and electricity - are taken from existing energy scenarios and clustered via GIS. In the center of the model architecture a GAMS based linear optimization model balances demand and supply. The required grid capacities are calculated via a simplified grid model with one grid node per country. In the third step, the costs are calculated. The model setup is illustrated in Figure 9.



**Figure 9:** Setup of the REMix Inventory and Model (Source: Scholz, 2012<sup>39</sup>)

The REMix model is a resource assessment tool with a high spatial and time resolution, but an extreme simplified grid analysis module. Therefore bottom-up optimization for regional power grids is not possible due to the low resolution of grid nodes.

### Bridging the Gap Between Energy- and Grid Models:

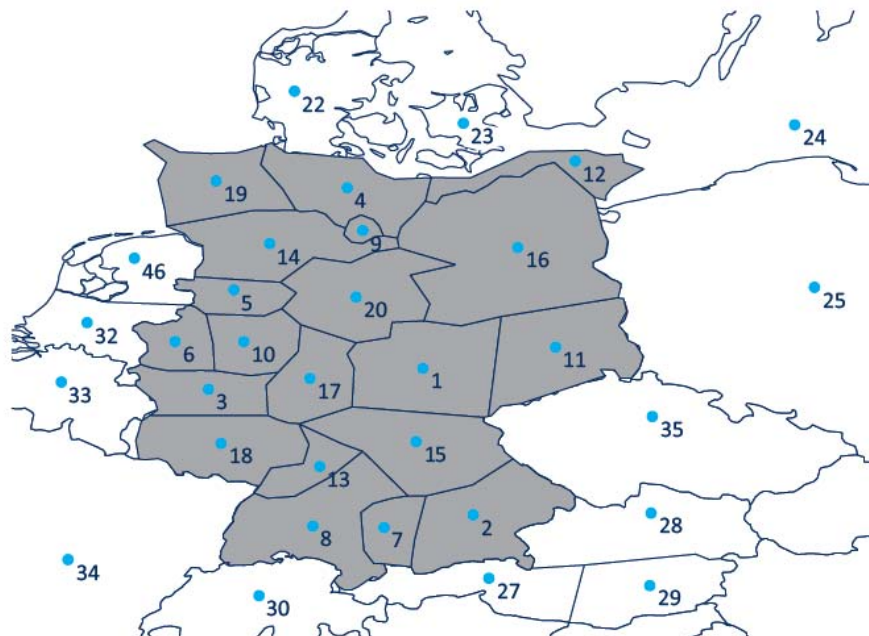
Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

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## 3.3 Multiple Region-Model – RWTH Aachen

The RWTH Aachen developed a multiple region model to calculate future transmission network requirements for Germany in case of high renewable energy deployments, especially flexible power generation from wind and solar photovoltaic. Due to the long observation horizon and the associated uncertainties regarding energy mix, load, and other factors, the analysis is not based on a node- sharp high-resolution model of the European electricity transmission grid (RWTH 11-2012<sup>40</sup>). Instead, the transmission capacity needed in the future will be determined on the basis of a pan-European Regions model. Germany has been divided into 20 regions which represents a higher spatial resolution than regions outside Germany.

The model defines that the level of detail for the neighboring European countries decreases with increasing distance from Germany. The reason for this is the expected ever decreasing operational impact from load variations with increasing distance from the German power grid<sup>40</sup>. Figure 10 shows the regional breakdown of Germany for the network simulation. The RWTH regions for Germany are identical with those of the Dena grid study (see 3.7.1 Detailed Low Voltage Grid Analysis Methodology) In all other European countries, the regions are determined on the basis of national borders and boundaries between electrically less strongly coupled network areas. The Institute for High Voltage Technology (IFHT) of the RWTH Aachen supplied the data base for the European transmission network model.



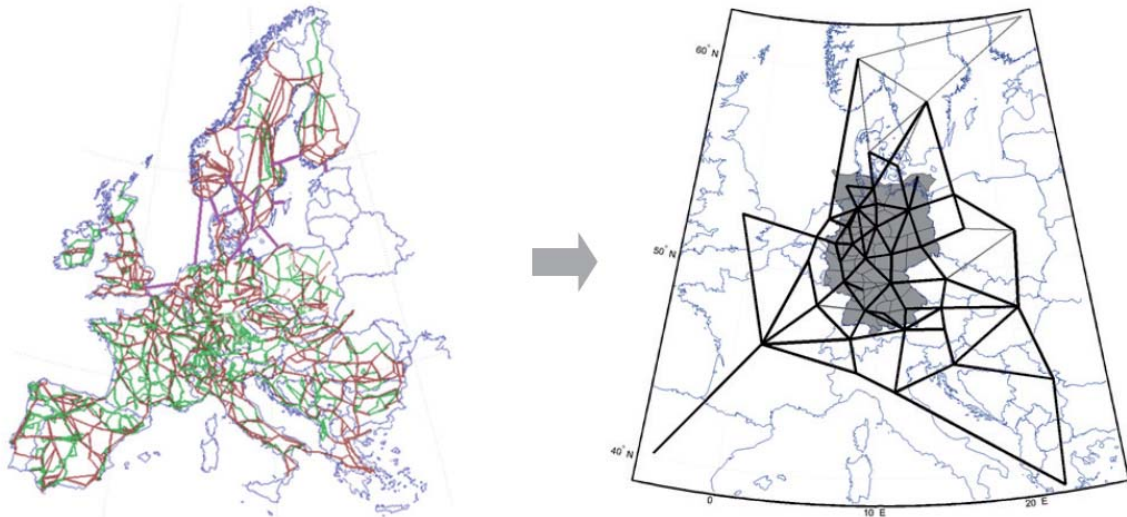
**Figure 10:** RWTH Aachen Multiple Region Model Clusters for Germany and neighboring countries (Source: RWTH 11-2012<sup>41</sup>)

In a second step, the required transmission capacity between regions can be determined. Figure 11 (left) shows the European transmission network model and Figure 11 (right) shows the simplified illustration of the regions model. The power transmission capacities between zones are calculated on the basis of verified



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interconnection capacities between countries (Net Transfer Capacities - NTCs). Similarly other electrical parameters (network impedances) are determined on the basis of the high resolution mesh model. The network model also includes future transmission lines expansion plans such as the ENTSO-E TYNDP (Ten - Year Network Development Plan).



**Figure 11:** RWTH Aachen Multiple Region Model – Transfer from Regions to Grid Nodes (Source: RWTH 11-2012<sup>42</sup>), page 13)

The RWTH model represents a hybrid between regional cluster model and a grid node model. The regional resolution is higher than in the ReMix model (Figure 9) however different voltage levels are not included in the model.

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## 3.4 TradeWind: EU Grid Model for Large Scale Integration of Wind Power

The European Wind Energy Association (EWEA) carried out an extensive survey about the possibilities of integrating large amounts of wind power in the European power grid (van Hulle 2009<sup>43</sup>). The project was divided in seven work packages shown in

Table 10. For this thesis, only the grid modeling methodology of Work package 3 (WP3) is relevant and therefore only this part will be presented.

The TradeWind model has been developed to optimize the integration of large scale wind power and therefore was not aimed to do a grid system analysis across all technologies including solar photovoltaic.

Phase 1 Preparation		
WP2 (GH) Wind power scenarios	WP3 (Sintef) Grid modeling and power system data	WP4 (Risø- DTU) Identification of market rules
Phase 2 Simulation and analysis		
WP5 (VTT) Continental power flows	WP6 (Sintef) Grid scenarios	WP7 (3E) Analysis of market rules
Phase 3 Recommendations		
WP8 (EWEA) Recommendations for grid upgrade, market organization and policy development		

Source: TradeWind / EWEA "Integrating Wind"<sup>44</sup>

**Table 10:** Project Structure of the TradeWind Project

The TradeWind model has been developed to optimize the integration of large scale wind power and therefore was not aimed to do a grid system analysis across all technologies including solar photovoltaic. Thus the model architecture only reflects the needs of wind power. While technical aspects are included in the modeling, the emphasis was on regulatory, institutional and market aspects of wind integration.

According to TradeWind *"it was neither the purpose to do an in-depth grid dimensioning study, nor to consider dynamic grid behavior and reliability aspects such as N-1 considerations"* (van Hulle 2009<sup>45</sup>).

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### 3.4.1 TradeWind Model Architecture

The simulation approach of the grid model focuses on cross border flows and is a combination of separate equivalent power system models of UCTE, Nordel and Great Britain plus Ireland (van Hulle 2009<sup>46</sup>). The model consists of 1380 nodes, 2220 branches and nine HVDC connections with 560 generators (excluding wind). The transmission lines assumed in the model have standard resistance values in [Ohm/km] of voltage levels from 220kV and above. Planned power lines – both AC and DC – according to Transmission Grid Operator (TSO) across Europe are included in the model. Thus the grid model does not reflect the current situation, but a possible future case.

Expected wind power production in relation to specific wind speeds for each grid nodes are of great importance for this model. TradeWind used a clustered time series from *Reanalysis* Wind data covering the whole of Europe (see Figure 12).



Figure 12: Reanalysis Data Nodes Covering Europe; TradeWind 2009<sup>47</sup>

Load profiles are taken from published data from the Transmission System Operator (TSO) for the demand input. No demand side management or any change in future demand patterns is assumed.

### Bridging the Gap Between Energy- and Grid Models:

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On the basis of the previous description power grids as well as the demand and supply structure, from the Power Flow Simulation Tool (PSST) was used. The structure of the PSST is shown in Figure 13.

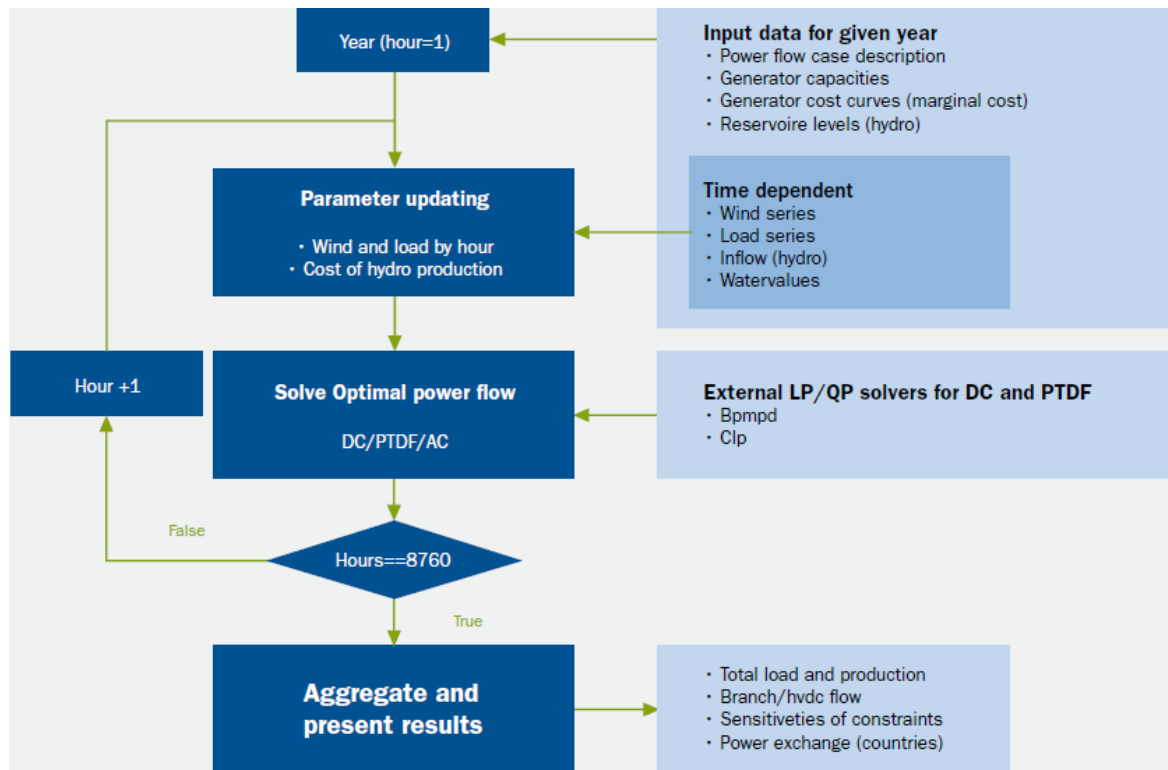


Figure 13: Power Flow Simulation Structure; TradeWind 2009<sup>48</sup>

The TradeWind model used DC power flow description (not AC) due to the availability of data and the shorter calculation time. Simulation results are the hourly production of each power plant, the power flow, sensitivities for each branch and HVDC connection as well as total cost of production. According to (van Hulle 2009<sup>49</sup>) the model makes several simplifications such as:

- An assumed ideal market
- No start-up costs are taken into account
- No grid losses are modelled
- Power plants are always available and 100% flexible accept nuclear plants

The entire calculation methodology consists of different model-modules which operate independent from each other. Calculations are therefore an iterative process.

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### 3.5 Grid Node Model: EU Grid Model from ENERGYNAUTICS (EN)

This section describes a European power system model, which has been developed by Dr. Thomas Ackermann and Dr. Eckehard Tröster / ENERGYNAUTICS (Tröster et.al. 2010<sup>50</sup>) and (Tröster et. al. 2011<sup>51</sup>) on the basis of the methodology proposed by (Zhou et. al. 2005<sup>52</sup>) and programmed with the commercial simulation software *DigSILENT PowerFactory*. The model uses grid nodes representing all major load and generation sites in the European power grid area ENTSO-E.

#### 3.5.1 Methodology Background of the EN EU Grid Model”

Zhou et. al. 2005 developed an approximate load flow model for the UCTE (Union for Coordination of Transmission of Electricity) region on the basis of publically available data. Due to security reasons, grid operator and utilities do not publish measured load flow and generation profiles<sup>53</sup>. In order to build the model, published grid maps of the European transmission network from the extra high voltage level of 750kV down to the medium voltage level of 110kV have been digitalized by transferring all transmission line lengths and the geographical position of their connections into a Geographic Information Software (GIS). The model uses a DC power flow method for simplification purposes. Therefore further electrical parameter such as resistance and shunt admittance are not included<sup>54</sup>.

Zhou et. al. 2005 classified the data to build up the load flow model into the following categories<sup>54</sup>:

- Transmission network data
- Power plant locations, fuel types and capacities
- Load center locations and capacities

The data has been collected from publically available sources and uploaded in the program *PowerWorld simulator*. Based on this information data points representing power generation capacities and load centers are connected with each other. Those connections represent power lines and an equilibrium model calculates the load flow between demand and supply data points. The interconnected data points forms a meshed grid, the junctions of different lines are grid nodes. Further information and the model data files can be downloaded from the website of the University of Edinburgh<sup>55</sup>.

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### 3.5.2 DIgSILENT “PowerFactory”

DIgSILENT PowerFactory is a commercial simulation tool specialized in the analysis of power networks and the impact of distributed generation. A load flow analysis combined with an extensive range of specific virtual grid technologies applications allows the simulation of close to real conditions in meshed grids. PowerFactory is a technology optimization tool, mainly used by grid operators and utilities to optimize the operation of electricity grids, operational planning of power transformers, power frequency analysis, power factor correction and other measures in the field of network management (DIgSILENT 2013<sup>56</sup>). The software has not been developed for energy scenario calculations. The EN EU grid model uses the load flow methodology documented in 3.5.1 Methodology Background of the EN EU Grid Model” carried out with the DIgSILENT PowerFactory Optimal-Power-Flow.

### 3.5.2 EN EU Grid Model Methodology and Architecture

Based on the methodology of (Zhou et. al. 2005), the consulting company ENERGYNAUTICS GmbH (EN) developed its own European Transmission Network model between 2008 and 2013 for the European Network for Transmission System Operators (ENTSO-E), a successor organization of the UCTE. At the time of the writing of this thesis (2014) the EN EU grid model used over 200 grid nodes representing major generation and load centres within the ENTSO-E area as well as 400 high voltage alternating current (HVAC) transmission lines (from 220kV to 380kV) and all the high voltage direct current lines (HVDC)(Ackermann et. al. 2013<sup>57</sup>). Figure 14 shows the overall EU grid model. The model has been validated against publicly available information from ENTSO-E and is capable of performing both the full AC and linearized “DC” load flows<sup>58</sup>.

Furthermore the ENTSO-E's Ten Year Network Development Plan (TYNDP) - broken down into mid- and long-term projects was used in the model architecture. Finally an *overlay HVDC grid* connecting the main load centers (large cities or industrial areas) and generation hubs like offshore wind areas with each other is optimized for the model, based on the methodology developed by EN. This specific overlay grid aims to model the effect of a super grid on the basis of HVDC cables which can be independently dispatched (Brown et al., 2013<sup>59</sup>). The model assumptions are documented in Table 37, in chapter 8. The EN Grid model is connected to a linear optimization tool programmed in *Python*. In a first step dispatch of all power plant technologies are optimized with a dispatch order algorithm in combination with the grid capacity. Therefore the best possible combination of curtailment of variable renewables (= reduced capacity factors), dispatch of conventional generators, deployment of storage technologies and expanding the grid capacity of certain lines is calculated.

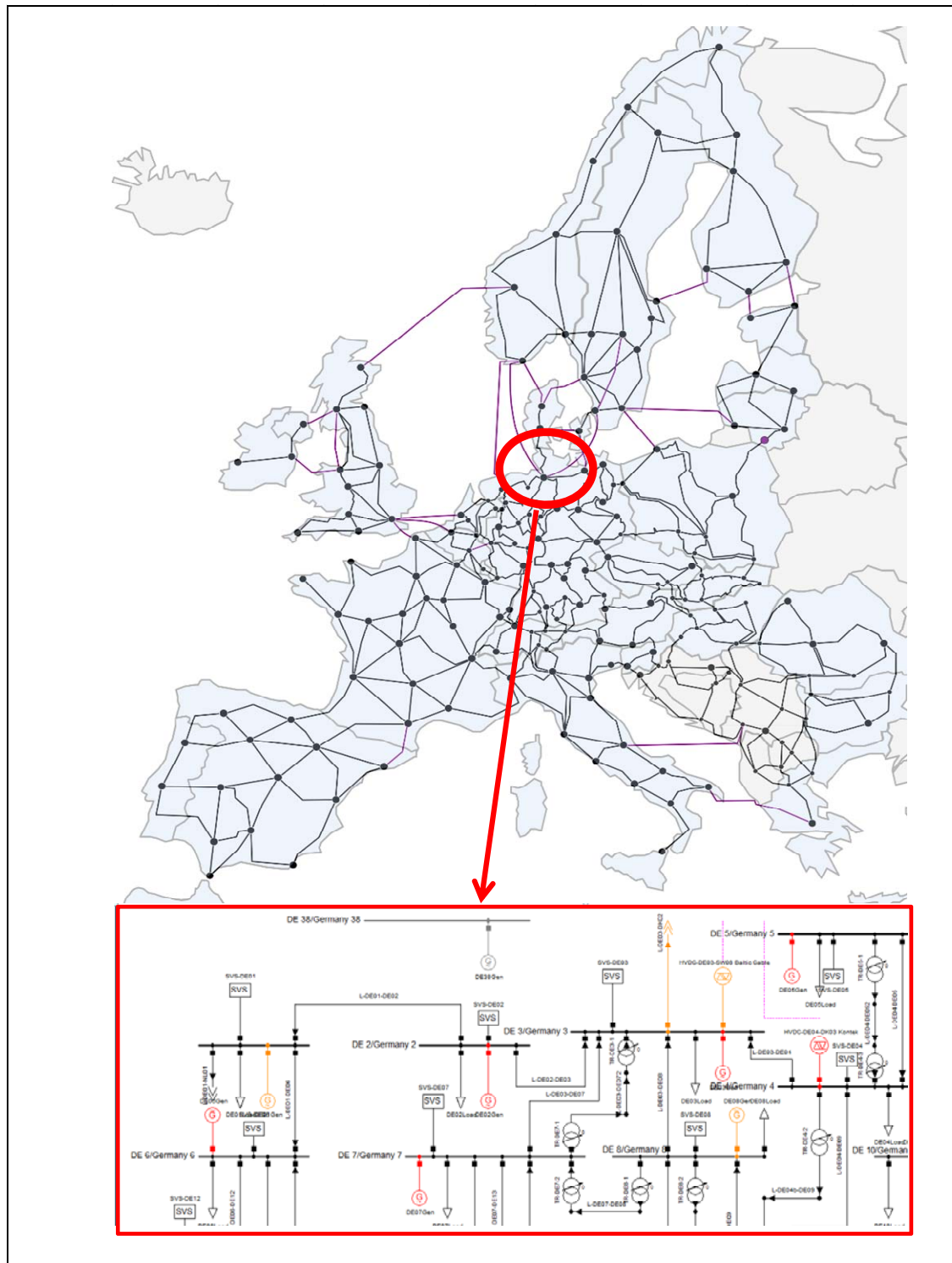


Figure 14: ENERGYNAUTICS EU Grid Model (Ackermann et. al. 2011<sup>60</sup>)

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### **3.5.3 Grid Model Input and Outputs**

According to the ENERGYNAUTICS methodology (Teske et.al.2014)<sup>61</sup> the current or future planned European high voltage transmission network and a given set of installed capacities for various renewable, fossil and nuclear power generation are taken as inputs. The dispatch of these technologies and their effect on network flows are linearly optimized to reduce network expansions necessary to accommodate the given generation technologies while guaranteeing security of electricity supply.

#### **Inputs:** (Teske et.al.2014<sup>62</sup>)

- Initial network topology for High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC) and line capacities in Mega-Volt-Ampere [MVA] or Mega-Watt [MW] and impedances from EN' aggregated grid model for Europe
- Installed capacities for all power plant technologies in Giga-Watt [GW] and yearly electrical load in Terawatt hours per year [TWh/a] for all European countries
- An assumed distribution key for how the technologies are distributed in each country (wind and PV according to potential, conventional generation sources according to existing capacity)
- Time series for one weather year to calculate the feed-in for variable renewables, including wind and solar insolation; load profile for a full year in hourly time steps per country taken from ENTSO-E published profiles

#### **Outputs:** (Teske et.al.2014<sup>62</sup>)

- The necessary network extensions and costs
- Dispatch per node of technologies, including curtailment for variable renewables and load/capacity factors for controllable generators
- Network flows for AC and DC lines



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### 3.6 Economic Distribution Grid Model: DANCE -Dynamic Avoidable Network Cost Evaluation

The Dynamic Avoidable Network Cost (DANCE) model is an economic analysis and mapping tool and has been developed within an interdisciplinary work program at the Institute for Sustainable Futures – University of Technology Sydney / Australia (Langham 2011<sup>63</sup>). The DANCE model uses electricity network planning investment cost and electricity demand projections to calculate possible bottlenecks in the grid and how to avoid them with renewables and/or demand side management. The calculation is done via Excel and visualization via GIS mapping tools. The visualization via maps is intended to make results more accessible for renewable energy and energy efficiency companies and to help initiating non-network options to avoid network expansion. The economic model is based on primary substation level data and therefore provides specific economic results for each substation. The aim is, to find the most cost effective measures – demand side management, decentralized energy generation or grid expansion – for low voltage distribution grid operators (Langham 2011<sup>64</sup>).

The economic (Excel) model requires input data from the substation level (current and projected 5 year winter and summer peak demand in *Mega Volt Ampere* [MVA] and hourly load curves for the whole year), from the grid level (secure capacity in MVA in summer and winter – 2 data points per substation) and geographic information (GIS positions and names of all substations). Besides that several economic parameters are needed such as the weighted average costs of capital in percent per year, depreciation value for the network and the discount rate.

Current and future load curves and network costs are calculated. In case the load exceeds the grid capacity network expansion costs are calculated in US\$ per kilowatt-hour. Both the utilization of the grid and possible additional costs are visualized via a GIS mapping tool. On the basis of the first results, more scenarios are calculated with either additional decentralized generation capacity to support the power supply in low voltage grids or with demand side management and/or peak shaving options to find the least costs network solution.

Sample outputs from DANCE are shown in Figure 15, Figure 16 and Figure 17. Figure 15 shows a map of Sydney with all the substations and the color code indicates where rising peak demand might exceed current transmission capacities. Those indicated areas are then re-calculated with additional decentralized power generation and/or demand side management assumptions in order to reduce transmission demand and/or reduce peak demand. The investment needs of additional power generation are compared to grid improvement costs. The results are illustrated with a GIS mapping tool for specific years, months and days.

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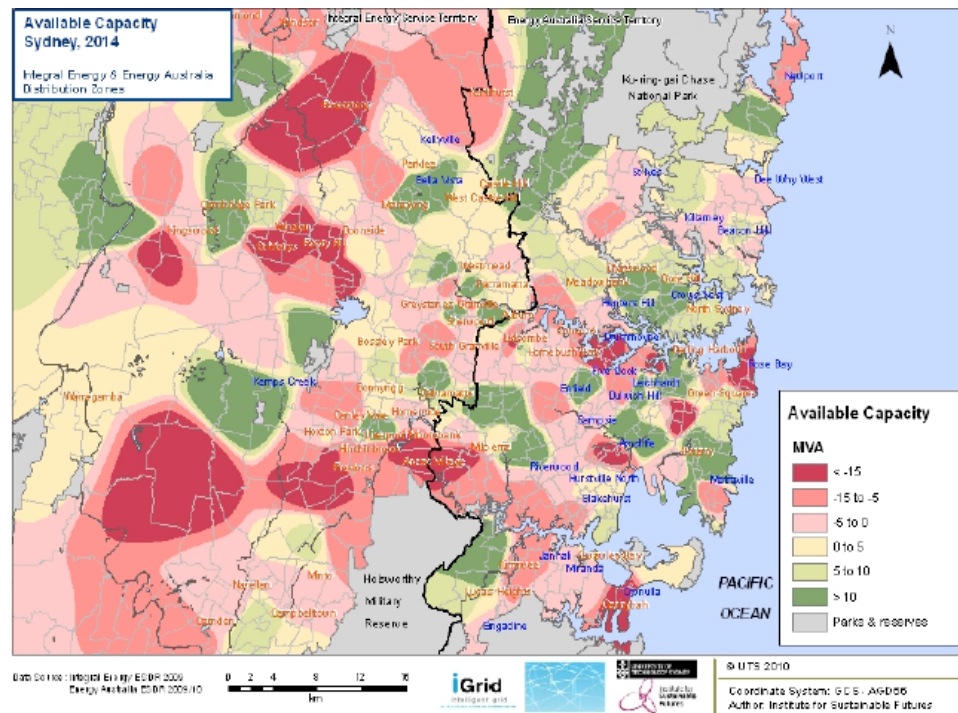


Figure 15: DANCE Visualization of Available Capacity (Langham 2011<sup>65</sup>)

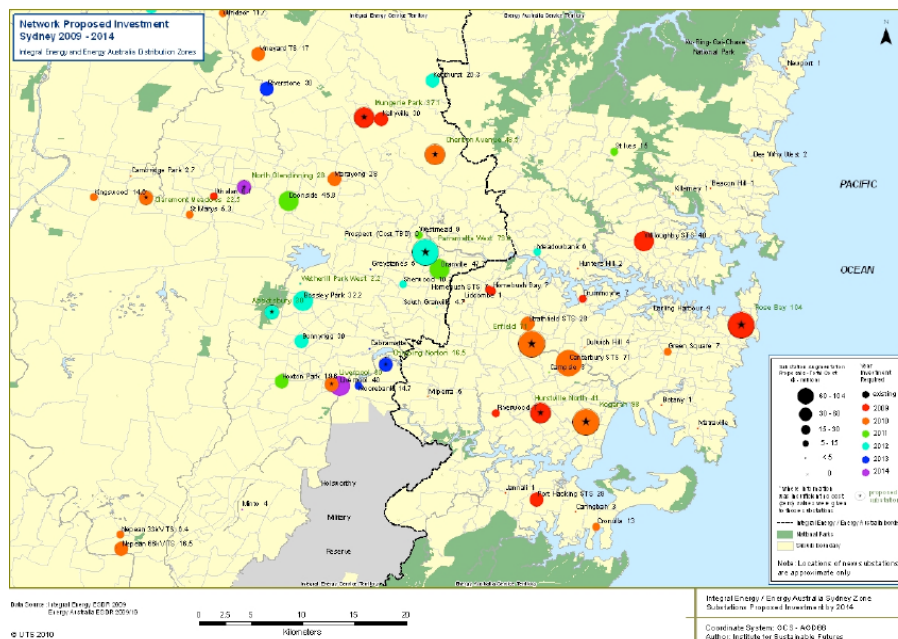
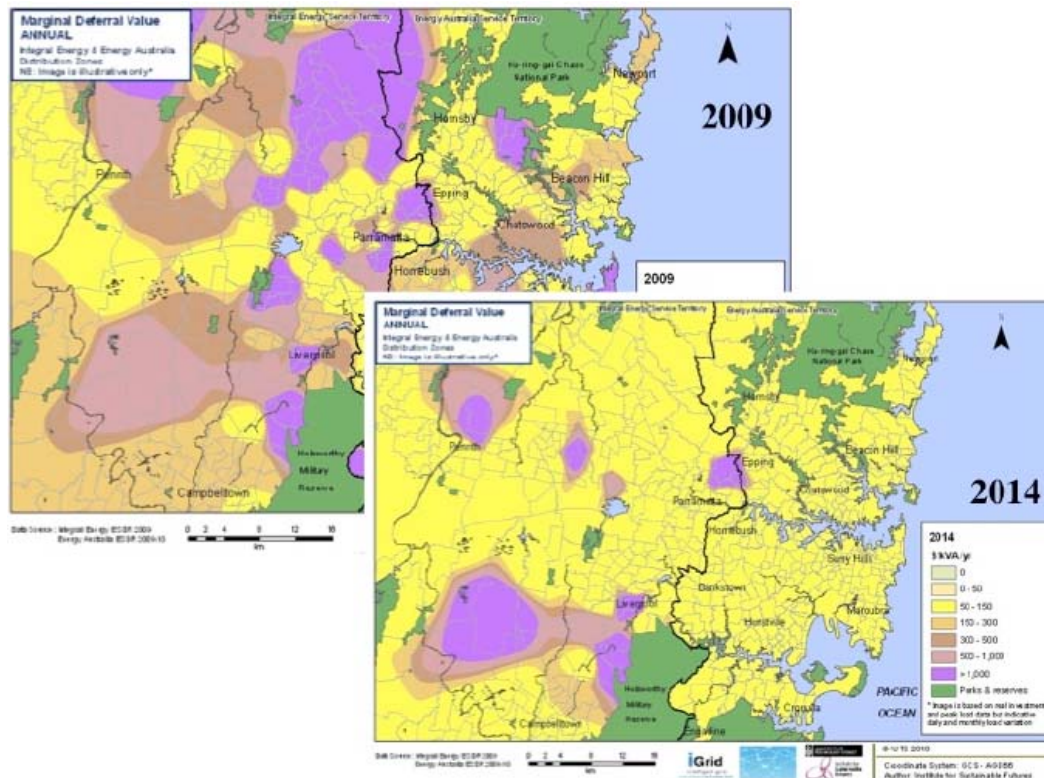


Figure 16: DANCE Visualization of Total Investment Requirements in Network Expansion (Langham 2011<sup>65</sup>)



**Figure 17:** DANCE Visualization Annual Marginal Deferral Value for Different Years (Langham 2011<sup>66</sup>)

Figure 17 shows the marginal deferral values which are calculated with the planned investment and the rate of growth in demand via the long run marginal cost calculation.

The DANCE model represents an economic grid model for low voltage distribution grids and requires substation specific data. Thus, the DANCE model is currently not applicable for transmission grid planning. However it could be transferred to high voltage transformer stations. Moreover the need for substation specific data limits the regions in which such a model can be used as that data is classified in several countries e.g. Germany and China.

### 3.7 Technical Analysis Methodology for Distribution Grids

The German Energy Agency's (DENA2012<sup>67</sup>) report "*Development and innovation needs of the power distribution network in Germany until 2030*" analysed grid enforcement and grid expansion requirements for a large penetration of fluctuating decentralized power generation. Two different methods have been used:

- Detailed Low Voltage Grid Analysis (DENA 2012)
- The Restriction Curve Analysis (RCA)

Both methodologies are presented in the section because a simplified, combined version is used for the [R]E 24/7 model.

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#### 3.7.1 Detailed Low Voltage Grid Analysis Methodology

The Detailed Low Voltage Grid Analysis (DENA 2012<sup>68</sup>) methodology uses original geographical and topographical grid maps of distribution grid operators in Germany and converts them into a 1:1 grid model including the technical data of cables, grid connection capacities and real distances between grid connections of customers (DENA 2012). Figure 18 shows step 1 of this process.

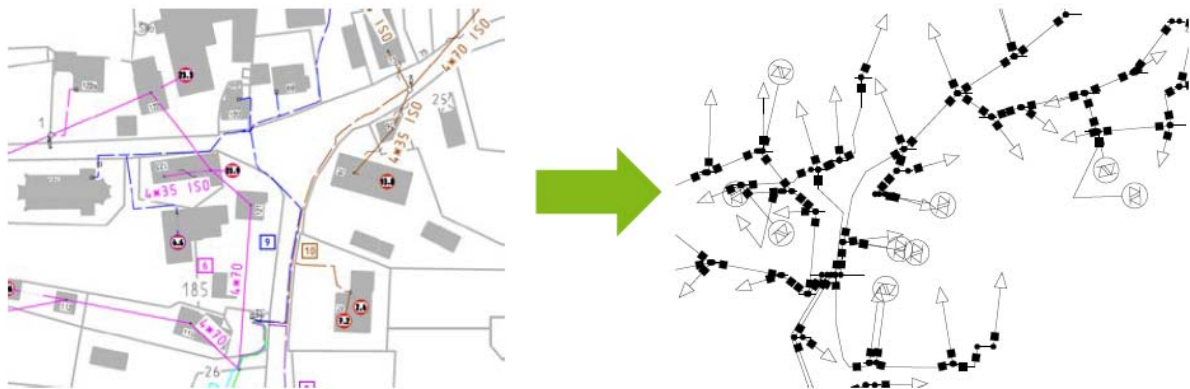


Figure 18: Detailed Low Voltage Analysis from DENA – Step 1

Step 2 of this analysis as shown in Figure 19 adds the expected addition solar photovoltaic capacity installed in the analysed grid. The estimation of photovoltaic capacity increase is based on known projects and estimations of future projects which takes the available roof space and size of individual transformers into account.

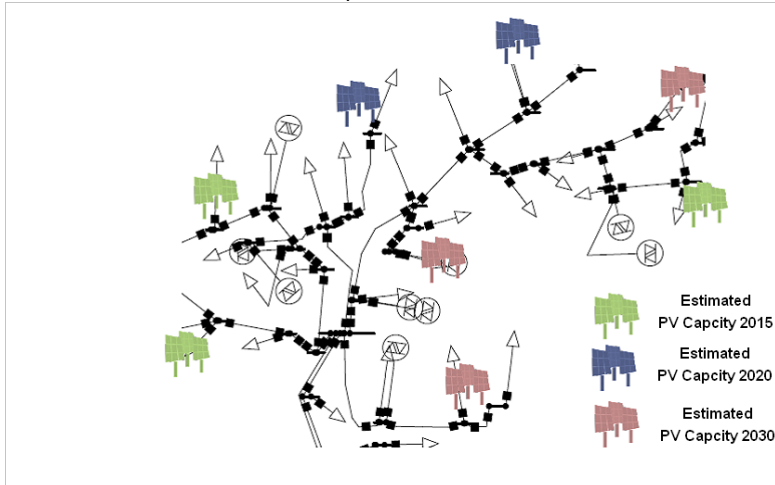


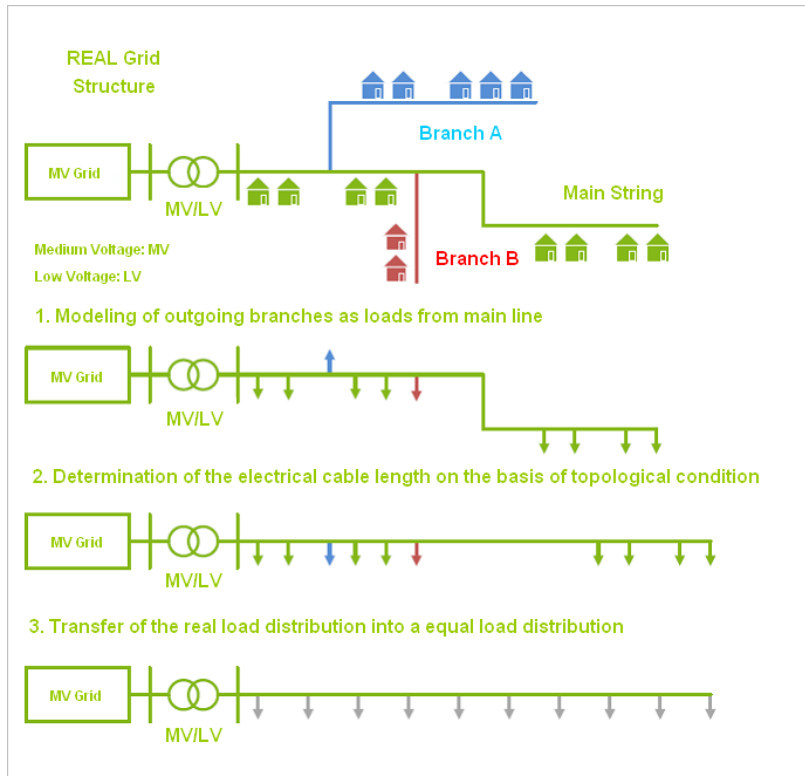
Figure 19: Detailed Low Voltage Analysis from DENA – Step 2

The electricity flow with the estimated solar photovoltaic capacity in 2015, 2020 and 2030 was calculated including the effect on grid stability, and also to discover whether or not the grid operation would be in compliance with all safety regulations.

#### 3.7.2 Restriction Curve Analysis (RCA) for Low Voltage Grids

The Restriction Curve Analysis (RCA) for Low Voltage Grids is the second methodology applied in (DENA 2012) and based on (Gwisdorf et al, 2010<sup>69</sup>). This section provides a brief overview about this methodology and cites (Gwisdorf et al 2010) and (DENA 2012) until the end of this section. According to Gwisdorf et. al 2010 the primary technical

limitations of low voltage distribution grids are voltage band compliance and connected loading equipment, which depends on the number of customer, distributed power generators and the cable length of the system. The RCA simplifies real power grid topologies in order to analyse large meshed power networks. Figure 20 explains the methodology for branched networks (DENA 2012<sup>70</sup>).



**Figure 20:** Simplification of Branched Network under the RCA Methodology (DENA 2012<sup>70</sup>)

To evaluate the real power structures, the outgoing branches of the main string are modelled as load from the main string. Thus, a grid enforcement requirement of the main track can be identified, which is caused by loads or decentralized power generation within the main string or the outgoing branches. The RCA methodology cannot identify whether grid enforcement is requirement at the outgoing branches or the main string. (DENA 2012<sup>70</sup>). For a technical analysis of a grid string, only the electrical length is relevant and is determined from the topological analysis (Figure 18 Step 1 and Figure 19, Step 2) (DENA 2012).

Finally, the actual load distribution along a string needs to be transferred into a typical load distribution (Figure 20 Step 3). The real distribution of decentralized power generation will also be converted to a typical distribution (DENA 2012<sup>71</sup>).

Thus real power structures are transferred into simplified grid structures via following parameters (DENA 2012):

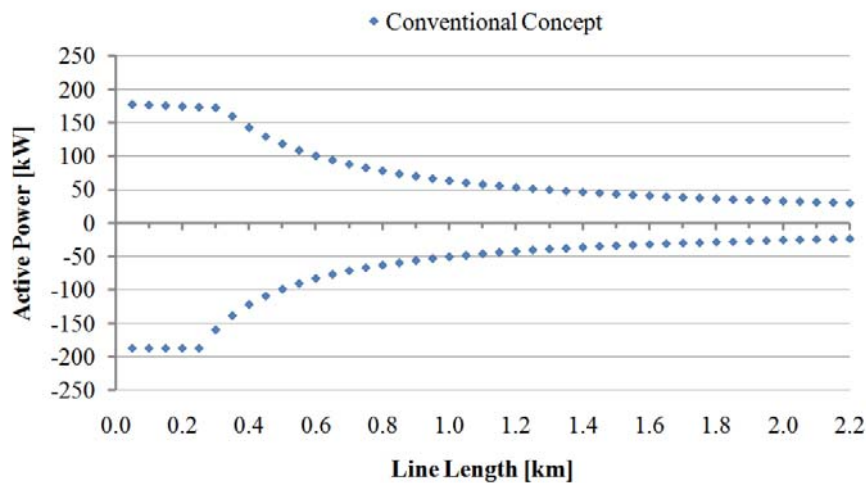
- Cable length
- Dominant cable type
- Capacity and distribution of the load
- Capacity and distribution of decentralized power generation



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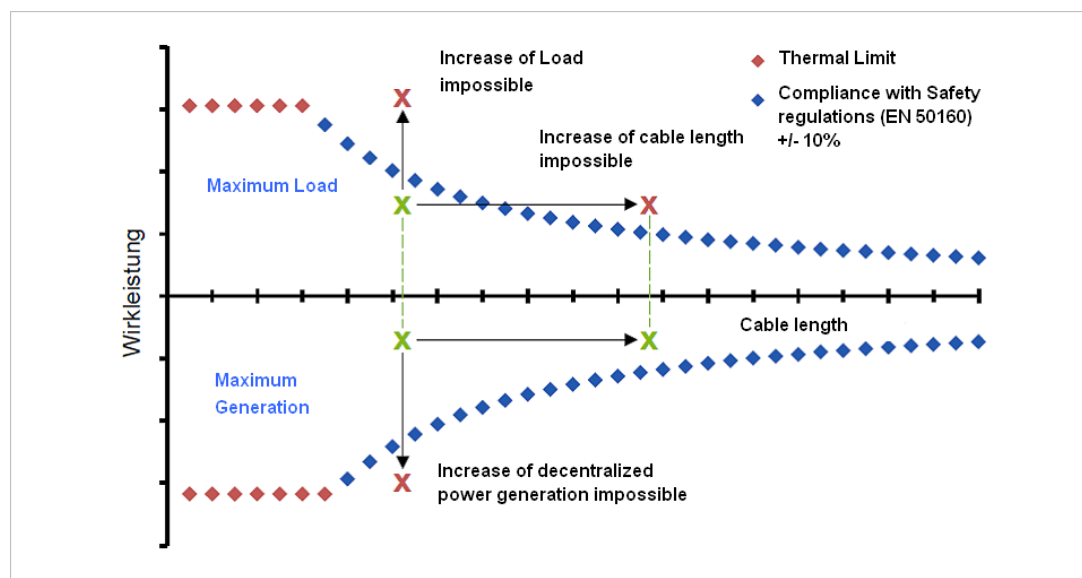
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### Restriction Curves



**Figure 21:** Illustration of Maximum Admissible Load and Maximum Admissible Power of Distributed Generation as a Function of Line Length (Gwisdorf et al 2010)

According to (Gwisdorf et al 2010<sup>72</sup>) the maximum acceptable load and distributed generation is a function of the cable length. The transmission capacity decreases with increasing length of the cable. The positive area in the graph shows the transport capacity for distributed generation, the negative part transport capacity for loads. The operating conditions of a cable are shown in Figure 22 and outlined by two parameters – the cable length and the grid capacity - both in the case of the maximum load and the maximum power generation. Operating conditions within the limiting curves meet all technical requirements, while conditions outside the curves identify violation of safety regulations or that technical limits are exceeded and grid enforcement or grid expansion measures are necessary.



**Figure 22:** Schematic Overview for Restriction Curves for a Grid in Operation (DENA 2012<sup>73</sup>)

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### 3.8 Suitable Grid Modeling Methodology for the Development of an Infrastructural Planning Tool

On the basis of the seven presented grid modeling tools this section summarizes the different approaches and seeks to draw a conclusion. All analyzed models have different objectives and serve different purposes thus various methodologies have been used. However the methodologies can be categorized in line with their characteristics:

- Transmission Grid models for infrastructural planning (RWTH11-2012<sup>40</sup>); (van Hulle 2009<sup>43</sup>); (Tröster et.al. 2011<sup>51</sup>)
- GIS Cluster models for the optimal distribution of power generation (Scholz 2012<sup>38</sup>)
- Economic models to calculate trade-off between network expansion and non-network expansion related measures (Langham 2011<sup>63</sup>)
- Distribution Grid models for infrastructural planning (DENA 2012<sup>71</sup>); (Gwisdorf et.al. 2010<sup>72</sup>)

The [R]E 24/7 has specific requirements in relation to the methodological model characteristics:

- Transmission and distribution grid levels must be covered
- Regional clusters for the distribution of decentralized power generation, especially with respect to locally available renewable energy resources, are needed
- Economic calculation module required

While the [R]E 24/7 model should cover a whole range of different tasks, it should also be user friendly and data requirements low to allow short calculation times. Thus simplifications are required.

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# 4. Development of the [R]E 24/7 Methodology

This thesis aims to develop an infrastructural planning tool which bridges the gap between energy models and grid analysis programs. In order to connect energy models with power grid simulations tools the respective programs needed to fit together. This refers to both to the methodology as well as the computer software.

## 4.1 The Selection of an Energy Model for [R]E 24/7

Energy models must allow a high technical resolution of the various power generation and transportation technologies. Furthermore, the time resolution of the energy model must be variable and allow steps of one hour or less. In addition, the software of the energy model needs to be able to map its various interrelated levels. This is necessary to simulate the different network levels. In Chapter 2, the analysis of the meta-studies from EMF 28, IPCC and Connolly et al. were used for finding the right model.

Step 1 is to find the matching methodology. According to (Connolly et.al. 2012 - Table 9) there are two fundamentally different methodologies for energy scenarios: *Top-down* and *bottom-up*. As opposed to (Connolly et. al. 2012) the EMF 28 (Knopf et.al 2013) identified two *general solution methodologies: equilibrium and optimization models* (Table 6). For energy scenario models, which are designed to represent different technical aspects of power systems in combination with a high time resolution in order to simulate fluctuating solar and wind power generation, energy engineering bottom-up models equilibrium are most suitable. In regard to the analysis summarized in 3.8 Suitable Grid Modeling Methodology for the Development of an Infrastructural Planning Tool partial models of energy systems are most suitable for the development of [R]E 24/7. Moreover there is a need for a high technology resolution – both on the supply and demand side.

The second step is to select the appropriate energy model. **Table 11** shows a selection of five energy models which use a methodology suitable for the development of an infrastructural planning tool. However there are more models which have been presented and analyzed in chapter 2 with a suitable combination of model characteristics for the development of [R]E 24/7.

	Equilibrium model for the energy sector	regional resolution / number of regions	time resolution	sectorial / technical resolution
DLR [MESAP/PlaNet]	yes	variable	years > seconds	high
PRIMES	yes	25	years	high
EMILIE-ESY	yes	29	years / hours	high
POLES	yes	27	years > hours	high
MARKAL / TIMES	yes	not available	years > hours	high

Knopf et. al. 2013, Conolly et. al. 2012, own research

**Table 11:** Possible Energy Models for the Development of [R]E 24/7s



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In a third step, the software for programming has been selected. The software must be user friendly, flexible with the technical ability to connect the selected energy model with the new model developed for this thesis via a computer interface at a later stage. Further details about the software selection process are documented in section 5.1.

## 4.2 The Selection of Grid Analysis Methodology for [R]E 24/7

Energy models have been analyzed according to their used methodology and abilities of the software itself. In order to find a suitable grid analysis model for developing an infrastructural planning tool, only the methodologies were examined in terms of their ability for coupling a grid analysis with energy scenario models.

Power grid simulation software uses typically high-resolution models which are designed for the simulation of certain technical processes. For the representation of a state-wide power supply or for projections of energy system developments over several decades, power grid simulation models are not suitable because of their high accuracy.

In chapter 3, different methodologies for power grid simulation were presented. Again, there are two fundamentally different approaches: The *grid node* method and the *regional cluster* method.

### 4.2.1 Grid Node Methodology

The grid node methodology reduces all power production and the total load of all consumers to one point. At this point – the grid node – all power production capacities which feed into the grid at the given hour are added up and compared with the available network capacity. In case the available network capacity exceeds total generation capacity, a network bottleneck is identified.

A simulation of an entire year in hourly steps determines how often this network bottleneck occurs. The more frequent the network capacity has been exceeded, the more it indicates the need for network reinforcement. However, other measures can be considered to resolve the bottleneck, for example curtailment of power plants or use of storage systems. In this case, the model will recalculate the power flow with different assumptions.

For the assignment of the respective consumption and the generation capacity to a specific grid node, the corresponding distance is used. In case a power plant is located between two nodes, it must be determined to the closest node; distributing the power plant capacity over two or more grid nodes is not possible. The location chosen for the model grid nodes does not necessarily reflect real power grid nodes, but can stand for large power plant sites or large consumption centers such as cities. For the grid node method all voltage levels are added up to one point as well. Differentiation of voltage levels such as the transmission or distribution grid capacity has not been done in the four analyzed models (Scholz 2012, RWTH 11-2012, Ackermann et. al. 2011, van Hulle 2009).

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#### 4.2.2 Regional Cluster Methodology

As opposed to the grid node methodology, the regional cluster methodology adds up the power generation capacity across a specific area. It is assumed that the area is a “copper plate” either with no specific transmission capacity or maximum transmission capacity for the entire region. This methodology is typically used in combination with GIS software. Scholz 2012 combined renewable energy resource assessments with a very low resolution grid node methodology in order to get first indications of required grid capacities. The advantage of this “copper plate” method is the possibility for a high resolution renewable energy resource assessment. The disadvantage is that although there are hourly time steps and a possible mismatch of demand and supply can be identified, the realities of power grids are not reflected. However Scholz 2012 and RWTH 11-2012 both combined the regional cluster method with the grid node methodology but set different priorities. While Scholz 2012 focused on high spatial resolution), RWTH 11-12 focuses on a higher resolution of grid nodes.

Moreover TradeWind (van Hulle 2009) used the grid node method and combined it with a wind resource cluster while Scholz 2012 used all renewable energy resources. Thus the TradeWind model has been primarily used to integrate the maximum capacity of wind power generation.

Modell	Number of Clusters (Germany)	Number of Grid Nodes (Germany)
REMix (Scholz 2012)	5° x 5° spatial resolution	1
RWTH	20	20
ENERGYNAUTICS	-	34
Tradewind	12 (Wind Clusters)	approx. 100

**Table 12** Overview Regional Cluster and Grid Node Resolution of Different Models

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#### 4.2.3 Strength and Weaknesses: Grid Nodes versus Regional Cluster

GIS based models like REMix (Scholz 2012) capture the locally available renewable energy resource with a high resolution and therefore are suitable for “green field developments”. REMix indicates where the RE resources is highest hence delivers locations where RE operates most economically. However REMix does not portray the actual situation in power grids, but indicates where future production centers of RE should be built. Therefore REMix could also be classified as a top-down tool as local optimization is not possible due to only one grid node per country. While REMix stands for regional cluster model (“copper plate”), the EN model represents a typical grid node model as regional clusters are not used at all. The grid node model can identify bottlenecks at - or in between - grid nodes and can therefore be used to determine if and where grid enforcement and/or grid expansion is required. Regional *bottom-up* simulation is not possible as different voltage levels and the locally available resources are not captured by this method.

#### 4.2.4 Transmission Grid Analysis Methodologies

The four models for transmission grids presented in chapter 3 serve different purposes and therefore deliver different outputs. The GIS Cluster model (Scholz 2012) provides no specific data for the power grid itself besides required transmission capacities between countries, but calculates the best possible distribution of renewable and distributed generation capacities. The Multiple-Region model (RWTH-11-12) identifies required transmission capacities and possible constrains. TradeWind (van Hulle 2009) provides the optimal distribution of wind power in order to integrate large wind generation capacities. Thus the optimization of the entire power generation and transmission system is not covered. Finally the EN model (Tröster et. al. 2011) aims to provide technically optimal grid expansions strategies but lacks the analysis of the distribution level.

#### 4.2.5 Distribution Grid Analysis Methodologies

The presented distribution grid analysis methods (3.6 Economic Distribution Grid Model: DANCE -Dynamic Avoidable Network Cost Evaluation, 3.7.1. and 3.7.2) focus on detailed regional grid analysis with a high technical and geographical resolution. Thus side specific input data – preferably measured data from the local grid operator - is required. This level of detail exceeds the scope of the model to be developed for this thesis, because both the amount of input data required as well as their availability would limit the model application area significantly. High data volumes lead to long calculation times, which further reduce the practicality of the model. Therefore the methodology must be simplified in order to reduce data volume while getting insights for the situation of distribution grids.

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### 4.3 [R]E 24/7 Grid Analysis Methodology

Based on results of the analysis in chapter 2 and 3 a *bottom-up* infrastructural planning tool which allows the optimization of local or regional 100% RE systems, needs to combine the regional cluster methodology with the grid node approach. While the RWTH 11-2012 represents such a hybrid model, it does not allow local optimization as different voltage levels are not included in the model.

#### 4.3.1 Grid Node and Cluster Combination

Therefore, a combination of cluster and grid node methods was carried out three-dimensionally for [R]E 24/7. As in the RWTH model a grid node has been assigned in the center of each cluster. The clusters were placed one above the other. Each layer represents a voltage level. The size of the clusters decreases from top to bottom, which is intended to represent the average transfer length for each voltage level. In this manner, each cluster can be separately optimized from the bottom upwards. This approach is intended to relieve the use of the transport network and at the same time use regional resources as effective as possible.

The [R]E 24/7 model calculates the physical flow between clusters for specific geographical positions and for each grid level. Figure 23 shows the schematic [R]E 24/7 methodology.

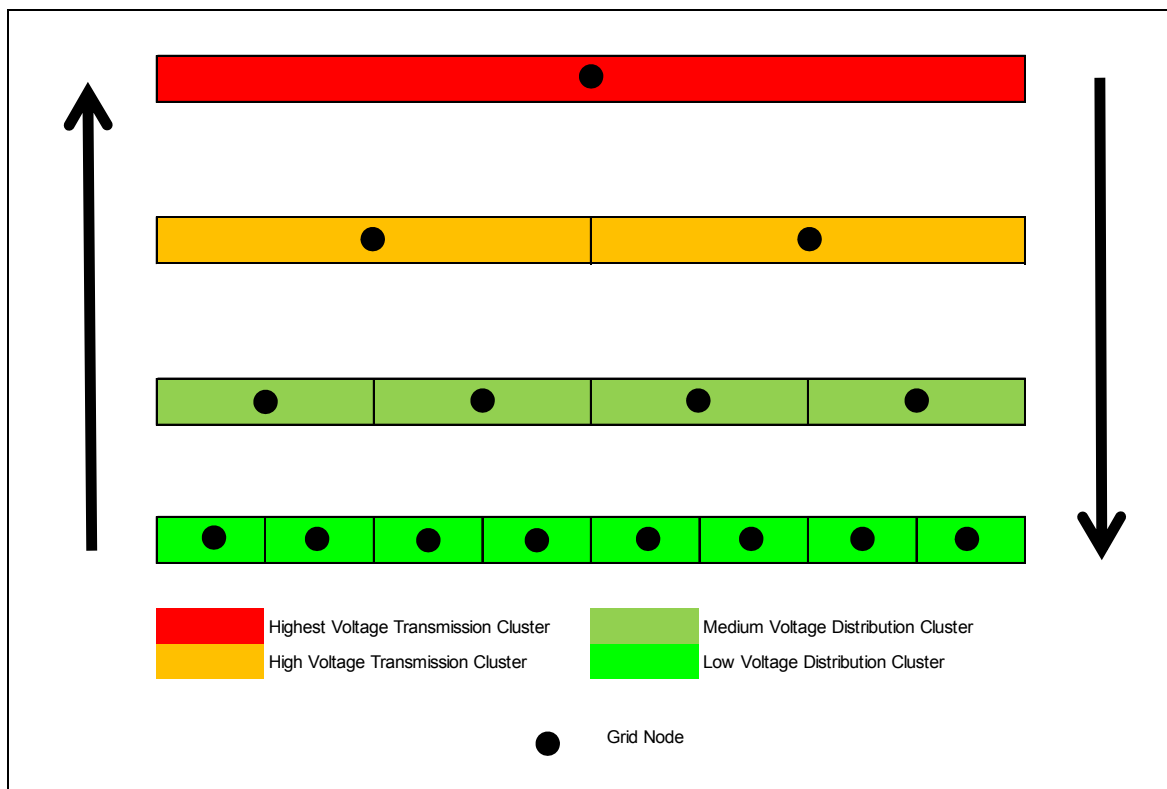


Figure 23: Schematic Representation of the RE 24/7 Methodology

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### 4.3.2 Methodology within Clusters

With reference to 3.7 Technical Analysis Methodology for Distribution Grids the [R]E 24/7 methodology within clusters simplifies the low voltage grid analysis of (DENA 2012<sup>Fehler! Textmarke nicht definiert.</sup>) significantly. Instead of using topographical maps to distribute generation capacity and load centres, digitalization of low voltage grids with string specific analysis and assigned GIS data, the model developed for this thesis bundles all available grid capacities, power generation and load centres into one point and standardizes input and output parameters to a large extent. The aim for the [R]E 24/7 model is to develop a methodology which is transferable to different regions and grid topographies and links energy models with grid models. However the model allows multiple processes for demand, generation and storage as well as calculating each cluster individually with regard to different technology mixes and associated costs.

Taking into account the overall grid capacity of distribution grids is of particular importance because low voltage distribution systems are able to transport electricity only over short distances (Gwisdorf et. al 2010<sup>74</sup>). The overall required grid capacity in meshed distribution grids depends on the simultaneity of the overall power demand and might lead to high additional grid expansion needs (DENA 2012<sup>75</sup>). In order to reflect this in a simplified way, the [R]E 24/7 model introduces the *simultaneity function* according to (DENA 2012<sup>76</sup>) as an additional parameter for low voltage clusters (see also input parameters Table 29).

Based on (DENA 2012) the *simultaneity function* is required to identify the total electrical load which accrues in a low voltage string under the Restriction Curve Analysis (RCA) (see 3.7.2 Restriction Curve Analysis (RCA) for Low Voltage Grids) for  $n$  households. The mathematical formula to calculate the simultaneity function:

$$g(n) = g_{\infty} + \frac{1 - g_{\infty}}{n^x}$$

**Formula 1:** Simultaneity Function (DENA 2012<sup>76</sup>)

$$\begin{aligned} g_{\infty} &= 0.17 \text{ (VDEW 1984)}^{77} / \text{(DENA 2012)}^{76} \\ x &= 0.75 \text{ (VDEW 1984)}^{77} / \text{(DENA 2012)}^{76} \\ n &= 1; 10; 100; 1.000; 10.000; 100.000; 1.000.000 \end{aligned}$$

The calculation results for different numbers of households in Table 13 shows that the simultaneity factor is 0.17 if more than 1.000 households are connected to one string. The [R]E 24/7 model does not calculate single strings but whole clusters. It is assumed that each cluster will have 1,000 households or more and therefore the simultaneity factor in the [R] 24/7 model is a fixed factor of 0.17 which represents a simplification of the documented RCA methodology.

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Number of Households [n]	Simultaneity Factor
1	1,00000
10	0,31760
100	0,19622
1.000	0,17467
10.000	0,17083
100.000	0,17015
1.000.000	0,17003

**Table 13** Simultaneity Factor for Different Numbers of Households

The simultaneity factor  $g(n)$ , the annual peak load for an average household  $P_{maxWE}$  and the total number of households ( $n$ ) are required to calculate the overall cumulative maximum power of all households (DENA 2012<sup>76</sup>) which again defines the required low voltage grid capacity in each string.

$$P = P_{maxWE} * n * g(n)$$

**Formula 2:** Maximum Cumulative Household Power Demand (DENA 2012, page 115)

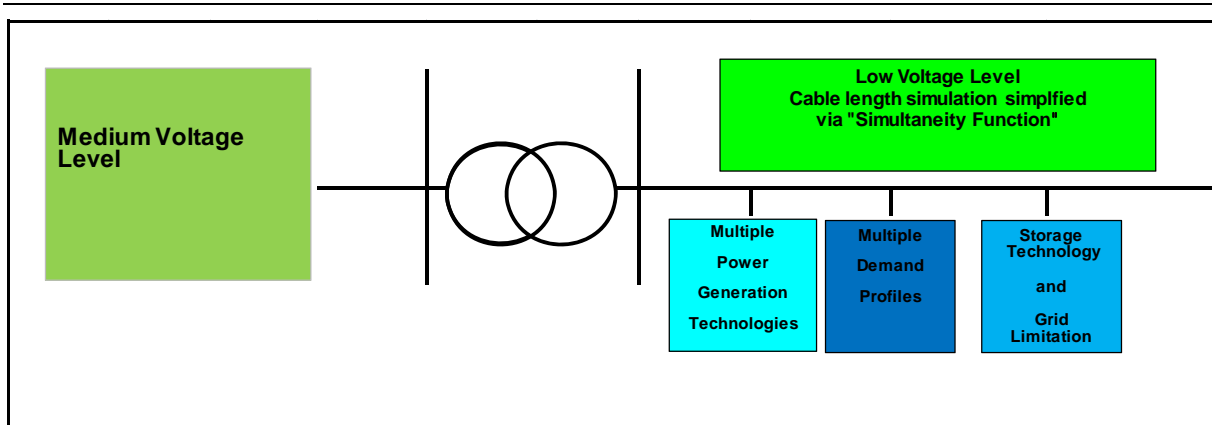
$P_{maxWE}$	= 4.5 kW
$n$	= 1; 10; 100; 1.000; 10.000; 100.000; 1.000.000
$g(n)$	= 0.17 (see Table 13)

Table 14 shows calculation results of the required grid capacity for different numbers of households with Formula 2, both with calculated simultaneity factor (Table 13) and simplified simultaneity factor of  $g(n) = 0.17$ . The simplification would lead to a deviation of 13.2% in case a cluster covers only 100 households and 2.7% for a cluster of 1.000 households.

For the [R]E 24/7 methodology it is assumed that each household requires a secured grid capacity of 0,765 kW.

Number of Households [n]	Simultaneity Factor $g(n)$	Required Grid Capacity [kW]	Required Grid Capacity [kW]	Deviation with simplified $g(n) = 0,17$ [%]
			$g(n) = 0.17$	
1	1,00000	4,500	0,765	83,0
10	0,31760	14,292	7,650	46,5
100	0,19622	88,200	76,500	13,3
1.000	0,17467	786,015	765,000	2,7
10.000	0,17083	7.687,350	7.650,000	0,5
100.000	0,17015	76.567,500	76.500,000	0,1
1.000.000	0,17003	765.135,000	765.000,000	0,0

**Table 14:** Calculated Required Grid Capacity in a Low Voltage Grid (own calculation)



**Figure 24:** Functions of Low Voltage Grid Cluster of the [R]E 24/7 Model

Figure 24 shows different functions of a low voltage grid cluster within the [R]E 24/7 model. Besides simplified grid capacity calculation, there are three groups of input data:

1. **Power Generation Capacity:** Input limited to solar PV, small wind turbines, bio energy- and gas generators
2. **Demand Profiles:** Input limited to three different consumer groups with a total of 14 demand profiles: Households (four profiles), Business (seven profiles), Farms (three profiles)
3. **Storage technology and grid limitation:** Input limited to one storage technology and a specific function to indicate when grid limits have been reached or exceeded (see Figure 31)

There are no model specific limits for power generation and storage capacities within the cluster. The grid limit of the cluster is calculated via the number of households as documented (Table 14). Power generation capacity will either directly supply the demand within the cluster, charge batteries or – in case of oversupply – will flow to the next voltage level. The [R]E 24/7 model bundles the entire grid capacity of the cluster into one grid node. The hourly supply and demand capacity are calculated and define the power flow. If there is more supply than demand, the cluster exports electricity; if there is a supply deficit electricity will flow to the next higher voltage level.

The model cannot identify possible bottlenecks in specific strings within one cluster. Therefore results of the [R]E 24/7 simulation are not sufficient for grid planning on community level. However the model can calculate up to 14 different demand profiles and individual maximum power demand for each of the profiles. Thus the determination of the overall grid limit within one cluster can be specified further. For the calculation documented in chapter 8, the simplified method with a simultaneity factor of 0.17 and an average secured grid capacity of 0.765 kW has been used. The model provides information on when and by how much the net limit has been exceeded, but simulation will continue and there is no optimization process within one cluster.

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### 4.4 Conclusion: A suitable Methodology for the [R]E 24/7 Model

The [R]E 24/7 aims to combine energy and grid models which requires compatibility of the methodologies from both models. Therefore the output parameter of the energy model needs to match the input parameter requirements of the grid model. While most energy models presented in chapter 2 cover all energy sectors (power, heating/cooling and transport), the grid model focuses on the power sector only. The level of technical detail in which the power sector is calculated in an energy model – both in terms of demand and supply – is of great importance. Table 15 provides an overview of different energy- and grid model methodologies, the requirements for the interface parameters and the chosen [R]E 24/7 methodology.

Energy Model	Requirement for Interface	Grid Model	[R]E 24/7 - Methodology
<b>Economic Coverage</b>			
a Full Economic Coverage b Partial Equilibrium Model overall energy sector c Partial Equilibrium Model power sector only d Energy Engineering Simulation Tools	<b>High Resolution required</b> > Power Generation Technologies > Demand Structure	a High Voltage Level (DC) b High + Medium Voltage Level (DC) c All Voltage Levels (DC) d All Voltage Levels (AC)	All Voltage level (DC)
<b>Geographic Coverage</b>			
a Global b National c Regional d Side Specific	<b>High Resolution preferred</b> > National Level > regional energy parameter available	a GIS Cluster b Multiple Region c Grid Node d Distribution Grid Analysis	Grid Node - Cluster Combination with simplified Distribution Grid Analysis
<b>Time Resolution</b>			
a Year b Year > Days c Year > Hours	<b>High Resolution preferred</b> > Installed Capacity in MW for one specific year > Energy Parameter in MWh/a	a Representative days - 24h/day b Representative weeks - 24h/day c 8760 hour per year	Representative weeks - 24/day

**Table 15:** Suitable Methodology for the [R]E24/7 Model

The left column of Table 15 lists model specific characteristics in terms of their economic / technical and geographical resolution as well as the calculated time steps and classifies them. In that regard, “a” marks the lowest resolution and “c” respectively “d” the highest resolution. The [R]E 24/7 methodology seeks to find the best possible combination between high resolution input and output, data availability and data volume on one hand and largest possible scope and transferability to various world regions and network conditions on the other hand.

The combination of the grid node and cluster methodology allows electricity flow simulation throughout a network with different voltage levels, but has the disadvantage that relative large amounts of data for a region are required. The grid node methodology was chosen for the simulation of the upper voltage levels, while the cluster methodology is intended to reflect the distribution network level.

The model prioritizes renewable generation and power generation capacities on the level of the demand. The dispatch order can be changed in each cluster, however decentralized solar and wind capacities will be dispatched ahead of capacities from higher voltage level. It is however possible to prioritize solar and wind capacities from higher voltages ahead of dispatch capacities. This changed dispatch order needs to be done manually in each cluster which is a weakness of the model.

Each process throughout the entire simulation is connected to an individual economic calculation module. The [R]E 24/7 methodology deliberately assigned an individual cost calculation algorithm for each process and commodity throughout all levels, in order to allow cluster specific cost calculation for both centralized and decentralized power



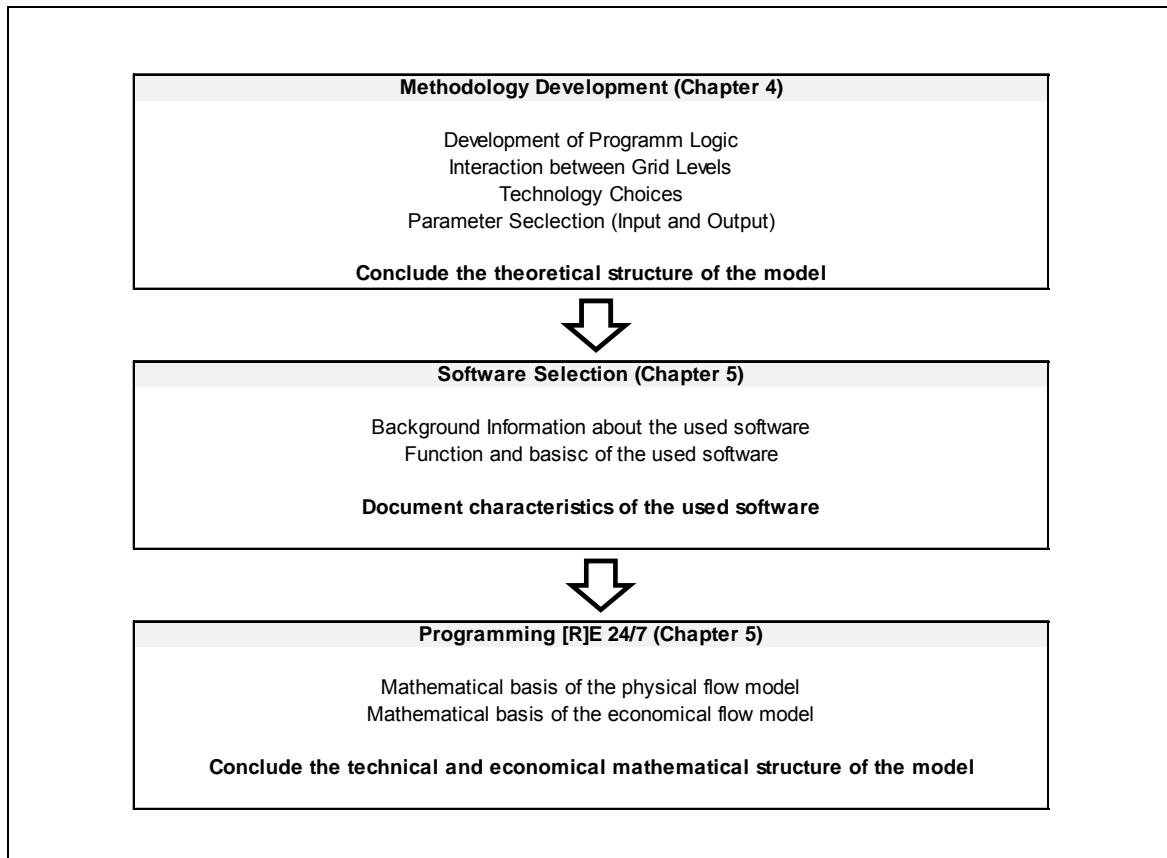
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generation strategies. Different grid costs and external and / or political costs such as a CO<sub>2</sub> price calculation scenarios should be possible as well as the evaluation of e.g. business models for storage or generation technologies. While the physical flow can be calculated separately without costs calculation, it is not possible to do cost calculation only (see 5.13) which leads to high data volumes and long calculation times which is a disadvantage of the model.

Finally the [R]E 24/7 methodology focused on technical resolution in order to carry out economic calculations of very detailed supply and demand strategies. This increased the number of individual technical input parameters and led to a significant amount of variables which again made a downstream optimization process impractical. Therefore the [R]E 24/7 model needs to start calculating extreme scenarios and enhance with additional simulation runs which represent a disadvantage of the model.

## 5. Development Infrastructural Planning Tool [R]E 24/7

While chapter 4 documented the development of the [R] 24/7 methodology, chapter 5 provides an overview about the software, why it was selected and the process of the programming.



**Figure 25:** Overview Development Process and Programming of [R]E 24/7 Methodology and Model

The [R]E 24/7 model has been programmed on the basis of commercial available software which is used by energy traders, emission control agencies and utilities for documentation purposes and reporting of energy and CO<sub>2</sub> flows. The software has been selected due to its flexibility and its extensive ability to model processes and (energy) flows in three dimensions and with detailed cost allocations as well as its interfaces to different database systems such as MICROSOFT SQL and Oracle.

However, the software only provides the toolbox as a basis for the programming work – equal to e.g. GAMS is used for the development of new models.

The model developed for this thesis has been built up from a “blank screen”, bottom-up from the household demand side level to the 400kV supply side across all four voltage levels, over more than two years. All commodities, processes and their interaction via mathematical functions, which define the logical flow of the model, have been developed for this thesis. Chapter 5 provides a detailed overview of the programming process.

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## 5.1 Software Selection for [R]E 24/7

There are numerous software tools available to program energy- or grid models which again use different programming languages. This thesis focuses on the development of a suitable methodology for an infrastructural planning tool with existing software tools. Therefore the software should be user-friendly, flexible and have the ability to interface with widely used databases such as *Microsoft SQL* and applications for data processing such as *Excel*.

Furthermore the software tool should be able to simulate physical and financial flows across different interconnected levels to calculate processes of meshed electricity grids. While the open source software GAMS would be suitable to program the [R]E 24/7 methodology, the commercial software tool MESAP/PlaNet offers many features which reduce the actual programming work and allow to focus on the implementation of the developed methodology of [R]E 24/7. Finally this software is used by the German Space Agency (DLR) for energy scenario development e.g. for the German Government<sup>78</sup> or Greenpeace Internationals Energy [R]evolution Scenarios<sup>79</sup>. Thus the interconnections between the model developed for this thesis and existing energy models might be feasible in the future. However this is not part of this thesis.

### 5.1.1 MESAP/PlaNet Production Information from seven2one GmbH, Germany:

PlaNet is designed to analyse energy demand and to simulate energy supply systems including their environmental impacts. It is intended to be used for strategic long term planning on a national, regional or local level. PlaNet is an accounting type linear simulation model that uses the scenario technique to explore the impact of different political strategies in the future. The model structure is based on the Reference Energy System and thus offers a flexible temporal, regional and sectorial aggregation. The degree of detail of the analysis can be adapted to the goals and objectives of the case study. PlaNet consists of three components:

- A module to simulate the physical flows through the RES and to calculate energy and emission balances
- A module to calculate capacity requirements of the conversion technologies
- A module to determine the specific and total costs caused by the activities and processes within the analysed system

A linear equation system is used for the simulation of the commodity flows within the RES. Market shares can be used to allocate competing technologies. The demand is given exogenously by specifying the quantity of the demanded commodity. Linear transformation equations allow establishing fixed relations between flows within a

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process. The number of input and output flows for a process and the number of transformation equations is not limited in order to model cogeneration technologies and the various emissions. The time resolution for the simulation is flexible (yearly, monthly, daily, hourly).

The cost calculation determines for each process in the RES the total costs split into investment costs, fix operating costs, fuel costs and other variable operating costs. Taxes and DSM program costs may be included. Production costs are calculated for each outflow. The average specific production costs for the commodities and the total costs of the whole RES are calculated. Finally these total costs are discounted to determine the system costs over the whole modelling horizon.(seven2one 2013<sup>80</sup>).

## **5.2 Background: Software Tools MESAP and PlaNet**

The MESAP, Microcomputer based Energy Sector Analysis and Planning System, software was originally developed at the University of Stuttgart in the 1970<sup>th</sup> (Schlenzig, 1998<sup>8182</sup>) and uses a number of software modules such as MADE-II (Saboochi, Y, 1989<sup>83</sup>)<sup>84</sup> and MAED (Charpentier, J.P. et. al, 1983<sup>85</sup>) for energy demand analysis and energy supply analysis. MESAP has been developed as a planning tool for developing countries (Schlenzig, 1998<sup>86</sup>).

**PlaNet** has been developed by Dr Ing. Christoph Schlenzig; University of Stuttgart; 1998; and the following paragraph quotes the abstract of his thesis in which he described PlaNet:

*“(...) Following the methodological approach of structured planning a specification for the (...) planning tool PlaNet is derived covering data management, modelling flexibility, transparency, decision support and user friendliness. The methodological approach for a comprehensive analysis is based on systems engineering and assists all phases of decision making and structured planning. PlaNet integrates an energy system model, (...) a central database management system and several decision support tools for scenario management, data analysis and multi criteria evaluation. Energy systems are described as a network of commodities and transformations using the “Reference Energy System (RES)” accounting framework. The separation of the energy system topology from the data management and the mathematical structure of a model allowed (...) a standardized formulation of the relational data interface. Different energy system models (...) exchange input data, assumptions and results and may share the same data entry and analysis tools thus allowing a tighter integration of existing and new modelling methodologies. The module PlaNet-Flow simulates the energy system and calculates energy and emission balances. PlaNet-Cost makes a detailed cost analysis and determines the installed capacities, the annual investment costs, fuel costs, fixed and variable operating costs for each technology and the specific production costs for all commodities. In addition it computes the total energy system costs discounted over the modelling period.” (Schlenzig, 1998<sup>87</sup>)*

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However *MESAP/PlaNet* is simply the tool which provides the basic software system for the development of energy models and various functions for cost calculations. However the software does not provide any prefabricated energy models / reference energy systems. The entire [R]E 24/7 methodology and model architecture has been developed exclusively for this thesis. This includes all mathematical formulas required to simulate energy and financial flows in a power grid system.

### 5.2.1 The Basic Function of the Reference Energy System

Planet uses a “reference energy system” (RES) as a modelling scheme for energy systems. The RES describes the topology of the energy sector in form of a network and has been developed in the 1970 by a software engineer who developed the energy planning software MARKAL (Abilock, H. et al.<sup>88</sup>). The RES is a bipolar graph based on the Petri-Grid-Theory, which does not take dynamic effect into account (Schlenzig 1998).

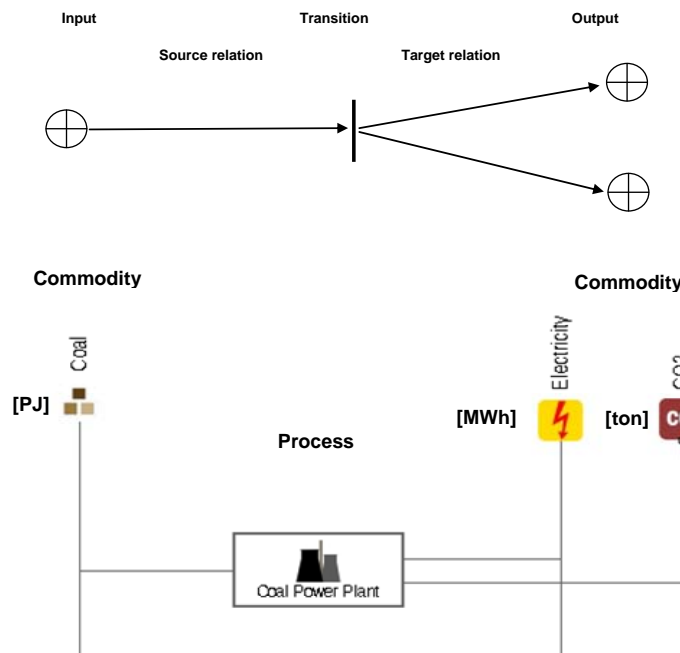
The RES as a Petri Grid has two types of knots: Commodities and Processes. Figure 26 shows a RES for a coal power plant. The commodity – in this case coal – gets converted from a process (the coal power plant) into two outputs: Electricity and CO<sub>2</sub>. (Schlenzig, 1998<sup>89</sup>) The term *commodity* describes all materials or resources a specific process requires. The *process* transforms commodities. The example shows the process of a coal power plant which converts the commodity coal into electricity and CO<sub>2</sub>. A process is not necessarily related to power plants, but could also be a car, an industrial process or could represent the demand of private energy consumers who use electricity for different consumer appliances.

Commodities and goods are connected via links representing the flow of the commodity into and out of the process. Input commodities and output goods in a *Petri Grid* equal the inlet and outlets in a port (Burgin, 2006<sup>90</sup>).

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**Figure 26:** Definition of a Petri Grid and the Energy Reference System (RES) (Schlenzig, 1998<sup>91</sup>)

The RES is a bipolar graph; two processes cannot be connected directly, instead commodities and processes must always alternate with each other. Every process must have at least one input and one output which are both defined as commodities. However an output commodity e.g. electricity can be an input commodity for the following process, therefore a flow via several processes can be simulated. Commodities are always presented as vertical lines, while processes are presented as boxes connected with a horizontal line between commodities. The PlaNet model has been developed on the basis of those *Petri Grids* and *reference energy systems* (RES).

#### 5.2.2 The PlaNet Database System NetWork

The *NetWork* model is a model for databases originally invented by Charles Bachman and published 1969 by CODASYL<sup>92</sup>. PlaNet uses *NetWork* database model and the topology of a reference model (*“Real Model”*) in order to keep technology related information separate from different assumptions and calculated cases. The PlaNet RES is used as the basis of the *NetWork* data structure in order to provide unique data access keys for all energy system related information. As a matter of principle all numerical information will be saved in the database as a time series, as they can change over the modelling period. The access key of a time series however consists of an attribute which describes further details, such as technical life time of a process, and a mapping key (*“Zuordnungsschlüssel”*) to organize the relation of the information towards one or more objects. (Schlenzig, 1998<sup>93</sup>)

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### 5.2.3 The Key Building Blocks for the PlaNet Networks: Commodities, Processes and Attributes

There are three key components for the PlaNet database necessary to build models such as the [R]E 24/7 modelling tool. The following three definitions are taken from (MESAP 2012):

- Commodity: contains all kinds of substances and numerical quantities, such as energy carriers, emissions, population, capital etc.
- Process: determines the processes, in which input commodities go in and output commodities come out. In many cases these are technologies such as power plants or energy consuming processes such as electrical appliances
- Attribute: defines the property of a parameter and a time series. It determines the way commodities are calculated with each other

Combinations of those three components form the basis of a RES. This section explains the basic functions of these components and how they have been used in the new RES for the modelling tool. Figure 27 visualizes the basic principle of the information structure of a RES and the use of data access keys.

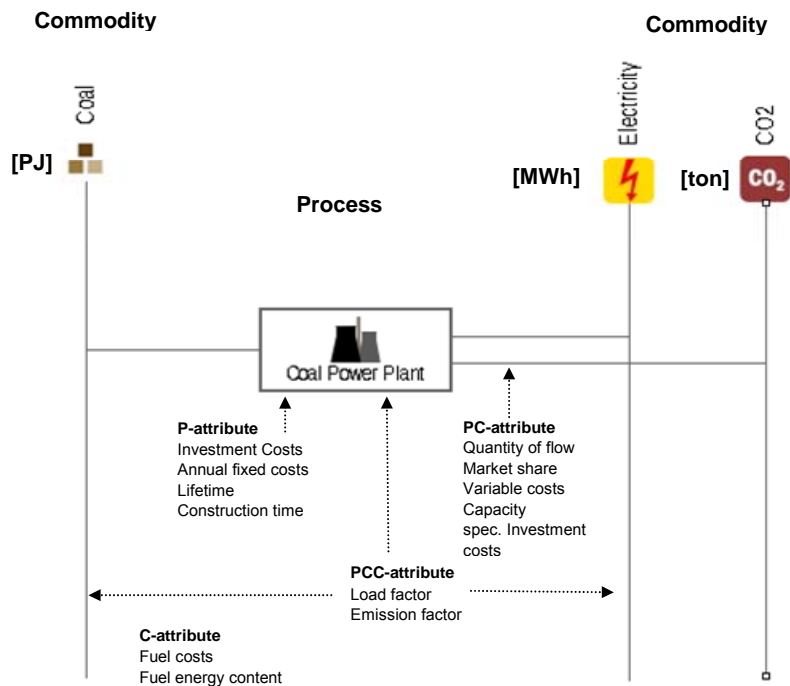
There are five different types of information:

- “P”-attributes are related to a process, such as the technical lifetime of a power plant
- “C”- attributes are related to the commodity such as the CO<sub>2</sub> content of coal
- “PC” attributes represent the combination of the commodity and the process, such as the coal demand of a coal power plant
- “PCC” attributes which provide the information about the interaction of two commodities via a process e.g. the annual load factor of a power plant
- Finally “G” attributes relate to the entire RES such as the used discount rate

Therefore the data access key is made out of four components: attribute, process, input commodity and output commodity (Schlenzig, 1998<sup>94</sup>). An overview about the specific access key used in the [R]E 24/7 model can be found in Figure 27.

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**Figure 27** Visualisation of a RES as a function of data access key for a NetWork system (Schlenzig, 1998)

### 5.3 The [R]E 24/7 Model Structure

The [R]E 24/7 used the commercial software *MESAP/PlaNet* - an energy modelling tool called *MESAP* which uses *PlaNet* as a basis - under the licence of the German company *seven2one* based in Karlsruhe. *MESAP/PlaNet* has been used for environmental databases and to calculate energy scenarios such as the Energy [R]evolution scenario series (Teske et. al 2010<sup>95</sup>). Energy scenarios project the development of the energy sector over several years or even decades, while the development of an RES which simulates the electricity flow across several grid layers over a specific region and with a very precise time resolution (down to 15 minute steps), requires substantial changes. A number of additional processes which represent the function of power grids are needed in order to calculate the use of different technologies in a specific order and or cascade as exogenous input. The following section provides an overview of the different commodities and processes used for each layer of the [R]E 24/7 RES.

Table 16 provides an overview about a standard energy system from energy supply (left), energy distribution (middle) and energy demand (right) as a function of the economic activity.



Energy Supply				Distribution			Energy Demand	
Energy Resources		Conversion	Locations					
Natural Renewable Energy	Fossil Fuels + Minerals	available Technologies		Grids	Grid Technologies	Grid Management	Demand Management	Sectors
Sun		Photovoltaic	Decentralized - connected to Distribution Grids	Distribution Grids	Interconnections	Supply Forecast	Demand Side Management	Consumes connected to Distribution levels
Wind		Concentrated Solar Power						
Kinetic Energy from Water		Onshore Wind						
Geothermal Energy		Offshore Wind						
		Hydro Power Stations						
		Geothermal Power Station						
Ocean Energy		Different Conversion Technologies for Wave and Tidal Energy	Centralized - connected to Transmission Grids		Transformer	Demand Forecarst	Electric Mobility	
Bio energy	Gas	Thermal Power Plants	Centralized - connected to Transmission Grids	Transmission Grids	Storage Facilities	Demand Side Management	Consumer based Storage	Consumes connected to Transmission levels
	Oil							
	Coal							
	Lignite							
	Uranium							

**Table 16:** Block Diagram - Structure [R]E 24/7 Modelling Tool

To simulate the physical flow within a complex electricity grid system, which reflects the interaction between electricity generation and demand in dependence of availability of variable renewable energy sources, requires a network of commodities and processes. Table 17 also shows that not only technical measures are involved, but also external events, such as the availability of wind to produce electricity or the increased or decreased demand from a large variety of consumers.

In order to keep the balance between supply and demand at all times, a cascade of technical responses and management decisions have to be made in a very short time frame. The [R]E 24/7 model aims to simulate different situations of increased or decreased demand and/or supply in order to find the most efficient - both in technical and economic terms - strategy to guarantee a secure electricity supply. As solar and wind power generation varies largely in time and by region, as well as the consumer demand, the most efficient and economic supply strategy is likely to be different for each climate zone. Even cultural differences between countries which lead to different demand patterns can play a significant role in the management of complex power systems.

Electricity grids have several layers of different voltage levels in order to transport over large distances and distribute electricity to consumers. Therefore the [R]E 24/7 model consists of a spatial and temporal dimension in order to differentiate between different grid layers as well as the geographical distribution of electricity input and output points within the system.

The following section provides an overview about all commodities, processes, their attributes and the mathematical formula used in the [R]E 24/7 model.

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### 5.3.1 Commodities in [R]E 24/7

The MESAP/Planet model represents commodities as vertical lines, while processes are shown as boxes. One commodity can input in several processes while a process can also have a variety of different output commodities. Commodities can be exogenous, calculated or independent. Commodities which are in between different processes are defined as “internal goods” (Schlenzig 1998<sup>96</sup>). Each commodity has a descriptor which identifies the function of the commodity within the model. An internal good or commodity in the [R]E 24/7 model for example with the descriptor of “Electricity POS” is located between the exogenous input commodity “Sun” and the “independent output commodity” and represents the electricity transport from the higher voltage level towards the lower voltage level. The commodity “Electricity POS” has a key function in the overall model logic of [R]E 24/7 which are described in detail in section 5.6.

A commodity can have a unit e.g. kWh or a factor e.g. energy intensity which is used for the demand side of the model.

Table 17 provides an overview about all commodities used in [R]E 24/7, their functions within the model and associated units. Internal good or commodities connect the different layers of the model with each other (see Figure 29 and Figure 31).

	Descriptor	Commodity			Input/Output	Unit	Remark
		exogenous	calculated	independent			
Supply	Sun	X			Input	kJ	Solar radiation measured in W/m <sup>2</sup> converted into kJ - Quantity of commodity exogenous input
	East-West Sun	X			Input	kJ	
	Onshore Wind	X			Input	kJ	
	Offshore Wind	X			Input	kJ	
	Bio Energy		X		Input	kJ	Quantity of commodity calculated
	Hydro		X		Input	kWh	
	Gas		X		Input	kJ	
	Coal		X		Input	kJ	
	Lignite		X		Input	kJ	
	Nuclear		X		Input	kJ	
Distribution	Voltage Level (e.g 400kV)		X	X	Input/Output	kWh	Voltage level commodities connect different grid levels and cluster with each other
	Voltage Level (e.g 400kV) (DS)		X	X	Input/Output	kWh	The Demand Side (DS) voltage level commodities connect power generation technologies of each voltage level and the demand/load with each other.
	Electricity POS		X	X	Input/Output	kWh	System Commodities which organize the positive (top down) and negative (bottom up) electricity flow.
	Electricity NEG		X	X	Input/Output	kWh	
	New Grid		X		Input/Output	kWh	A calculated output commodity as an indicator when grid expansion would be required.
	Sun Storage		X	X	Input/Output	kWh	Storage capacity is an exogenous input
	Wind Storage		X	X	Input/Output	kWh	
	Storage Load Input		X	X	Input/Output	kWh	Manages input and output of storage capacity
	Storage		X		Input/Output	kWh	
Load	Population			X	Output	factor	The amount of people and/or the economic activity multiplied by the specific demand per head defines the overall energy
	Economic Activity			X	Output	factor	

Table 17: Overview Commodities used in the [R]E 24/7 Model

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### 5.3.2 Exogenous, Calculated and Independent Commodities

Within the [R]E24/7 model the only exogenous commodities are those which related to meteorological data of the available solar irradiance and the wind speed. All other commodities have at least one calculated input and one independent output or vice versa. If there are more inputs and outputs, at least one input and one output needs to be independent. Mathematical equations from processes connected to the commodity define if a commodity is exogenous, calculated or independent (Figure 28).

All mathematical formulas which control the electricity flow throughout the model, all commodities and processes, as well as all interconnections and sub-processes have been defined for this thesis; this includes all parameter names, units etc.

### 5.3.3 Processes

A process requires at least one input and one output commodity. The interconnection between a commodity (vertical lines) and processes are horizontal lines which represent the flow of electricity. The relationships between commodities and processes need to be defined mathematically, therefore conversion equations for each flow and allocation rules for commodities are necessary. Out of those single equations a whole equation system will be compiled. During the compiling process of the equation system time series are generated for all input and output data. Time series are required to change input data across model periods and to display output projections. (MESAP 2012<sup>97</sup>)

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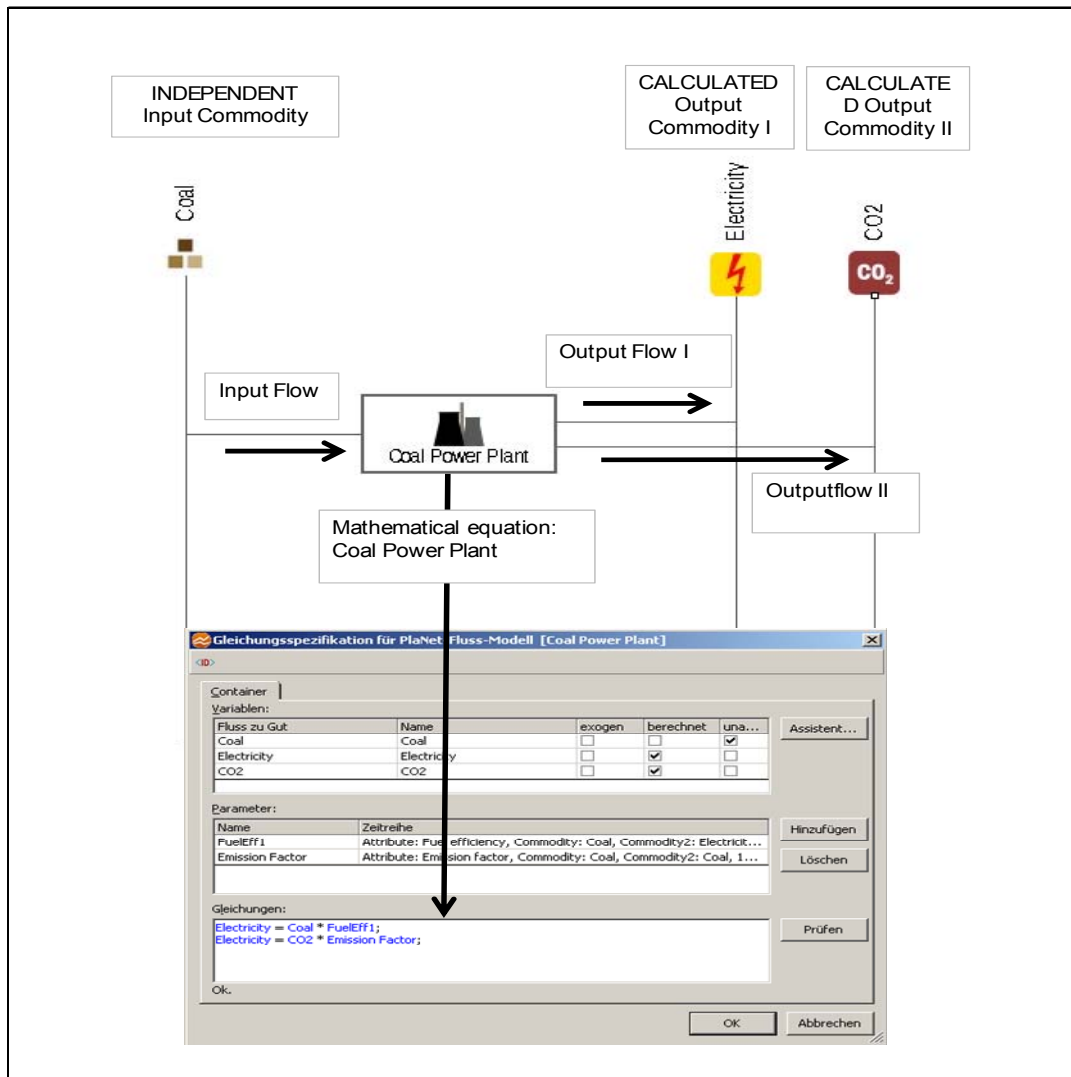


Figure 28: Basic RES for a Coal Power Plant

## 5.4 Processes used in [R]E 24/7 Model

Table 18 provides an overview about all required process for the [R]E 24/7 model. There are specific processes for power generation processes (Table 18; No. 1 -10), processes for the electricity grid simulation (Table 18; No. 11 -13) as well as for the demand side. While processes for electricity grids are universal for all grid systems, the supply process [1 – 9] and demand process [19 onwards] can be adapted to each country or region. More power plant technologies can be added as well as processes representing the load. If a power plant technology is not present in a certain region, the input data is “0”.

No	Process	Commodities		Attribute for Calculation
		Input	Output	
1	PV Optimal	Sun		Efficiency
2	PV East-West	Sun East-West	Voltage Level (DS)	Efficiency
3	Onshore Wind	Wind		Efficiency
4	Offshore Wind	Offshore Wind		Efficiency
5	Hydro Power Plant	Hydro		Plant Efficiency
6	Bio Energy Power Plant	Bio Energy		Fuel Efficiency
7	Gas Power Plant	Gas	Electricity POS	Fuel Efficiency
8	Coal Power Plant	Coal		Fuel Efficiency
9	Lignite Power Plant	Lignite		Fuel Efficiency
10	Nuclear Power Plant	Nuclear		Fuel Efficiency
11	Power Flow manager	Volage Level	Electricity POS Electricity NEG	
11	balance POS	Electricity POS New Grid	Voltage Level (DS)	net max
12	balance NEG	Electricity NEG New Grid	Voltage Level (DS)	net max
13	Transformer	Voltage level	Voltage Level (DS)	Efficiency
14	PV Storage	Sun> Storage	Storage Load Input	Efficiency
15	Wind Storage	Wind > Storage	Storage Load Input	Efficiency
16	Storage Load	Storage Load Input	Storage	Efficiency
17	Storage Manager	Storage	Voltage Level (DS)	Efficiency
18	Demands e.g Industry	Voltage Level (DS)	Economic Activity	Intensity
19	Consumer profiles	Voltage Level (DS)	Population	Intensity
20+X	additional consumer profiles	Voltage Level (DS)	Population	Intensity

Table 18: Processes in [R]E 24/7 Model

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### 5.5 Attributes

Each attribute defines the property of a parameter and a time series and determines the way commodities are calculated. MESAP/PlaNet provides a set of attributes which are usually required for energy processes, such as fuel efficiency. However new attributes can be added. For the [R]E 24/7 model a number of new attributes had to be defined e.g. “grid limits”. This represents an additional tool to define grid capacities apart from the “maximum flow” attribute. The introduction of “grid limit” attribute was necessary to define the grid limits in process formulas in grid related processes (Table 19).

#### 5.5.3 Attributes used in [R]E 24/7 Model

The attributes listed in in Table 20 have a particular high relevance for the financial calculation within the model while attributes in Table 19 are important to simulate the physical flow of an electricity grid system. Both tables provide an overview if the attributes are connected to the input or output commodity which defines their classification as p (process), pc (process connected to one process) or pcc (process connected to two processes) see also Figure 27.

Technical Attributes					
No.		Definition	Class	Input	Output
1	Efficiency	Process efficiency in [%]	pcc	X	
2	Fuel efficiency	Fuel Efficiency in %	pcc	X	
3	Transformer Efficiency	Electricity losses from change of voltage level [%]	pcc	X	
4	Ratio between flows		pcc	X	
5	Grid Limit	Maximum cable capacity in [MW]		X	
6	Max flow	Maximum value of a process or commodity		X	
7	Initial storage quantity	Charging level of batteries at calculation start [MWh]	pcc	X	
8	Max storage charge / discharge rate	Maximum input/output in [MW]	pcc	X	
9	Upper storage limit	Maximum capacity of a battery in [MWh]	pcc	X	
10	quantity of commodity	Quantity of commodity - process input in [kJ] or [MWh]	pc		X
11	Quantity of flow	Quantity of commodity - process output in [kJ] or [MWh]	pc		X
12	Storage difference	Delta input / output [MWh]	pc		X
13	Exceed of storage limits	Defines over/under capacity of storage medium	pc		X

Table 19: Technical attributes of the [R]E 24/7 model which define the physical flow

Technical Attributes with high relevance for financial calculation					
No.		Definition	class	Input	Output
14	Installed Capacity	Name plate capacity of the process [MW]	pc	X	
15	Load factor	average annual capacity factor in [h/a]	pcc	X	
16	Technical lifetime	Maximum Lifetime - indicates replacement needs in [a]	p	X	
17	Intensity	Demand of energy per capita [kWh/capita]	pcc	X	

Table 20: Technical Attributes with High Relevance for Financial Calculation.

## 5.5.4 Interaction between Attributes, Process and Commodities

While Section 5.3 provides an overview of the basic functions of MESAP/PlaNet, this section will go into further details about the used formula and program structure of [R]E 24/7.

## 5.5.5 Simple Conversion Processes Related to Energy Supply

Table 21 provides an overview of the simple conversion processes used in the [R]E 24/7 model. The large majority of the processes multiply an input commodity with an exogenous efficiency factor into an output commodity. However, all solar and wind resources within the RES are defined as *exogenous* commodities, while all other commodities representing energy sources (e.g. hydro, gas) are defined as calculated commodities. As a result solar and wind generators are “must run” power plants, while all other power plants on the dispatch level are “can-run” power plants further details are shown in Figure 35 and Figure 36.

No	Process	Formula			Remark
1	Supply	PV Optimal	generated electricity =	solar irradiation X pv system efficiency	"must-run" power plant - close to demand
2		PV East-West	generated electricity =	solar irradiation East-West X pv system efficiency	
3		Onshore Wind	generated electricity =	wind speed X wind turbine efficiency	
4		Offshore Wind	generated electricity =	wind speed X wind farm efficiency	
5	Supply	Hydro Power Plant	generated electricity =	available hydro power X plant efficiency	"can-run" power plant - connect to the dispatch level
6		Bio Energy Power Plant	generated electricity =	bio energy X fuel efficiency	
7		Gas Power Plant	generated electricity =	gas X fuel efficiency	
8		Coal Power Plant	generated electricity =	coal X fuel efficiency	
9		Lignite Power Plant	generated electricity =	lignite X fuel efficiency	
10		Nuclear Power Plant	generated electricity =	uranium X fuel efficiency	
13	Distribution	Transformer	electricity grid 2 =	electricity grid level 1 X transformer efficiency	
14		PV Storage	pv storage electricity =	solar irradiation storage X pv-storage system efficiency	
15		Wind Storage	wind storage electricity =	wind power storage X pv-storage system efficiency	
16		Storage Load	total storage load =	battery/storage X efficiency	
18	Load	Demands e.g. Industry	electricity =	EconomicActivity X Intensity	
19		Consumer profiles	electricity =	number of costumer X Intensity	
20+X		additional consumer profiles	electricity =	number of costumer X Intensity	

Table 21: Simple Conversion Processes of the [R]E 24/7 Model

Figure 29 shows the basic function of the [R]E 24/7 model architecture. On the left side power plant process are connected with associated commodities, on the right side process which represent the demand side are connected with commodities (vertical lines) representing transport (= grid) capacities.

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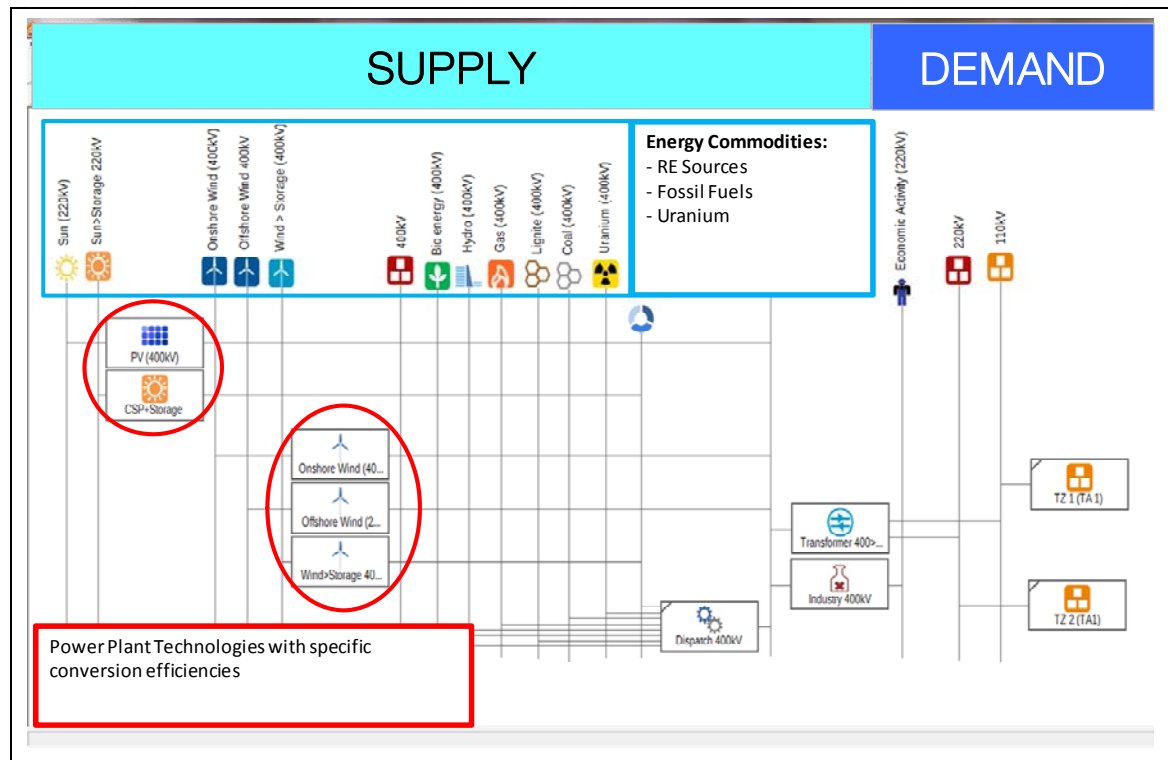


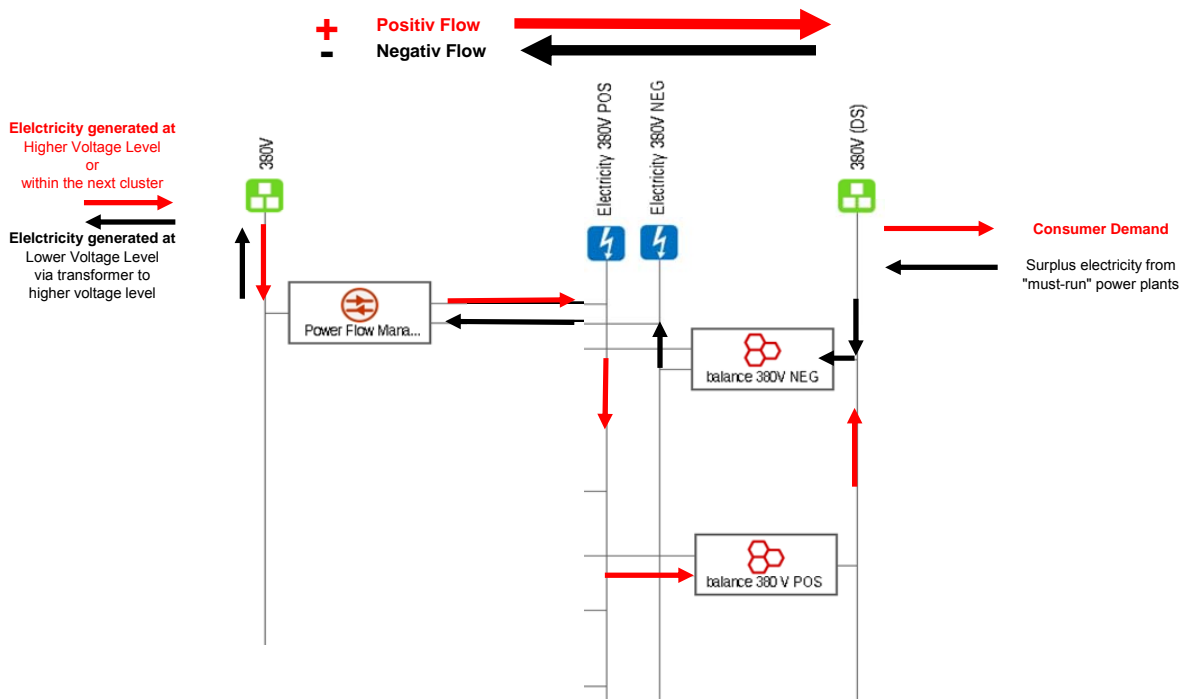
Figure 29: Commodities and Process for Electricity Production

## 5.6 Processes Required for Grid Simulation

There are four key processes within the [R]E 24/7 model which manage the power flow. In order to simulate not only electricity flowing from transmission levels down to distribution levels but also in the reverse direction. For the analysis of an electricity system with large shares of power generation on the distribution level, a reverse power flow may appear at peak times from e.g. solar photovoltaic generators. Therefore, the electricity flow needs to be separated in the positive flow (top-down) and a negative flow (bottom-up). Three processes are needed to organize the simulation of reversible electricity flow within the RES: two process which separate positive and negative flows and one which coordinates the flow from one cluster to the next one.

The “balance POS” and the “balance NEG” processes separate the flow on the dispatch level as shown in Figure 30, while the “Power Flow Manager process” reconnects both flows and connects the cluster with the next cluster or – via the transformer – with next higher grid level. The two commodities “Electricity POS” and “Electricity NEG” in Figure 30 (vertical lines) connect these processes with each other.





**Figure 30:** Reverse Power Flows in the RES – Simplified Overview

The required formulas to manage the electricity flow are more complex than simple technical conversion processes.

The *power flow manager* (left side of the figure) calculated the flow to commodity “380V), while both flows to “balance NEG” and “balance POS” are independent, with the following formula:

$$IF\ elpos > 0\ THEN\ net = elpos,\ ELSE\ net = elneg$$

With:  $elpos$  = positive flow;  $elneg$  = negative flow and  $net$  = 380 V (commodity)

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#### 5.6.1 New Grid Function

The commodity *new grid* plays a key role in the [R]E 24/7 model and indicates if specific grid limits have been reached or exceeded. Figure 31 shows the connection between the commodity new grid and the two processes *balance POS* and *balance NEG*.

The *balance NEG* process separates the negative flow from demand side commodity – in the given example “380V (DS)” with the following formula:

$$IF\ el < 0\ THEN\ el_{neg} = el,\ ELSE\ el_{neg} = 0,$$

$$IF\ el < -net_{max}\ THEN\ newnet = el,\ ELSE\ newnet = 0,$$

With:  $el = 380V$  (DS),  $el_{neg}$  = negative flow, and  $net_{max}$  = exogenous input via the database which defines the maximum load capacity of the grid. In case the maximum grid capacity has been exceeded, the surplus electricity will flow in the *newnet* process. The simulation will continue even if the maximum grid capacity is reached and/or exceeded.

The *balance POS* process calculates commodities  $el_{pos}$  and *newnet* with following formula:

$$IF\ el > 0\ THEN\ el_{pos} = el;\ ELSE\ el_{pos} = 0,$$

$$IF\ e > net_{max}\ THEN\ newnet = el;\ ELSE\ newnet = 0,$$

With:  $el_{pos}$  = positive flow;  $el_{neg}$  = negative flow and  $net = 380\ V$  (commodity)

The formula of processes “balance NEG and “balance POS” only work, if the demand side commodity (“380V (DS)” uses a hierarchical order (see 5.8).

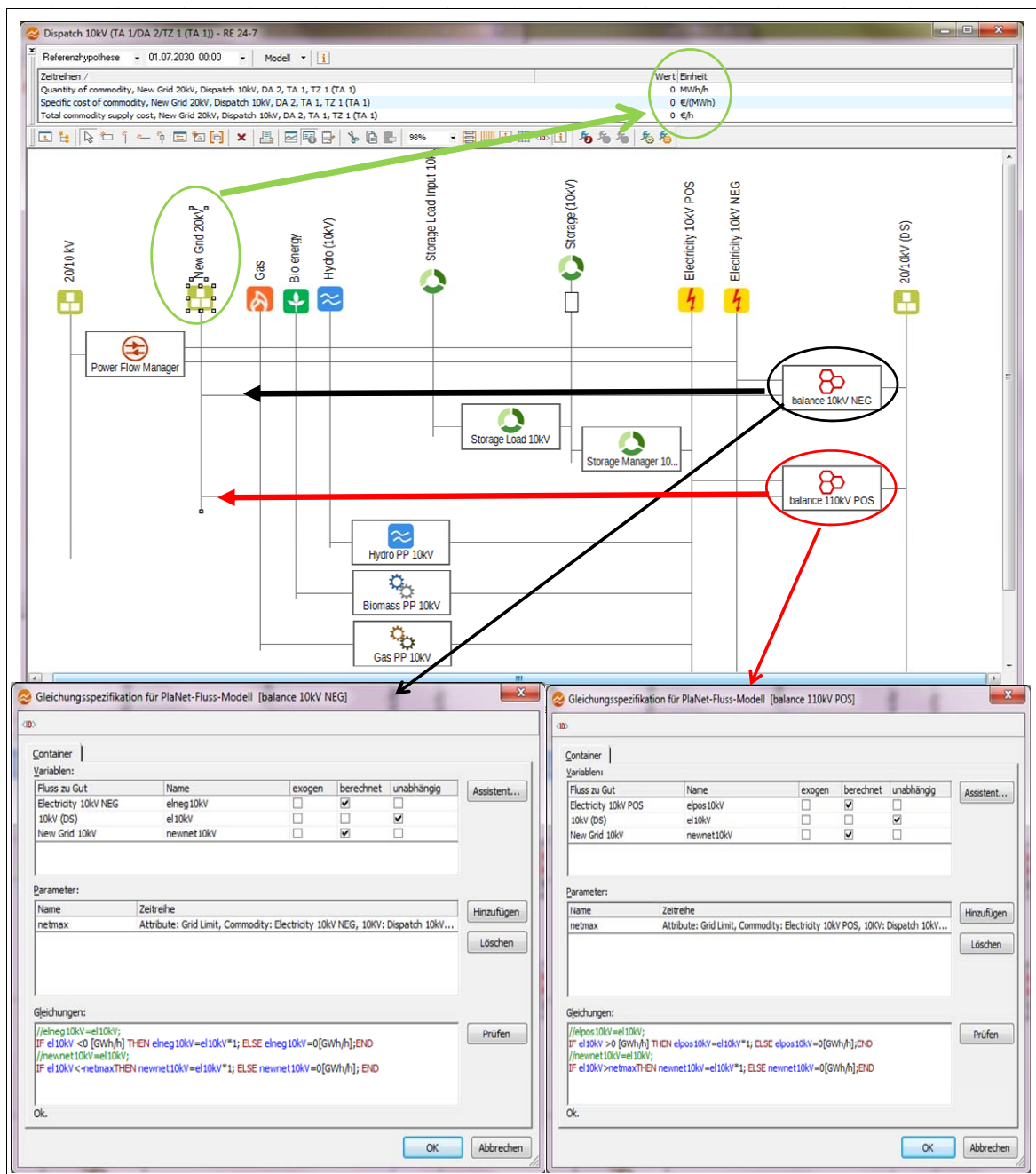


Figure 31: New Grid Function – Same Methodology Across all Voltage Level and Clusters

The total load of the *new grid* commodity as seen in Figure 31 (green circle and arrow) is 0 MW for the simulation date 01.07.2030, therefore specific costs and total costs are also zero (costs calculation see 5.13.1 Definitions for Economic Calculation Terms). In case a grid limit has been reached or exceeded, both the time of the event and the value of the required grid expansion for this particular hour, are provided in the output data sheet.

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### 5.7 Processes Required for Storage Function

There are two processes and two commodities for the management of the [R]E 24/7 storage function. The **storage load** process is connected with a commodity and calculates the losses of the (dis-) charging process via an efficiency factor in each cluster and across all grid levels:

$$\text{Storage}_{10kV} = \text{Storage Load Input}_{10kV} * \text{Eff}_{bat}$$

With:  $\text{Storage}_{10kV}$  = Stored Load after conversion losses;

$\text{Storage Load Input}$  = Load flows via Storage Manager in / out of  $\text{Storage}_{10kV}$ ;

$\text{Eff}_{bat}$  = Efficiency Factor which is an exogenous input via database.

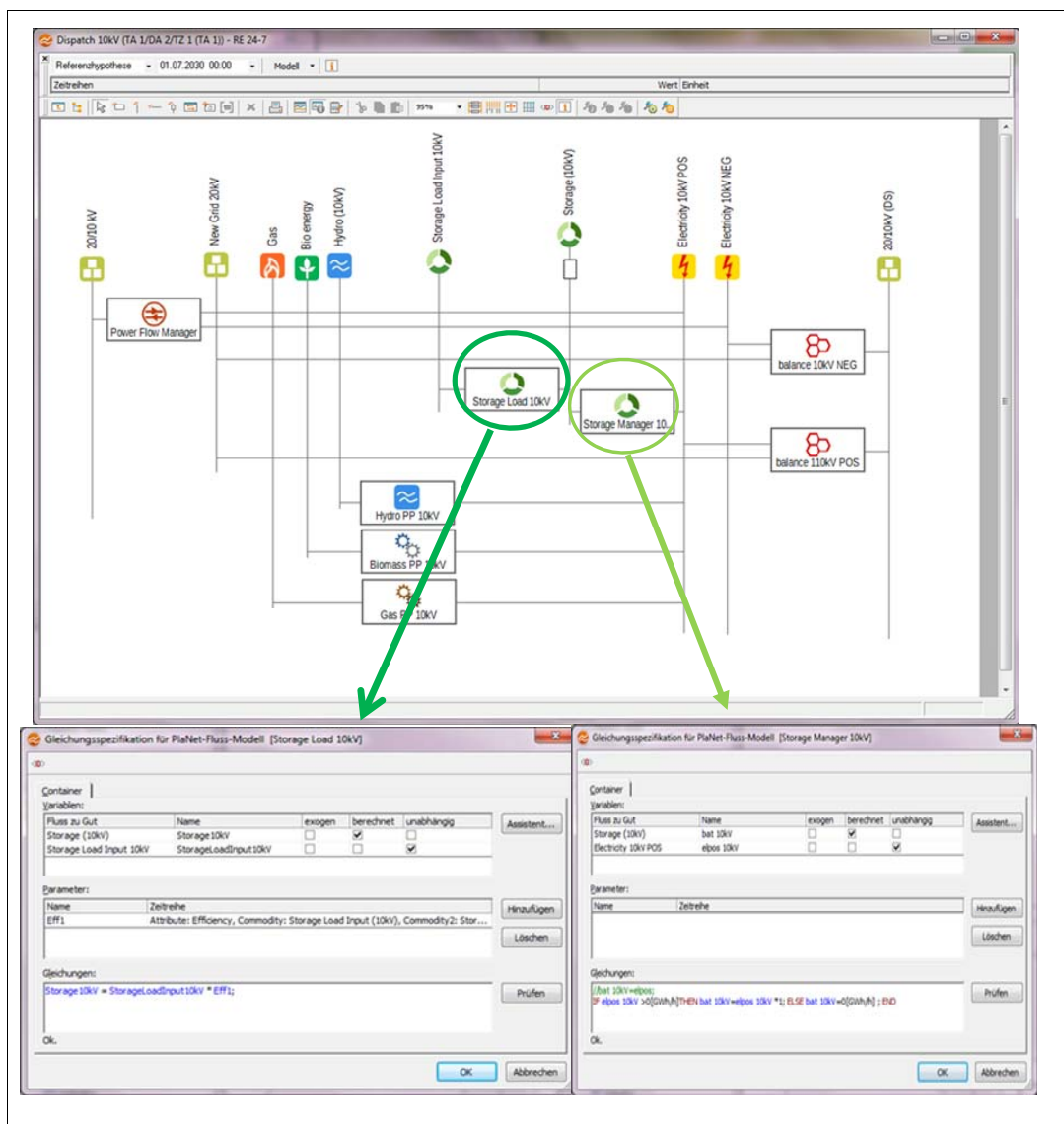


Figure 32: Storage Function – Same Methodology Across all Voltage Level and Clusters

The *Storage Manager* organizes the actual flow in /out of the battery (*Storage<sub>10kV</sub>*) via another IF function in case the process gets activated from the dispatch order 5.8.

*IF  $e_{pos\ 10kV} > 0$  [GWh/h] THEN  $bat\ 10kV = e_{pos} * 1$ ; ELSE  $bat\ 10kV = 0$  [GWh/h]*

With  $e_{pos}$  =positive flow and  $bat\ 10kV$  =electricity flow from /to the battery.

The formula controls the charging / discharging process which take place when there is an under / over supply within the cluster and the storage function is activated with the *Hierarchical use* function descript in 5.8.

## 5.8 Hierarchical Use of Processes

In case commodities have several inputs, market shares, market allocations or the order in which the processes will be calculated, the input order must be specified. Figure 33 gives an example of a commodity with several input flows and only one output flow. The commodity, “Electricity 380V POS” has input (1), (2), (3) and (4), identified by green arrows. Those inputs are calculated results or outputs of the previous processes. For the commodity however it is an independent input. The amount of electricity which will flow into the next process “balance 380V POS” (5) – marked with a red arrow - is dependent of the demand identified by the next commodity “380V (DS)”. If the overall demand, on the right side of the commodity is lower than the available supply, on the left side of the commodity, the order of specific input can be identified (see Figure 34).

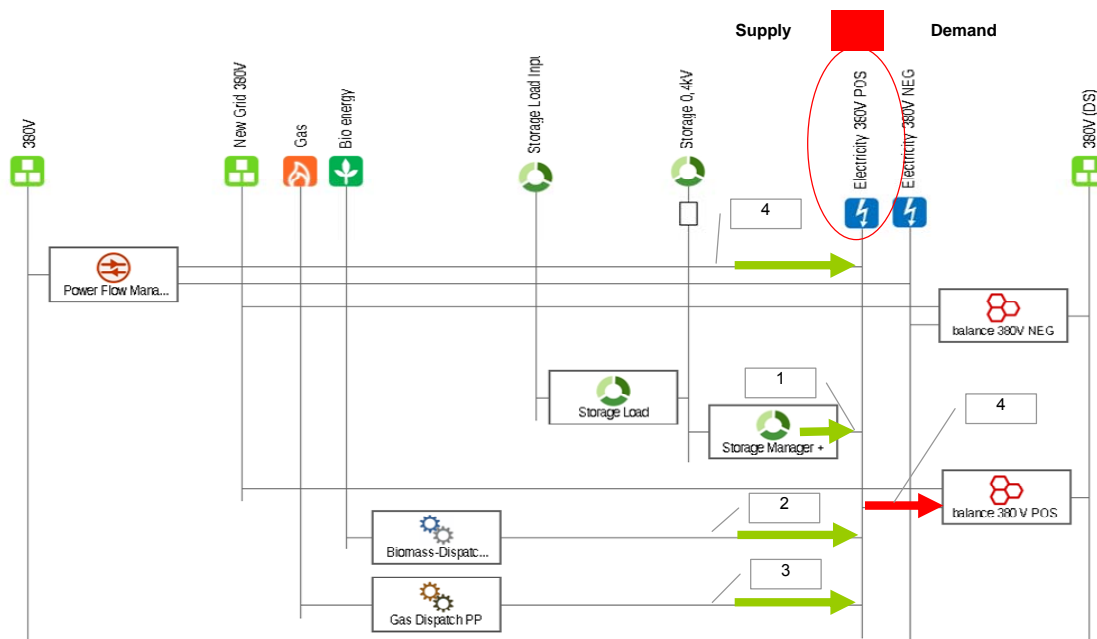


Figure 33 Commodity with Several Inputs and Only One Output Flow – Example Dispatch Level

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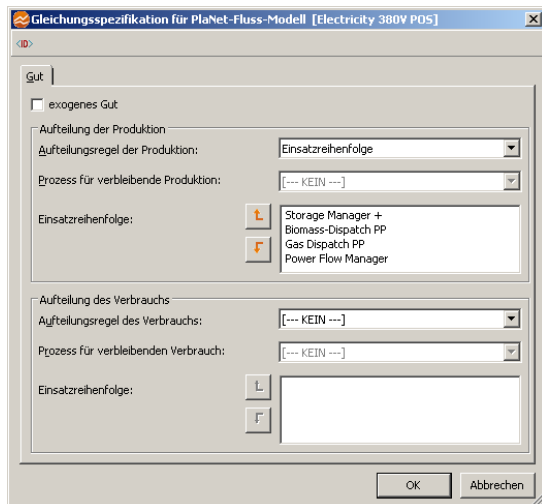


Figure 34: Operational Order of Processes

The operation order for commodity “Electricity 380 V POS”:

1. Storage
2. Bio energy
3. Gas Generator
4. Power Flow Manager (= Electricity from outside the cluster)

The amount of electricity which flows from each process is limited via the exogenous input attribute “maximum flow”. If storage can provide the entire required electricity, all other processes will not be used. Commodities which use market shares, market allocations and the order of used processes all play a key role in the [R]E 24/7 as they define the “logic” of the system. The order in which power plants, storage technologies or power from other grids are imported will be used to match the demand, and can be changed in different scenarios. Specific market shares or market allocations for each process is an exogenous input and can therefore be changed for different scenarios. This provides a maximum of flexibility to calculate different scenarios without changing the RES structure.

### 5.8.1 Change of Dispatch Sequence

[R]E 24/7 aims to prioritize decentralized generation and therefore prioritizes locally available dispatch capacity, thus electricity from higher voltage levels comes last in the dispatch order. Thus the “Power Flow Manager” is the last process in the ranking list. In order to change the dispatch sequence the *operational order* for each “Electricity POS” commodity (see Figure 34) needs to be changed. If centralized electricity generation from a higher voltage level gets priority over decentralized power generation from a lower voltage level, the *Power Flow Manager* must be first in the operational order. This setting will ensure that all electricity available from higher voltage levels as well as all available wind and solar pv capacity from within the cluster will be used **before** dispatch capacity. However, this change must be set individually in each cluster, which is time consuming and represents a weakness of the program.

## 5.8.2 Power Plant Priorities (“Must Run” versus “Can Run”)

The model architecture of the [R]E 24/7 programmed for this thesis predetermines the dispatch order for solar and wind generators ahead of other power generation capacities. If there is an input in solar or wind commodities, it must be processed into the system, while all other commodities in the CAN Run category will only be used when there is a lack of demand.

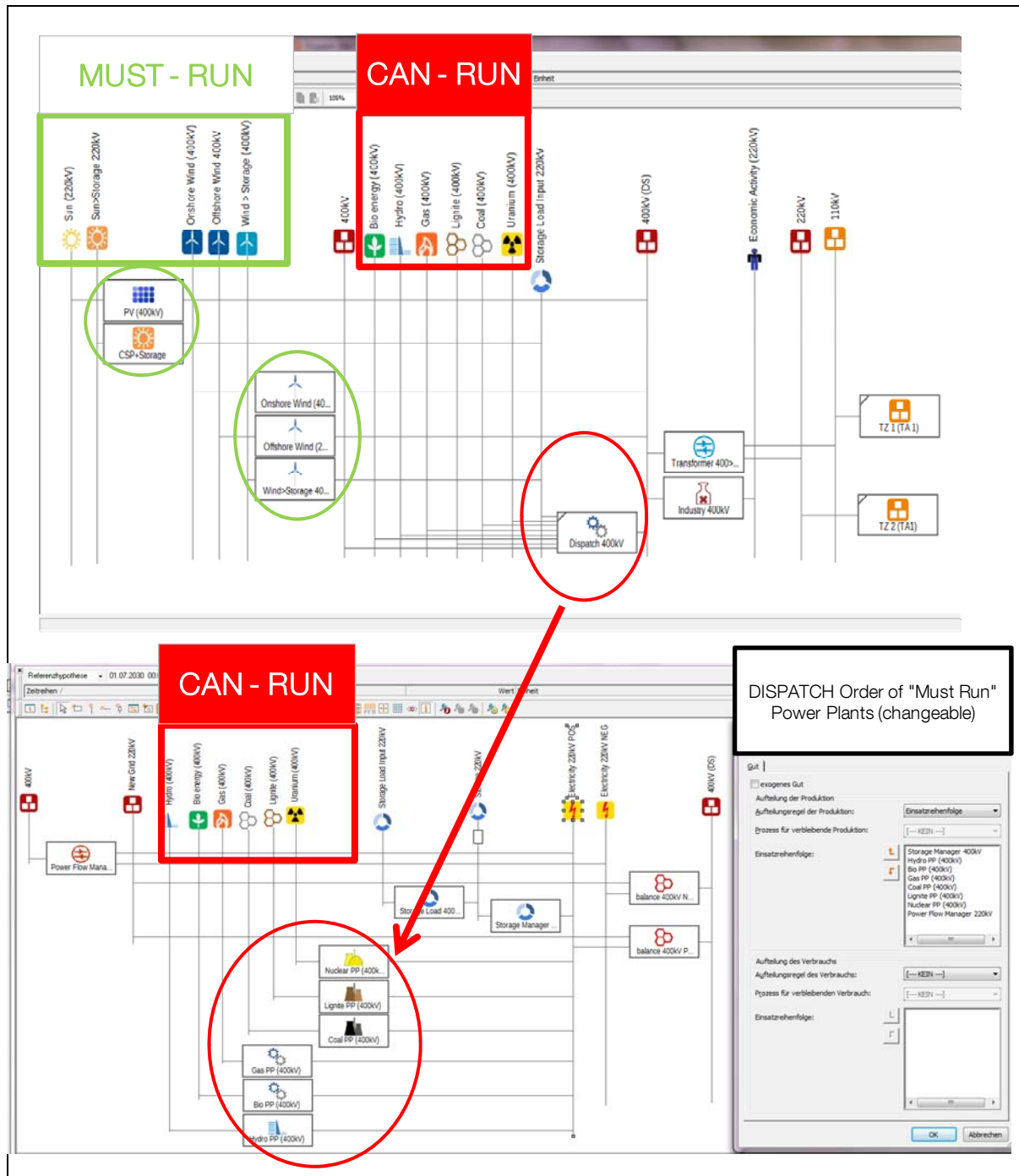


Figure 35: Overview “Must Run” and “Can RUN” Power Plants in the [R]E 24/7 Model

In the [R]E 24/7 methodology all “*Must Run*” commodities are defined as exogenous commodities. Therefore input is required, while all “*CAN RUN*” commodities are defined

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as calculated commodities as illustrated in Figure 36. The MESAP/PlaNet software allows changing this assumption. However it would significantly change the entire logic of the program and might require further changes of the overall model architecture and methodology. The aim for this thesis is, to develop an infrastructural planning tool for 100% RE systems, therefore the dispatch order *must-run* ahead of *can-run* will be maintained.

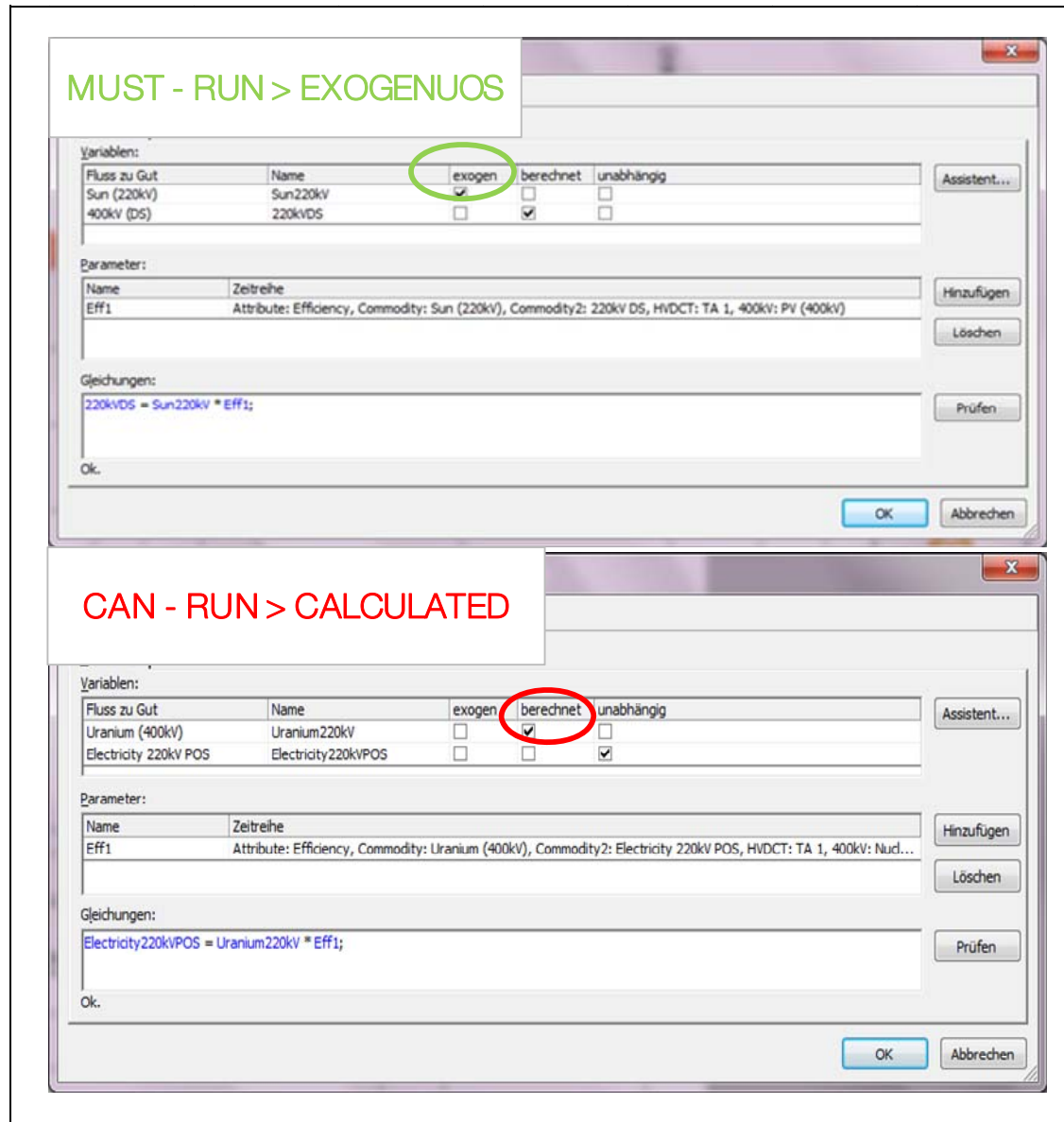


Figure 36: Defining "Must-Run" and "Can-Run" Power Plants



## 5.9 Series of Sub-Processes with Definite Market Shares

In order to specify processes and/or specific sectors of processes, sub-processes can be created. Figure 37 shows an example of the demand side of [R]E 24/7 which is divided into three demand sectors (Housing, Business and Farm), which again have a number of different subsectors. This is required, to integrate specific demand profiles for each consumer group in order to simulate the actual load curve in each cluster. While the process can define the actual load in kW, the commodity identifies the quantity of customers and their share within the sub-process. In Sub-process 1 the quantity of customers per sector will be identified as input data for the commodity "population". The housing sector has e.g. 175,000 households connected to the grid in a certain cluster. The sub-process 2 can break down the housing sector into a large number of household types with different load curves. The market share of each household type can be defined via commodity "population". Therefore, the commodity has two input data, the quantity and the quality of the specific sub-process.

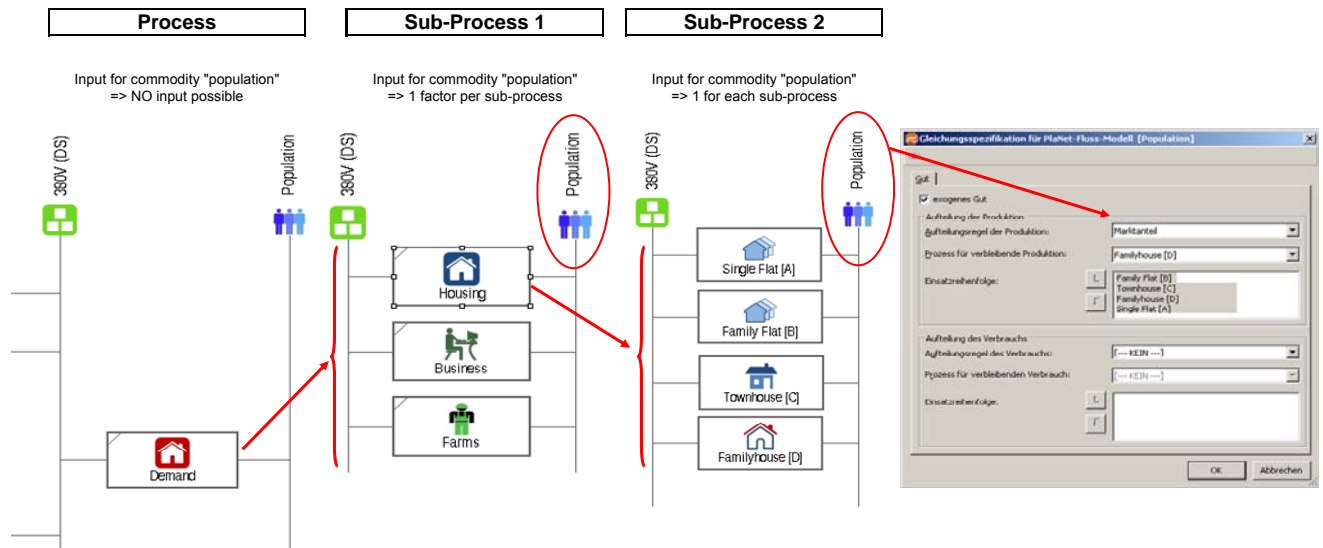


Figure 37: Sub-Process in the [R]E 24/7 Model and the Definition of Market Shares

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### 5.10 Summary: Overview all Attributes used in the [R]E 24/7 Model

Table 22 shows all [R]E 24/7 attributes and their abbreviated use in formulas as well as their units.

All Attributes in Alphabetical Order			
No.	Term	Formula name (Programm ID)	Unit
1	Actual Installed Capacity	CapAct	[kJ/h] / [kW/h]
2	Capital cost (annuity)	CostCp	[€/a]
3	Capital cost of new capacity	CostCpCapNew	[€/kJ] / [€/kWh]
4	Cost allocation factor	CAF	[1]
5	Cost of RES	CostRES	[€/h]
6	Cost recovery factor	CRF	[1]
7	Costs of flow	CostFlow	[€/h]
8	Depreciation Period	DepPeriod	[%/a]
9	Discount rate	DiscRate	[%/a]
10	Emission factor	Emi	[kg/kWh]
11	Fixed costs of process	CostFix	[€/h]
12	Fuel efficiency	FuelEff	[kWh/kJ]
13	Grid Limit	Grid_Limit	[kW/h]
14	Initial storage quantity	StorDef	[kWh]
15	Installed capacity	CapInst	[kW]
16	Intensity	Int	[kWh/head]
17	Load factor	LF	[h/h]
18	Market assignment	MktAssig	[1]
19	Market share	MktShare	[%]
20	Maximum flow	MaxFlow	[kJ/h] / [kWh/h]
21	Maximum Storage Charge + Discharge rate	StorMaxRate	[kWh/h]
22	New installed capacity	CapNew	[kW]
23	Other variable costs of process	CostVar	[€/h]
24	Product assignment	ProdAssig	[1]
25	Product share	ProdShare	[1]
26	Quantity of flow	QtyFlw	[kJ/h] / [kWh/h]
27	Quantity of commodity	QtyCom	[kJ/h] / [kWh/h]
28	Ratio between flows	Ratio	[1]
29	Specific capital cost	SpecCostCp	[€/kJ*h] / [€/kWh*h]
30	Specific cost of commodity	SpecCostCom	[€/kJ] / [€/kWh]
31	Specific cost of flow	SpecCostFlow	[€/kJ] / [€/kWh]
32	Specific cost of new capacity	SpecCostCpCapNew	[€/kJ] / [€/kWh]
33	Specific cost of output flow	SpecCostOutFlow	[€/h]
34	Specific fixed costs	SpecFixCost	[€/kJ*h] / [€/kWh*h]
35	Specific other variable costs	SpecCostVar	[€/kJ] / [€/kWh]
36	Storage difference	StorDiff	[kWh/h]
37	Storage efficiency	StorEff	[1]
38	Technical lifetime	TecLife	[h]
39	Total commodity supply cost	CostCom	[€/h]
40	Total input commodity cost of process	CostInComProc	[€/h]
41	Total process costs	CostPro	[€/h]
42	Transformer Efficiency	TransEff	[kWh/kWh]
43	Violation of Storage Capacity (Overcharged)	StorViolation	[kWh/h]

Table 22: Over: All attributes in Alphabetical Order

## 5.11 Structure of the [R]E 24/7 RES

Section 5.3 and 5.5.4 showed how commodities, processes and attributes can be combined into a complex energy flow model for one [R]E 24/7 RES cluster. One cluster represents one grid level with one specific geographical region. The section summarizes the function of the entire cluster and the simulated physical flow of the electricity.

Figure 38 visualizes the electricity flow, within one voltage level and one geographical cluster, from the generation side via the grid infrastructure to the demand side (= load); from left to right.

The sub process *dispatch*, marked with a light blue circle, hosts the grid relevant processes (5.6), storage facilities as well as dispatch power plants (= “can-run”). The sub process demand, marked with a dark blue circle, hosts all demand and consumer categories and the following sub process includes all load profiles used in a specific region.

The supply is primarily driven by the available solar and wind resources, while the demand or load is driven by the quantity of connected consumer and their demand profiles. All processes within the sub process dispatch will only be used if supply and demand of the first level will not match. The commodity voltage level (here **380 V** marked with a black and red arrow) is the only connection to other geographical areas and, via a transformer, to the next grid level.

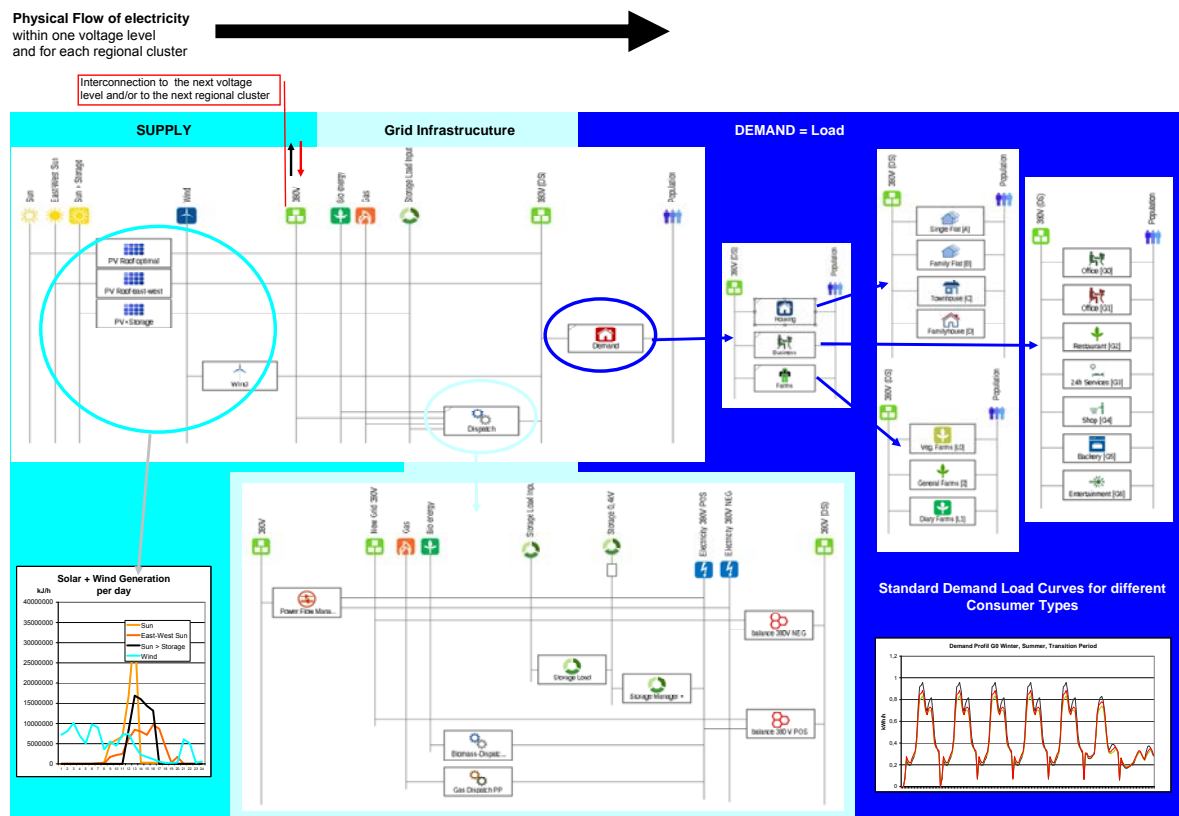


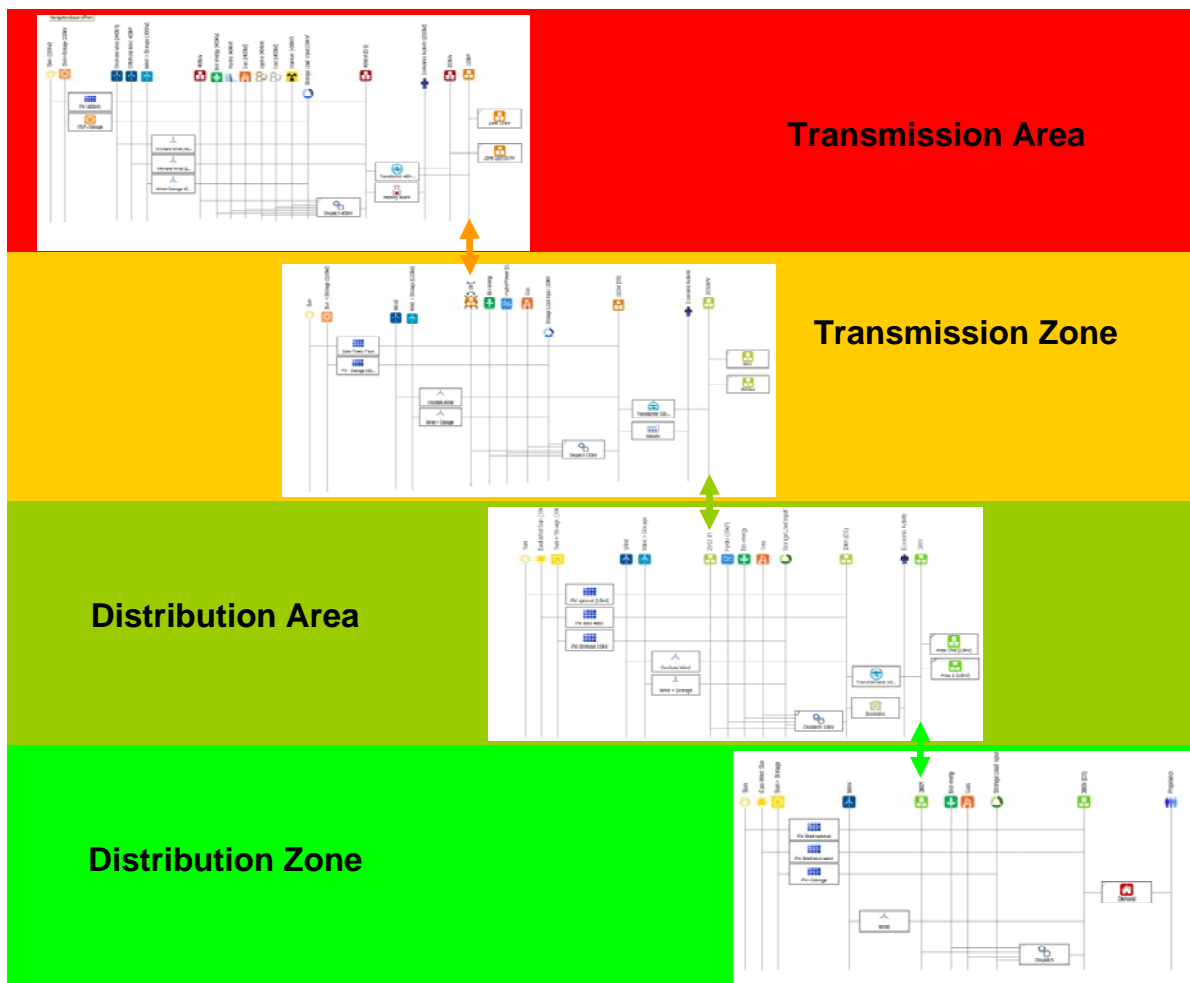
Figure 38: Physical Flow of Electricity within One Voltage Level and Regional Cluster

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### 5.12 Physical Flow [R]E 24/7: Simulation of Grid Systems Across all Voltage Levels

A series of identical clusters as shown in Figure 38 for all geographical regions all voltage levels - from the transmission to the distribution level – form the [R]E 24/4 model. This section provides an overview of how the interaction between different voltage levels will be simulated. Figure 39 shows the cascade of four different voltage levels (see Table 25). The electricity can flow via transformer both from the high voltage level to the lower voltage level and vice versa. The transformer is a process connected with the “*demand side*” (DS) of the higher voltage level and the “*supply side*” of the lower voltage level. There are no other interconnections between different voltage levels. So the transformer process is the gatekeeper for each voltage level and identifies the residual load for each cluster.



**Figure 39:** Physical Flow between Different Voltage Levels

[R]E 24/7 allows flows from the high voltage level towards the lower voltage level, which is currently the usual flow in electricity grids, and has a positive arithmetic sign. In case the generation capacity is higher than the demand within a grid level, the flow turns around from the lower to the higher voltage level, the arithmetic sign gets negative. Thus the model identifies the load flow within a certain cluster. For the first calculations of a new region, the transformer efficiencies are set to “1” as the top-down electricity flow would be calculated correctly as losses, but bottom-up load flow would result in

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additional electricity once the power has passed the transformer. Therefore transformer losses can only be calculated once the load flow is known. The dispatch sequence can be changed as documented in Figure 34 and electricity with a higher voltage level will get priority. Unfortunately changing the setting from *bottom-up* towards *top-down* is time consuming as a manual change in 43 clusters is required which represents a weakness of the model.

### 5.13 Economic Calculation Module of [R]E 24/7

Once the physical flow of the [R]E 24/7 model has been verified the cost calculation module can be implemented. PlaNet is a macro-economic cost model which calculates the costs of flows, commodities and processes. While the physical flow simulation can be calculated without the cost module, it is not possible to calculate the costs as a stand-alone application. Thus the data volume of simulations with cost calculations is significantly larger than physical flow only. Hence calculation time for financial flow analysis is longer.

In the energy sector, costs are mainly driven by installed capacities e.g. from power plants or from capacities of cables, the technical lifetime and the investment costs needed to install the required equipment and fuel costs – if fuel is required. Besides that, all technical equipment requires service and maintenance which are considered as fixed costs in the model. PlaNet allows defining “other variable costs” as well, so for example carbon tax or other political and external driven costs can be added to each process. Fuel costs from commodities such as coal or gas are an input for each process. However, each commodity and processes require the same set of input parameters.

According to (MESAP 2012<sup>98</sup>) *“PlaNet calculates with real numbers, that means inflation-adjusted costs, interest rates etc. In contrast to the flow equations the cost equations themselves are not editable. Cost equations always refer to existing processes (not to flows or commodities) and the options are provided in a special dialogue.”*

In order to calculate costs with PlaNet the following input parameter are required (MESAP 2012<sup>99</sup>):

- Global discount rate
- Specific costs of the commodity e.g. fuel cost

In addition each process is cost relevant in PlaNet and an input for each of the below listed parameter is mandatory:

- Installed Capacity
- Load factor
- Technical lifetime
- Specific capital cost
- Specific fix costs

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- Specific other variable cost

In case one or more parameters are not connected to costs, the input will be “0”:

#### 5.13.1 Definitions for Economic Calculation Terms

This section defines all used terms in the economical calculation of the model.

##### *Depreciation:*

Depreciation defines the time period during which a power plant or other technical equipment of the energy sector will be written off. This time period might relate to the technical lifetime or repayment term. The depreciation time is dependent on the finance concept and external factors such as the length of a power purchase contract. The longer the depreciation time, the lower the specific depreciation costs are. The [R]E 24/7 model has a very specific time resolution – hourly steps or even 15 minute steps are possible – therefore the depreciation rate has a very minor effect on the costs calculated within the model. However the depreciation rate has a significant effect on specific fixed costs which are an input for the cost calculation.

##### *Discount Rate:*

The annual effective discount rate is the annual interest rate of invested capital in relation to the return of investment of current market values. The discount rate refers to a risk-free rate of return adjusted by a project dependent risk premium (SRREN 2011<sup>100</sup>).

##### *Capital Cost Annuity:*

Capital cost annuity defines the annual capital costs of e.g. a power plant. The annual capital costs with the [R]E 24/7 model are broken down according to the used time resolution. For example if an hourly resolution is used, the annual capital costs have to be divided by 8760.

$$\text{CostCp}_p(t) = \text{CRF}_p(t) \times \text{SpecCostCp}_p(t) \times \text{CapInst}_p(t)$$

Formula 3: Capital Cost Annuity (MESAP 2012<sup>101</sup>)

$\text{CostCp}_p(t)$	:	Capital Cost Annuity
$\text{CRF}_p(t)$	:	Cost Recovery Factor
$\text{SpecCostCp}_p(t)$	:	Specific Capital Cost
$\text{CapInst}_p(t)$	:	Investment Costs (e.g. a new power plant)
$P$	:	Defines the parameter as a <i>process</i>
$(t)$	:	time (= 8760 h)

---

### *Cost Allocation Factor:*

For processes which have more than one output, a cost allocation factor is required in order to assign the costs to one or more outputs. PlaNet provides the possibility to choose between three different methods for cost allocation:

- (a) user defined costs for each output flow
- (b) calculated costs for each output flow
- (c) proportional cost allocation

(a) User defined cost allocation

$$CAF_{c \text{ residual}}(t) = 1 - \sum CAF_{\text{exog}}(t)$$

Formula 4; Cost Allocation Factor – user Defined (MESAP 2012<sup>101</sup>)

$CAF_{c \text{ residual}}(t)$  : Cost Allocation Factor for a residual process  
 $CAF_{\text{exog}}(t)$  : user defined (= exogenous) Cost Allocation Factor(s)

(b) Calculated cost allocation factor for various energy flows :

$$CAF_{c \text{ residual energy flow}}(t) = \frac{\sum (\text{SpecCostFlow}_c \times \text{QtyFlow}_c)}{\text{CostProc}_p}$$

Formula 5: Cost Allocation Factor for Various Energy Flows (MESAP 2012<sup>101</sup>)

$CAF_{c \text{ residual energy flow}}$  : Cost allocation factor for various energy flows  
 $\text{SpecCostFlow}_c$  : Specific Costs for the Output Flow (see Formula 6)  
 $\text{QtyFlow}_c$  : Quantity of Output Flow (of a process)  
 $\text{CostProc}_p$  : Cost of the process  
Calculation of process costs

$$\text{CostFlow}_{c \text{ Output}}(t) = CAF_c(t) \times [\text{CostInpComProc}_p(t) \times \text{CostCp}_p(t) \times \text{CostFix}_p(t)] + \text{CostVar}_c(t)$$

Formula 6: Cost Calculation the Output Flow of a Process (MESAP 2012<sup>101</sup>)

$\text{CostFlow}_{c \text{ Output}}(t)$  : Costs of the Output Flow of a Process  
 $CAF_c(t)$  : Cost Allocation Factor (for the process)  
 $\text{CostInpComProc}_p(t)$  : Cost of Input-Commodity of Process  
 $\text{CostCp}_p(t)$  : Capital Cost Annuity  
 $\text{CostFix}_p(t)$  : Fixed Process Costs  
 $\text{CostVar}_c(t)$  : Variable Process Costs

---

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#### ***Cost of Input-Commodity of Process:***

Calculates total costs of all input commodities required for the process e.g. fossil fuel cost and cooling water costs.

$$\text{CostInpComProc}_p(t) = \sum \text{QuanFlow}_c(t) \times \text{SpecCostCom}_c(t)$$

Formula 7 Cost of Input-Commodity of Process (MESAP 2012<sup>102</sup>)

#### ***Cost Recovery Factor:***

The cost recovery factor defines costs related to re-procurement of equipment and are related to the technical lifetime and the depreciation rate.

$$\text{CRF}_p(t) = \frac{(\text{DiscRate} + 1)^{\text{TecLife}_p - 1} \times \text{DiscRate}}{(\text{DiscRate} + 1)^{\text{TecLife}_p} - 1}$$

Formula 8: Cost Recovery Factor (MESAP 2012<sup>101</sup>)

#### ***Market Share:***

The market share defines the shares in per cent of a commodity or within a process or sub-process. The [R]E 24/7 model uses market shares to define the size of specific consumer groups within the demand sector.

#### ***Fixed Costs of a Process:***

Fixed costs are accrued costs of a commodity or process independent from the actual use. For example operation and maintenance costs of a power plant are fixed costs.

$$\text{CostFix}_p(t) = \text{SpecCostFix}_p(t) \times \text{CapInst}_p(t)$$

Formula 9: Fixed Costs of a Process (MESAP 2012<sup>101</sup>)

$\text{CostFix}_p(t)$	:	Fixed Costs of a Process
$\text{SpecCostFix}_p(t)$	:	Specific Fixed Costs (e.g. per unit)
$\text{CapInst}_p(t)$	:	Installed capacity



---

### *Specific Other Variable Costs:*

Additional political or external costs like carbon tax broken down per unit e.g. kWh . This parameter offers the opportunity to add political or environmental costs to the model.

$$\text{CostVar}_p(t) = \sum \text{SpecCostVar}_c(t) \times \text{QtyFlow}_c(t)$$

Formula 10: Specific Other Variable Costs (MESAP 2012<sup>101</sup>)

CostVar <sub>p</sub> (t)	:	Specific other Variable Costs
SpecCostVar <sub>c</sub> (t)	:	Specific variable Commodity Costs (e.g. carbon tax)
QtyFlow <sub>c</sub> (t)	:	Quantity of Commodity

### *Specific Capital Costs:*

Capital Costs are broken down by unit in relation to the quantity of flow.

### *Specific Costs of Commodity:*

The specific costs of commodities define the cost for commodities such a coal or gas per unit.

### *Specific Fixed Costs:*

Fixed costs are the annual operation and maintenance costs broken down per unit e.g. kWh. Specific fixed costs add costs to the process even if the process has no quantity of flow.

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#### *Installed Capacity:*

The installed capacity as already defined in 5.5.3 has a significant impact on the specific fixed costs of a process. The PlaNet model offers two different possibilities to calculate capital costs for installed capacities:

- (a) user defined
- (b) via a load factor

The following formula is used for user defined capacity (a):

$$\text{CapInst}_p(t) = \text{CapInst}_{p \text{ exog}}(t)$$

Formula 11: Installed Capacity (MESAP 2012<sup>103</sup>)

$\text{CapInst}_p(t)$	:	Installed Capacity
$\text{CapInst}_{p \text{ exog}}(t)$	:	Fixed value - exogenous Input

In case of a load factor (b) is used, the following formula applies:

$$\text{CapInst}_p(t) = \frac{\text{QtyFlow}_p(t)}{\text{LF}_p(t)}$$

Formula 12: Installed Capacity Calculated with a Load Factor

$\text{CapInst}_p(t)$	:	Installed Capacity
$\text{QtyFlow}_p(t)$	:	Quantity of Flow (e.g. generated kilowatt-hours)
$\text{LF}_p(t)$	:	Load factor

The [R]E 24/7 model calculates capital costs of installed capacities with a load factor (b) for “must run” power plants (solar and wind) and with user defined (a) capacities for all “can-run” power plants (dispatch power plants).

---

### 5.13.2 Attributes for Results of [R]E 24/7 Model

The RES of the [R]E 24/7 model has a chain of alternating commodities and processes. The calculated costs of specific processes with associated input commodities lead to calculated costs. Those calculated costs are in many cases – in combination with an (internal) commodity - an input for the following process. This section provides an overview of the attributes of results or interim results. For every process and each commodity specific costs (costs per kWh) and total costs (costs per hour) are calculated.

#### *Input - Costs of Flow:*

The overall specific costs are in relation to the quantity of flow. in the case of the [R]E 24/7 model those costs are always costs per kWh.

$$\text{CostFlow}_c \text{ Input (t)} = \text{SpecCostCom}_c \text{ (t)} \times \text{QtyFlow}_c \text{ (t)}$$

Formula 13: Input - Cost of Flow (MESAP 2012<sup>101</sup>)

CostFlow <sub>c</sub> Input (t)	:	Input – Cost of Flow
SpecCostCom <sub>c</sub> (t)	:	Specific Costs of Commodity
QtyFlow <sub>c</sub> (t)	:	Quantity of Flow (commodity)

#### *Output – Costs of Flow:*

The costs calculated as a result of all commodities and processes throughout the entire model. The output shows accumulated costs either per kWh or per hour.

$$\text{CostsFlow}_c \text{ Output (t)} = \text{CAF}_c \text{ (t)} \times [\text{CostInpComProc}_p \text{ (t)} \times \text{CostCp}_p \text{ (t)} \times \text{CostFix}_p \text{ (t)}] + \text{CostVar}_c \text{ (t)}$$

Formula 14: Output – Cost of Flow (MESAP 2012<sup>101</sup>)

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#### 5.13.2 Summary: Attributes used for Cost Calculation in the [R]E 24/7 Model

Table 23 provides an overview of all financial attributes used in the [R]E 24/7 model defined in section 5.13.1 including their formula names (= program ID), units and whether it is defined as input or output.

Financial Attributes					
No.	Term	Formula name (Program ID)	Unit	Input	Output
18	Depreciation	DepPeriod	[%/a]	X	
19	Discount rate	DiscRate	[%/a]	X	
20	Capital costs (annuity)	CostCp	[€/a]	X	
21	Cost allocation factor	CAF	[1]	X	
22	Cost recovery factor	CRF	[1]	X	
23	Market share	MktShare	[%]	X	
24	Fixed cost of process	CostFix	[€/h]	X	
25	other variable cost of process	CostVar	[€/h]	X	
26	Specific capital costs	SpecCostCp	[€/kJ*h] / [€/kWh*h]	X	
27	Specific cost of commodity	SpecCostCom	[€/kJ] / [€/kWh]	X	
28	Specific fixed costs	SpecFixCost	[€/kJ*h] / [€/kWh*h]	X	
29	Specific other variable costs	SpecCostVar	[€/kJ] / [€/kWh]	X	
30	Total input commodity cost of process	CostInComProc	[€/h]		X
31	Total process costs	CostPro	[€/h]		X
32	Specific costs output flow	SpecCostFlow	[€/h]		X
33	Cost of flow	CostFlow	[€/h]		X

Table 23: Financial Attributes used in the [R]E 24/7 Model

#### 5.13.3 Assigning Costs with PlaNet for [R]E 24/7

It is required to define the cost calculation method for each process used in the [R]E 24/7 model. The first step is to determine whether it is a cost relevant process. Then, the cost relevant input flows are defined and the calculation method needs to be chosen. If needed, other variable costs – both for input and output flow(s) - can be added. Finally cost allocations for the output flow(s) specify if the total process costs are equally distributed across all outputs, or if one specific output will be more costly than another. Within the [R]E 24/7 model, only two processes have two output flows:

- The transformer which connects the 400kV high voltage level with the medium voltage transmission grids of 220kV and 110 kV
- PowerFlow Manager** process to manage negative/ positive load flows (see 5.6)

In both cases the output flows are defined as cost relevant and a proportional cost allocation has been selected.

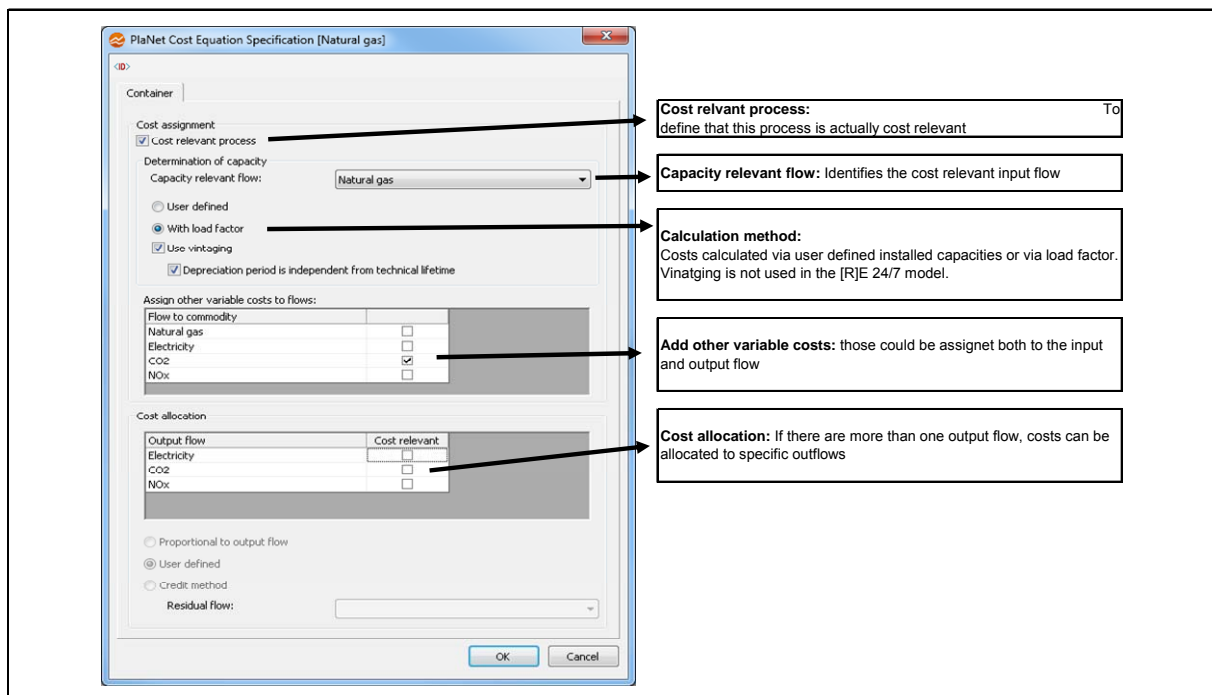


Figure 40: Example how to Implement the Cost Calculation into MESAP/PlaNet (MESAP 2012)

## 5.14 Economic Flow [R]E 24/7: Simulation of the Grid System with Associated Costs

In relation to the physical flow shown in Figure 39 the economic calculation takes place. Processes, commodities and all involved cost relevant parameters defined in Table 23 lead to an economic flow within the [R]E 24/7 model.

### 5.14.1 Cost Flow within One Cluster

Figure 41 shows four cost categories which are calculated within each cluster:

- (a) Power generation costs
- (b) Distribution and grid management costs
- (c) Costs for storage facilities
- (d) Costs for electricity generated and transmission for “imported” from another cluster

Costs (a) to (d) add up to the real hourly supply costs (e) ,both specific costs per kWh and total costs per time resolution of one hour.

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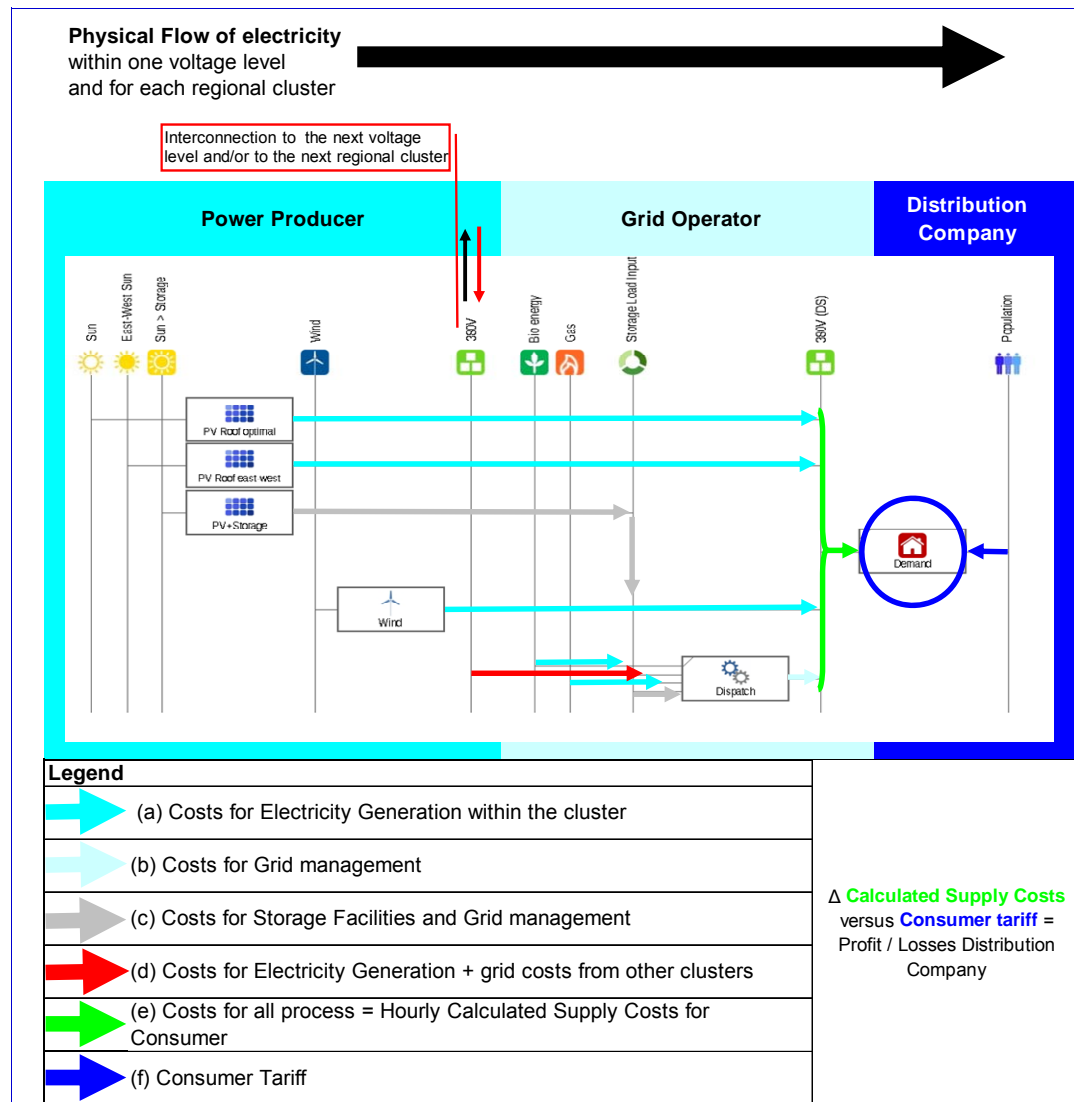


Figure 41: Overview Cost Flow within One Cluster

Table 24 shows a sample calculation for fluctuating power supply costs within a low voltage cluster due to changing distributed generation shares and various generation costs. The relationship between near-consumer generation and electricity imports from higher network levels, in combination with battery-use leads to strongly fluctuating supply costs. [R]E24/7 performs these calculations across all network levels and for all clusters and determines resulting actual power supply costs for consumers.

Cost Category	Costs (for this example) [€/kWh]	Assumed Total Cluster Demand per hour [kWh/h]	Supply share [%]			Total Electricity (within one hour) [kWh/a]			Total Costs [€/h]		
			Example 1	Example 2	Example 3	Example 1	Example 2	Example 3	Example 1	Example 2	Example 3
(a) Costs for Electricity Generation within the cluster:		100.000									
> Solar Photovoltaics	0.150		100%	0%	0%	100.000	0	0	15.000	0	0
> Onshore Wind	0.075		0%	75%	20%	0	75.000	20.000	0	5.625	1.500
> Gas CHP unit for dispatching (0.380kV - level)	0.060		0%	0%	20%	0	0	20.000	0	0	1.200
total (a)						100.000	75.000	40.000	15.000	5.625	2.700
(b) Process Costs for Grid management:											
> Dispatch Process (0.380kV - level)	0.080		100%	100%	100%	100.000	100.000	100.000	8.000	8.000	8.000
(c) Process Costs for Storage:											
> Battery	0.090		10%	5%	0%	10.000	5.000	0	900	450	0
(d) Costs for Electricity Generation + grid costs from other clusters:	0.050		0%	25%	60%	0	25.000	60.000	0	1.250	3.000
(e) Costs for all processes = hourly supply costs for consumer:									23.900	15.325	13.700
(f) Consumer Tariff:	0.250								25.000	25.000	25.000
Delta [d] - [e]									1.100	9.675	11.300

Table 24: Sample Calculation: Fluctuating Supply Costs in Low Voltage Clusters

---

Specific calculation results are documented in Chapter 9, both for one sample cluster and across all voltage level.

Rapidly fluctuating supply costs due to distributed generation are also reported in IEA's *Insights Series 2013 – Electricity Networks: Infrastructure and Operations* publication according to (OECD/IEA 2013<sup>104</sup>).

*“(...) The share of operational costs on total costs for transmission networks varies by region and network technical specifications. The same cost variation also often applies for the disaggregation of shares within the operational costs. Additionally these costs can vary over time with changing patterns of investments, system tasks or system design changes.”*

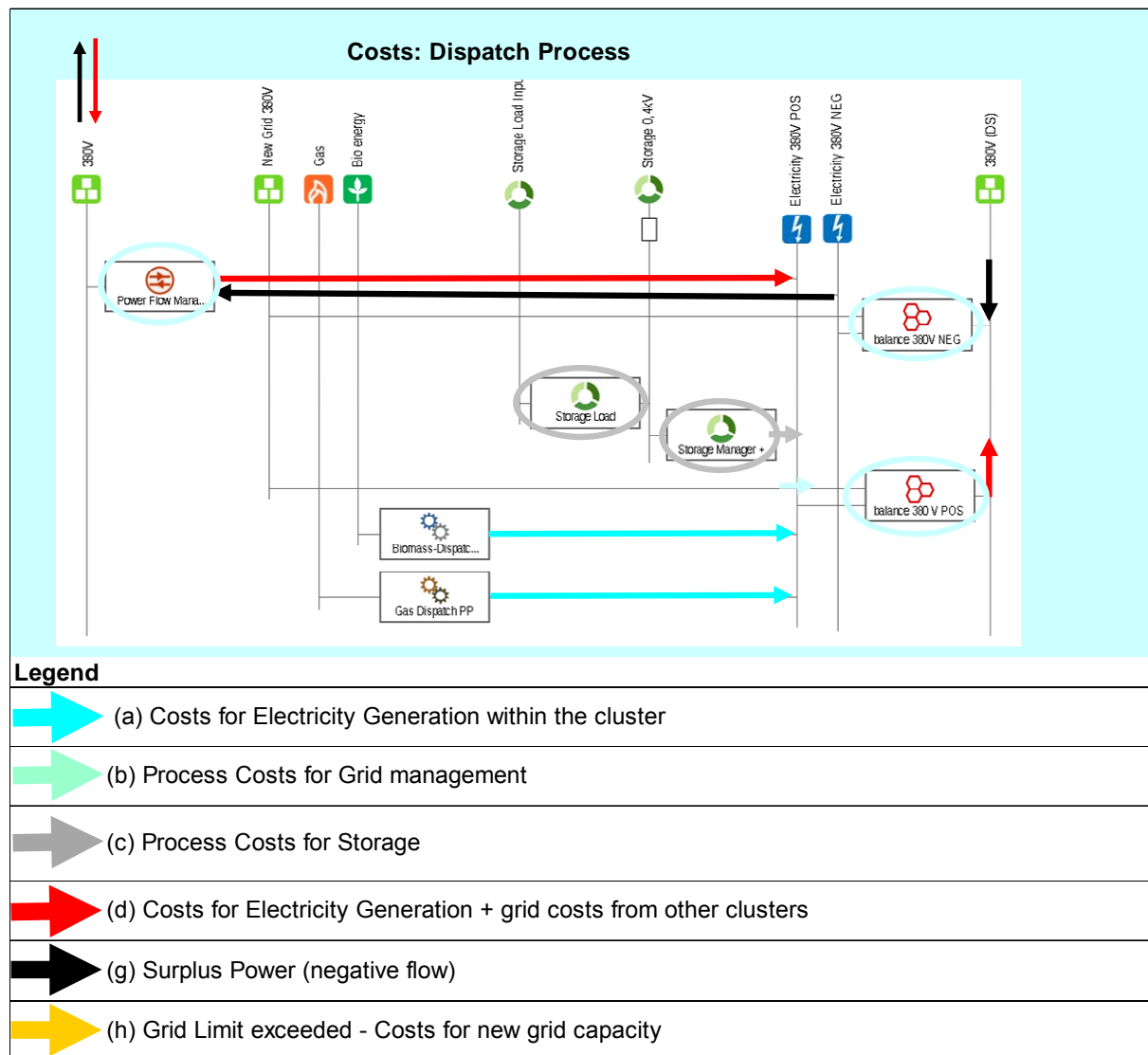
The analysis of real supply costs over a longer period, with different generation compositions, can determine cost-effective power supply schemes for specific customer groups or a specific region.

#### 5.14.2 Dispatch Costs

Each cluster requires a sub-process in which all grid related processes including dispatch power plants, storage facilities and possible needs for grid expansion are located. The dispatch area bundles all grid operator tasks for each voltage level. The total costs for all processes required to simulate the physical flow of the grid represents the total grid costs for each voltage level. The allocation for the calculated costs for dispatch power plants and storage facilities are allocated to the *Dispatch* sub-process (see also Figure 33).

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**Figure 42:** Costs within the Dispatch Area

The processes for grid management (power flow manager, balance POS and balance NEG) shown in Figure 42 does not correspond to real processes for grid management. They are necessary to simulate the physical flow of the electricity grid under the MESAP/PlaNet program logic. The associated costs with those grid management processes reflect the real costs of grid management and are allocated accordingly.

If the grid limit is exceeded, costs for grid expansion will be added to the processes *balance POS* or *balance NEG*. These additional costs are only an indication of the required additional costs for grid enforcement or expansion. These costs appear only for the specific moment, when the grid limit has been exceeded which obviously would not be possible during real grid operations. Therefore a further analysis is required which compares increased storage capacity with the costs of grid expansion for when the grid limits are increasingly exceeded over the entire simulation period.



### 5.14.3 Cost Flow across all grid levels

Figure 43 shows the cost flow across all grid levels. For customers connected to the distribution level, grid costs from each level will be added to the generation costs. In general, the calculation of supply costs will take all voltage levels between the power plant connection and consumer outlet into account.

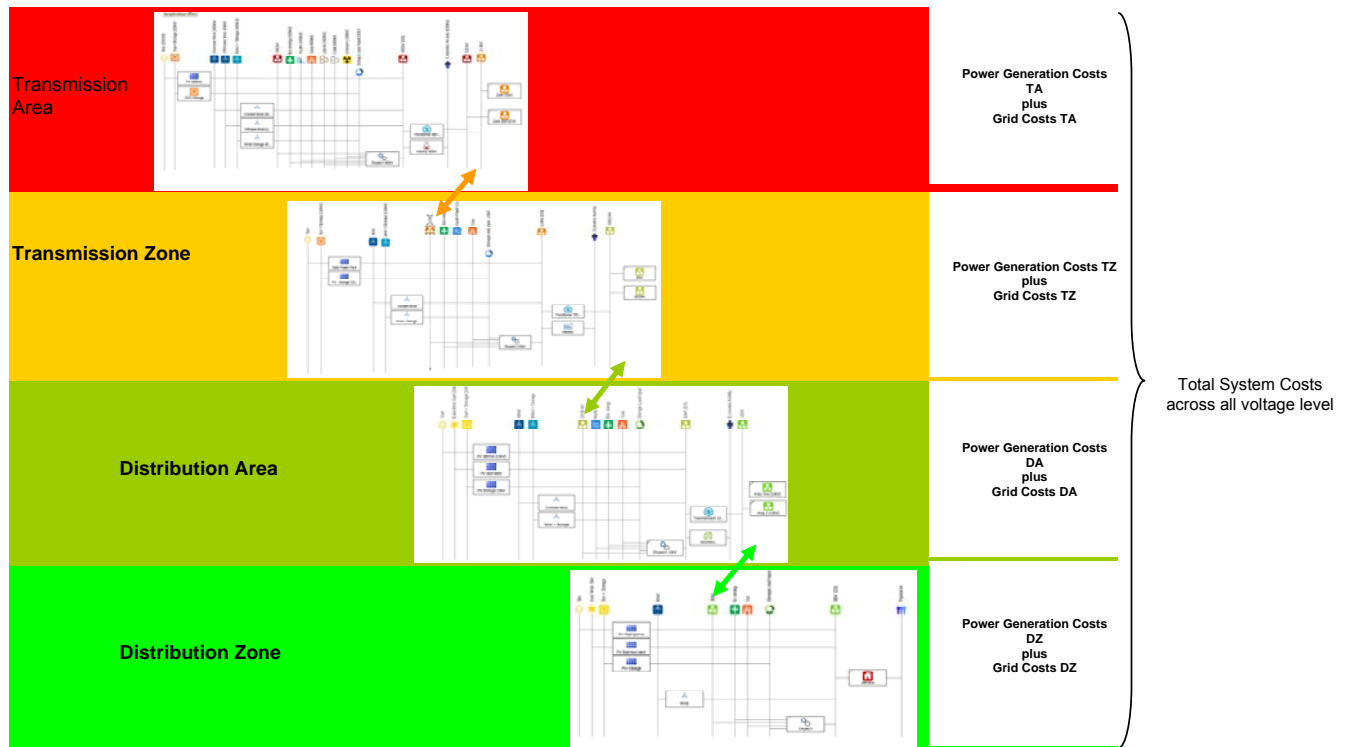


Figure 43: Costs Across all Voltage Level

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## **5.15 Conclusion – Development of an Infrastructural Planning Tool**

Chapter 5 has documented the entire technical development process for the infrastructural planning tool [R]E 24/7. The selection of software for programming significantly determined the model architecture. Therefore a detailed description of all model components is required to make the development process of the [R]E 24/7 as transparent as possible. While the selected software MESAP/PlaNet is user friendly and very flexible, there are also certain limitations. Detailed models go hand in hand with high data volumes and long calculation times. The original software was unable to handle the calculation processes with data volumes over 500 MB. In order to develop the [R]E 24/7 methodology idea further, the software capacity needed to be extended to adapt to the greater computing performance.

The [R]E 24/7 model was programmed to reflect a great level of technical detail across all voltage levels. The advantage of a detailed technology simulation in three dimensions, across all voltage levels, turns out to be a disadvantage as well. The large number of data points – 18.000 parameters for the entire [R]E 24/7 model – leads to a very high number of variables which made an optimization process impractical. The lack of an optimization function therefore represents a weakness.

Programming the model required the progression of various new processes, sub-processes, external- and internal commodities needed to simulated power grids. The software MESAP/PlaNet has never been used to model electricity grids and the high time resolution of one hour in combining load flow calculation with a high possibility of reverse flows, made it necessary to develop new mathematical function and use multi-level sub-processes such as the *Dispatch* process and the *Power Flow Manager* process.

All parts of the model, especially those required for grid simulations with all necessary parameters were constantly accompanied with test runs to verify the mathematical correctness of the model results.

The cost module allows detailed simulations of the financial flow across all voltage level and enables the modeler to include external and / or political costs as well. However the resulting large data volumes limit the length of model period to one month or less depending on the capacity of the computer. Therefore instead of calculating a full year, some extreme days, weeks or months should be analyzed. Finding the optimal energy solution is an iterative process and requires multiple model runs. The lack of an optimization module represents a weakness of the model.

In a next step, the model developed for this thesis is applied to a specific region and compared with the calculation results of another model.

---

## 6. Topographical Concept of [R]E 24/7

The [R]E 24/7 model calculates the electricity flow within and across a range of clusters. One cluster represents one specific voltage level in a specific region. The objective for the [R]E 24/7 model is to develop a software tool which can simulate electricity flows for all countries. Therefore the model uses a modular system of clusters. The individual combinations and the number of those basic model clusters depend on the geographical and technical conditions of the grid.

### 6.1 Grid topography of the Model and the Real Situation

While the electricity grid in OCED countries has been built and expanded over more than 50 years, developing countries currently build up new infrastructure for power transmission and distribution (IEA 2013<sup>105</sup>). The constant developments of electricity grid technologies of the past decades lead to very different technology combinations depending on where and when the grid has been built. Therefore electricity grids around the world use a combination of different voltage level for long distance transmission and distribution. In order to reflect this, four different grid categories have been developed specifically for the [R]E 24/7 model (Table 25).

Grid category	Voltage Level	Abbreviation	Name in the literature
Transmission Area:	$\geq 300$ kV	TA	Highest Voltage
Transmission Zone:	$\geq 100$ kV	TZ	High Voltage
Distribution Area:	$\geq 10$ kV	DA	Medium Voltage
Distribution Zone:	$\leq 10$ kV	DZ	Low Voltage

**Table 25:** Grid Categories for the [R]E 24/7 Model

While high voltage lines transmit electricity over several hundred kilometres, low voltage lines in distribution zones transport electricity only across short distances. The cluster size for each voltage level is therefore different. Transmission areas of several hundred kilometres can cover areas of 400 km by 400 km and more, the [R]E 24/7 therefore defines this area as the average TA cluster size. For lower voltage levels, the model needs to simplify and reduce the number of clusters.

Grid category	Real transmission distance	[R]E 24/7 Average Cluster Size	Average number of clusters per grid category	Total No. clusters
TA	400 km – 500 km	400 km X 400 km	2 X TZ	2
TZ	100 km – 200 km	200 km X 200 km	4 x DA	8
DA	10 km – 20 km	100 km X 100 km	4 X DZ	32
DZ	1 km – 2 km	50 km X 50 km		
<b>Total</b>				<b>43</b>

**Table 26:** Cluster Sizes in the [R]E 24/7 Model

Table 26 shows the assumptions made for the [R]E 24/7 cluster sizes and number of clusters within each grid level. However, cluster sizes can vary (see Figure 46 and Figure 47) due to geographical or technical conditions in the research region.

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The numbers of clusters for each grid level has been reduced in the model developed for this thesis in order to keep calculation time for each simulation short and to limit the required amount of input data. If necessary more than four clusters e.g. for the DZ level can be implemented in the model. In order to identify specific geographical areas for each cluster and to assign the actual grid topology in this region, each cluster represents a grid node (Table 12).

Figure 44 shows the horizontal structure of [R]E 24/7 model. For simplification purposes it is assumed that the grid node is in the centre of each cluster, but this is not mandatory as the grid node could be anywhere within the cluster. Each grid node is connected to a GIS position. This position helps to identify the installed power plant capacity within a cluster as well as the localisation of consumer data. It is not possible to take different geographical position within one cluster into account. (Note: Due to limited data capacity and to reduce calculation time, the number of TZ fields has been reduced to two fields for this thesis.)

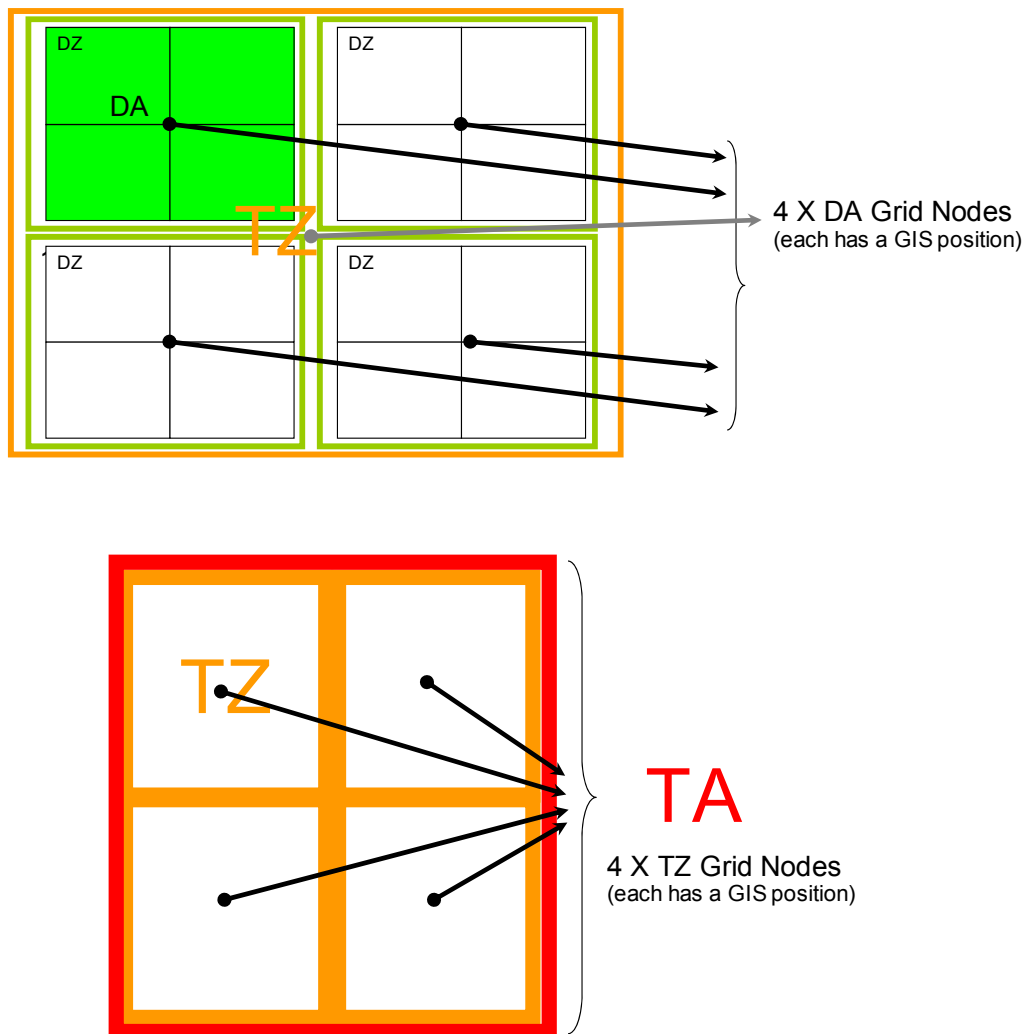


Figure 44: Horizontal Structure of the [R]E 24/7 Model

Figure 45 provides an overview of the vertical structure of the [R]E 24/7 model. In order to reflect differences within one grid level, a sub-process (Figure 35) is used in the RES. There is a possibility to use more clusters – indicated with TZ3 and TZ4 in Figure 45 – as *virtual containers* which are clones of TZ1 and TZ2 therefore no changes in the model structure of virtual containers are possible. However, due to the large data volumes, virtual containers have not been used in practice for this thesis.

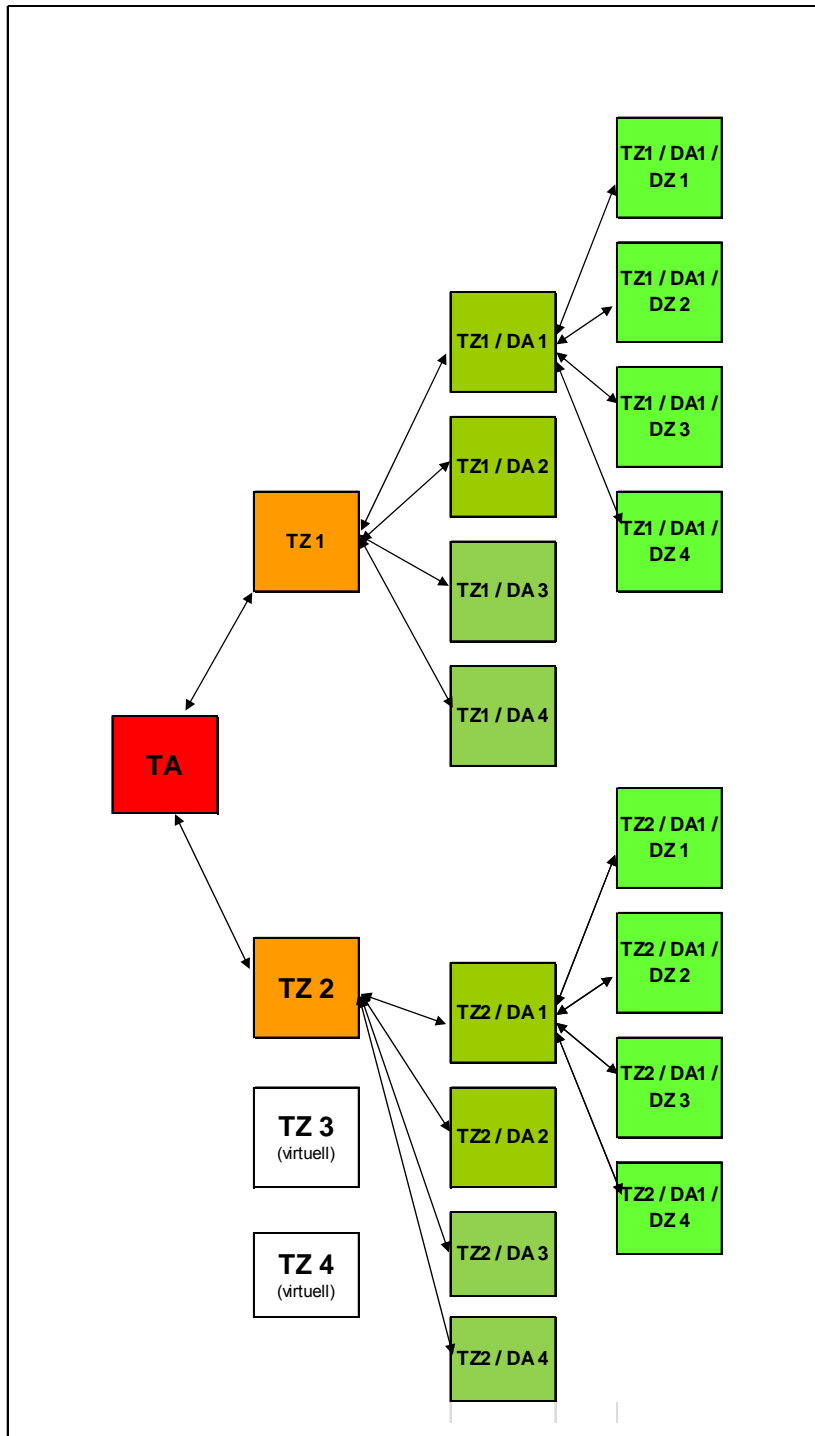


Figure 45: Vertical Structure of the [R]E 24/7 Model

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### 6.2 Geographical Concept

In order to simulate specific grid areas, the geographical positions for each cluster as well as the grid node must be assigned. Clusters can have different sizes and the grid node is not necessarily in the centre, depending on geographical and technical circumstances. Figure 46 and Figure 47 shows the geographical allocation of clusters and grid nodes for the example of New Zealand. New Zealand has been chosen, because of the relative simple grid structure and the availability of the grid map which allowed the best possible visualization of the geographical concept.

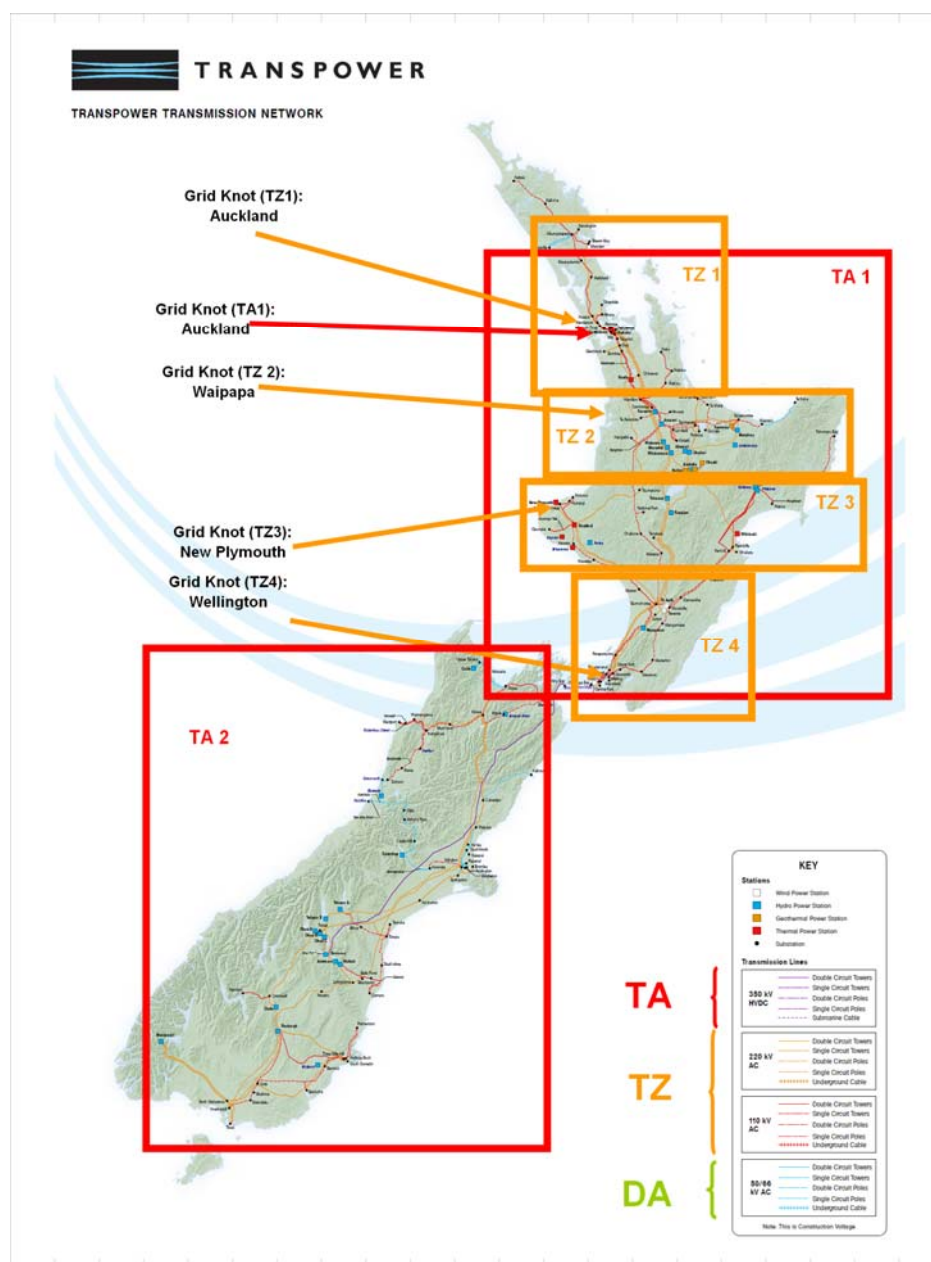


Figure 46: Geographical Concept of [R]E 24/7 – Transmission Level



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## 7. Data Input Concept for [R]E 24/7

The energy model developed for this thesis uses a complex data set of 6872 different parameters therefore a user friendly interface between datasheets and the actual model is indispensable. Consequently an input concept to make [R]E 24/7 as user friendly as possible has been developed. This section provides an overview about the input concept and how it is structured.

### 7.1 Standard Inputsheets

Figure 48 shows the data input structure for the model. There are four different kinds of input sheets. There are two kinds of blue colored smart input sheets Firstly ones which are for manual input of data and remain the same over the entire model period such as the installed capacity of power plants, the second provide the overview across all cluster and voltage levels (Figure 49). The yellow colored sheets carry original data such as load profiles, actual production data from wind farms or meteorological data. Those sheets have also been used for data transfer from the EN model to undertake tests for verification of the [R]E 24/7 model (see chapter 8).

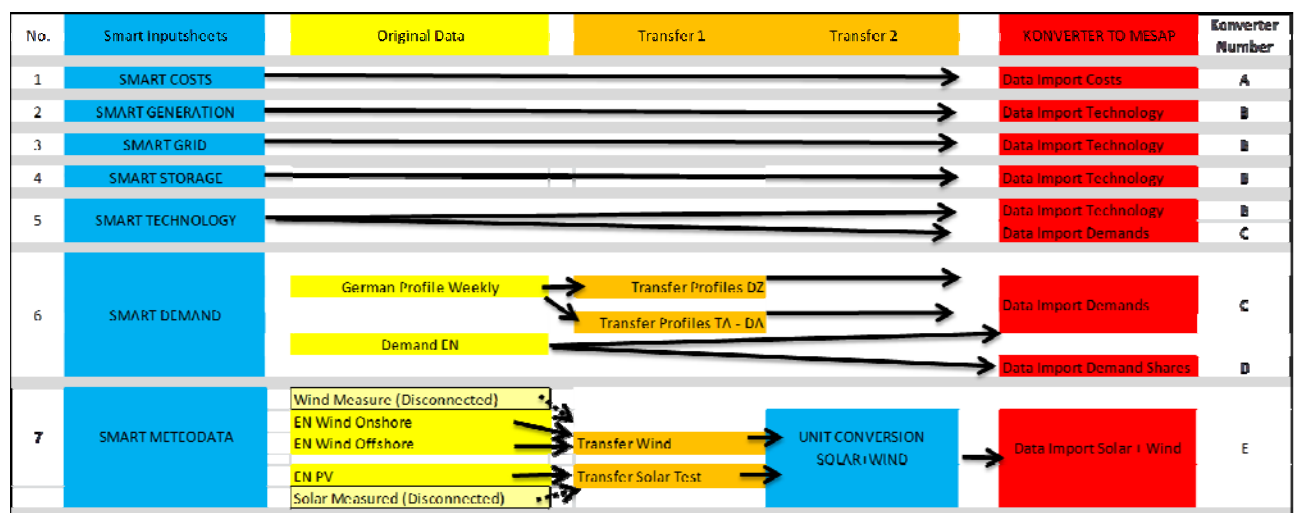


Figure 48: Data Input Structure of [R]E 24/7

The orange colored sheets are used to convert units or data formats according to the needs of the model. Finally the red sheets are the actual input sheets, which carry all parameters in the required format to upload data into the model (see Figure 50).

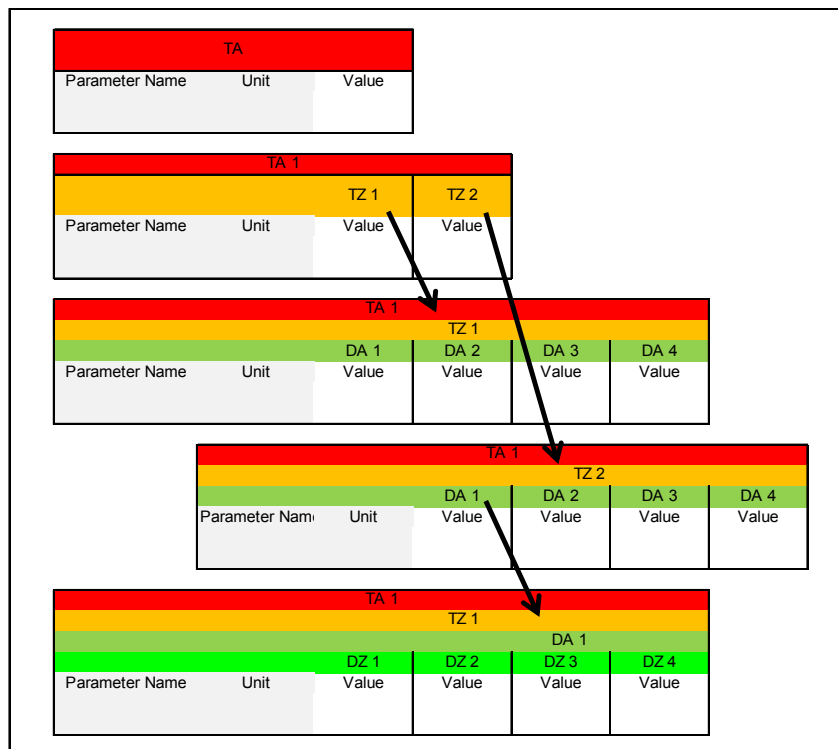


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### 7.1.1 Smart Input Sheets

There are seven different parameter categories: costs, power generation, grid and storage capacities, general technology parameter, demand and meteorological data for solar and wind energy. For each category a *smart* input sheet has been developed. Those *smart* input sheets have a dashboard function for the model data management. All parameters for each specific data category follow the same concept.

The parameters are arranged from top to bottom according to the power level and marked with a specific color code to avoid input errors. The input values for hours are extrapolated to annual values and installed capacities e.g. of power plants or loads for each voltage level. This aggregation has been done to ensure a better overview during the input phase. *Smart* sheets are designed for plausibility checks of assumptions to avoid unnecessary calculations.



**Figure 49:** Structure and Color Code of Smart Input Sheets

Figure 49 shows the basic structure of smart input sheets. Each Voltage level has a specific color throughout the entire model: red and orange for the transmission levels and dark and light green for the distribution level. For all technical data and cost assumptions, which typically remain the same throughout the modeling period, although the model could handle dynamic value inputs, a second type of smart sheet has been developed. Figure 50 shows the structure of the smart input sheets for technical and economic data.

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Power generation					Load					
No	Process	Inputs which are the same in all clusters	With Missing Data Input	With PV/Wind Generation Data	No	Process	Attribute	Unit	Value	
1.00	PV Optimal / Power plant	Efficiency	0.16	1.00	TA 1					
		Load factor	0.13	1.00	TZ 1	DA 1	Business	Installed Capacity		1500.00
		Technical lifetime		6760.00		DA 2	Note: Installed capacity is also linked to Ecom activity (MWh/head)	Installed Capacity		1.50
2.00	PV East-West					DA 3		Installed Capacity		1.50
		Efficiency	0.16	1.00		DA 4		Installed Capacity		1.50
		Load factor	0.13	1.00	TA 1					
		Technical lifetime		6760.00	TZ 2	DA 1	Business	Installed Capacity		1.50
3.00	PV-Storage					DA 2	Note: Installed capacity is also linked to Ecom activity (MWh/head)	Installed Capacity		1.50
		Efficiency	0.14	1.00		DA 3		Installed Capacity		1.50
		Load factor	0.13	1.00		DA 4		Installed Capacity		1.50
		Technical lifetime		6760.00		TZ 1		Installed Capacity		0.01
4.00	CSP					TZ 2	Industry	Installed Capacity		0.01
		Efficiency	0.23	1.00		TA 1	Industry	Installed Capacity		0.00
		Load factor	0.20	1.00						
		Technical lifetime		6760.00						
5.00	(Onshore) Wind									
		Efficiency	0.45	1.00				av. installed Cap.	kWh/h	2.00
		Load factor	0.26	1.00				av. installed Cap.	kWh/h	75.00
		Technical lifetime		6760.00				av. installed Cap.	kWh/h	100.00
6.00	Offshore Wind									
		Efficiency	0.45	1.00						
		Load factor	0.40	1.00						
		Technical lifetime		6760.00						
7.00	Wind Storage									
		Efficiency	0.43	1.00						
		Load factor		1.00						
		Technical lifetime		6760.00						

Figure 50: Sample Structure of Smart Input Sheets for Technical and Economic Parameters

All “Smart Input Sheets” are shown in the Annex (A1.1 – A1.8), complete input data will be archived for documentation purposes.

## 7.2 Interface to [R]E 24/7

The input sheets for all categories finally connected to a data sheet which serves as an interface to MESAP.

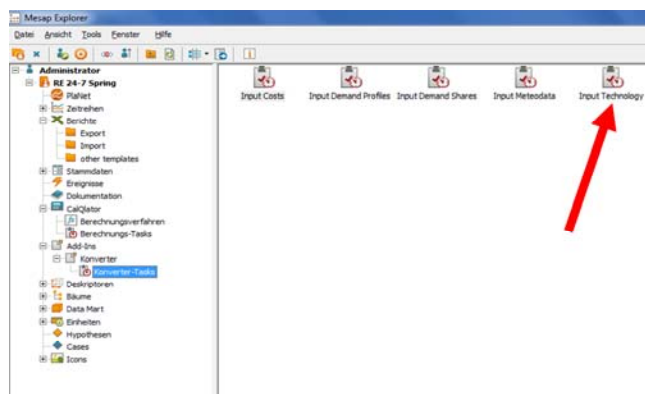
Figure 51 shows a data sheet example. Each parameter is assigned to a unique ID and carries all relevant model information about the grid level, attributes etc.

ID	Attribute	Commodity	Process	Sub-process	10kV	110kV	400kV	HV/OCT	Enthell	hypoth	21.05.2020 05:00
#100346	Efficiency	220kV-400kV (DS)					Transformer 400-2 TA 1		TW/h/TWh	REF	1.00
#107800	Fuel efficiency	Electricity 380V POS*Bi Balance 380V	Biomass-Dispatch PP		OZ 3 (DA1/TZ1)	DA 1	TZ 1 (TA 1)	TA 1	PJPJ	REF	0.38
#107805	Fuel efficiency	Electricity 380V POS*Gk Balance 380V	Gas Dispatch PP		OZ 3 (DA1/TZ1)	DA 1	TZ 1 (TA 1)	TA 1	PJPJ	REF	0.51
#107808	Efficiency	Storage Load Input*Store Balance 380V	Storage Load		OZ 3 (DA1/TZ1)	DA 1	TZ 1 (TA 1)	TA 1	MWh/kWh	REF	0.65
#107872	Efficiency	San - Storage*Storage I (PV)-Storage			OZ 3 (DA1/TZ1)	DA 1	TZ 1 (TA 1)	TA 1	PJPJ	REF	1.00
#107874	Efficiency	East-West Sun*380V (D-PV) Roof/east-west			OZ 3 (DA1/TZ1)	DA 1	TZ 1 (TA 1)	TA 1	PJPJ	REF	1.00
#107875	Efficiency	San*380V (DS)	PV Roof/optimal		OZ 3 (DA1/TZ1)	DA 1	TZ 1 (TA 1)	TA 1	PJPJ	REF	1.00
#107897	Fuel efficiency	Electricity 380V POS*Bi Balance 380V	Biomass-Dispatch PP		OZ 4 (DA1/TZ1)	DA 1	TZ 1 (TA 1)	TA 1	PJPJ	REF	0.38

Figure 51: Structure of the Data Sheet which serves as an Interface to RE 24/7

The *Converter* function of MESAP is assigned for data transfer from Excel or other formats. By activating “Input Technology” only relevant parameters will be uploaded. The categorized data transfer prevents unmodified data being uploaded again, reduces model run times and allows quick corrections of individual parameters.

The [R]E24/7 model uses just over 18.000 program ID's thus each commodity and attribute in each cluster has a unique code to avoid possible data errors. The *Converter* function ensures that only data with the same ID will be transferred from input sheet to the database of [R]E 24/7.



**Figure 52:** Converter Function Tool of MESAP/PlaNet Assigned for Data Transfer

Finally Table 27 shows all input parameters of the model. While the number of processes vary in each cluster, each voltage level has the same set of processes.

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### 7.3 Summary of all Input Data

Overview all input parameter			
	Voltage Level	No of Clusters	
	TA	1	
	TZ	2	
	DA	8	
	DZ	32	
	Total	43	
No.	Term	Formula name (Programm ID)	Unit
<b>Commodities</b>			
<b>Supply</b>			
1	Sun	sun	[kJ/h]
2	East-West Sun	east_west_sun	[kJ/h]
3	Onshore Wind	Onshore_Wind	[kJ/h]
4	Offshore Wind	Offshore_Wind	[kJ/h]
5	Bio Energy	Bio_Energy	[kJ/h]
6	Hydro	hydro	[kWh/h]
7	Gas	gas	[kJ/h]
8	Coal	coal	[kJ/h]
9	Lignite	lignite	[kJ/h]
10	Nuclear	nuclear	[kJ/h]
<b>Distribution</b>			
11	Voltage Level (e.g 400kV)	400kV	[kWh/h] / [MWh/h] / [GWh/h]
12	Voltage Level (e.g 400kV) (DS)	400kV (DS)	[kWh/h] / [MWh/h] / [GWh/h]
13	Electricity POS	Electricity_OS	[kWh/h] / [MWh/h] / [GWh/h]
14	Electricity NEG	Electricity_NEG	[kWh/h] / [MWh/h] / [GWh/h]
15	New Grid	New_Grid	[kWh/h] / [MWh/h] / [GWh/h]
16	Sun Storage	Sun_Storage	[kWh/h] / [MWh/h] / [GWh/h]
17	Wind Storage	Wind_Storage	[kWh/h] / [MWh/h] / [GWh/h]
18	Storage Load Input	Storage_Load Input	[kWh/h] / [MWh/h] / [GWh/h]
19	Storage	storage	[kWh/h] / [MWh/h] / [GWh/h]
<b>Load</b>			
20	Population	population	[1]
21	Economic Activity	Economic_Activity	[1]
<b>Attributes</b>			
22	Actual Installed Capacity	CapAct	[kJ/h] / [kW/h]
23	Capital cost (annuity)	CostCp	[€/a]
24	Capital cost of new capacity	CostCpCapNew	[€/kJ] / [€/kWh]
25	Cost allocation factor	CAF	[1]
26	Cost of RES	CostRES	[€/h]
27	Cost recovery factor	CRF	[1]
28	Costs of flow	CostFlow	[€/h]
29	Depreciation Period	DepPeriod	[%/a]
30	Discount rate	DiscRate	[%/a]
31	Emission factor	Emi	[kg/kWh]
32	Fixed costs of process	CostFix	[€/h]
33	Fuel efficiency	FuelEff	[kWh/kJ]
34	Grid Limit	Grid_Limit	[kW/h]
35	Initial storage quantity	StorDef	[kWh]
36	Installed capacity	CapInst	[kW]
37	Intensity	Int	[kWh/head]
38	Load factor	LF	[h/h]
39	Market assignment	MktAssig	[1]
40	Market share	MktShare	[%]
41	Maximum flow	MaxFlow	[kJ/h] / [kWh/h]
42	Maximum Storage Charge + Disch	StorMaxRate	[kWh/h]
43	New installed capacity	CapNew	[kW]
44	Other variable costs of process	CostVar	[€/h]
45	Product assignment	ProdAssig	[1]
46	Product share	ProdShare	[1]
47	Quantity of flow	QtyFlw	[kJ/h] / [kWh/h]
48	Quatity of commodity	QtyCom	[kJ/h] / [kWh/h]
49	Ratio between flows	Ratio	[1]
50	Specific capital cost	SpecCostCp	[€/kJ] / [€/kWh]
51	Specific cost of commodity	SpecCostCom	[€/kJ] / [€/kWh]
52	Specific cost of flow	SpecCostFlow	[€/kJ] / [€/kWh]
53	Specific cost of new capacity	SpecCostCpCapNew	[€/kJ] / [€/kWh]
54	Specific cost of output flow	SpecCostOutFlow	[€/h]
55	Specific fixed costs	SpecFixCost	[€/kJ] / [€/kWh]
56	Specific other variable costs	SpecCostVar	[€/kJ] / [€/kWh]
57	Storage difference	StorDiff	[kWh/h]
58	Storage efficiency	StorEff	[1]
59	Technical lifetime	TecLife	[h]
60	Total commodity supply cost	CostCom	[€/h]
61	Total input commodity cost of prod	CostInComProc	[€/h]
62	Total process costs	CostPro	[€/h]
63	Transformer Efficiency	TransEff	[kWh/kWh]
64	Violation of Storage Capacity (Ove	StorViolation	[kWh/h]

Table 27: Summary of all Input Data

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## 8. Verification of [R]E 24/7 Model Results

### 8.1 Methodology for Verification of the [R]E 24/7 Model

In order to verify the function of the [R]E 24/7 model developed for this thesis, original input data from a grid node analysis carried out by Dr. Tom Brown, ENERGYNAUTICS (EN) published under the title *powE[R] 2030* in March 2014 (Teske et. al. 2014<sup>106</sup>) was used. The calculation results of both models are presented and analyzed in this chapter. The aim of this analysis is to verify the mathematical correctness of [R]E 24/7 outputs with EN model results. Furthermore possible variations of model results due to different applied methodologies will be documented and analyzed.

While the EN model represents a grid node model described in section 4.2.1 Grid Node Methodology, the [R]E 24/7 is a hybrid between a grid node model and a regional cluster model. In order to compare both models with each other, the data delivered from EN needs to be transferred into a regional cluster matrix. Therefore data input follows different methodologies in both models.

While the EN grid node model merges all voltage levels into one (GIS) position, the [R]E 24/7 model has four voltage levels and each voltage level has two or more clusters. Hence the model breaks down each EN grid node in 43 different clusters each with a different GIS position. The location and the voltage level for generation capacities and demand centers assumed for the [R]E 24/7 model are crucial for the residual load and supply within clusters which add up to one specific grid node in the EN model. It is of high importance if the grid node is set in the middle of the cluster or at a different location within the cluster. Therefore this step must be documented carefully as it influences calculation results of the grid analysis (see 8.1.1 Cluster versus Grid Nodes – Demarcation Problem).

Figure 53 and Figure 54 show how grid nodes are transferred to clusters. For the analysis and comparison of both models the grid nodes from EN *DK02* and *DE03* have been transferred to the northern and southern end of the transmission region cluster *TA* which represents the highest voltage level. Therefore Schleswig Holstein and Hamburg is region *TA1* according to the geographic concept described in 6.2.

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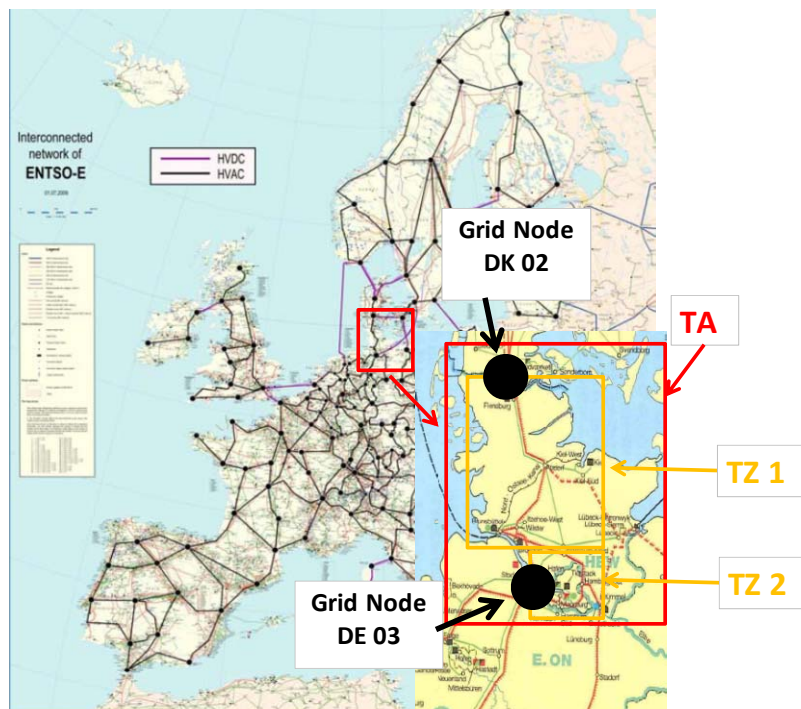


Figure 53: Data Transfer Methodology Grid Nodes to [R]E 24/7 Clusters – Transmission Level

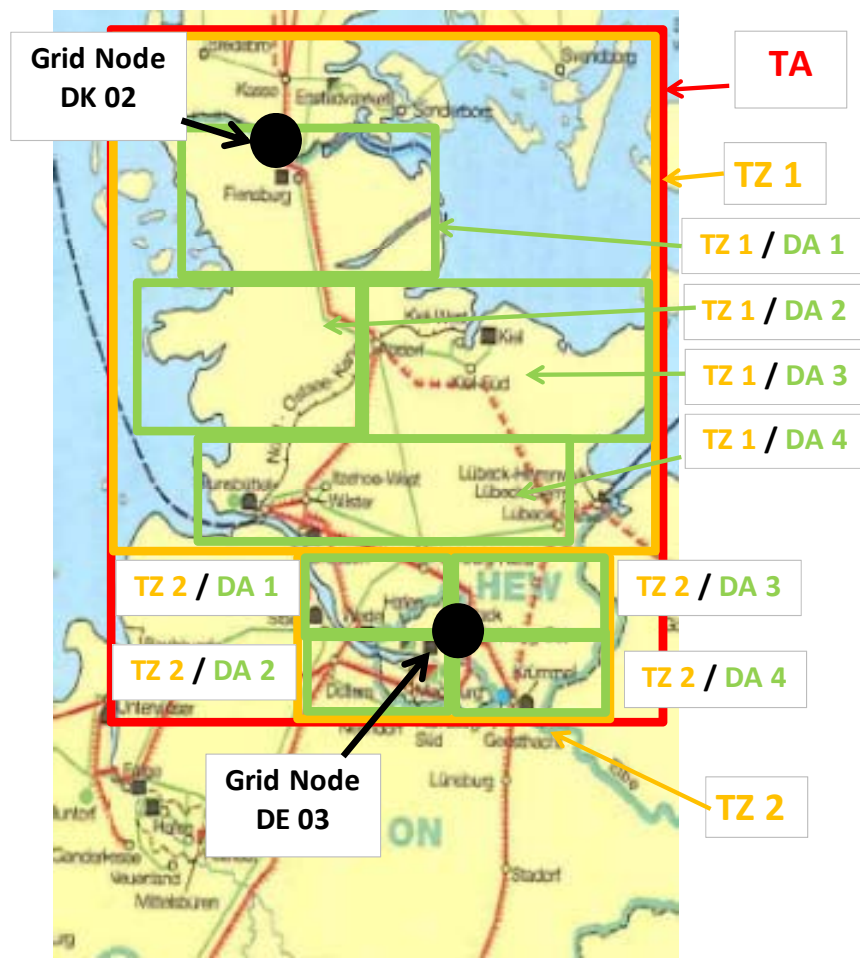


Figure 54: Data Transfer Methodology Grid Nodes to [R]E 24/7 Clusters – Distribution Level

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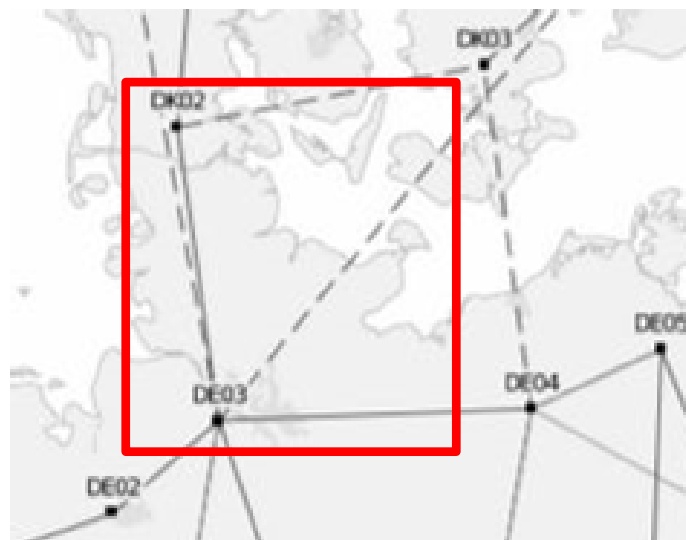
The generation capacity and the load for each grid node have been allocated to one transmission zone; *DK02* data has been transferred to *TZ1* and *TZ2* represents *DE03* data. This decision is justified by the described methodology for the regional cluster model [R]E 24/7 (see chapter 6) which uses the average transmission distances for each voltage level in relation to the demand within that region.

The *TA 1* region's voltage level is 380kV –with multiple lines – while the actual maximum grid capacity for the entire mashed system is in the range of 14.360 MW (8.1.1 Cluster versus Grid Nodes – Demarcation Problem) according to the EN input data. The *TA1* area stretches over 220 km from north to south and 200 km from west to east and therefore is smaller than the theoretical size of 400 km by 400 km (see 6.1).

For the same reason in *TZ1* and *TZ2* respectively the distribution area clusters *DA 1* to *DA 4* are smaller than the theoretical maximum as well. There are no load curves for communities publically available for the low voltage level of Schleswig Holstein and Hamburg, therefore the distribution zones *DZ 1* to *DZ 4* have been equally distributed within each distribution area; each *DA* area is divided into four equally sized *DZ* areas.

### 8.1.1 Cluster versus Grid Nodes – Demarcation Problem

The EN grid nodes model forms a mashed system – electricity not only flows from *DK02* to *DE 03* or vice versa, but also via interconnected grid nodes around them (Figure 55). For a cluster model a mashed, interconnected grid causes a demarcation problem. In this thesis the overall grid capacity of the entire cluster *TA 1* is defined as the total capacity of all lines connected to grid node *DK02* (= *TZ1*) and *DE03* (= *TZ2*). According to the data delivered from EN, the total grid capacities connected to *DK02* add up to 3.890 MW and *DE03* has a total capacity of 10.470 MW. This includes the additional transmission capacity (dashed lines in Figure 55) assumed in the grid node model, which calculates a high renewable energy deployment scenario for the year 2030.



**Figure 55:** Overview North Germany - Grid Nodes EN Model and Cluster Region [R]E 24/7

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Grid Node	Capacity [MW]
DE 02	3.500
DE 03	10.470
DE 04	7.421
DE 05	4.262
DK02	3.890

Cluster TA	[MW]
DE03 + DK02	14.360

Transmission between DK02 and DE03	[MW]
Range	2.200 - 1540

**Table 28:** Grid Capacities for Cluster TA1

(Source: Original EN Input Data – Assumptions for the Year 2030)

In order to transfer the assumed EN grid capacities shown in Table 28 into the [R]E 24/7 model, grid capacities for all lower voltage clusters are required.

**Table 29:** Input – Grid Limits

Table 29 shows the transfer methodology of the input sheet (see A1.4: Input Sheets – Smart Grid). For the transmission zone and the distribution area grid capacities, the number of actual power lines is an additionally required input. If this information is not available, the grid capacity for each voltage level will be estimated and cross checked with the demand per voltage level. For the distribution zones (DZ), the grid capacities are calculated as documented in 4.3.2 Methodology within Clusters.

Assumption:					
Name	Voltage Level in [kV]	Transport Capacity per Line in [MW]	Number of available lines	Total Transport Capacity per grid level	Check demand input
TA	380	380	10	3.800	0
TZ 1	220	220	7	1.540	615
TZ 2	110	110	20	2.200	2.016
TZ 1 / DA	20	20	40	800	615
TZ2 / DA	10	10	220	2.200	2.016
DZ	0,40	0,40		0	
	Simultaneity Function	0,765			
TZ1/DZ	Secured Capacity (with Simulatneity Factor 0,765)			3697,85	615
TZ1/DZ	Secured Capacity (with Simulatneity Factor 0,765)			2377,85	2.016
Total System				16.616	7892

**Table 29:** Input – Grid Limits



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## 8. 2 Documentation of Data Implementation

Data implementation is crucial for the verification process of the [R]E 24/7 model, therefore this section documents this process. Generation capacities, load curves (8760 data points per year) as well as estimated grid limits and solar photovoltaic, onshore and offshore wind generation data (8760 data points per year) are from EN. The original input data has been used for the grid analysis project *powE[R] 2030* (Brown et. al. 2014<sup>107</sup>). Data for all other technical parameters such as power generation efficiencies for all used technologies are taken from (DLR – Pregger 2013<sup>108</sup>).

### 8.2.1 Data Format from the ENERGYNAUTICS Model

This section provides an overview about the data which has been provided from *EN*. For each grid node there are time-series for the total demand in hourly steps, but there are no further break downs by voltage level or consumer groups available. Besides that, the maximum, minimum and average load data has been provided as well as the capacity factor (full-load hours).

The supply side has three different data groups:

- Non-controllable Renewables
- Controllable Renewables
- Controllable Conventional

For the “*Non-Controllable Renewables*”, time series for solar photovoltaic, onshore wind and offshore wind are provided as well as the maximum, minimum and average generation capacity as well as the total installed capacity and capacity factors (full-load hours) for all solar and wind power generation.

“*Controllable Renewables*” are defined as bio energy and hydro power plants, while “*Controllable Conventional*” is defined as gas, coal, lignite and nuclear power plants. For both groups, the installed capacity has been provided as well as capacity factors.

Time-series for each power generation technology are available, but those are the results of the model. The assumed dispatch order has a direct influence on resulting capacity factors. For example in case of prior dispatching for “non-controllable Renewables” which is assumed in the EN model, solar and wind generators will operate ahead of conventional power plants and might therefore reduce their capacity factors. Table 30 provides an overview about the basic input parameters from EN.

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	Data Input		Calculated Data				
	Profile [MW/h]	Installed capacity [MW]	Generation Profile [MW/h]	Maximum Load [MW]	Minimum Load [MW]	Average Load [MW]	Capacity Factor [h/a]
Load	X			X	X	X	X
Solar PV	X	X		X	X	X	X
Onshore Wind	X	X		X	X	X	X
Offshore Wind	X	X		X	X	X	X
Bio Plant		X	X	X	X	X	X
Hydro Power Plant		X		X	X	X	X
Gas Power Plant		X	X	X	X	X	X
Coal Power Plant		X	X	X	X	X	X
Lignite Power Plant		X	X	X	X	X	X
Nuclear Power Plant		X	X	X	X	X	X
Hydro Pump Storage		X	X	X	X	X	X
Grid Limit		X		X	X	X	X

**Table 30:** Basic input Parameter from ENERGYNAUTICS

### 8.2.2 Data Preparation for [R]E 24/7 Model Input

The main task of the data preparation for the [R]E 24/7 model input is, to distribute the load and supply data from one grid node to all clusters of four voltage levels. Table 31 shows the methodology how the load data provided by EN has been distributed to different clusters.

The demand on the high voltage level (400kV) has been set to “0” in order to distribute the entire demand of *TA1* to *TZ1* and *TZ2*. The load assumptions for the distribution zones in Schleswig Holstein are based on the low voltage cluster methodology (see Table 14 ). For all Hamburg’s *DZ* clusters the load is estimated to be higher due to a significantly higher share of businesses which are connected to the low voltage level as well. The remaining load data from EN has been distributed to the voltage levels *TZ* and *TA* based on statistical data from Schleswig-Holstein and Hamburg (Statistics 2013<sup>109</sup>). However it is important to note, that this load distribution is for model verification purposes only and does not reflect the actual load flows.

Thus the industry demand for Schleswig Holstein is estimated to represent 15% of the total load; this would be assigned to the transmission zone (*TZ*), medium size businesses and production facilities that are connected to the distribution area (*DA*) with a demand of e.g. 10% of the total load.

	Max Load DK02 [MW/h]	Share from total Demand	Population / Economic Activity => head/h	DA Shares (SUB DIVISION OF total DA)	Share DA 01	Share DA 02	Share DA 03	Share DA 04
Industry 400kV for TZ 1	0	0%	1	Business	25,0%	25,0%	25,0%	25,0%
Industry TZ 1	277	15%	1					
Business DA (total)	184	10%	1					
Demand DZ (total)	1.383	75%	2.800.000	Max Load In [MW]	46,1	46,1	46,1	46,1
Total Demand				DA	DA 1 / DZ 1	DA 2 / DZ 1	DA 3 / DZ 1	DA 4 / DZ 1
EN-Input	1.844			DA Population Share	6,25%	6,25%	6,25%	6,25%
Total Check	1.844	100%	2.800.000	Max Load In [MW]	86,4	86,4	86,4	86,4
	For Grid-Input			DA Population	175.000	175.000	175.000	175.000
					DA 1 / DZ 2	DA 2 / DZ 2	DA 3 / DZ 2	DA 4 / DZ 2
				DA Population Share	6,25%	6,25%	6,25%	6,25%
				Max Load In [MW]	86,4	86,4	86,4	86,4
				DA Population	175.000	175.000	175.000	175.000
					DA 1 / DZ 3	DA 2 / DZ 3	DA 3 / DZ 3	DA 4 / DZ 3
				DA Population Share	6,25%	6,25%	6,25%	6,25%
				Max Load In [MW]	86,4	86,4	86,4	86,4
				DA Population	175000	175000	175000	175000
					DA1/DZ 4	DA2/DZ 4	DA3/DZ 4	DA4/DZ 4
				DA Population Share	6,25%	6,25%	6,25%	6,25%
				Max Load In [MW]	86,4	86,4	86,4	86,4
				DA Population	175000	175000	175000	175000

DK 02 = TZ 1  
Schleswig Holstein

Table 31: Input Parameter Preparation for the Distributed Demand Case for Schleswig Holstein

In order to represent different demand patterns for each grid level and to distribute load curves in relation to the actual situation, the load curve delivered from EN has been divided in three parts:

1. TZ: load curves - percentage of the assumed load of this voltage level
2. DA: load curves - percentage of the assumed load of this voltage level
3. DZ: load curves - per capita multiplied by regional population

Based on the load curve from EN and the population in region TZ1 (Schleswig-Holstein: 2.8 million) and TZ 2 (Hamburg: 1.8 million) (Statistics 2013<sup>10</sup>) per capita load curves have been calculated.

	Max Load DE03 [MW/h]	Share from total Demand	Multiplier per Grid level => head/h	DA Shares	Share DA 01	Share DA 02	Share DA 03	Share DA 04
Industry 400kV for TZ 2	0,00	0%	1	Business	25,0%	25,0%	25,0%	25,0%
Industry TZ 2	1209,56	20%	1	DA MW				
Business DA (total)	907,17	15%	1	Business				
Demand DZ (total)	3931,07	65%	1.800.000	Max Load In [MW]	226,8	226,8	226,8	226,8
Total Demand				DA	DA 1 / DZ 1	DA 2 / DZ 1	DA 3 / DZ 1	DA 4 / DZ 1
EN-Input	6.048			DA Population Share	6,25%	6,25%	6,25%	6,25%
Total Check	6.048	100%	1.800.000	Max Load In [MW]	245,7	245,7	245,7	245,7
	For Grid-Input			DA Population	112.500	112.500	112.500	112.500
					DA 1 / DZ 2	DA 2 / DZ 2	DA 3 / DZ 2	DA 4 / DZ 2
				DA Population Share	6,25%	6,25%	6,25%	6,25%
				Max Load In [MW]	245,7	245,7	245,7	245,7
				DA Population	112.500	112.500	112.500	112.500
					DA 1 / DZ 3	DA 2 / DZ 3	DA 3 / DZ 3	DA 4 / DZ 3
				DA Population Share	6,25%	6,25%	6,25%	6,25%
				Max Load In [MW]	245,7	245,7	245,7	245,7
				DA Population	112.500	112.500	112.500	112.500
					DA1/DZ 4	DA2/DZ 4	DA3/DZ 4	DA4/DZ 4
				DA Population Share	6,25%	6,25%	6,25%	6,25%
				Max Load In [MW]	245,7	245,7	245,7	245,7
				DA Population	112.500	112.500	112.500	112.500

DE 03 = TZ 2  
Hamburg

Table 32: Input Parameter Preparation for the Distributed Demand Case for Hamburg

For the data preparation of the supply side, the generation capacities have been distributed across voltage levels in two scenarios. The *centralized-generation* scenario concentrates all power generation capacities on the transmission zone level (TZ), which

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aims to reflect the grid node methodology. The *distributed-generation* scenario distributes the generation equally across all levels (*TZ*, *DA*, *DZ*).

Table 33 shows the distributed generation scenario for Schleswig Holstein and Hamburg. The assumption for power generation capacities are based on the EN data for *powE[R] 2030* (Brown et. al. 2014<sup>111</sup>) and represents a high RE scenario – with no coal and nuclear capacities remaining in the grid by 2030.

DK02 = TZ 1			TA1	Share DK02 - per Grid Level	[MW]	DA Shares	TZ 1 / DA 01	TZ 1 / DA 02	TZ 1 / DA 03	TZ 1 / DA 04
<div>[MW]</div> <div>Nuclear0</div> <div>Coal0</div> <div>LigniteND</div> <div>Hydro0</div> <div>Offshore Wi2.005</div> <div>Gas1.044</div> <div>Biomass376</div> <div>Onshore Wi1.926</div> <div>PV768</div>	<div>[MW]</div> <div>0</div> <div>0</div> <div>0,00</div> <div>0</div> <div>2.005</div> <div>1.044</div> <div>376</div> <div>1.926</div> <div>768</div>	Nuclear	0%	0	Hydro	0,0%	0,0%	0,0%	0,0%	
		Coal	0%	0	Hydro [MW]	0	0	0	0	
		Lignite	ND	0,00	Biomass	17,0%	17,0%	16,5%	16,5%	
		Hydro	0%	0	Biomass [MW]	64	64	62	62	
		Biomass	0%	0	Gas	17,0%	17,0%	16,5%	16,5%	
		Gas	0%	0	Gas [MW]	177	177	172	172	
		Onshore Wind	0%	0	PV Optimal	8,0%	8,0%	8,0%	8,0%	
		Offshore Wind	100%	2.005	PV Optimal [MW]	61	61	61	61	
		Solar PV Plant	0%	0	PV East-West	0,0%	0,0%	0,0%	0,0%	
		CSP-Storage	ND	0	PV East-West [MW]	0	0	0	0	
	TZ 1	Share DK02 - per Grid Level	TZ 1 [MW]	Onshore Wind	17,0%	17,0%	16,5%	16,5%		
	Hydro	0%	0	Onshore Wind [MW]	327	327	318	318		
	Gas	33%	344	Onshore Wind Storage	0,0%	0,0%	0,0%	0,0%		
	Biomass	33%	124	Onshore Wind [MW]	0	0	0	0		
	Solar	33%	254	DZ	DA 1 / DZ 1	DA 2 / DZ 1	DA 3 / DZ 1	DA 4 / DZ 1		
	Solar-Storage	0%	0	PV Share	3,0%	3,0%	3,0%	2,0%		
	Onshore Wind	33%	636	PV MW	23	23	23	15		
					DA 1 / DZ 2	DA 2 / DZ 2	DA 3 / DZ 2	DA 4 / DZ 2		
				PV Share	2,0%	2,0%	2,0%	2,0%		
				PV MW	15	15	15	15		
					DA 1 / DZ 3	DA 2 / DZ 3	DA 3 / DZ 3	DA 4 / DZ 3		
				PV Share	2,0%	2,0%	2,0%	2,0%		
				PV MW	15	15	15	15		
					DA 1 / DZ 4	DA 2 / DZ 4	DA 3 / DZ 4	DA 4 / DZ 4		
				PV Share	2,0%	2,0%	2,0%	2,0%		
				PV MW	15	15	15	15		

Table 33: Input parameter *Distributed-Generation* scenario for Schleswig-Holstein

DE03 = TZ 2			TA1		Share DE03 - per Grid Level		[MW]	DA Shares	TZ 2 / DA 01	TZ 2 / DA 02	TZ 2 / DA 03	TZ 2 / DA 04
			Nuclear	0%	0	Hydro	0,0%	0,0%	0,0%	0,0%		
			Coal	0%	0	Hydro [MW]	0	0	0	0		
			Lignite	ND	0,00	Biomass	17,0%	17,0%	16,5%	16,5%		
			Hydro	0%	0	Biomass [MW]	68	68	66	66		
			Biomass	0%	0	Gas	17,0%	17,0%	16,5%	16,5%		
			Gas	0%	0	Gas [MW]	79	79	77	77		
			Onshore Wind	0%	0	PV Optimal	8,0%	8,0%	8,0%	8,0%		
			Offshore Wind	0%	0	PV Optimal [MW]	62	62	62	62		
			Solar PV Plant	0%	0	PV East-West	0,0%	0,0%	0,0%	0,0%		
CSP-Storage	ND	0	PV East-West [MW]	0	0	0	0					
[MW]		[MW]	TZ 2		Share DE03 - per Grid Level		TZ 2 [MW]	Onshore Wind	17,0%	17,0%	16,5%	16,5%
Nuclear	0	0	Hydro	100%	0	Onshore Wind [MW]	681	681	661	661		
Coal	132	467	Gas (+Coall!)	33%	154	Onshore Wind Storage	0,0%	0,0%	0,0%	0,0%		
Lignite	ND	0,00	Biomass	33%	132	Onshore Wind [MW]	0	0	0	0		
Hydro	0	0	Solar	33%	257	DZ	DA 1 / DZ 1	DA 2 / DZ 1	DA 3 / DZ 1	DA 4 / DZ 1		
Offshore Wi	0	467	Solar-Storage	0%	0		PV Share	3,0%	3,0%	3,0%	2,0%	
Gas	467	467	Onshore Wind	33%	1.322	PV MW	23	23	23	16		
Biomass	401	401					DA 1 / DZ 2	DA 2 / DZ 2	DA 3 / DZ 2	DA 4 / DZ 2		
Onshore Wi	4.006	4.006					2,0%	2,0%	2,0%	2,0%		
PV	780	780					16	16	16	16		
							DA 1 / DZ 3	DA 2 / DZ 3	DA 3 / DZ 3	DA 4 / DZ 3		
							2,0%	2,0%	2,0%	2,0%		
							16	16	16	16		
							DA1 /DZ 4	DA2 /DZ 4	DA3 /DZ 4	DA4 /DZ 4		
							2,0%	2,0%	2,0%	2,0%		
							16	16	16	16		

Table 34: Input Parameter *Distributed-Generation* Scenario for Hamburg

The annual generation data for solar photovoltaic, onshore and offshore wind in MW per hour from EN has been transferred to specific generation curves per installed MW to allow the distribution of generation capacity across all voltage levels.

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### 8.3 Assumptions for Grid Limits

Finally the grid limits need to be identified in order to analyze possible bottle necks in the system and to compare the results from EN and the [R]E 24/7 model. The grid node model from EN is based on the simulation software *DlgSILENT PowerFactory* (

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3.5.2 DIgSILENT “PowerFactory”). This software is able to simulate a variety of electrical parameters of power grids, such as inductive power, reactive power and frequency stability, while the [R]E 24/7 model can only detect if the power grid capacities have been exceeded. Therefore the EN model requires more electrical parameters than the model developed for this thesis. However there is only one total grid limit for each node in the grid node model, while [R]E 24/7 needs to identify grid limits for each cluster.

#### **8.3.1 Input Data for Grid Limits in the [R]E 24/7 Model**

The [R]E 24/7 model simplifies the grid limits by using maximum transport capacities in MW regardless of the outdoor temperature, transmission distances and the operating state of the specific power lines, because this would exceed the scope of this model. However transport capacities for each voltage level are based on state of the art transmission technologies. For the distribution level, the grid limit assumptions are based on the analysis methodology of (DENA 2012, chapter 5.2 page 114ff) described in (3.7 Technical Analysis Methodology for Distribution Grids) Grid limitation estimations for the transmission level are based on technical cable data compiled by (Ackermann, Tröster, Braun 2013<sup>112</sup>) .

Table 35 compared three standard transmission technologies and the technical capabilities of each system. For each cluster the voltage level in *Volt* and the average transport capacity in *MW* must be identified. Besides that the overall number of lines per cluster will provide an overview of the total transport capacity which is compared to the maximum load. However for the verification of the [R]E 24/7 model, the grid node capacities provided by EN are used in the calculations documented in this chapter in order to compare results of both models (see Table 28 and Figure 64).

	HVAC	LCC HVDC	VSC HVDC
Maximum available capacity per system	Cable system: <ul style="list-style-type: none"> <li>• 200 MW at 150 kV;</li> <li>• 350 MW at 245 kV;</li> </ul> Overhead lines: <ul style="list-style-type: none"> <li>• 2000 MW at 800 kV</li> <li>• 4000 MW at 1000 kV (under development)</li> </ul>	Cable system: <ul style="list-style-type: none"> <li>• ~ 1200 MW</li> </ul> Overhead lines: <ul style="list-style-type: none"> <li>• 3150 MW at <math>\pm 600</math> kV</li> <li>• 6400 MW at <math>\pm 800</math> kV (under development)</li> </ul>	Cable/Overhead: <ul style="list-style-type: none"> <li>• 400 MW</li> <li>• 500 - 800 MW announced</li> </ul>
Voltage level	Cable system: <ul style="list-style-type: none"> <li>• Up to 245 kV realistic, short cables up to 400 kV possible</li> </ul> Overhead lines: <ul style="list-style-type: none"> <li>• Up to 800 kV</li> <li>• 1000 kV under Development</li> </ul>	Cable system: <ul style="list-style-type: none"> <li>• Up to <math>\pm 500</math> kV</li> </ul> Overhead lines: <ul style="list-style-type: none"> <li>• Up to <math>\pm 600</math> kV</li> <li>• <math>\pm 800</math> kV under development</li> </ul>	Cable: <ul style="list-style-type: none"> <li>• Up to <math>\pm 150</math> kV, higher voltages announced</li> </ul> Overhead lines: <ul style="list-style-type: none"> <li>• Up to <math>\pm 350</math> kV</li> </ul>
Transmission capacity distance depending?	Yes	<ul style="list-style-type: none"> <li>• No</li> </ul>	<ul style="list-style-type: none"> <li>• No</li> </ul>
Total system losses	<ul style="list-style-type: none"> <li>• Distance depending</li> </ul>	<ul style="list-style-type: none"> <li>• 2 - 3 % (plus requirements for ancillary services offshore)</li> </ul>	<ul style="list-style-type: none"> <li>• 5 – 10 %</li> </ul>
Black start capability	<ul style="list-style-type: none"> <li>• (Yes)</li> </ul>	<ul style="list-style-type: none"> <li>• No</li> </ul>	<ul style="list-style-type: none"> <li>• Yes</li> </ul>
Technical capability for network support	Limited	<ul style="list-style-type: none"> <li>• Limited</li> </ul>	<ul style="list-style-type: none"> <li>• Large range of possibilities.</li> </ul>
Space requirements for substation.	Small	<ul style="list-style-type: none"> <li>• Depending on capacity. Converter larger than VSC.</li> </ul>	<ul style="list-style-type: none"> <li>• Depending on capacity. Converter smaller than LCC but larger than HVAC substation.</li> </ul>

**Table 35:** Overview of the Three Main Transmission Solutions (Ackermann, Tröster, Braun 2013)

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## 8.4 Mathematical Comparison of Calculated Results

In order to mathematically verify the [R]E 24/7 model, original input data from ENERGINAUTICS has been used and outputs of both models have been compared with each other. The following parameters have been analyzed:

- Demand in MWh for each voltage level
- Supply in MWh for each generation technology and voltage level
- Overall generation in MWh
- Overall supply shares by technology in per cent

The comparison has been done with input data for two different ENERGINAUTIC scenarios: before and after curtailment of wind and solar capacities. The scenario *After Curtailment* model was compared with the [R]E 24/7 calculation results achieved with different dispatch order settings:

- *Top-down*: priority for Offshore wind (TA) over dispatch capacity (TZ)
- *Bottom-up*: priority of (TZ) generation capacity over (TA) offshore wind
- *Distributed generation*: Supply and demand distributed across all voltage levels

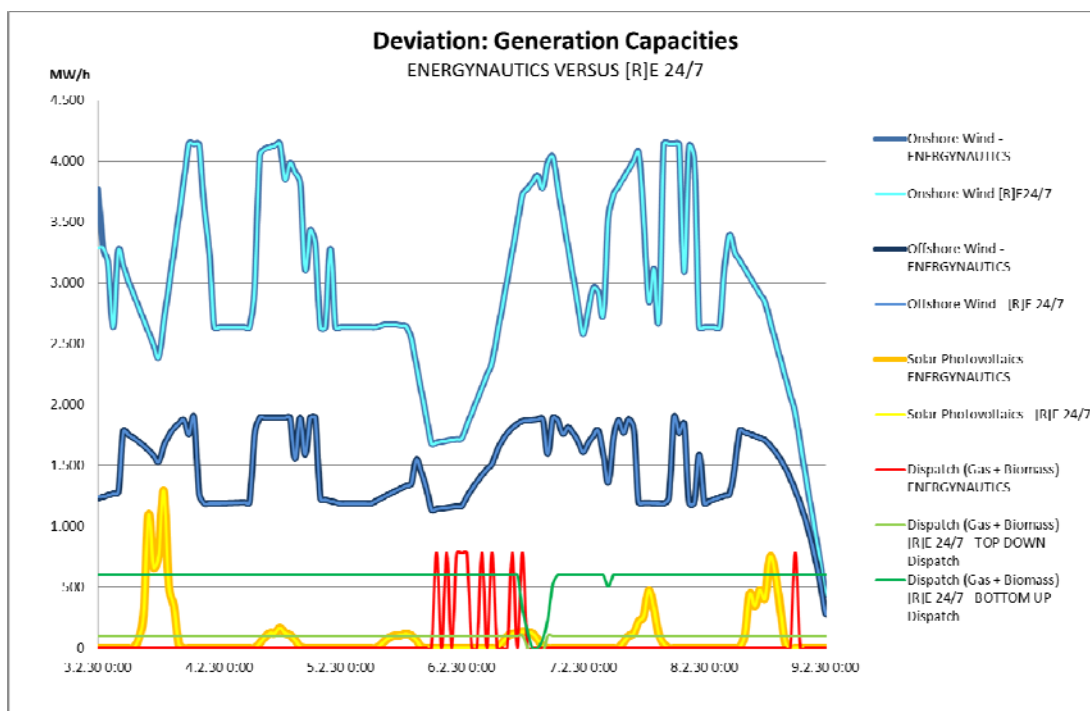


Figure 56: Deviation: Generation Capacities EN versus [R]E 24/7 (TZ1)



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Figure 56 shows the deviation of generation capacities for different technologies. While the onshore / offshore wind and solar photovoltaic supply curves are within  $\pm 0.5\%$  of the ENERGYNAUTICS results, dispatch capacities vary significantly more.

This variation is due to the different model architectures. The offshore wind capacity is connected to the highest voltage level (TA), while all other supply capacities as well as the entire demand are located at the transmission zone (TZ), because the [R]E 24/7 model has no offshore wind process within TZ clusters. Thus, supply and demand balance takes place BEFORE offshore wind capacity will be added in case of supply deficit. A changed dispatch order from bottom-up to top-down - when high voltage level offshore wind gets priority over lower voltage level bio energy and gas generation – less dispatch capacity will be calculated. Moreover [R]E 24/7 and ENERGYNAUTICS model results still differ as the supply and demand ratio of each cluster has an influence of the dispatch power requirement as well.

If the supply within cluster TZ1 is lower than the demand, additional generation capacity either from TA or TZ2 will be used. When there is not enough offshore wind capacity available, dispatch capacity from other clusters will be used. The ENERGYNAUTICS data is taken from a wider meshed grid node system which is connected to more grid nodes, while the [R]E 24/7 has no further connections besides TZ1 and TZ2 (see 8.1.1 Cluster versus Grid Nodes – Demarcation Problem). Thus the ENERGYNAUTICS model might use offshore wind capacity from other grid nodes – which always has priority over dispatch capacities under their model assumption.

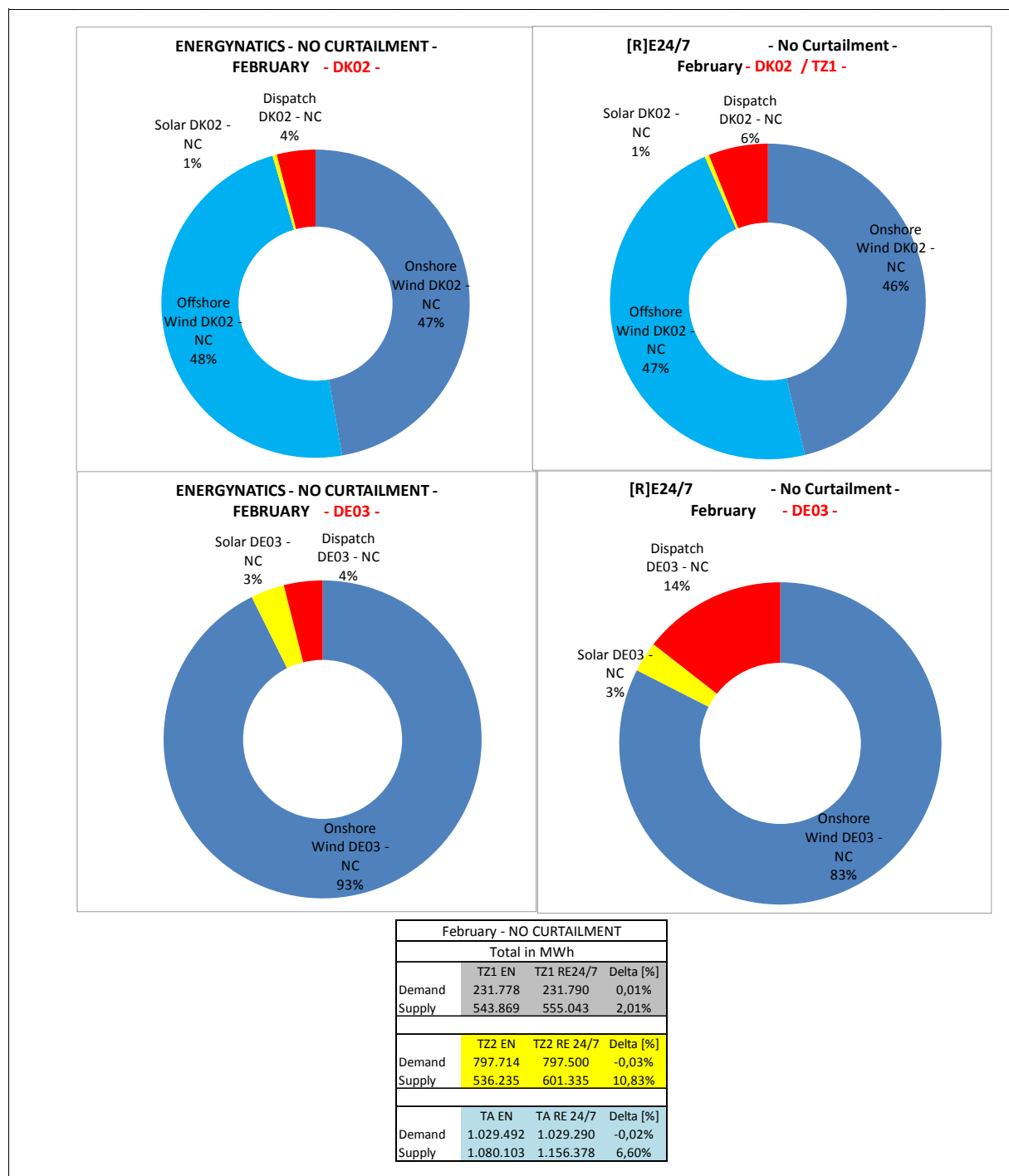
Although the hourly dispatch capacity results of the ENERGYNAUTICS and the [R]E 24/7 model never matched in all analysed time series (see 8.5 Comparison of Model Results at Time with Extreme Wind and Solar Conditions) the overall supply shares of dispatch capacity in percent remained within a range of  $\pm 5\%$  in case of top-down dispatch (Figure 60), and  $\pm 10\%$  in the case of bottom-up dispatch and centralized generation (all generation capacities within the TZ level except offshore wind (TA) (Figure 61).

Significant differences of up to 20% of required dispatch capacity appear when demand and supply capacities are distributed across different voltage levels as documented in Figure 62 and section 8.5 Comparison of Model Results at Time with Extreme Wind and Solar Conditions.

Figure 57, Figure 60, Figure 61 and Figure 62 show simulation results of the [R]E 24/7 model compared to ENERGYNAUTICS results. Each figure compares the overall supply share by technology, total supply and demand values in MW/h and the deviation in percent for TZ1, TZ2 and combined (TA).

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**Figure 57:** Supply Share by Grid Node – ENERGYNAUTICS versus [R]E 24/7 – Before Curtailment  
Bottom-Up Dispatch – Supply and Demand on TZ Level Only – Except Offshore Wind (TA)

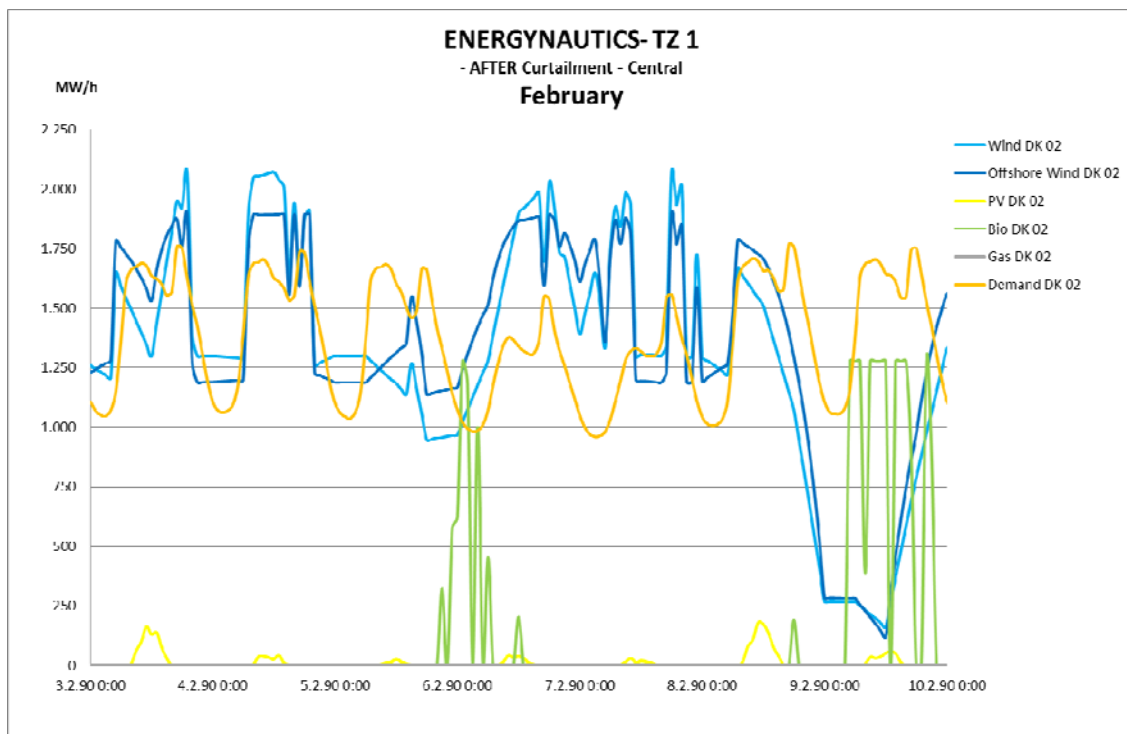


Figure 58: Original Data from ENERGYNAUTICS – After Curtailment - February

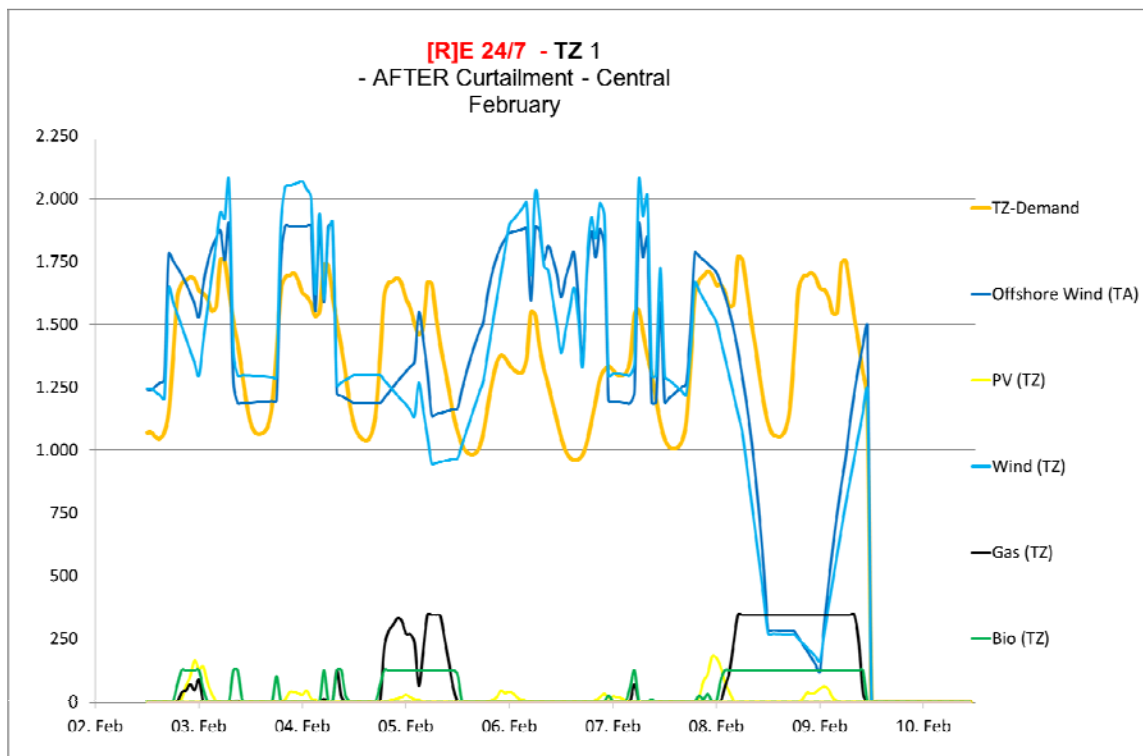
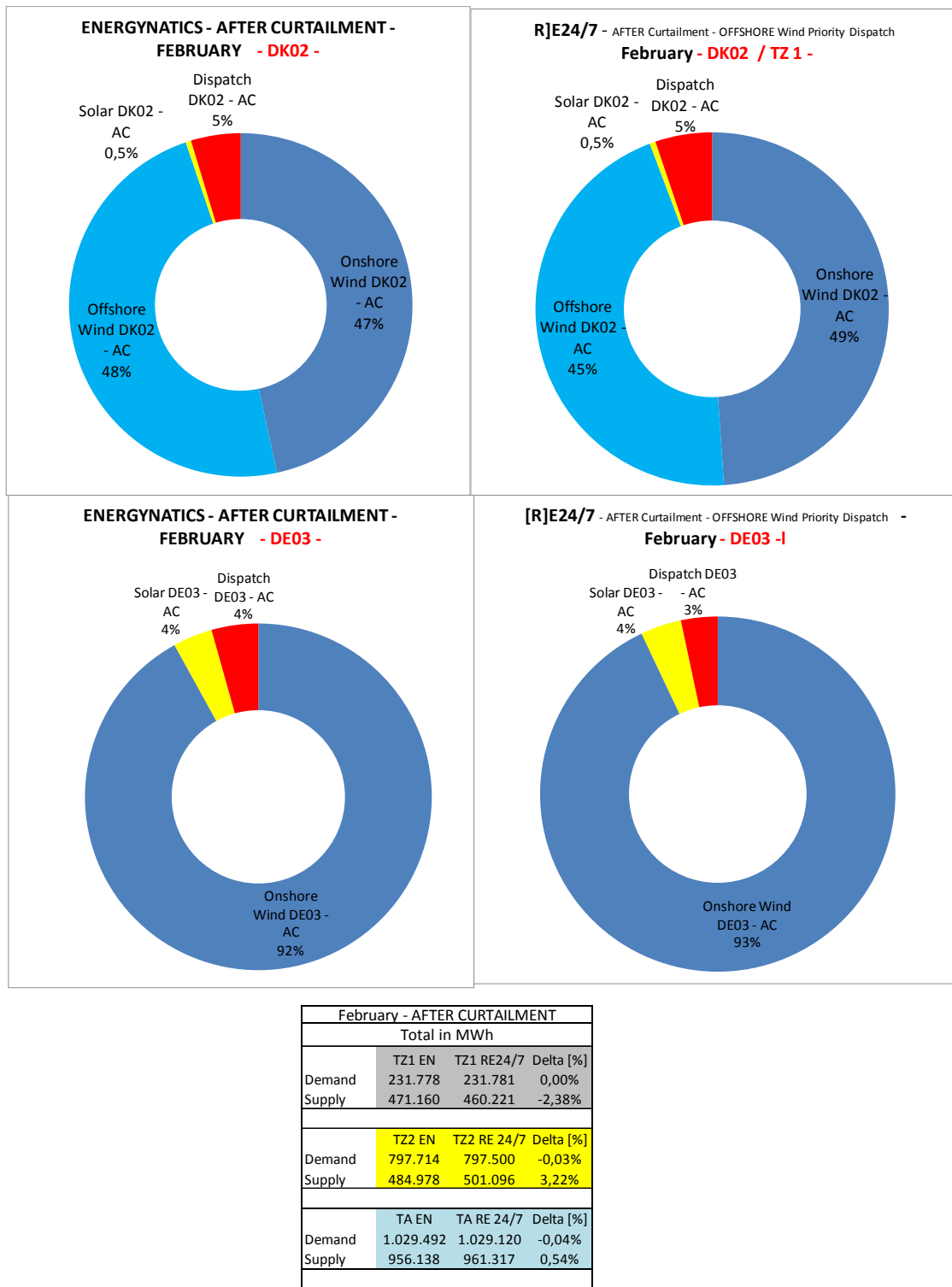


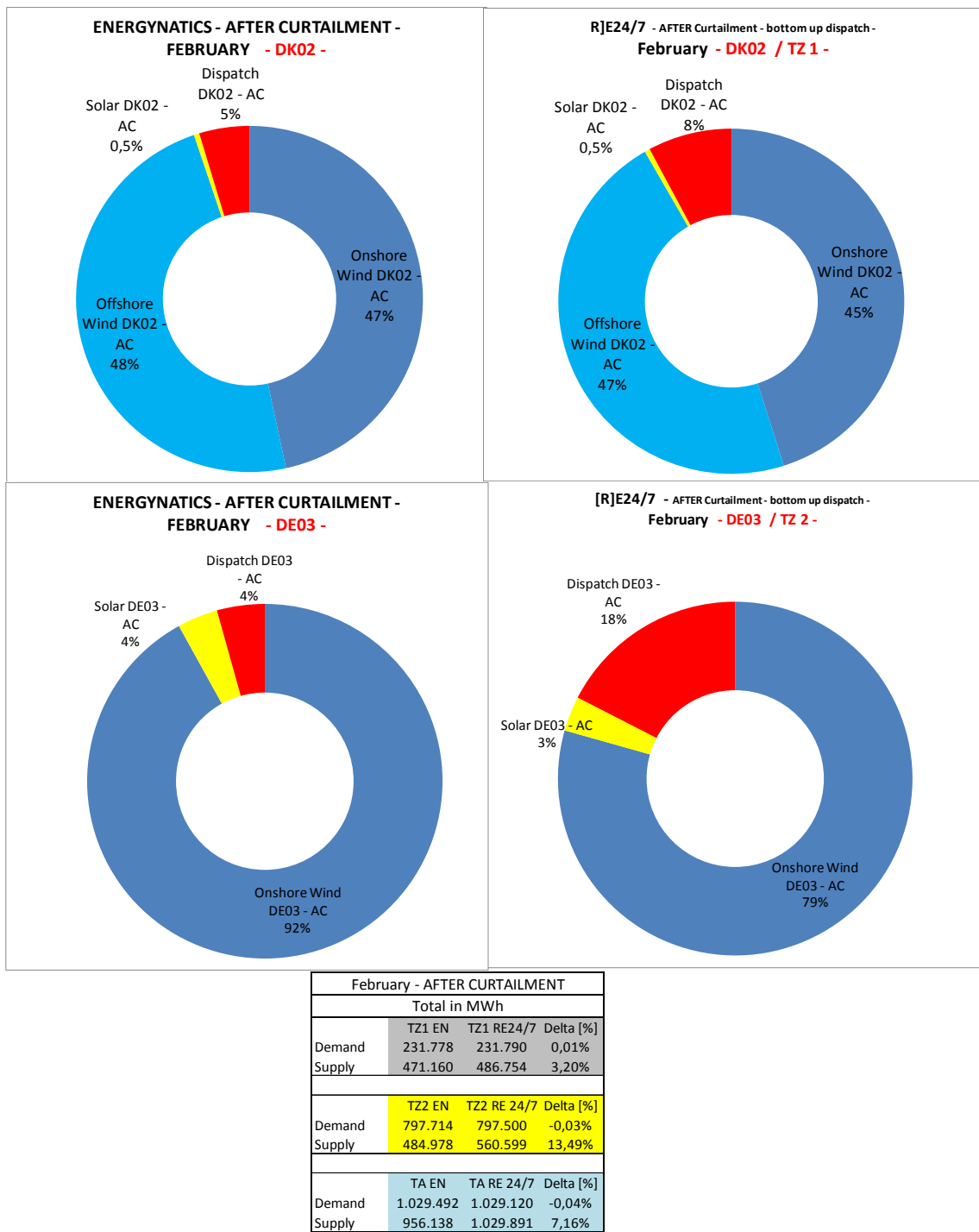
Figure 59: Recalculated with EN Data for February - [R]E 24/7 Result

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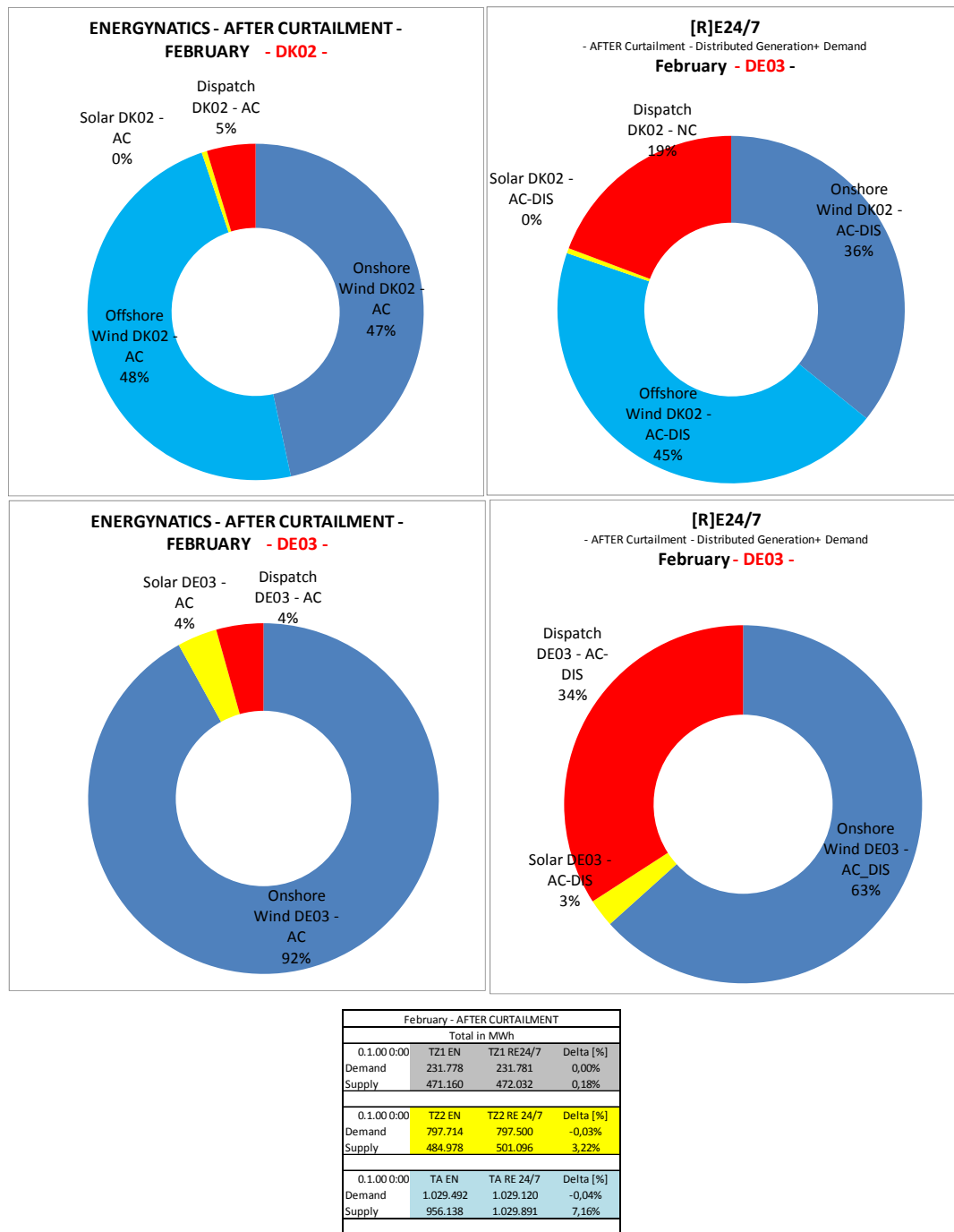
**Figure 60:** Supply Share by Grid Node – ENERGYNAUTICS versus [R]E 24/7 – After Curtailment – Top-Down Dispatch – Supply and Demand on TZ Level Only – Except Offshore Wind (TA)



**Figure 61:** Supply Share by Grid Node – ENERGYNAUTICS versus [R]E 24/7 – After Curtailment – Bottom-Up dispatch – Supply and Demand on TZ Level Only – Except Offshore Wind (TA)

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**Figure 62:** Supply Share by Grid Node – ENERGYNATICS versus [R]E 24/7 – After Curtailment – Bottom-Up Dispatch – Supply and Demand Distributed Across all Voltage Levels.

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## 8.5 Comparison of Model Results at Time with Extreme Wind and Solar Conditions

While the verification process of the last section 8.4 focused on the mathematical comparison of the EN and [R]E 24/7 model by taking measures to get close to EN results and to calibrate the model developed for this thesis. This section compares scenario results of both models under specific extreme wind and solar conditions. The bottom-up dispatch order of the [R]E 24/7 model remained in all cases to evaluate deviations of grid node and cluster methodologies. In order to limit the amount of presented data and to focus on the main differences, four time series with the highest curtailment rates and changes in the load flow for the transmission line between TZ1 (DK02) and TZ2 (DE03) have been selected:

Time series	Event	Exact time of the event
3.Feb. - 10. Feb.	High Wind Generation	5.Feb. 4am - 5 am; 7.Feb. 2pm
7.May - 8.May	High Solar Generation	7. May and 8.May around noon
25. Nov. - 30.Nov.	High Wind Generation	26. and 27. November (at night)
1.Dec. - 31. Dec.	High Wind Generation	3, 9, 13, 28, 2 December several times a day

**Table 36:** Selected Time Series at Special Events

The wind data is based on *Reanalysis* wind data (Van Hulle 2009<sup>113</sup>) and represents the average wind speed of the analyzed EN grid nodes DK02 and DE03 between January 2000 and December 2006. Due to high wind penetration – especially offshore wind for grid node TZ 1 - during February, November and December, these time series have been broken down to two weeks each. As opposed to the wind data, all solar data is not based on grid node specific historical figures, but represents average historical data (between 2006 and 2010) across Germany and has been taken from the SMOOTH PV grid analysis (Ackermann et. al. 2013<sup>114</sup>). Section 8.5.3 to 8.5.6 compares the data of the EN model with two different distribution scenarios of the [R]E 24/7 model.

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## 8.5.1 Model Assumptions

In order to compare scenario results, this section provides an overview about the key assumptions of the EN grid node model and the [R]E 24/7 cluster model. Besides the scenario based assumptions, there are different model specific methodologies which potentially lead to different results. Table 37 provides an overview about the key scenario assumptions and model specific differences.

Technology type	Technologies	Scenario Assumption		Model specific methodology	
		Dispatch order	Operation mode	ENERGYNAUTICS	[R]E 24/7
Variable	Solar Photovoltaic, Onshore Wind, Offshore Wind	0	Fixed availability profiles, can be curtailed	Model Input: Maximum Curtailment rate [%/a] per grid node	Curtailment for each cluster only via different model runs
Renewable controllables	Biomass, Hydro, Gas	1	Full flexibility	Dispatch order for each grid node depending on individual costs per technology	Dispatch order for each cluster and voltage level, depending on model settings (see 5.8)
Conventional controllable	Coal, Lignite, Nuclear	2	Limited shutdown and ramping	Model Input: Minimum capacity factor	Dispatch order for each cluster and voltage level, depending on model settings (see 5.8)
Storage	Pumped hydro	3	Stores, dispatches, efficiency losses	Exoginus input during optimization process	Exoginus input during optimization process

**Table 37:** Scenario and Model Specific Assumptions

## 8.5.2 Curtailment and Optimization in DigSilent PowerFactory

The DigSILENT PowerFactory software is an optimization tool as opposed to the [R]E 24/7 scenario software which does not have this possibility. The EN model identifies the transmission grid capacity (= capacity of the grid node) as the limiting factor and uses two parameters for the optimization process; the level of curtailment of wind and solar generation and capacity factors for dispatch power plants.

In order to understand and compare EN simulation results and those from [R]E 24/7 two sets of solar and wind input data are used for calculations:

- Without any curtailment
- After curtailment

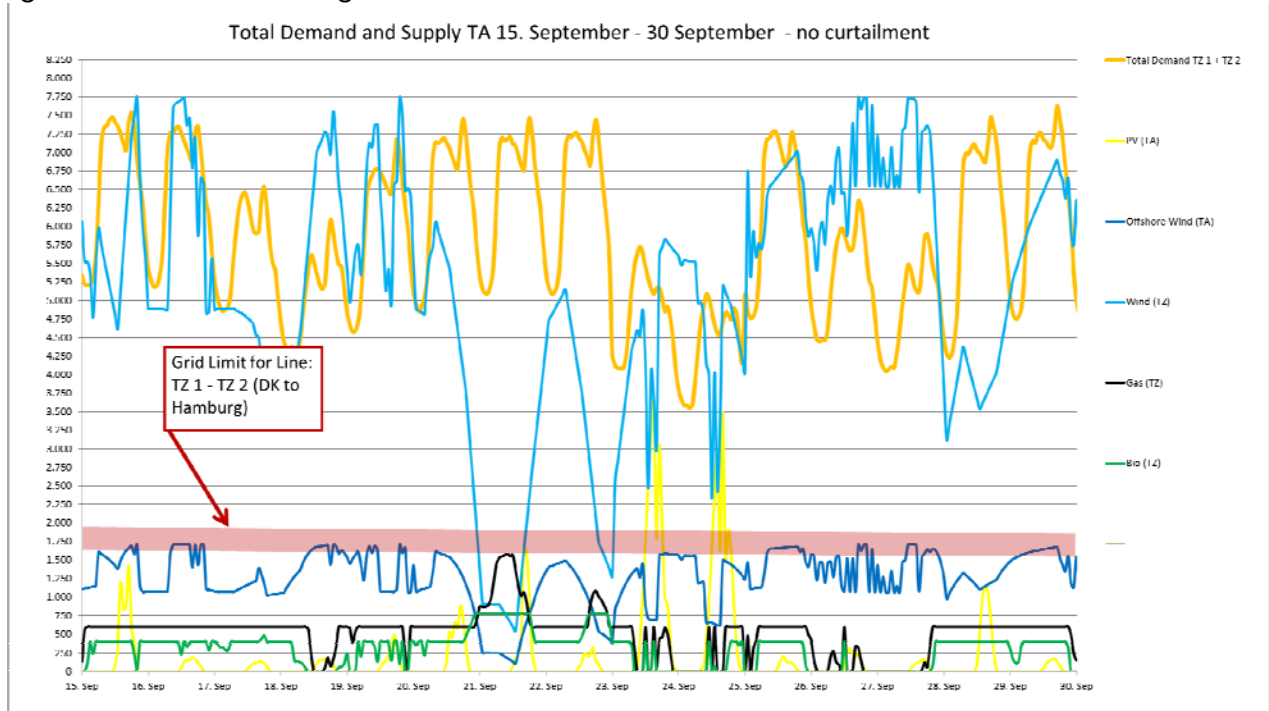
The deviations of both simulations with the [R]E 24/7 are discussed and results are presented in Table 39.

Whether or not curtailment would be needed will be indicated by the grid limits function of the [R]E 24/7 tool – for more details see Figure 31, chapter 5.



### 8.5.3 Model Results With and Without Curtailment

In the first step of the verification process original EN data from grid node *DK02* (= *TZ1*) and *DE03* (= *TZ2*) has been added up to the overall demand and all supply curves (across all technologies) of region TA1 shown in Figure 63. The yellow marked curve represents the total demand of the cluster for the period 15<sup>th</sup> to 30<sup>th</sup> September and the light blue line total wind generation.



**Figure 63:** Total Generation and Demand in Region TA 1 (TZ1 +TZ2) Before Curtailment – EN Data

Figure 63 shows the centralized generation scenario before any curtailment of solar and/or wind capacity took place. The combined generation capacity from onshore wind generation is during the entire period significantly above the maximum grid capacity of the line *TZ1 – TZ2* line, but within the grid node limit of *TA1* of 14.360 MW (Table 28).

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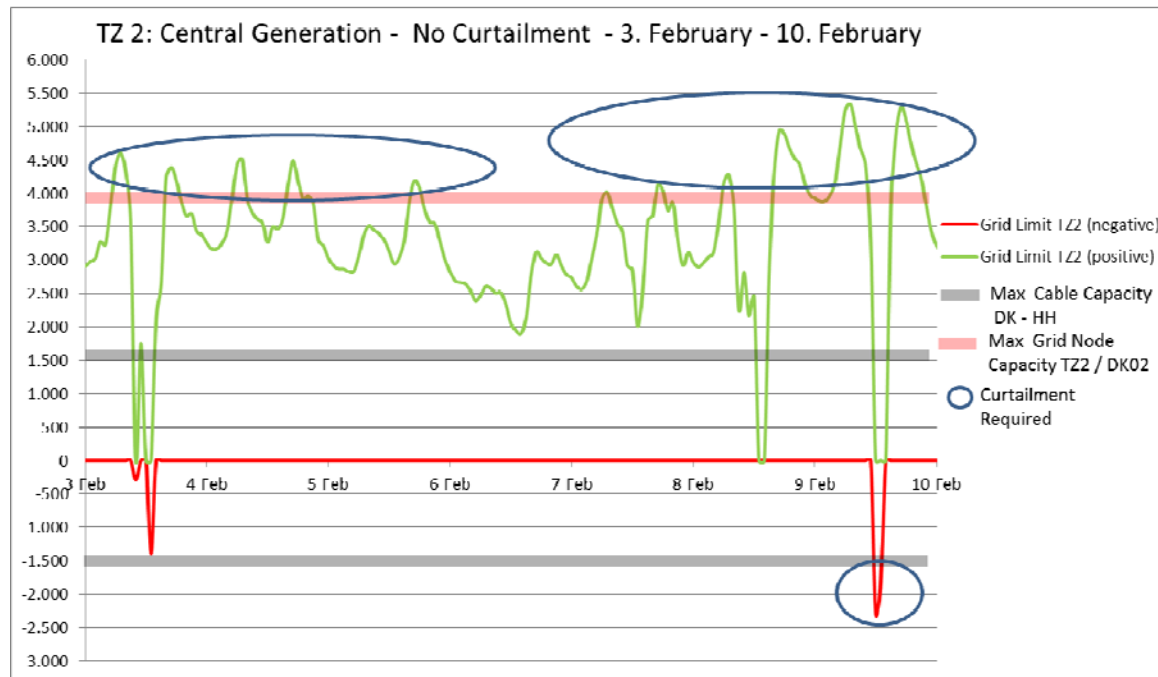


Figure 64: Total Generation and Demand for Grid Node TZ 2 (EN data)

In order to further evaluate possible infrastructural requirements, a specific analysis for each grid node has been done in a second step. Figure 64 is based on the output of the [R]E 24/7 model and shows the calculated grid limits (see 5.5.3). The grey line indicates the maximum cable capacity of the line *TZ1 – TZ2* and the red one indicates the grid node limit of *TZ 2*. Positive values stand for load flows from north to south (*TZ1 to TZ2*) while negative values are reversed load flows. Between the 3<sup>rd</sup> and the 6<sup>th</sup> February as well as between the 8<sup>th</sup> and 10<sup>th</sup> February the positive grid limit of grid node *TZ2* has been exceeded seven times, which requires either curtailment or other measures such as load management. There are two short peaks during the night of the 3<sup>rd</sup> and 9<sup>th</sup> February when the load flow turned around – electricity flew from Hamburg to Denmark. While the exceeded grid limit during the 3<sup>rd</sup> February was marginal and would still be within the safety margin of the power line, the event on the 9<sup>th</sup> February would require curtailment as well.

However this result would not provide sufficient data to verify whether or not the grid limit of individual grid nodes within region *TA1* would be reached or exceeded.

In order to verify the influence of the different methodologies of [R]E 24/7, the input and output data from the EN calculation are compared in a third step. The chosen time series are compared to model results of the **centralized-generation** and **distributed** generation scenario (Figure 65, Figure 66, Figure 67 and Figure 68).

The **centralized generation** scenario was calculated with solar and wind data before and after curtailment. The **after curtailment** data is the result of the EN optimization process, while the **no curtailment** time series represents data before the EN optimization process took place. Both scenarios have been re-calculated in order to test the dispatch process as well as the grid limit process of the [R]E 24/7 model.

The following table provides an overview about the calculated scenarios:

No	Grid Node	Figure	Scenario Name	Curtailment	Supply	Demand	Scenario Characteristics
1	TZ1	65	EN	No	Central	Central	(1) No differentiation between voltage levels (2) priority dispatch for RE independent from voltage level (3) Entire Solar and Wind generation used (4) demand not distributed across voltage levels
		66	[R]E 24/7	No	Central	Central	(1) Four differentiation between voltage levels (2) priority dispatch for RE within each voltage level (3) All generation capacity on TZ accept Offshore (TA) (4) demand allocated to TZ level
2	TZ2	67	EN	No	Central	Central	(1) No differentiation between voltage levels (2) priority dispatch for RE independent from voltage level (3) Entire Solar and Wind generation used (4) demand not distributed across voltage levels
		68	[R]E 24/7	No	Central	Central	(1) Four differentiation between voltage levels (2) priority dispatch for RE within each voltage level (3) All generation capacity on TZ accept Offshore (TA) (4) demand allocated to TZ level
3	TZ1	69	EN	Yes	Central	Central	(1) No differentiation between voltage levels (2) priority dispatch for RE independent from voltage level (3) Solar and Wind generation curtailed (4) demand not distributed across voltage levels
		70	[R]E 24/7	Yes	Central	Central	(1) Four differentiation between voltage levels (2) priority dispatch for RE within each voltage level (3) All generation capacity on TZ accept Offshore (TA) (4) demand allocated to TZ level
4	TZ1	71 (=69)	EN	Yes	Central	Central	(1) No differentiation between voltage levels (2) priority dispatch for RE independent from voltage level (3) Entire Solar and Wind generation used (4) demand not distributed across voltage levels
		72	[R]E 24/7	Yes	Equal Distribution	Equal Distribution	(1) Differentiation of 4 voltage levels (2) priority dispatch for RE only within each voltage level (3) dispatch power plants within cluster have priority (4) demand equally distributed across voltage levels
5	TZ2	73	EN	Yes	Central	Central	(1) No differentiation between voltage levels (2) priority dispatch for RE independent from voltage level (3) Solar and Wind generation curtailed (4) demand not distributed across voltage levels
		74	[R]E 24/7	Yes	Central	Central	(1) Four differentiation between voltage levels (2) priority dispatch for RE within each voltage level (3) All generation capacity on TZ accept Offshore (TA) (4) demand allocated to TZ level
6	TZ2	75 (=73)	EN	Yes	Central	Central	(1) No differentiation between voltage levels (2) priority dispatch for RE independent from voltage level (3) Entire Solar and Wind generation used (4) demand not distributed across voltage levels
		76	[R]E 24/7	Yes	Equal Distribution	Equal Distribution	(1) Differentiation of 4 voltage levels (2) priority dispatch for RE only within each voltage level (3) dispatch power plants within cluster have priority (4) demand equally distributed across voltage levels

**Table 38:** Calculated and Documented Scenario of Chapter 8.5

This methodology has been chosen in order to document the influence of variable distribution from power generation and demand across voltage levels on required dispatch capacities within each cluster and for the entire region. While scenario number 1 and 2 mirrors the EN model, scenario 3, 4 and 5, 6 gradually increase the differences for cluster TZ 1 and TZ2.

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### 8.5.4 Results EN versus [R]E 24/7 by Grid Node with Bottom-Up Priority Dispatch

Scenario 1 (see Table 38) compares the results of the EN *top-down* dispatch scenario with the [R]E 24/7 *bottom-up* dispatch setting for each grid node. The centralized generation scenario takes into account that the grid node model only uses one voltage level. Therefore all generation capacities are allocated to one voltage level – the TZ level – accept offshore wind which is always connected to the TA level in the [R]E 24/7 model.

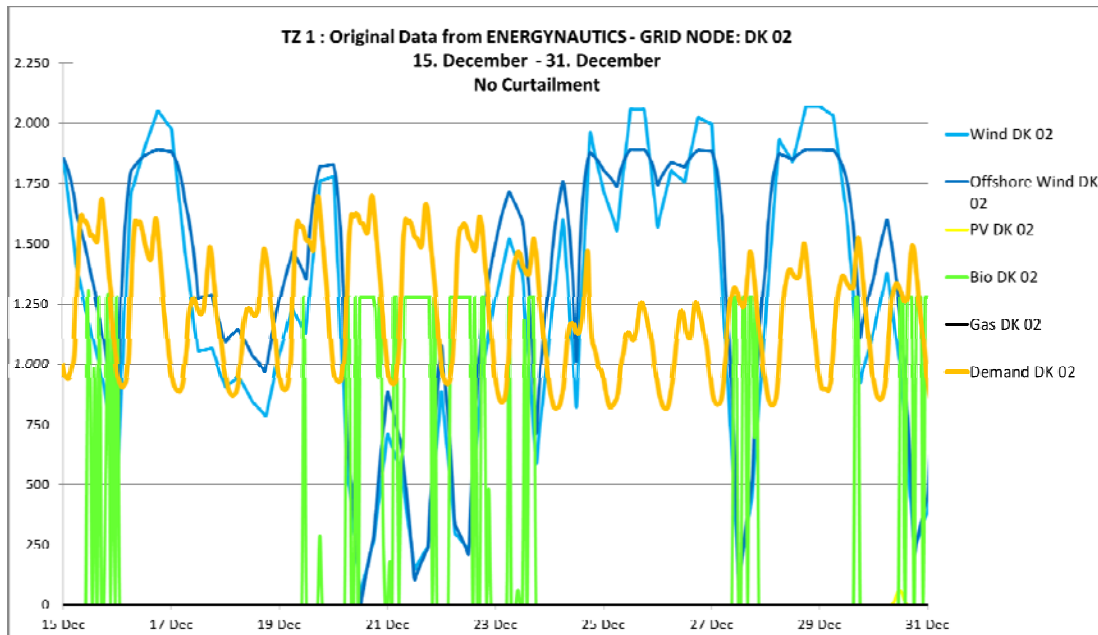


Figure 65: Original Data from ENERGINAUTICS Grid Node DK02 (= TZ1) – Before Curtailment

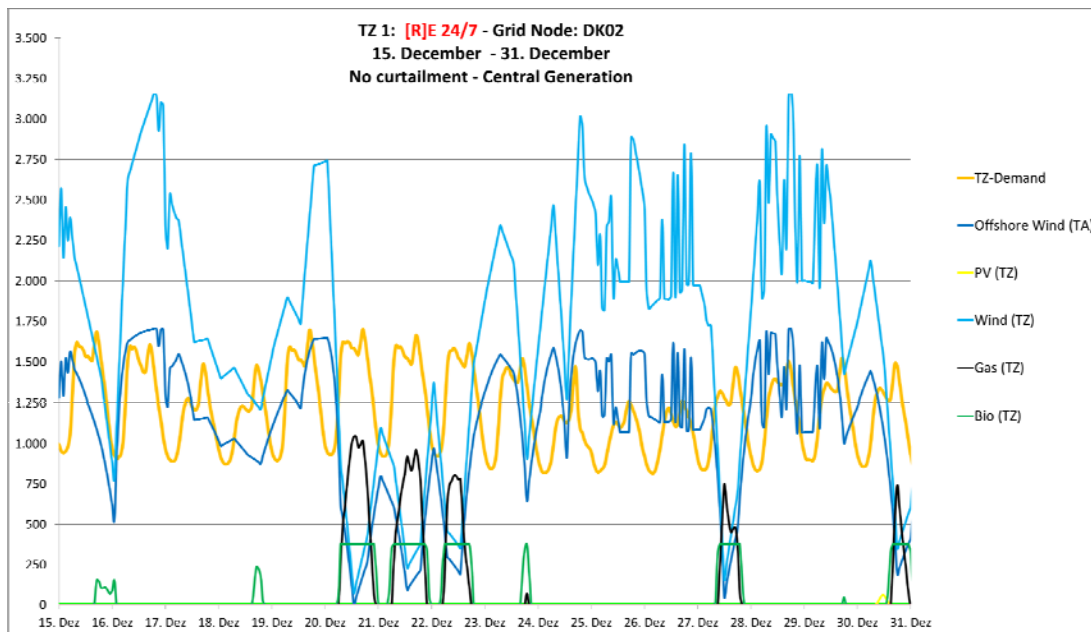


Figure 66: [R]E 24/7 Calculation Results; Grid Node DK02 (=TZ1); No Curtailment + Centralized Generation.

Figure 65 shows EN simulation results from grid node TZ1 before curtailment and Figure 66 results of the [R]E 24/7 calculation with the same input data. While the demand curves are similar, there are significant differences on the generation side. As

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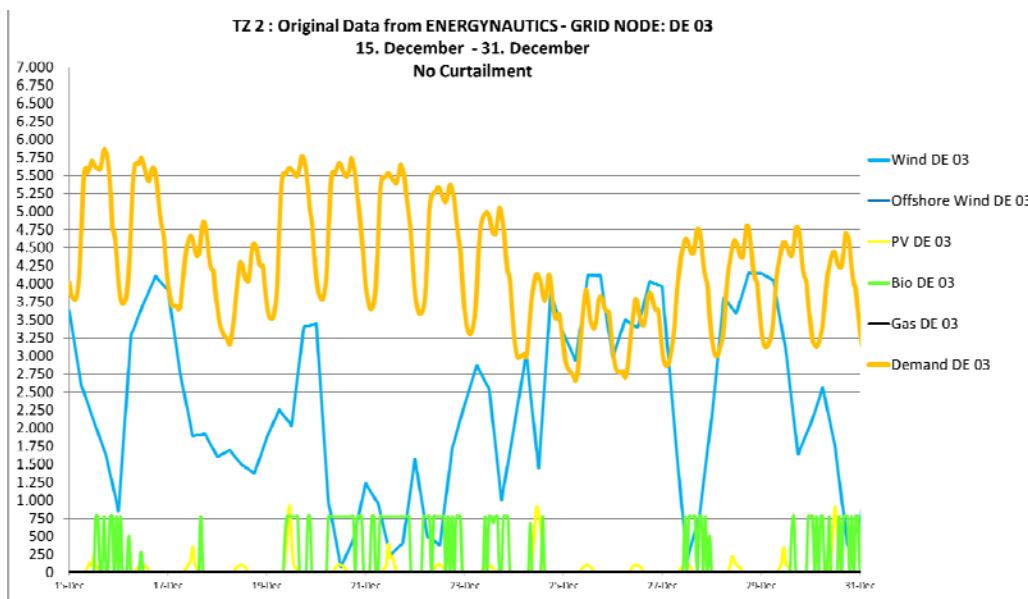
opposed to the EN model which does not differentiate between offshore and onshore wind, the [R]E 24/7 prioritizes generation capacities within one cluster over generation from other voltage levels and / or clusters.

In this case, the entire available onshore wind capacity supplied the demand of the TZ1 cluster and reduced the output of bio energy and gas. While the EN model introduced a second assumption: a minimum capacity factor for *controllable renewables* (see Table 37). Thus the overall resulting dispatch order of the EN and [R]E 24/7 model differentiate and less dispatch power from biomass are calculated.

#### Main Results Scenario 1: No curtailment and Central Generation and Demand – TZ1

- [R]E 24/7 prioritize onshore wind ahead of offshore wind
- Minimum capacity factor requirement of EN model leads to increase use of biomass compared to [R]E 24/7

Scenario 2 (see Table 38) documents the comparison of the same case (scenario 1) and time series with equal assumptions from EN and [R]E 24/7 for the second grid node DE03 (=TZ2) as shown in Figure 67 and Figure 68. The demand curve as well as the onshore wind and solar photovoltaic supply curves are similar, while dispatch capacities bio energy and gas differ from each other.



**Figure 67:** Original Data from ENERGYNAUTICS Grid Node DE03 (= TZ2) – Before Curtailment

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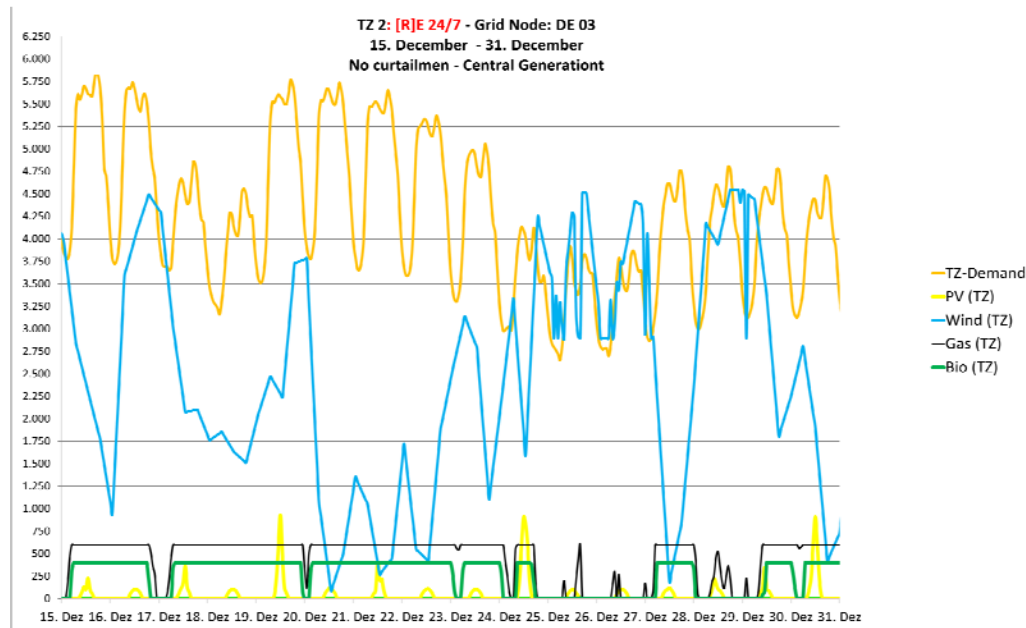
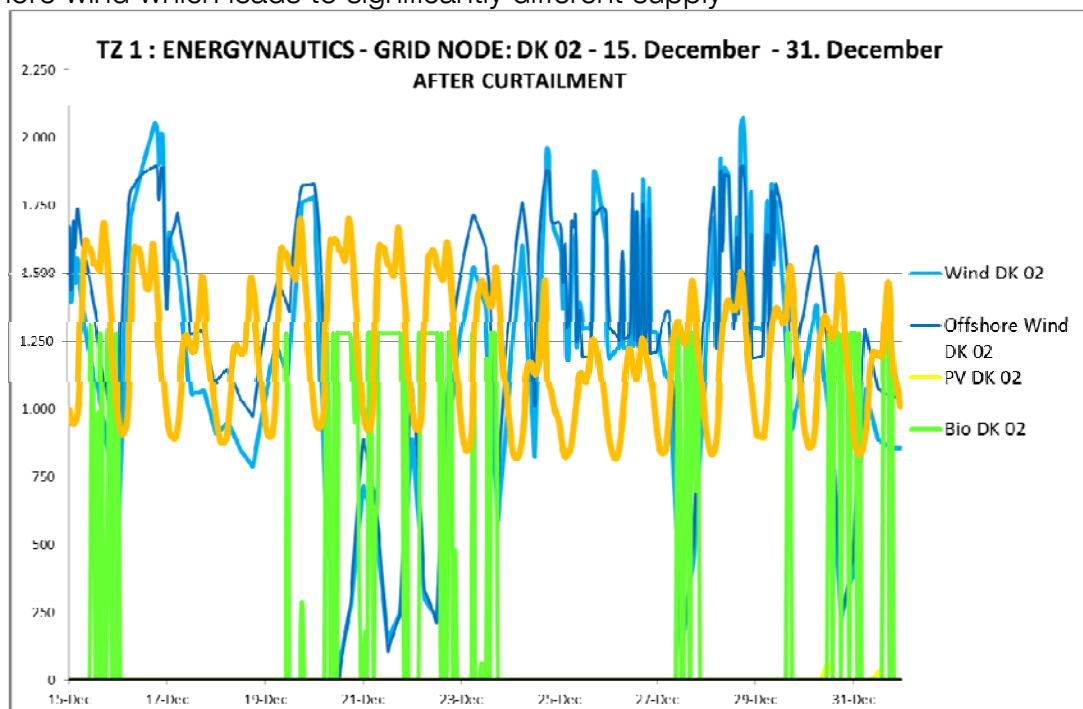


Figure 68: [R]E 24/7 calculation results; grid node DE03 (=TZ2); no curtailment +centralized generation.

### Main Results Scenario 2: No Curtailment and Central Generation and Demand – TZ1

- Onshore wind usage identical in both models
- Bio mass and gas power generation differ significantly due to minimum capacity factor requirement of the EN model
- EN model has faster reaction times (dispatch intervals shorter in EN model)

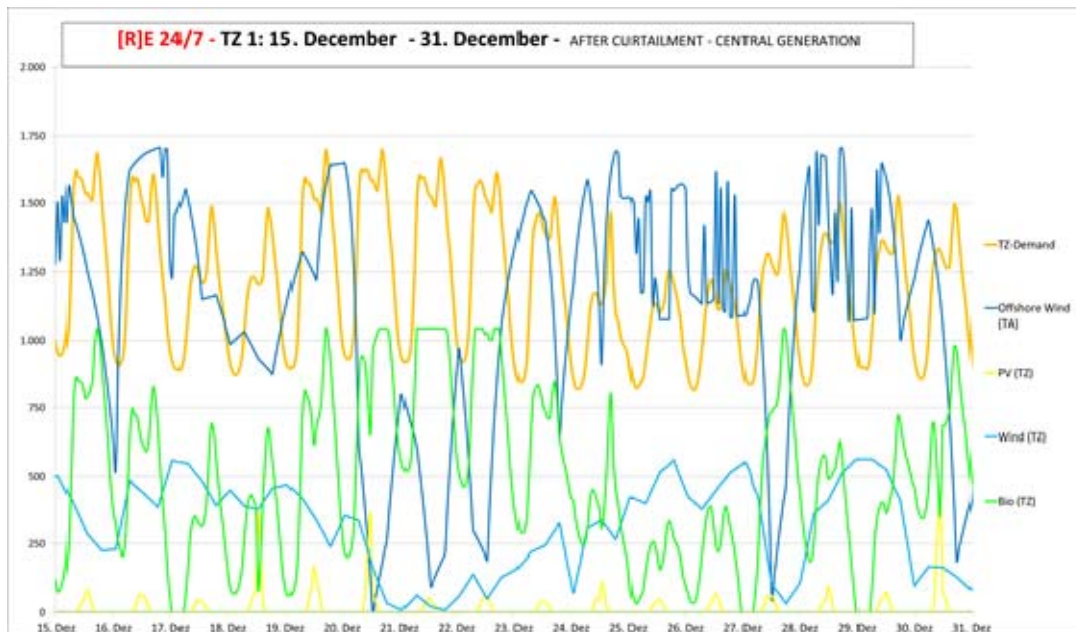
Scenario 3 (see Table 38) shows the supply and demand curves of TZ 1 under the same condition as the previous scenario but after curtailment. While all generation capacities and the demand are within one grid node in the EN model, offshore wind is on a higher voltage level in the [R]E 24/7 mode. Therefore bio energy has priority ahead of offshore wind which leads to significantly different supply



curves.

Figure 69: ENERGINAUTICS Result for December TZ1 – After Curtailment





**Figure 70:** [R]E 24/7 Result for December TZ1 – After Curtailment – Central Generation

Main Results Scenario 3: After Curtailment and Central Generation and Demand – TZ1

- Onshore wind, solar PV supply- and the demand curve identical in both models
- Bio energy priority dispatch over offshore wind due to voltage level difference
- Bio energy generation share grew on the expense of offshore wind in [R]E24/7

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Scenario 4 (see Table 38) uses the same time series as scenario 3 but generation capacities as well as the demand are equally distributed across the voltage levels TZ, DA and DZ. Dispatch capacities utilization across all voltage levels differ significantly as a result of the [R]E 24/7 model.

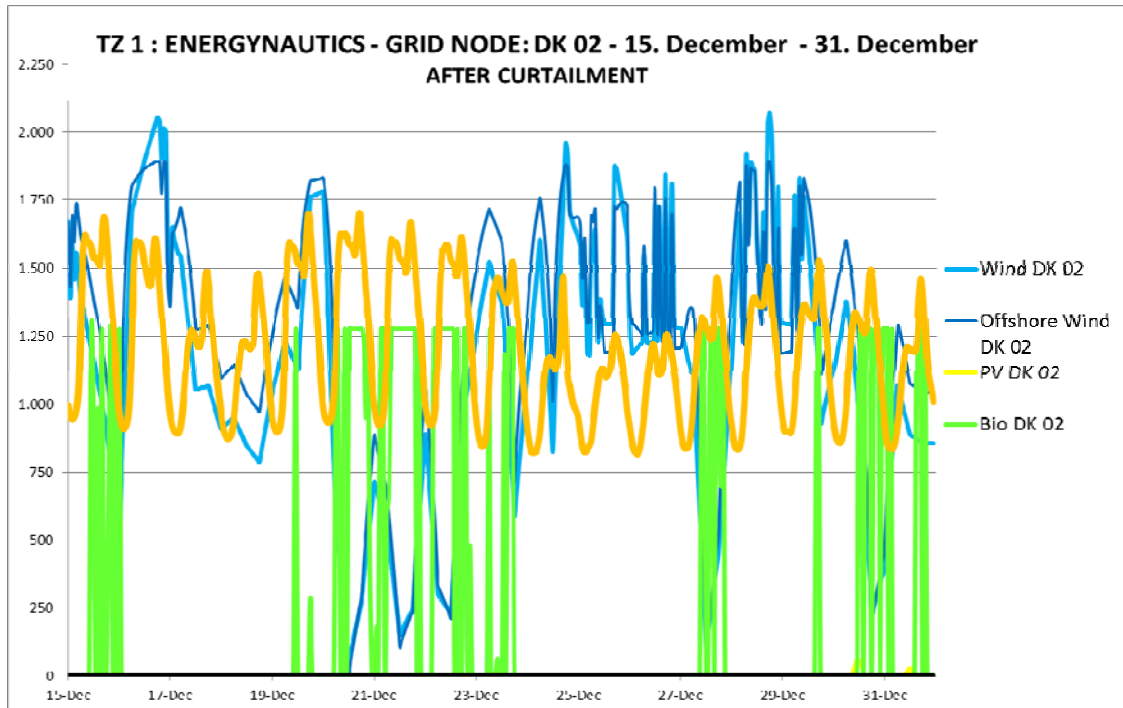


Figure 71: ENERGINAUTICS Result for December TZ1 – After Curtailment

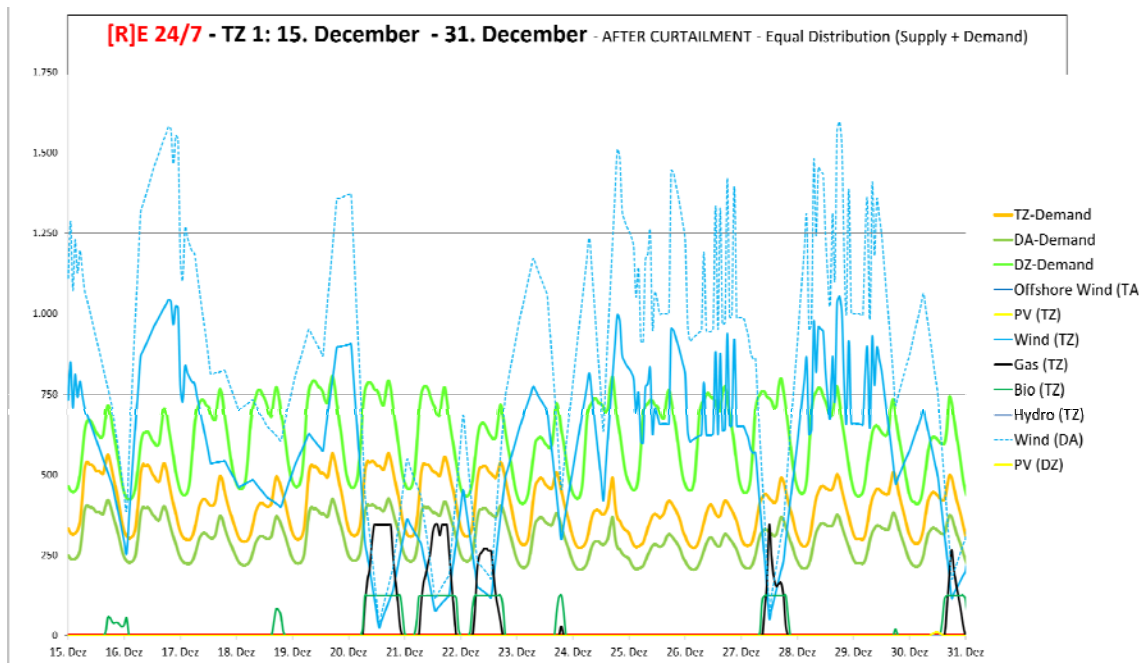


Figure 72: [R]E 24/7 Result December TZ1 – After Curtailment – Equal Distribution of Demand and Supply

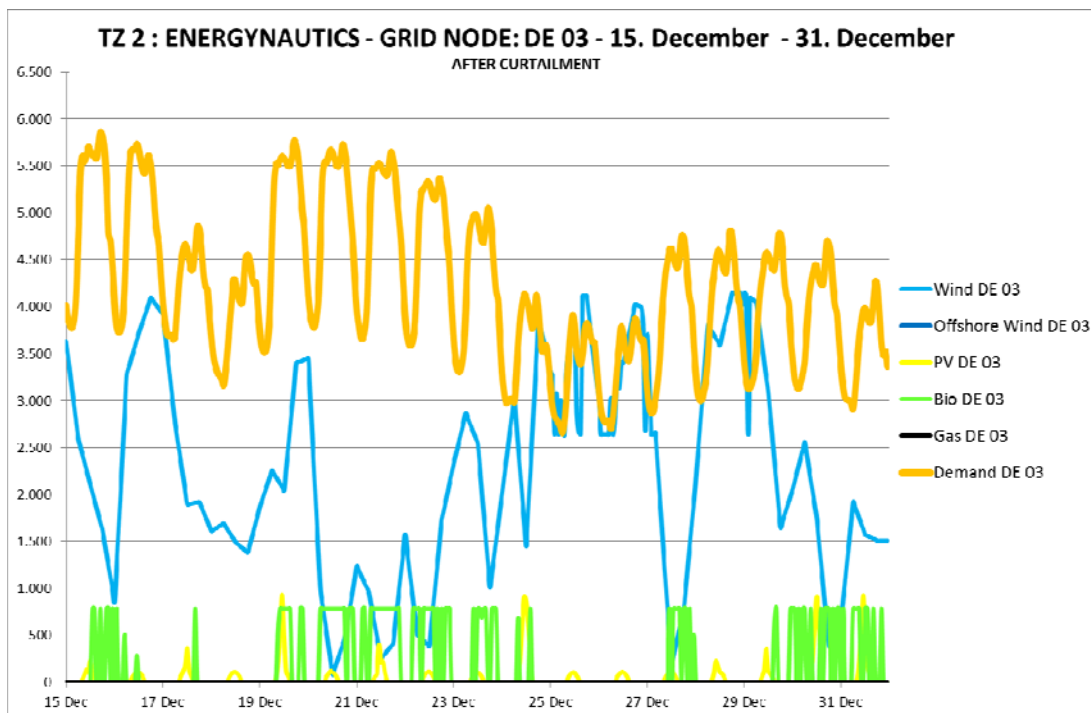


## Main Results Scenario 4: After Curtailment, Equal Distribution of Demand and Supply (TZ1)

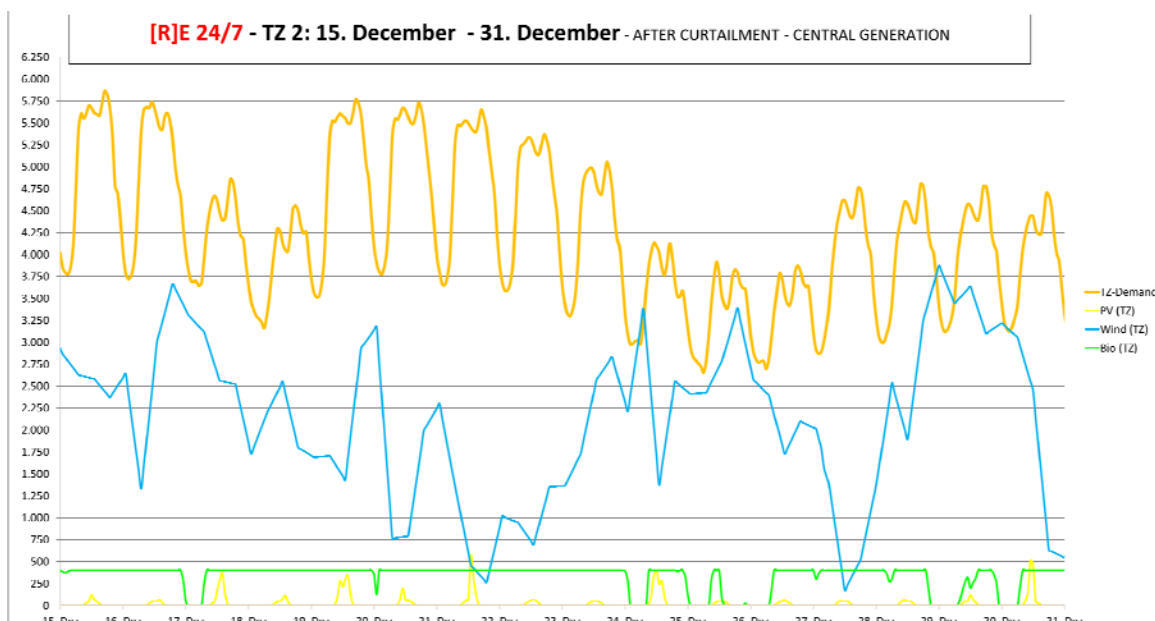
- All voltage levels use available dispatch capacities ahead of offshore wind
- Less bio energy and more gas for dispatch capacity used in [R]E 24/7– offshore wind not utilized

Scenario 5 (see Table 38) mirrors scenario 3, but for grid node TZ2.

Demand and supply capacities are similar in both models. However the EN has a much faster reaction time which leads to frequent on- and off switching of bio energy as dispatch capacity, which has an influence on the onshore wind supply curve of the [R]E 24/7 model.



**Figure 73:** ENERGINAUTICS Result for December TZ2 – After Curtailment



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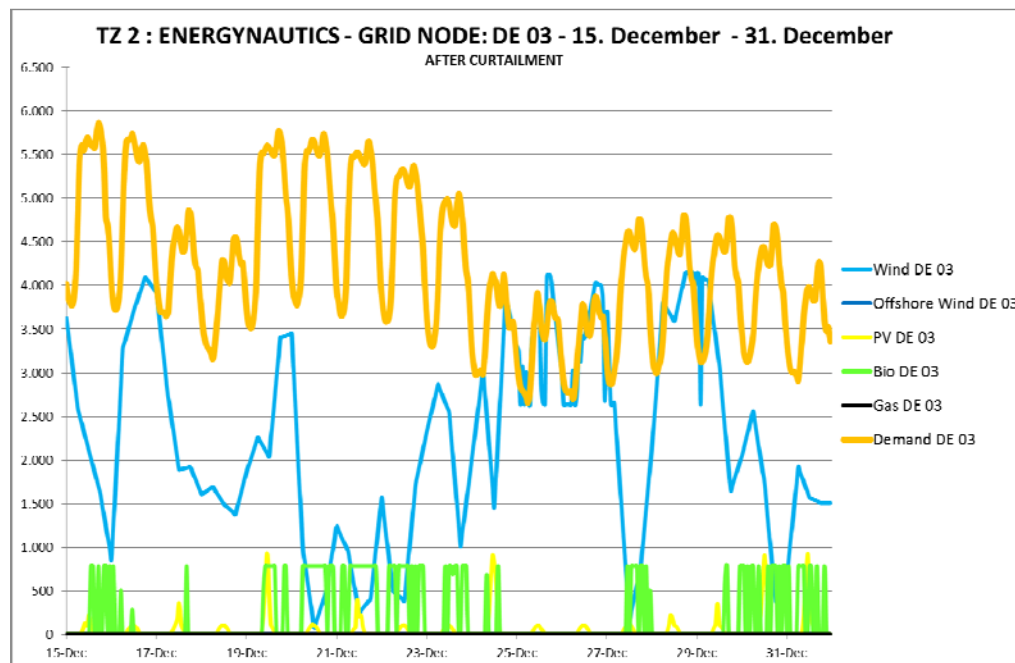
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**Figure 74:** [R]E 24/7 Result for December TZ2 – After Curtailment – Central Generation

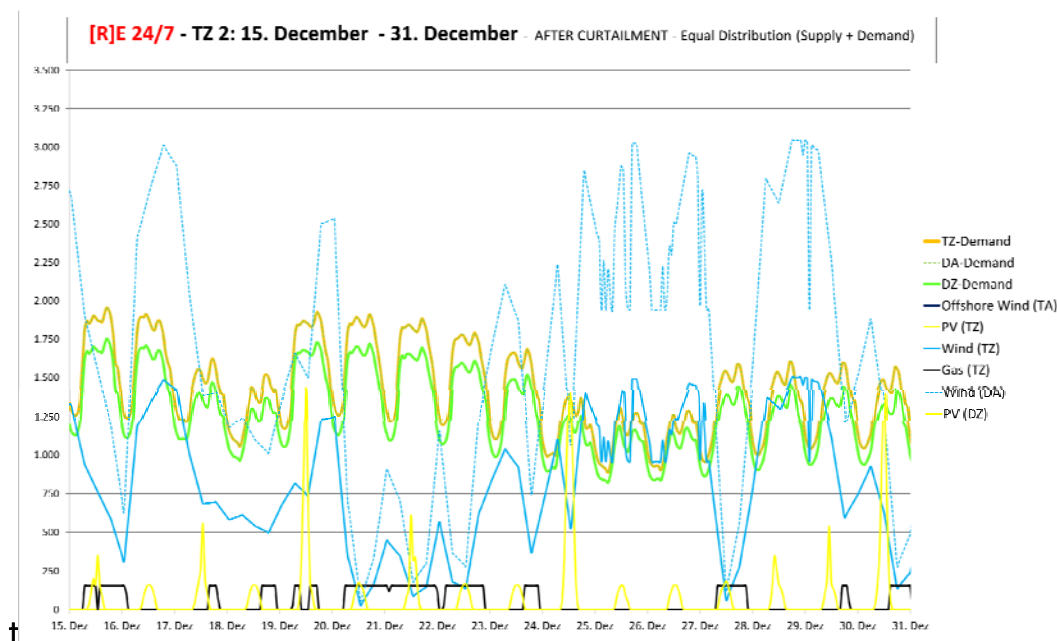
#### Main Results Scenario 5: After Curtailment and Central Generation and Demand – TZ2

- Similar utilization of onshore wind generation share in both models
- EN model reacts faster as [R]E 24/7 models which leads to different bio energy supply curves (more steady)

Finally Scenario 6 (see Table 38) uses the same time series as scenario 5 and distributes generation and demand equally across voltage level TZ, DA and DZ. Again dispatch order prioritized solar and wind ahead of bio energy and gas within each cluster. While each cluster priorities internal dispatch capacity over those from other clusters and voltage levels. Therefore generation profiles differ significantly in the [R]E 24/7 compared to EN. Besides that, gas capacity is located in TZ, while the bio energy capacity is only available in DA and DZ.



**Figure 75:** ENERGYNAUTICS Result for December TZ2 – After Curtailment



**Figure 76:** [R]E 24/7 Result for December TZ 2– After Curtailment – Distributed Generation and Demand

#### Main Results Scenario 6: After Curtailment, Equal Distribution of Demand and Supply (TZ2)

- Onshore wind production curve distributed across two voltage levels
- Gas dispatch capacity used in TZ2 on the expense of bio energy, due to different distribution of demand and supply
- 

#### **Conclusion Section 8.5.4**

Figure 69 to Figure 76 show simulation results of EN and [R]E 24/7 for grid nodes TZ 1 and TZ 2 with input data for the last two weeks of December. In each case demand curves for both models are identically calculated and always match the EN model +/- 1%, whether centralized or distributed demand has been assumed. However there are differences on the generation side due to the different model architectures.

All dispatch capacity supply shares deviate with bottom-up dispatch settings and variations are even more significant in case of distributed generation. In general the variations between EN and [R]E 24/7 results are larger for TZ1, where TA connected offshore wind is allocated, than for TZ2. The [R]E 24/7 model has only one *process* (Table 18) for offshore wind at TA level, thus the effect of the dispatch order as well as the demarcation problem (8.1.1 Cluster versus Grid Nodes – Demarcation Problem) lead to high deviations, especially for clusters with low RE and high dispatch capacities (bio energy or gas).

Besides the allocation of generation capacity by grid node and voltage level, another factor has a major impact on simulation results: The EN data is taken out of a wider meshed grid system which is reflected in the EN model but not with [R]E 24/7.

Differences also appear because the EN model can use wind power from other surrounding grid nodes within the meshed system, while [R]E 24/7 calculates a one

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dimensional cascade between two grid nodes. Thus, electricity can flow via a third grid node from TZ 1 to TZ 2, and more generation capacity of renewable *MUST-RUN* power plants like wind power will be accepted in the grid. In that regard, the [R]E 24/7 model leads to lower renewable energy concentration and higher dispatch power generation shares e.g. from bio energy because each grid node will prioritize generation capacity from within the cluster over generation capacity of higher voltage levels.

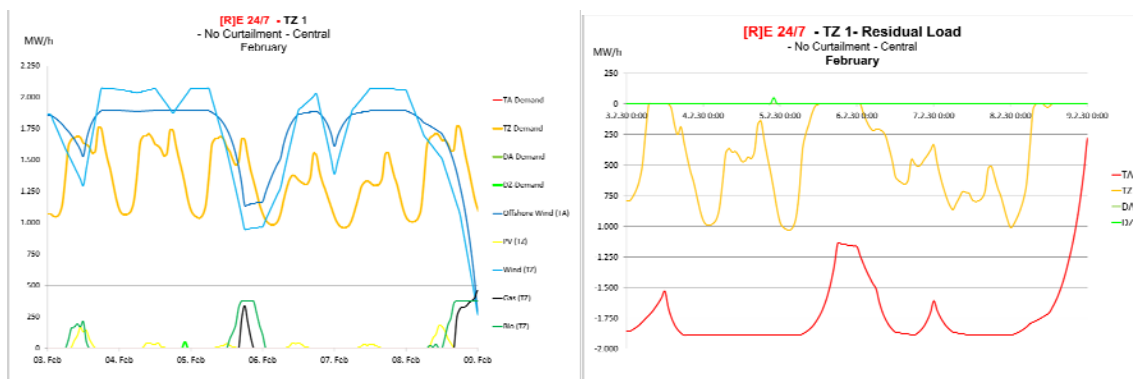
Under the distributed generation and demand case, results of the EN and the model developed for this thesis are significantly different. Each voltage level prioritizes local generation over imported generation, both from neighboring clusters as well as cluster of higher voltage levels which leads to substantially variant supply shares. Figure 62 shows that the dispatch generation share in the distributed generation and demand scenario in February was 34% in the [R]E 24/7 model, compared to only 4% in the EN calculation. Thus, the different methodologies lead to model results which are not comparable. The deviation grows with increased distribution of generation capacities across all voltage levels and clusters which lead to significant differences of residual loads per grid node and cluster.

### Summary Conclusion Scenario Analysis Section 8.5.4:

- A prioritization of control energy within each cluster prior to available dispatch capacity from higher voltage levels leads to a reduced use of centralized forms of renewable energy such as offshore wind
- Individual regional dispatch strategies increase the overall demand for dispatch capacity and / or storage requirements
- The deviation of EN and [R]E 24/7 model results increases the more generation and demand is distributed across voltage levels

### 8.5.5 Residual Loads by Grid Node under Different Generation Scenarios

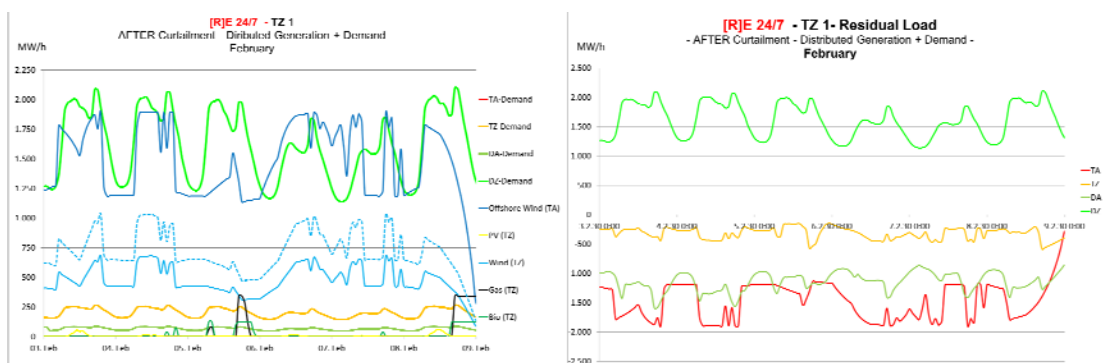
This section shows residual load curves for grid node TZ1 with equal installed capacities and for the same time series but with different generation scenarios. While Figure 79 displays the residual load situation for the distributed case, Figure 77 and Figure 78 show the central-generation case before and after curtailment. All three calculated residual load curves are significantly different due to different generation utilization in each voltage level. Especially the distributed generation scenario with curtailed wind power generation data from EN leads to a higher back-up capacity requirement on the TZ voltage level. Thus, the grid node model from EN and the [R]E 24/7 will lead to significantly different results even with small changes of assumptions.



**Figure 77:** Central Generation - no curtailment: supply / demand curves (left); resulting residual load curves (right)



**Figure 78:** Central Generation - after curtailment: supply / demand curves (left); resulting residual load curves (right)



**Figure 79:** Distributed Generation - After Curtailment: Supply / Demand Curves (left); Resulting Residual Load Curves (right)

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Direct comparison of residual loads from TZ1 and TZ2 under distributed (left) and centralized (right) generation scenario (Figure 80) shows significantly different residual load patterns. The residual load of the TZ1/DZ level with distributed demand is positive, thus supply comes entirely from higher voltage levels, mainly wind in the case of the February example.

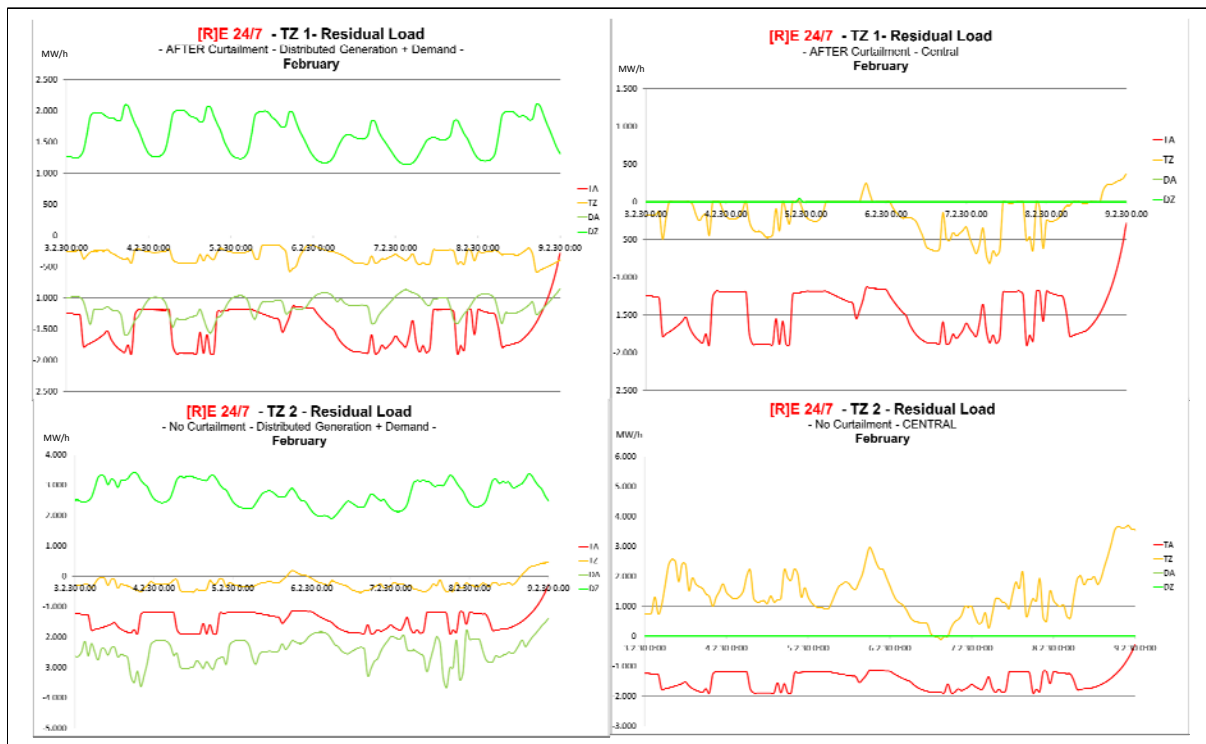


Figure 80: Direct Comparison of Residual Loads from Distributed and Central Generation Scenarios

If distributed generation would be available, including solar photovoltaic, small wind turbines or dispatch power plants, wind power from DA and TZ levels would not be utilized from the DZ level. As a result, available wind power would either supply other clusters and/or voltage level, or further transport or storage capacity would be required. Offshore and onshore wind connected to the TZ or TA levels therefore competes directly with distributed generation in the case of a bottom-up dispatch setting.

### Key Results: Residual Loads by Grid Node under Different Generation Scenarios

- Positive residual load curves show a higher demand within the voltage level than available supply
- Negative residual load curves emerge if generated electricity exceeds the demand within the same voltage level
- Different residual load curves change utilization for each power generation capacity significantly

### 8.5.6 Deviation for Results EN versus [R]E 24/7 for Different Time Series

Finally Table 39 shows deviations of the EN versus [R]E 24/7 model for different time series before and after curtailment – always under bottom-up dispatch settings. The higher the wind and/or solar supply shares, the higher the deviation with the EN model. However after curtailment, the overall average deviation after the simulation results of seven weeks for the entire TA remains at +/- 6.5% but each grid node can differ from EN results up to 17% with extreme wind or solar events.

NO CURTAILMENT									
								Deviation ENERGYNAUTICS - [R]E 24/7 - No Curtailment	
3.-10. Feb.		7. - 8. May		15. - 30. November		1. - 14. December		15.- 31. December	
								Average - 1126 Data points [h]	
Demand	Delta [%]	Delta [%]	Delta [%]	Delta [%]	Delta [%]	TZ 1 [DK02]		Delta [%]	
	-0,02%	0,00%	0,00%	0,00%	0,00%	Demand		-0,004%	
Supply	9,22%	21,47%	10,53%	11,29%	8,26%	Supply		12,155%	
Demand	Delta [%]	Delta [%]	Delta [%]	Delta [%]	Delta [%]	TZ 2 [DE03]		Delta [%]	
	-0,03%	2,15%	0,00%	0,00%	0,00%	Demand		0,422%	
Supply	20,20%	5,68%	20,00%	20,39%	21,60%	Supply		17,574%	
Demand	Delta [%]	Delta [%]	Delta [%]	Delta [%]	Delta [%]	TA [DK02 + DE03]		Delta [%]	
	-0,03%	1,70%	0,00%	0,00%	0,00%	Demand		0,335%	
Supply	15,00%	13,60%	15,51%	16,05%	15,12%	Supply		15,055%	

AFTER CURTAILMENT									
								Deviation ENERGYNAUTICS - [R]E 24/7 - After Curtailment	
3.-10. Feb.		7. - 8. May		15. - 30. November		1. - 14. December		15.- 31. December	
								Average - 1126 Data points [h]	
Demand	Delta [%]	Delta [%]	Delta [%]	Delta [%]	Delta [%]	TZ 1 [DK02]		Delta [%]	
	-0,02%	0,00%	0,00%	0,00%	0,00%	Demand		-0,004%	
Supply	-1,94%	16,92%	-13,38%	-16,04%	-9,92%	Supply		-4,871%	
Demand	Delta [%]	Delta [%]	Delta [%]	Delta [%]	Delta [%]	TZ 2 [DE03]		Delta [%]	
	-0,03%	2,15%	0,00%	0,00%	0,00%	Demand		0,422%	
Supply	17,28%	-4,54%	-6,41%	8,95%	17,24%	Supply		6,503%	
Demand	Delta [%]	Delta [%]	Delta [%]	Delta [%]	Delta [%]	TA [DK02 + DE03]		Delta [%]	
	-0,03%	1,70%	0,00%	0,00%	0,00%	Demand		0,335%	
Supply	8,74%	5,97%	-9,64%	-1,76%	5,26%	Supply		1,713%	

**Table 39:** Deviation of Results EN versus [R]E 24/7 for Different Time Series

### 8.6 Simulation of Low Voltage Clusters under Various Dispatch Options

This section provides an overview how low voltage clusters can be calculated with various dispatch options to analyze the effect of large distributed generation shares in terms of demand and supply patterns and economic effects. Four different situations on the low voltage level *DZ* have been calculated:

- Case 1A: Energy demand on *DZ* level only supplied with power generation capacity from outside the cluster (Figure 81)
- Case 1B: Energy demand on *DZ* level – same supply conditions as case 1 A but with grid limit reached (Figure 82)
- Case 2 Energy demand on *DZ* supplied partly with decentralized solar photovoltaic generators within the cluster (Figure 83)
- Case 3: Energy demand on *DZ* supplied to 100% by a mix of decentralized power generation capacities from within the cluster (Figure 84)
- Case 4: Energy demand on *DZ* supplied by a mix of decentralized power generation and storage capacities from within the cluster (Figure 85)



### Bridging the Gap Between Energy- and Grid Models:

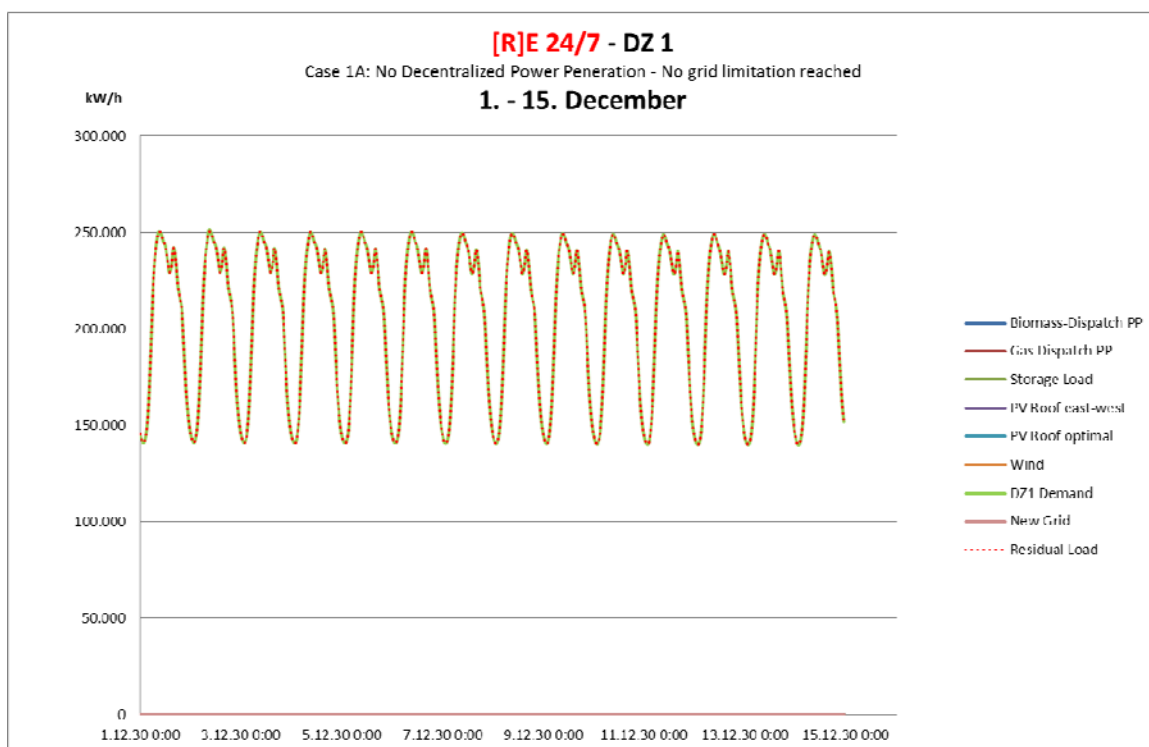
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Extreme situations in February, May, November and December have been calculated, however only the situation of 1<sup>st</sup> to 15<sup>th</sup> December is documented in this section in order to make the differences comparable.

### Case 1A: Energy Demand on DZ Level Only Supplied with Power Generation Capacity from Outside the Cluster

A load curve for low voltage cluster with a demand of max 251 MW with no regional power generation is shown in Figure 81. Parameter *Electricity 380V POS* (see section 5.6) represents the total load and is an output of the model. The delta between demand and supply within the DZ cluster – the *residual load* – is the commodity *380V* which is connected to the transformer and a positive value in case there is remaining supply from an upper voltage level, zero in case the demand and supply matches with the entire cluster, and negative in case the cluster produces more electricity than required. The latter case is only possible for solar and wind generation. If there is no power generation capacity within one region, the residual load is equal to the total demand.



**Figure 81:** Case 1A - Low Voltage Level (DZ) Supply without Decentralized Power Generation

### Key Results Case 1 A:

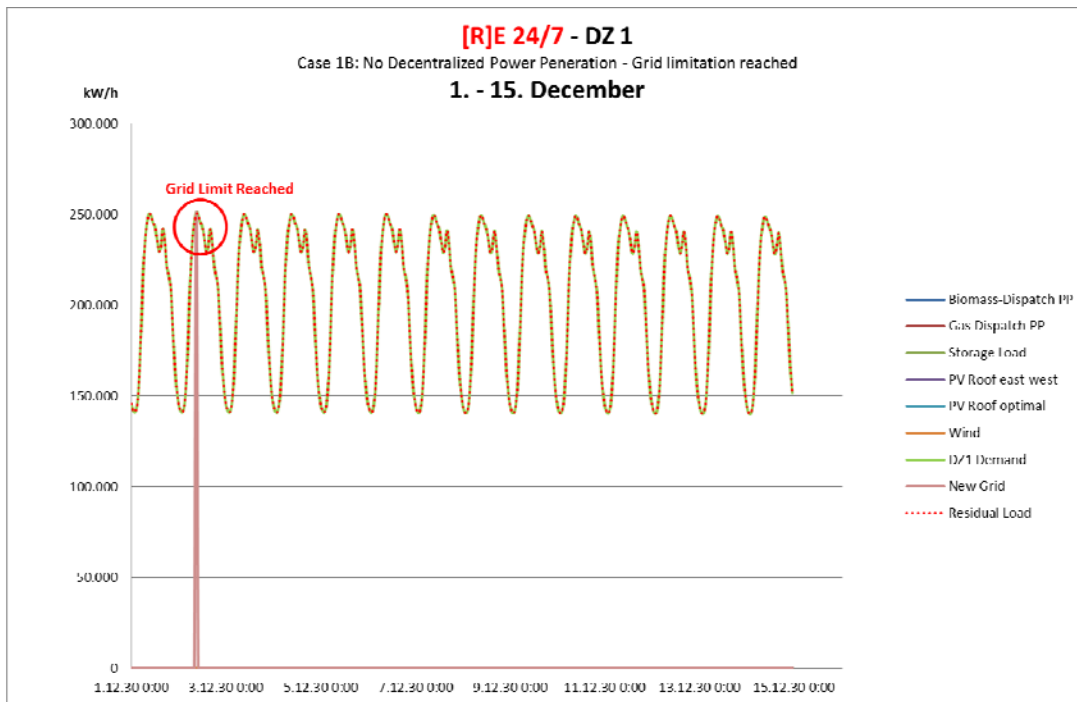
- No generation capacity available within low voltage level (DZ)
- Residual load equals demand curve
- No grid limitations reached



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## Case 1B: Energy Demand on DZ Level – Same Supply Conditions as Case 1 A -with Grid Limit Reached

Figure 82 shows the same demand curve for the same time series 1<sup>st</sup> to 15<sup>th</sup> December but a lower grid limit which was set at 251 MW, one MW lower than the highest annual peak demand of the DZ cluster to demonstrate the function only. In that example the grid limit was reached on the 2<sup>nd</sup> December at 9am which is marked with a red spike. The [R]E 24/7 model identifies only time series with exceeding grid limits, in case demand and supply are within grid limits, the parameter value is zero.



**Figure 82: Case 1B: Low Voltage Level Demand Curve – Grid Limit Reached**

### Key Results Case 1 B:

- No generation capacity available within low voltage level (DZ)
- Residual load equals demand curve
- Grid limitations exceeds load (indicated by red spike)

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## Case 2 Energy Demand on *DZ* Supplied Partly with Decentralized solar Photovoltaic Generators within the Cluster

Case 2 uses the same load curve as case 1A but with additional solar photovoltaic generation, thus the residual load (red dotted line) is below the overall demand curve.

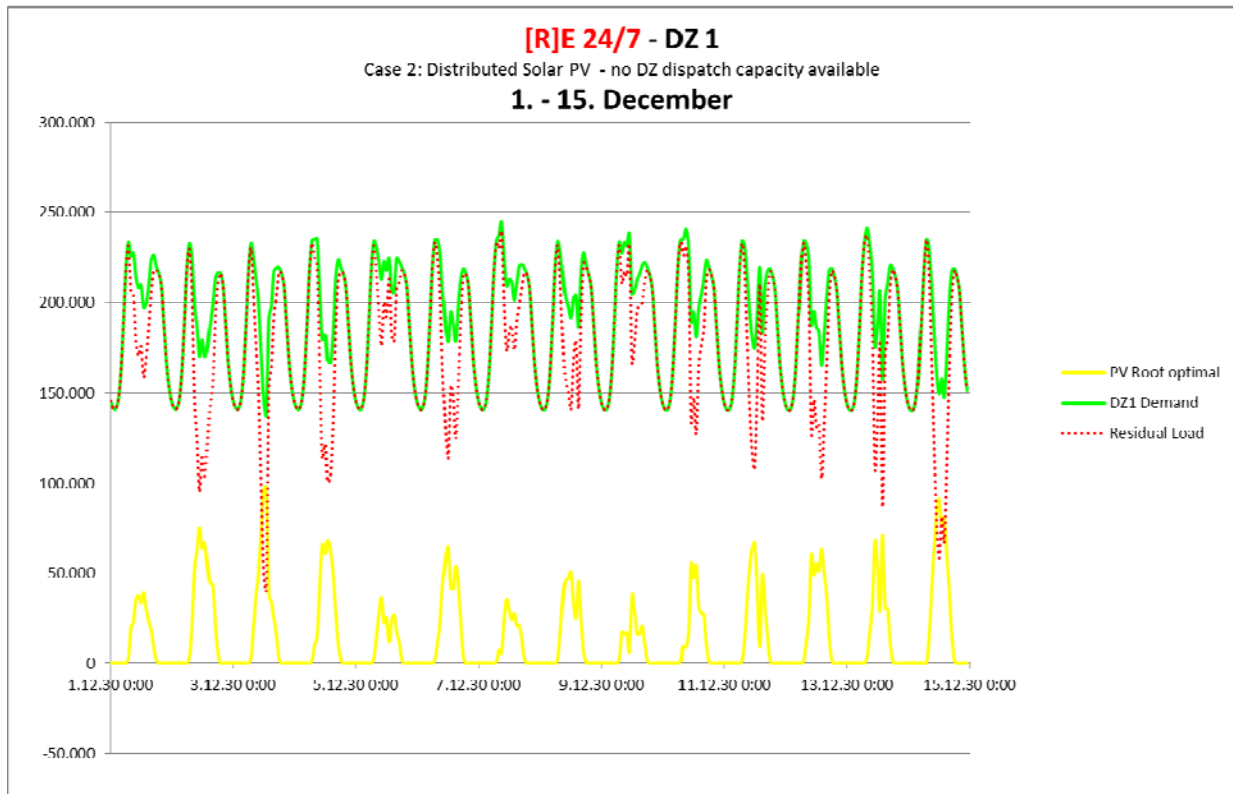


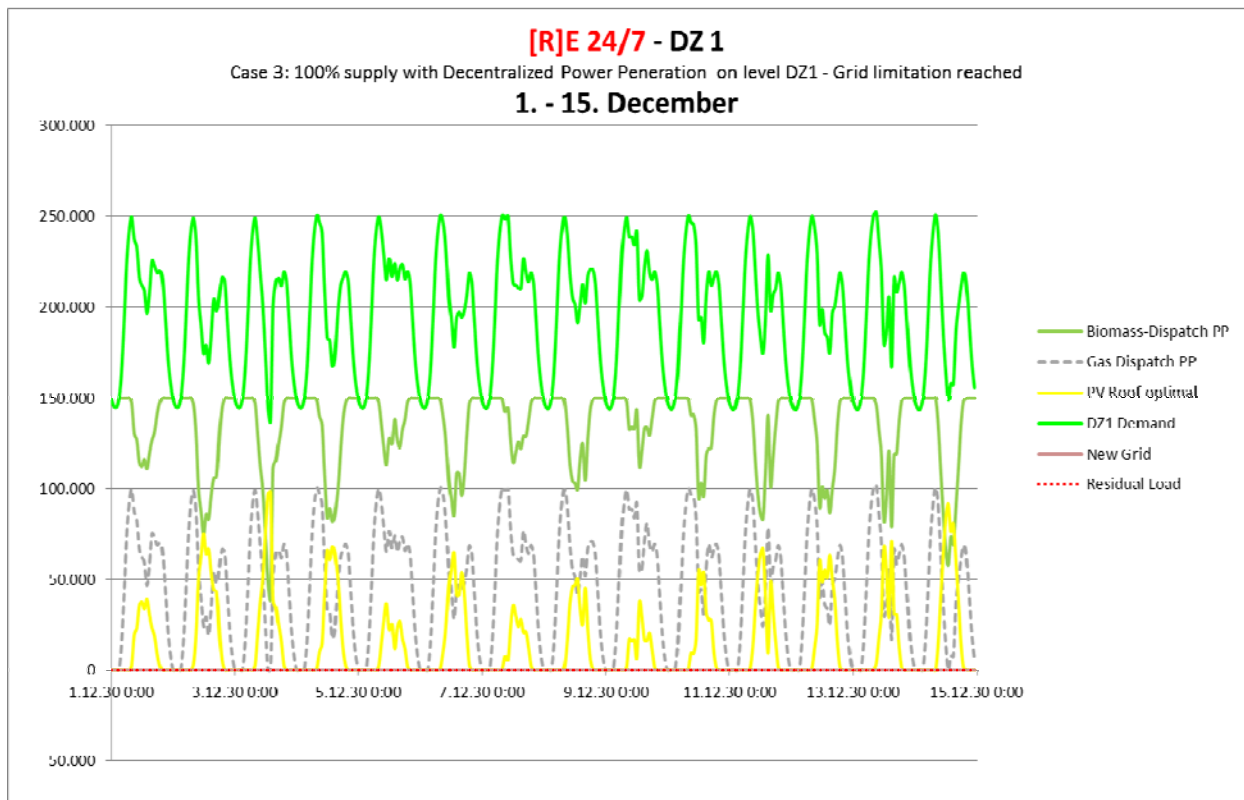
Figure 83: Case 2 - Low Voltage Level (DZ) Supply with Decentralized Solar Generation

### Key Results Case 2:

- Solar PV supplies part of demand in DZ1
- Residual load below demand curve
- Remaining demand supplied by upstream generation of higher voltage level(s)

### Case 3: Energy Demand on *DZ* Supplied to 100% by a Mix of Decentralized Power Generation Capacities from within the Cluster

Case 3 uses the same parameter as case 2 but with additional available bio and gas power generation capacity within cluster *DZ*. The residual load curve in Figure 84 remains zero which represents a 100% independent power supply and therefore no power flow from higher *DA* voltage level is required. The [R]E 24/7 model categorizes all solar and wind power generation capacities – flexible renewables – as “must run” power plants. Thus the entire generation capacity will be taken into account, while all other power plants are treated as “can run” power plants which will only generate power within the cluster if there is a supply shortage. In case there are neither flexible renewables nor dispatch power plants available, power generation from other clusters will be used. The hierarchical use of processes (Figure 34) represents the merit order and in this calculation bio energy has priority over gas, however different sequences are possible.



**Figure 84:** Case 3 - Low Voltage level (DZ) Supply with Decentralized Solar- Bio- and Gas Power Generation

#### Key Results Case 3:L

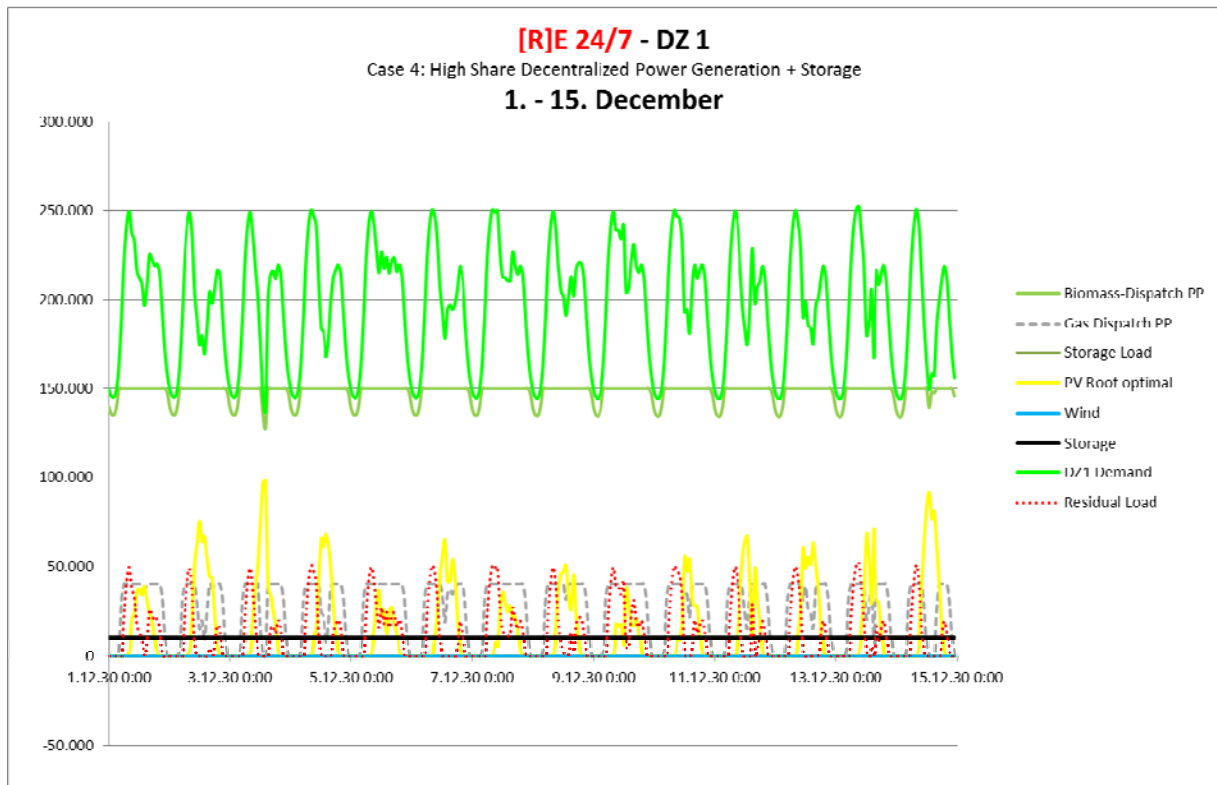
- 100% self-sufficient power supply
- Solar PV, bio- and gas power generation located in DZ
- Residual load zero

### Bridging the Gap Between Energy- and Grid Models:

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#### Case 4: Energy Demand on *DZ* Supplied by a Mix of Decentralized Power Generation and Storage Capacities from within the Cluster

Finally case 4 is based on the assumptions of case 3, but with lower gas capacity and includes storage capacities. It is assumed that 10% of the entire solar photovoltaic generation will charge solar batteries. Electricity from solar batteries – here in stable output mode - has priority over gas power generation in the calculation shown in Figure 85.



**Figure 85:** Case 4 - Low Voltage Level (DZ) Supply with Decentralized Solar- Bio- and Gas Power Generation plus Storage

The four cases presented in this section demonstrate how low voltage clusters can be analysed and how the effects of different supply shares required for grid capacity and storage requirements are calculated. This function of the [R]E 24/7 model can also be used to test whether centralized or decentralized power supply will be most economic for specific clusters. However the weakness of this model is that there is no optimization algorithm to find the optimum. In a next step, the economic results of the documented case 2, 3 and 4 will be presented.

#### Key Results Case 4:

- Solar PV, bio- and gas power generation supply 80% of cluster demand
- Storage used to increase utilization of generation capacity within DZ cluster
- Remaining residual load curve indicates upstream power supply

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## 8.7 Conclusion: Verification of Physical Flow Simulation Results

Chapter 8 documented the verification and calibration process of the [R]E 24/7 model. Original input data from the ENERGYNAUTICS grid node model has been used and simulation results have been compared with each other. When assumptions and dispatch setting are similar, [R]E 24/7 can re-calculate results of the EN model. Both the consumption and the *must-run* solar and wind generation profiles are calculated with an error of less than +/- 5% (Figure 59)

The results for *can-run* dispatch power plants however deviate from each other. In case of priority dispatch for offshore wind, which represents a change to top-down dispatch priority, calculated supply shares of the EN model can be reconstructed with a deviation of less than +/- 5%.

However if the [R]E 24/7 uses a bottom-up dispatch setting, results vary significantly depending on the distribution of supply capacity and demand by voltage level. In the case of large shares of distributed generation and scattered demand over several clusters and voltage levels, the deviation from EN results was up to 30%. Thus a direct comparison of both model results is no longer possible.

In addition, the demarcation problem (8.1.1 Cluster versus Grid Nodes – Demarcation Problem) leads to different simulation results as well. While the EN model simulates a meshed system in which power can flow over neighboring grid nodes back into the analyzed region (Loop-flows) the [R]E 24/7 model defines clear boundaries. In addition, the load flows in clear defined cascades top-down or vice versa and therefore possible loop flows are not recognized, which represents a clear disadvantage of the [R]E 24/7 model.

Furthermore, the EN model introduces specific capacity factors and a minimum power output for dispatch power plants, which is not possible for [R]E 7/24 and might lead to very low operational hours or power production in a partial load range, which has strong effects on the economy of these power stations (see 9.1 Specific Generation Costs of Dispatch Power Plants).

To conclude, the [R]E 24/7 model can re-calculate EN results with mathematical accuracy within an error of +/-5%. However, both model architectures lead to very different scenario results. In the case of a power grid analysis for multiple grid nodes for an entire country results will almost certainly be so widely divergent that a direct comparison is no longer possible.

The [R]E 24/7 model can simulate clear defined areas like distribution networks or small-scale power grid systems of e.g. island power systems as well as overlay DC network systems which connect only two grid nodes in detail across all voltage level. This represents the strength of the model. However the EN model reflects a meshed transmission network in more detail as opposed to [R]E 24/7 and therefore has significant advantages for the modeling of transmission networks.

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## 9. Sample Results of the [R]E 24/7 Economic Module

Once the physical flow of scenarios has been verified, the economic evaluation takes place. As documented in Chapter 5.11 estimated costs for cases presented in chapter 8 are calculated. A comparison with the EN model is not possible, as the methodologies significantly differ. While the [R]E 24/7 model calculates all involved costs in parallel with the physical flow simulation, the EN model doesn't provide hourly average generation costs but optimizes with exogenous cost values provided for processes and commodities.

### 9.1 Specific Generation Costs of Dispatch Power Plants

All power generation costs are calculated with the assumptions shown in Table 40 which are taken from one source (Pregger 2012<sup>115</sup>) in order to be consistent. Small scale bio energy dispatch power plants connected to the DZ level are assumed to have double installation costs than those with multi-megawatt capacities connected to higher voltage levels.

While the actual costs of different generation technologies can vary significantly – both by region and year of installation - it should be noted that [R]E 24/7 aims for a quantitative analysis. This research will explore the relative change of different production units, in relation to the degree of utilization and in which voltage level they operate.

Assumptions for power generation costs									
Process	Specific fixed costs		Specific capital costs		Installation Costs [€/kW]	Annual Maintenance Costs	Technical Life Time [a]	[h/a]	[€/kWh] - excluding fuel -
	Unit		Unit						
PV Optimal / Power plant	€/ (kJ)*h/h	0,00004667	€/ (kJ)*h	0,000035	2500,00	43,00	20,00	1000,00	0,13
PV East-West	€/ (kJ)*h/h	0,00006222	€/ (kJ)*h	0,000046	2500,00	43,00	20,00	750,00	0,17
PV-Storage	€/ (kJ)*h/h	0,00043333	€/ (kJ)*h	0,000333	6000,00	90,00	20,00	250,00	1,20
CSP	€/ (kJ)*h/h	0,00007012	€/ (kJ)*h	0,000037	9300,00	418,50	20,00	3500,00	0,13
(Onshore) Wind	€/ (kJ)*h/h	0,00001889	€/ (kJ)*h	0,000011	1800,00	63,00	20,00	2250,00	0,04
Offshore Wind	€/ (kJ)*h/h	0,00003667	€/ (kJ)*h	0,000021	6000,00	228,00	20,00	4000,00	0,08
Wind Storage	€/ (kJ)*h/h	0,00018750	€/ (kJ)*h	0,000104	7500,00	300,00	20,00	1000,00	0,38
Hydro Power Plant (10/20kV)	€/ (MWh)*h/h	37,40	€/ (MWh)*h	11,00	3300,00	132,00	60,00	5000,00	0,01
Hydro Power Plant (110/220kV)	€/ (GWh)*h/h	37400,00	€/ (GWh)*h	11000,00	3300,00	132,00	60,00	5000,00	0,01
Hydro Power Plant (400kV)	€/ (GWh)*h/h	37400,00	€/ (GWh)*h	11000,00	3300,00	132,00	60,00	5000,00	0,01
Bio Energy Power Plant	€/ (kJ)*h/h	0,00001861	€/ (kJ)*h	0,000010	3350,00	134,00	20,00	4500,00	0,04
Gas Power Plant	€/ (kJ)*h/h	0,00000847	€/ (kJ)*h	0,000007	750,00	30,00	7,00	4500,00	0,02
Coal Power Plant	€/ (kJ)*h/h	0,00000694	€/ (kJ)*h	0,000004	1250,00	50,00	20,00	4500,00	0,01
Lignite Power Plant	€/ (kJ)*h/h	0,00000806	€/ (kJ)*h	0,000004	1450,00	58,00	20,00	4500,00	0,02
Nuclear Power Plant	€/ (kJ)*h/h	0,00018750	€/ (kJ)*h	0,000021	7500,00	300,00	20,00	5000,00	0,08

Source for all values: DLR 2012

Table 40: Assumptions for Power Generation Costs

Specific electricity generation costs of **MUST-RUN** renewable power plants (Figure 35) are calculated via exogenous determined capacity factors thus costs are identical for each output capacity within the entire time series.

In contrast, all specific costs for **CAN-RUN** dispatch power plants are calculated with fixed costs per hour, such as operation and maintenance costs, and specific costs such as fuel costs. Those specific costs are based on assumptions shown in Table 40.

This methodology has been chosen in order to accomplish a quantitative cost analysis with a single model run. As opposed to a capacity factor based cost analysis, which requires two model runs. The first one to calculate the actual resulting capacity factor for each power plant and a second for the cost analysis based on the calculated capacity factor. Thus specific generation costs depend on the utilization factor in relation to total installed and available dispatch capacity which might lead to cost spikes.

When dispatch power plants only operate with a small fraction of their total installed capacity, specific generation costs can peak by a factor 20 or more.

Technology	Installed Capacity in [MW]	Utilization of dispatch capacity					
Bio (TZ1)	124	Used capacity in [MW]	124	106	56	24	10
		Used capacity in [%]	100%	85%	45%	20%	8%
		Specific generation in [€ cent/kWh]	7,48	8,63	15,68	35,04	86,55
Gas (TZ1)	344	Used capacity in [MW]	344	248	153	69	32
		Used capacity in [%]	100%	72%	44%	20%	9%
		Specific generation in [€ cent/kWh]	4,1	8,0	20,7	24,6	34,5

**Table 41: Assumption of Specific Generation Costs of Dispatch Power Plants in Relation to Utilization**

Table 41 shows the impact on specific generation costs of dispatch power plants which operate significantly below their maximum output capacity. An utilization factor of 45% doubles electricity production costs with the assumed fuel costs, fixed operational and capital costs for bio mass power plants (Pregger 2012<sup>116</sup>) and factor five for gas power plants with low fuel cost assumption. Figure 86 shows specific and average supply costs for the central generation case, without the limitation for minimum utilization of dispatch power plants.

This approach also mirrors the recent energy debate in Germany which has focussed on whether ‘capacity markets’ or ‘energy-only markets’ should be used in the German Energiewende (BMW 2015<sup>117</sup>), Germany’s transition to an energy portfolio dominated by renewable energy and energy efficient technologies. The methodology used in this chapter reflects the ‘energy-only-market’ approach, even though several different possibilities for the cost calculations of dispatch power plants are possible as well.

The decision to base dispatch costs on capacity utilization factors is a political, and aims to penalize overcapacity. The aim of this chapter is to simply verify the mathematical correctness of the [R]E 24/7 model. Results documented in chapter 9.2 and 9.3 are based on the assumption that capacity utilization factors are used. Changed assumptions for dispatch costs would lead to significantly different costs.

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## 9.2 Specific Generation Costs Across all Grid Levels

In order to evaluate the overall system costs across all grid levels specific costs of output flow as well as specific commodity costs (see Table 23) for both the supply (e.g. 20 kV) and demand side (e.g. 20kV(DS) ) can be compared with different generation compositions over time. The [R]E 24/7 model provides results for each hour, therefore changing supply costs with variable shares of wind, solar or other generation technologies are documented within each cluster and across all voltage levels.

The model allows adding specific costs for each process, thus grid costs can be added as well. However for this analysis only generation costs have been calculated in order to demonstrate the function and to limit parameters for clarity reasons. The costs calculation function leads to very large data volumes and it is not possible to calculate a full year without mainframes which is a weakness of the program.

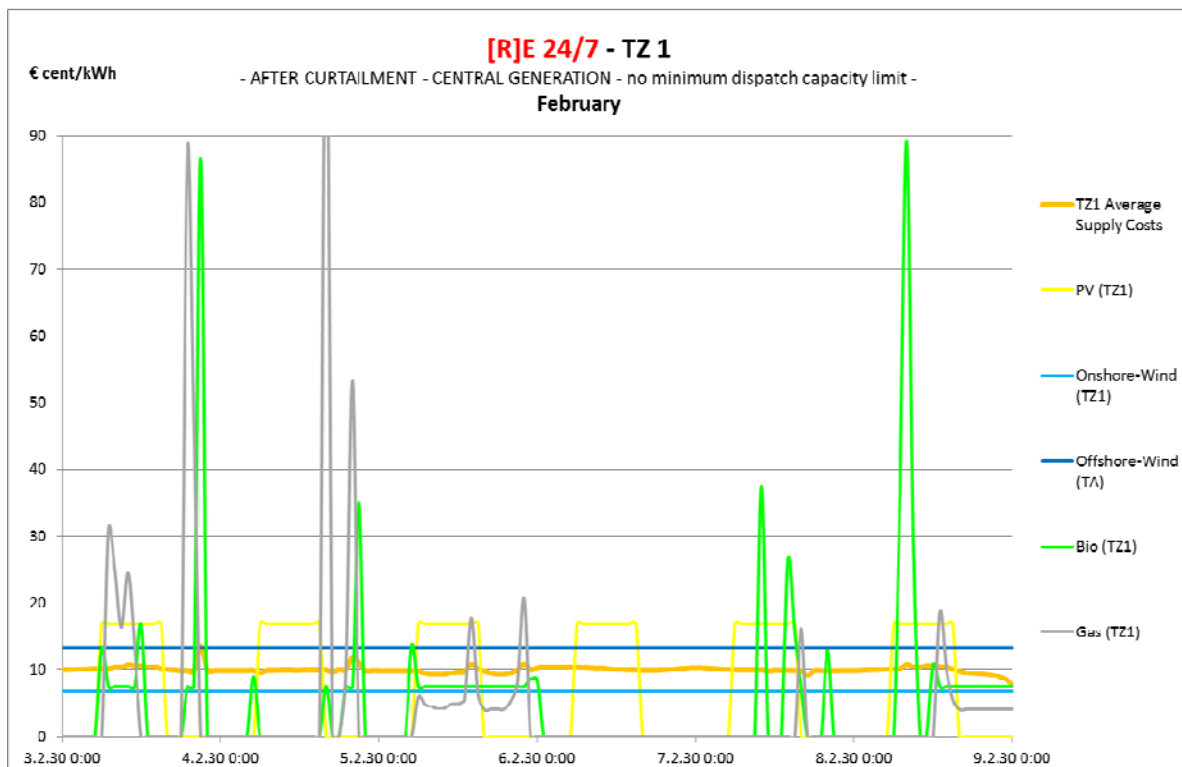
Thus the results shown in section



9.2 Specific Generation Costs Across all Grid Levels are calculated for one week, which takes 20 minutes to calculate. The week of the 3<sup>rd</sup> February has been chosen due to the high and variable wind generation throughout the week. The scenario numbers refer to Table 38: Calculated and Documented Scenario of Chapter 8.5, chapter 8.5.

### 9.2.1 Cost Analysis – Scenario 3: After Curtailment, Central Generation (TZ1)

Specific generation and average supply costs under the centralized scenario with no dispatch capacity limit are shown in Figure 86. Both bio and gas power plants operated with low capacity utilization factors during the 4<sup>th</sup> and 5<sup>th</sup> February, because wind and solar plants supplied most of the demand. Only a fraction of the available dispatch capacity was required for a short period of between one and three hours which caused cost spikes with dispatch costs of over 90 cents per kWh. As a result, the average supply costs went up from around 10 cents to 14 cents per kWh. In the morning of the 8<sup>th</sup> February, solar and wind was able to supply the majority of the demand, and only bio power was required for dispatch which caused a cost-spike to 88 cents per kWh for one hour



**Figure 86:** Cost Calculation for TZ1 without Minimum Dispatch Capacity Limit; Central Generation Case

During the afternoon of the same day, the entire bio power plant capacity and half of the available gas capacity was needed to secure supply. Thus, dispatch costs for gas power decreased below the level of wind, while bio power generation was at the same cost level. As a result average supply costs went down.

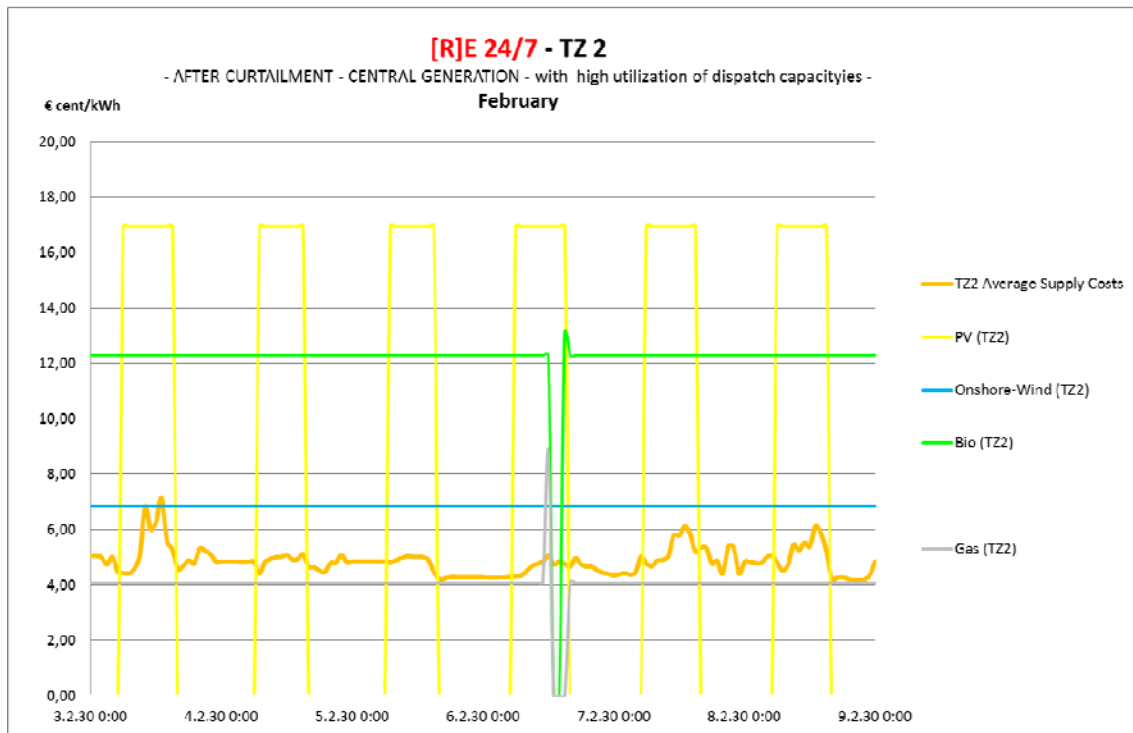
#### Main Results: After Curtailment, Central Generation (TZ1)

- Short periods of dispatch requirements significantly below available control power capacities needed
- Low dispatch capacity utilization leads to cost spikes
- Dispatch cost spikes only have minor impact on overall supply costs

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### 9.2.2 Cost Analysis – Scenario 5: After Curtailment, Central Generation (TZ2)



**Figure 87:** Cost Calculation for TZ2 with High Utilization of Gas and Medium Utilization of Bio Capacities; Central Generation Case, Dispatch Priority Gas over Bio Energy.

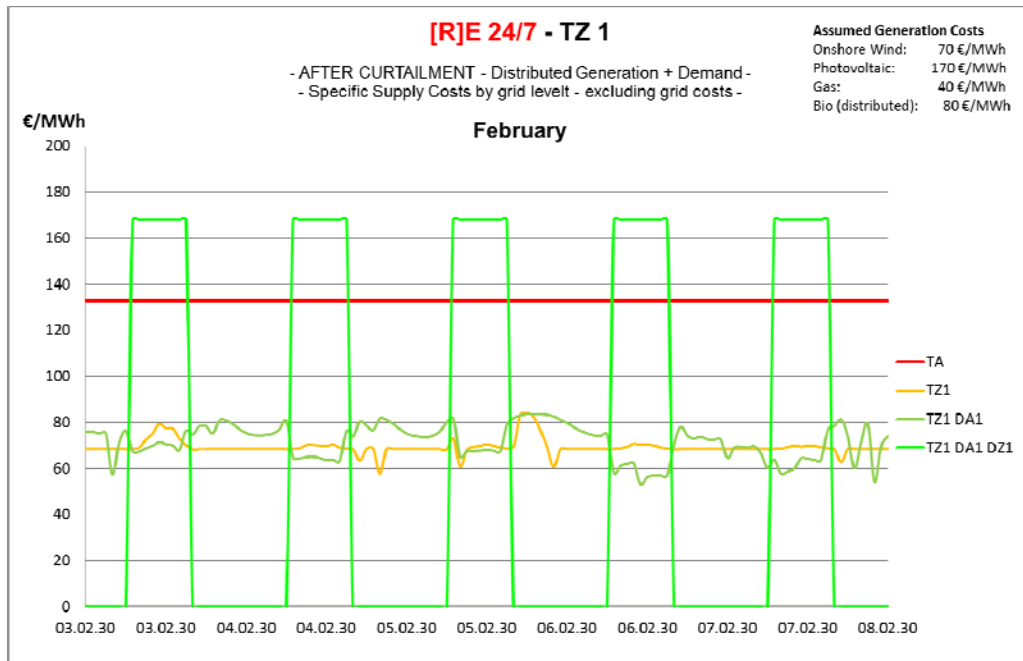
Specific generation costs for the central generation scenario included a changed dispatch order – gas ahead of bio – are shown in Figure 87. While gas operates with full capacity, the bio power capacities operate with 70% utilization. During the afternoon of the 6<sup>th</sup> February only half of gas and no bio dispatch capacity were required, leading to an increase of average gas electricity costs. The average supply costs (orange line) oscillates around 4 and 7 cents per kWh mainly dependent of the volume of available solar electricity with assumed generation costs of 17 cents per kWh.

#### Main Results: After Curtailment, Central Generation (TZ2)

- Bio energy utilization rate on average at 70% - no costs spikes
- Reversed dispatch order – gas ahead of bio energy – reduced average supply costs as opposed to the case calculated in Figure 86
- Costs of solar photovoltaic generation dominates the supply costs

### 9.2.3 Cost Analysis – Scenario 4: After Curtailment, Distributed Generation and Demand (TZ1)

Figure 88 shows the average supply costs across all voltage levels for the distributed generation and demand case. TA supply costs (red) represents offshore wind generation costs, while TZ (orange) is dominated by onshore wind generation costs. The DA level (dark green) reflects mainly gas generation with different proportions of bio energy. Finally generation costs of the DZ level (light green) represent only solar photovoltaic generation costs as the only available power generation technology.



**Figure 88:** Cost Calculation across all Grid Levels TZ1 – Supply Costs by Grid Level Excluding Grid Cost

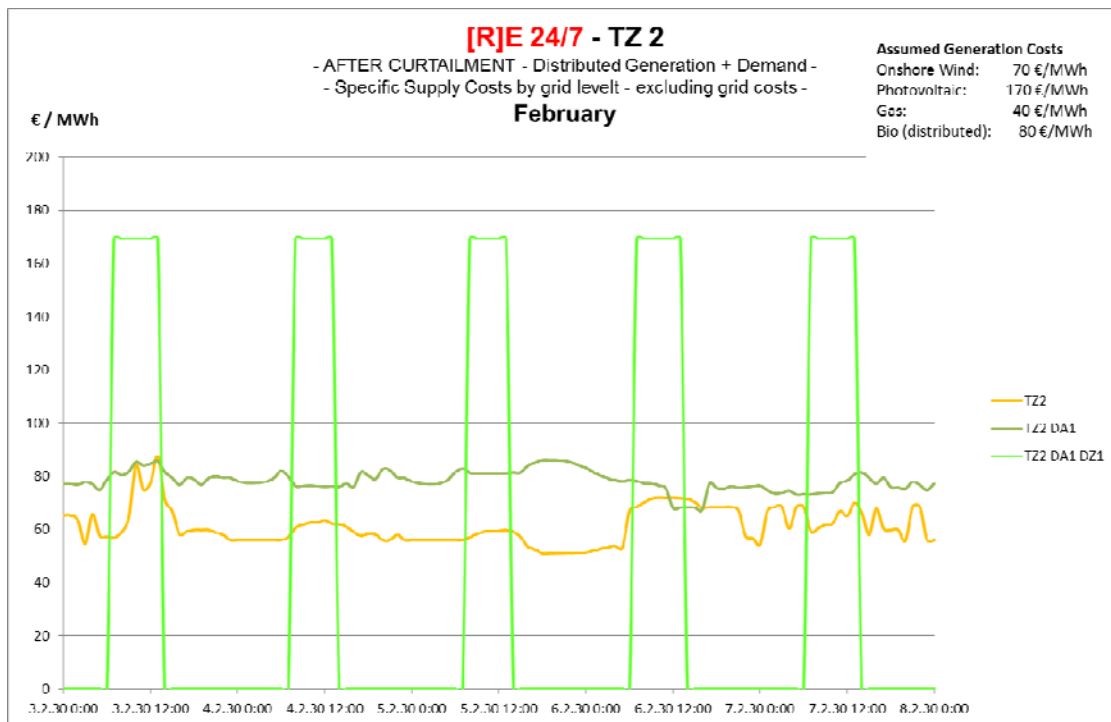
#### Main Results: After Curtailment, Distributed Generation and Demand (TZ1):

- Offshore Wind power is the only generation technology at TA level
- Solar photovoltaic is the only generation technology at DZ level
- Grid level TZ and DA achieve lowest generation costs due to high utilization of gas and bio energy

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#### 9.2.4 Cost Analysis Scenario 6: After Curtailment, Distributed Generation and Demand (TZ2)



**Figure 89:** Cost Calculation across all Grid Levels TZ2 – Supply Costs by Grid Level Excluding Grid Costs

Figure 89 shows specific supply costs of the TZ 2 cluster for the same case and time series shown in Figure 88. Again DZ supply costs are entirely from solar photovoltaic generation. Supply costs from TZ2 and TZ1 influence each other in case of power exchange due to under or oversupply. The assumed generation costs for distributed gas and bio energy are taken from (Pregger 2012)<sup>118</sup>

#### Main Results: After Curtailment, Distributed Generation and Demand (TZ2)

- Solar photovoltaic is the only generation technology at DZ level
- Lowest generation costs due to high utilization of gas at TZ level
- Average generation costs at DA level constantly higher than those in TZ accept during two short periods with high wind penetration and low dispatch utilization

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### 9.2.5 Key Results: Specific Generation Costs Across all Grid Levels

The economic analysis of the [R]E 24/7 model calculates the relative change of generation costs by technology and grid level and identifies specific dispatch costs and resulting supply costs e.g. for customers. Individual generation costs for each dispatch power plant are calculated in relation to the degree of utilization factor of the total installed capacity. This assumption leads to cost spikes for dispatch capacities. : If dispatch power plants would only operate with a small fraction of their total installed capacity, specific generation costs can peak by a factor 20 or more. This methodology has been chosen in order to accomplish a quantitative costs analysis with a single model run.

The key results of model runs shown in Figure 86, Figure 87, Figure 88 and Figure 89 are the following:

- Short periods of dispatch requirements with low capacity utilization factor leads to costs spikes which impact average supply costs
- Reversed dispatch order to accommodate utilization factors can reduce average supply costs significantly without actual changes of installed capacity within the cluster
- Shared dispatch capacities across different voltage levels increases utilization factor and decreases average supply costs
- The distribution of load and generation capacity by voltage level influences supply costs and can be used to reduce costs and grid expansion requirements

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## **9.3 Specific Generation Costs for the DZ level**

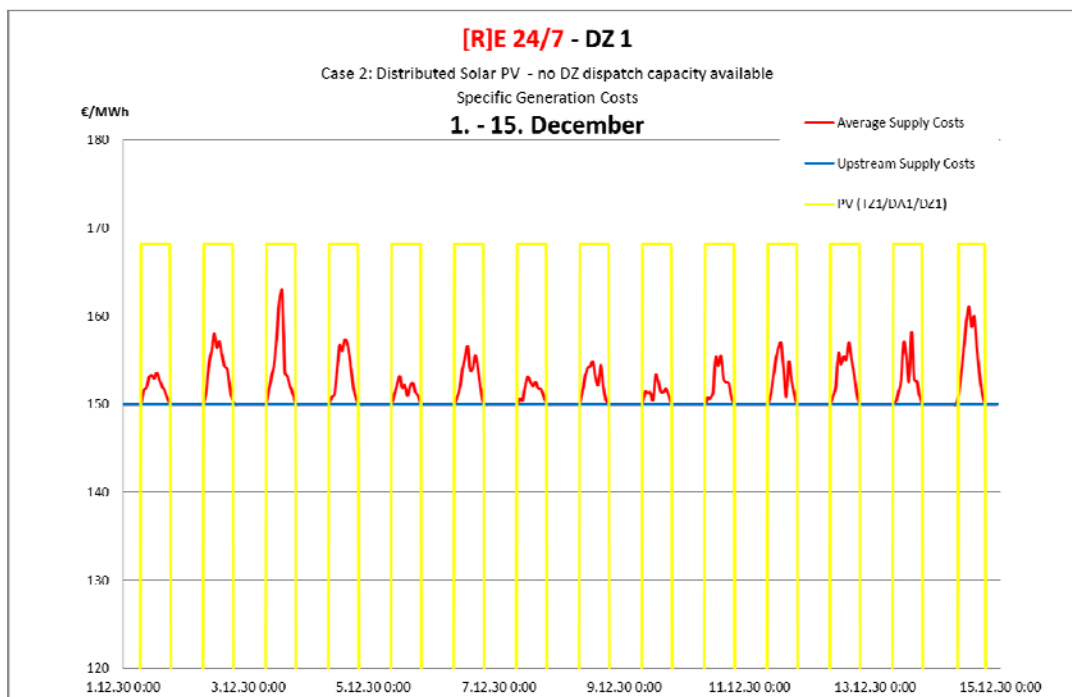
This section provides an overview of the financial calculations for the low voltage clusters scenarios documented in Chapter 8.6 Simulation of Low Voltage Clusters under Various Dispatch Options. Four different situations for the low voltage level *DZ* have been modeled with various dispatch options to analyze the effect of large distributed generation shares in terms of demand and supply patterns and their economic effects:

- Case 1A: Energy demand on *DZ* level only supplied with power generation capacity from outside the cluster
- Case 1B: Energy demand on *DZ* level – same supply conditions as case 1A but with grid limit reached
- Case 2 Energy demand on *DZ* supplied partly with decentralized solar photovoltaic generators within the cluster (Figure 83)
- Case 3: Energy demand on *DZ* supplied to 100% by a mix of decentralized power generation capacities from within the cluster (Figure 84)
- Case 4: Energy demand on *DZ* supplied by a mix of decentralized power generation and storage capacities from within the cluster (Figure 85)

For the cost analysis of this section only case 2, 3 and 4 have been calculated, because different generation concepts are reflected. In order to be consistent, the same costs assumptions as in chapter 9.2 – including the capacity utilization factor – has been used.

### 9.3.1 Costs Analysis Case 2: Energy demand on *DZ* supplied partly with decentralized solar photovoltaic generators within the cluster

Figure 90 shows specific generation costs for case 2 (Figure 83), a mix of decentralized solar photovoltaic electricity and power generated in other clusters. The blue line identifies the electricity supply costs from upstream power generation and grid costs – here 0.15 cents per kWh. The yellow lines show the solar photovoltaic generation costs of 0.17 cents per kWh and the red line represents total supply costs for the DZ1 cluster. Total supply costs are average regional power generation costs (e.g. solar pv and bio energy) and upstream electricity costs. In case 2 the resulting supply costs are increasing whenever solar photovoltaic generators are used.



**Figure 90:** Case 2 - Low voltage level (DZ) supply with decentralized solar generation – electricity costs from higher voltage levels including grid costs 0.15 cents / kWh.

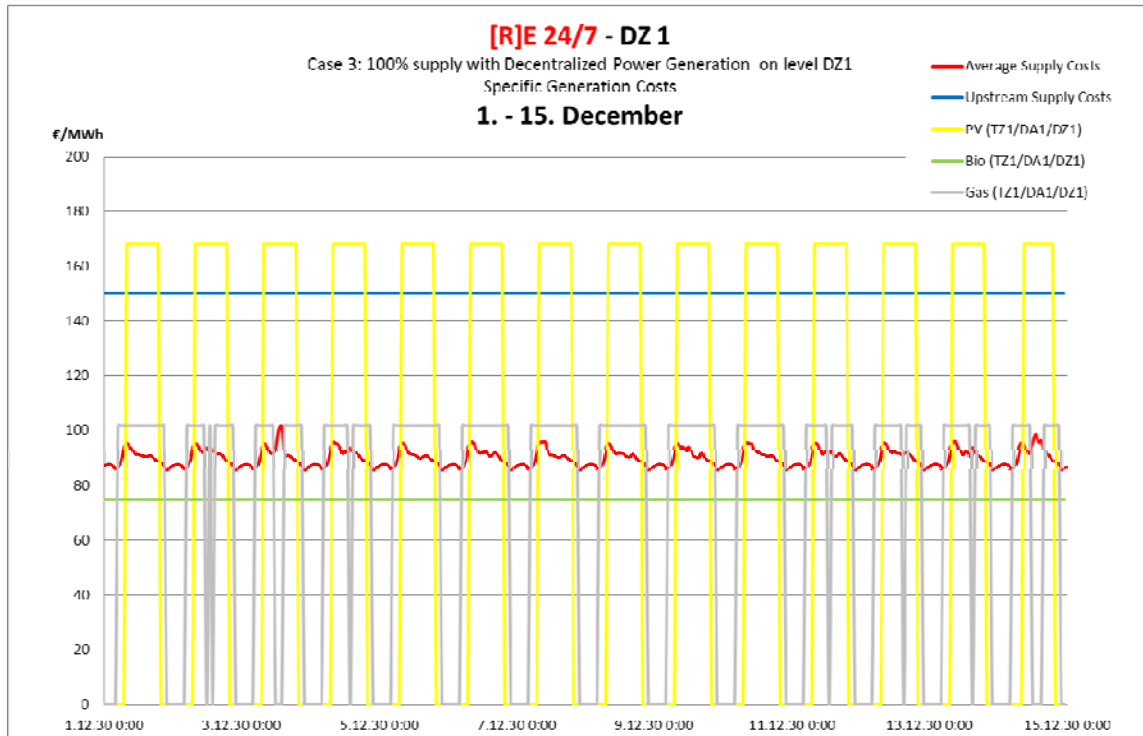
#### Main Results: Case 2 - Figure 90

- Solar photovoltaic is the only generation technology at DZ level
- Dispatch power from higher voltage levels
- Solar photovoltaic increases costs for supply case 2 significantly

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#### 9.3.2 Costs Analysis Case 3: Energy Demand on DZ Supplied to 100% by a Mix of Decentralized Power Generation Capacities from Within the Cluster



**Figure 91:** Case 3 - Low Voltage Level (DZ) - 100% Supply with Decentralized Solar- Bio- and Gas Power Generation – Electricity Costs from Higher Voltage Levels including Grid Costs 0.15 cents / kWh.

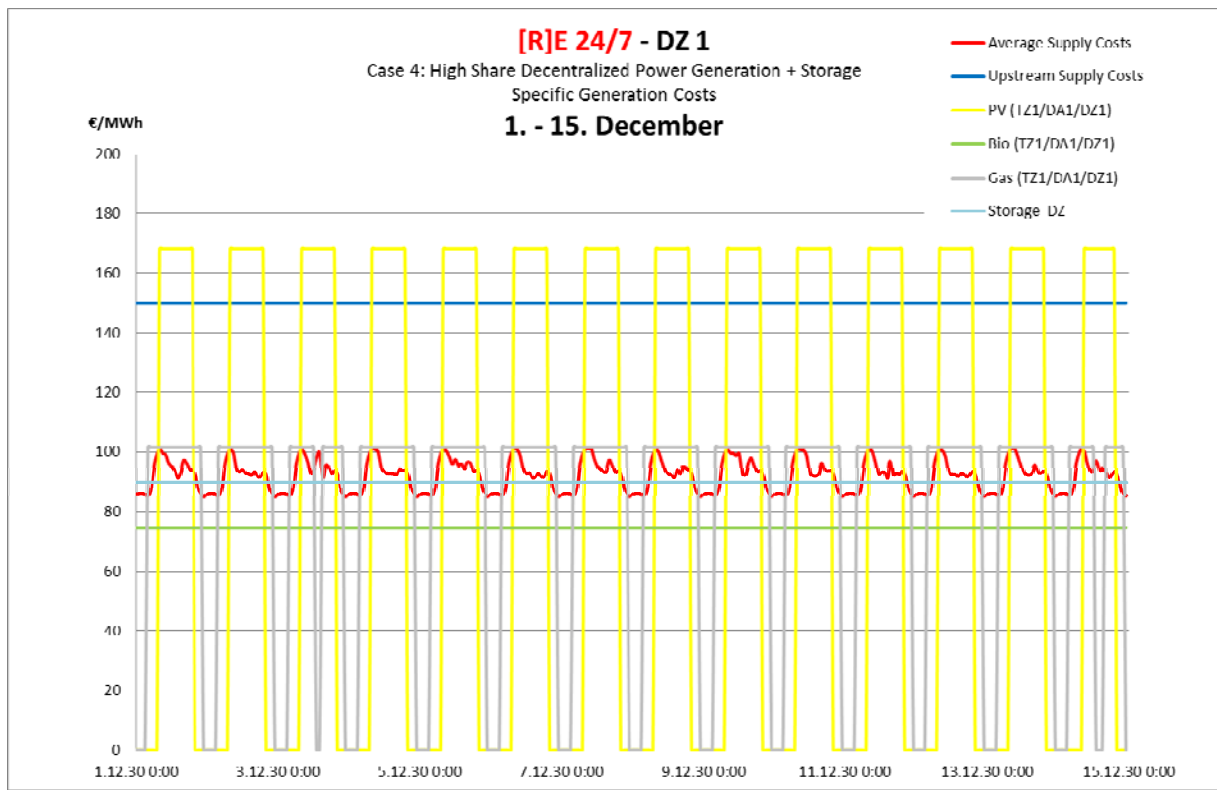
Case 3 shown in Figure 91 covers 100% of the demand of the cluster with decentralized generation capacity. It does not require any upstream electricity supply as it uses the *DZ* dispatch power plants but without any storage capacities. Both, regional bio energy and gas power generation, produces below upstream power costs, while solar pv produces just above up stream power supply costs. As a result, the average supply costs (red curve) of DZ oscillate between 9 and 10 cents and therefore significantly below the assumed upstream supply costs of 0.15 cents per kWh.

#### Main Results: Case 3 - Figure 91

- High capacity utilization of dispatch power (bio + gas) allow economic operation with costs below upstream supply costs – even with 100% autonomous cluster supply
- High solar photovoltaic use increases average generation costs by up to 20% but still remains under upstream supply costs



### 9.3.3 Costs Analysis Case 4: Energy Demand on DZ Supplied by a Mix of Decentralized Power Generation and Storage Capacities from Within the Cluster



**Figure 92:** Case 4 - Low Voltage Level (DZ) Supply with Decentralized Solar- Bio- and Gas power Generation plus Storage Generation – Electricity Costs from Higher Voltage Levels including Grid Costs 0.15 cents / kWh.

Finally case 4 shows supply costs for a cluster which covers 80% of its peak load demand with decentralized power generation while the remaining demand still requires upstream power supply. However the storage costs are assumed to be 9 cents/kWh, equal to average supply costs of all power generation capacities within the cluster. In order to avoid higher average supply cost of case 3 (100% supply – no storage) peak demand will be delivered from upstream generation outside of the cluster. The average supply costs in case 3 and 4 are equal, but use different concepts. In case storage costs will fall supply from higher voltage level could be reduced accordingly.

#### Main Results: Case 4 - Figure 92

- High capacity utilization of dispatch power (bio + gas) allow economic operation with costs below upstream supply costs
- Costs of high solar photovoltaic penetration are managed with a mix of storage capacity utilization and upstream power supply
- 80% self-supply with storage results in the same average generation costs as 100% self-supply (case 3), but requires less over capacities within the cluster

### **Bridging the Gap Between Energy- and Grid Models:**

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#### **9.3.1 Key Results: Specific Generation Costs for the DZ Level**

The cost analysis of three different supply strategies demonstrate the function of the economic calculation module of the [R]E 24/7 model. The results documented in Figure 90, Figure 91 and Figure 92 show how this tool can be used to test different supply strategies, and can also be used to evaluate a business concept e.g. for small scale utilities. The main findings are:

- High capacity utilization of dispatch power (bio + gas) allow economic operation with costs below upstream supply costs – even with 100% autonomous cluster supply
- Costs of high solar photovoltaic penetration can be managed with the utilization of storage capacity and upstream power supply
- A combination of self-supply within a cluster, storage and usage of upstream supply can decrease average generation costs while increase utilization factor for dispatch power plants

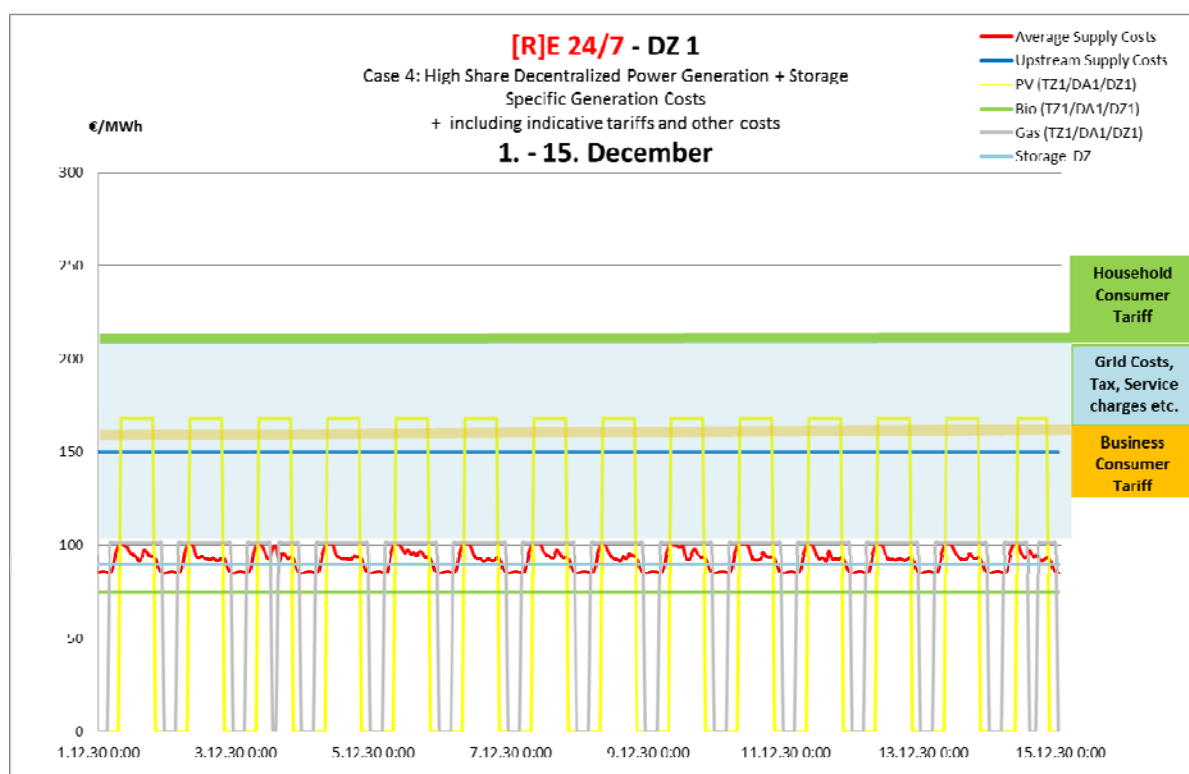
#### **9.3.2 Areas of Application for the Economic Analysis of DZ Clusters**

Section 9.2 and 9.3 provide an overview of the function of the [R]E 24/model and possible results. The aim of this costs analysis is to find the most economic supply mix for specific clusters and/or customers. Whether or not 100% self-supply of a cluster over one or more voltage level is cost efficient, or if centralized shared dispatch capacity is more economic can be simulated with this tool.

While the EN model has more advantages for grid simulation of regions with meshed and interconnected transmission grids, the [R]E 24/7 economic module has a clear advantage when undertaking the cost calculations for various power generation supply strategies.

Grid costs, taxes or service charge can be added either via the costs allocation for grid related processes (see Figure 42) or as additional parameter after the generation cost calculation took place. An example for the latter is shown in Figure 93.

Average and specific generation costs of case 4 are set in relation to different consumer tariffs and costs beyond the actual power generation – which make up the other important elements of power tariff calculations.



**Figure 93:** Case 4 - Low Voltage Level (DZ) Supply with Decentralized Solar- Bio- and Gas Power Generation plus Storage Generation – Plus Indicative Costs Extras and Tariffs

The average supply costs of the generation mix for case 4 (Figure 93) would be economically viable for the household consumer tariffs which adds up to 210 Euro per MWh including grid costs, tax and service charges. However the business consumer tariff of 160 Euro per MWh would require lower generation costs as grid costs, tax and service charges are fixed at around 100 Euro per MWh. In this case a bio and gas power generation mix – excluding solar – would lead to an economic generation mix.

This represents a simplified example to illustrate the function of this application. If other components such as batteries and/or other power producers from higher voltage levels are added, more complex calculations are possible with this model.

## 9.4 Conclusion: Economic Module

The economic calculation module of the [R]E 24/7 is connected to the physical flow simulation and cannot be separated. Thus the data volume of the economic calculation is very large and leads to calculation times of 2 hours for one month. This is a weakness of the program as economic calculations for a whole year would require 12 separate simulations if a personal computer with 8 GB RAM is used. However specific generation costs for all technologies and each grid level can be calculated to analyze supply costs for various cases.

Low utilization shares for dispatch power plants lead to cost spikes of a factor of 20 and higher above average specific generation costs which increase calculated dispatch costs significantly. These cost spikes have a great influence on the entire system cost analysis and may add up significantly across all grid levels. Thus a careful evaluation of simulation results is required, as possible high dispatch costs may only occur rarely throughout the entire year.

This methodology has been chosen in order to accomplish a quantitative costs analysis with a single model run. As opposed to a capacity factor based cost analysis, which requires two model runs: The first one to calculate the actual resulting capacity factor for each power plant, and a second for the cost analysis based on the calculated capacity factor.

This approach also mirrors the recent energy debate in Germany which has focussed on whether 'capacity markets' or 'energy-only markets' should be used in the German Energiewende (BMW<sup>i</sup> 2015<sup>119</sup>), Germany's transition to an energy portfolio dominated by renewable energy and energy efficient technologies. The methodology used in this chapter reflects the 'energy-only-market' approach, even though several different possibilities for the cost calculations of dispatch power plants are possible as well.

The decision to base dispatch costs on capacity utilization factors is a political, and aims to penalize overcapacity. The aim of this chapter is to simply verify the mathematical correctness of the [R]E 24/7 model. Results documented in chapter 9.2 and 9.3 are based on the assumption that capacity utilization factors are used. Changed assumptions for dispatch costs would lead to significantly different costs.

The analysis of average supply costs by voltage levels has been tested and model results of various simulations indicate reliable functioning. However the calculation of negative electricity flows, from low voltage levels towards high voltage levels is not possible as negative costs occur and the software does not allow individual changes of the economic calculation formulas. This represents an additional weakness of the program.

Supply costs for each voltage level add up from TA to DZ which allows calculations of all the up-stream supply costs for customers of each voltage level. The overall supply costs for a customer connected to the distribution area (DA) are a composition of average power generation costs of level TA, TZ and DA. Additional costs like assumed

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grid costs are taken into account with specific costs for each transformer process. However first simulations have been done without assumed grid costs in order to better control the accuracy of all power generation cost calculations.

To calculate costs for required grid expansion parallel to the system cost analysis is not effective as the decision to expand the power transport capacity would be a result of this analysis. Therefore the calculation for required investments in new power lines must take place after the overall system costs analysis is completed.

To conclude, the economic module of the [R]E 24/7 model allows the calculation of hourly supply costs for each cluster and across all grid levels. Detailed analysis for clusters under various supply compositions are possible and can be utilized for bottom-up cost calculations. However the high data volume does not allow an annual cost analysis with a single model run, and the lack of an optimization function represents a program weakness.

## 10. Conclusion

Due to the sharp increase of solar and wind power generation numerous scientific institutions are currently developing new grid modeling tools. Countries that have high shares of fluctuating renewable electricity in the power grid already invest in research programs including: the US Department of Energy (DoE) in cooperation with Pacific North west Laboratories<sup>120</sup>, the *Smart-Grid Initiative* from the Danish Ministry of Climate, Energy and Buildings<sup>121</sup>, the German Ministry of Economics and Energy (BMWi) in cooperation with the German Energy Agency (DENA)<sup>122</sup> or the “10 Year Development Plan” (TNYDP) for the European Union coordinated by European Network of Transmission System Operators for Electricity (ENTSO-E)<sup>123</sup>.

Thus numerous grid models are currently in use or under development worldwide. Their main tasks are transmission grid planning in order to transport large quantities of medium and large scale renewable power generation mainly onshore and offshore wind, and the integration of distributed generation – predominantly solar photovoltaic – in distribution networks.

In this context this thesis aimed to develop an integrated infrastructural planning model for 100% renewable energy systems to bridge the gap between energy scenarios and power grid simulation programs. It also aimed to reflect the two challenges – transmission and distribution grid planning – in a new simulation tool in order to optimize the interaction of flexible power generation, smart grids and storage technologies.

### *Thesis*

A bottom-up energy model which reflects multiple voltage levels of power systems and a time resolution adequate for dispatch analysis can be used as an infrastructural planning tool and bridge the gap between detailed grid simulation tools and energy scenarios. This model may be used to assess approximate indications of required grid capacities and to carry out economic calculations for alternative measures to grid expansion such as storage or demand side management. The exogenous optimization process takes place bottom-up, from the lowest voltage level to the highest in order to reduce electricity transport and to use local resources as efficient as possible.

The assumption of this thesis is that bottom-up models for 100% RE grids have advantages over top-down models, because possible bottlenecks in power grid systems can be allocated to the voltage level in which they appear. Increasing shares of solar photovoltaic systems are mainly connected to distribution grids and possible measures for a better integration can be calculated at all different voltages levels to find the most economical solution.

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### *Development of a New Methodology*

On the basis of three Meta studies (Knopf et. al. 2012, IPCC 2011 and Connolly et. al. 2009) the best suitable modeling methodology for energy scenarios which provides the required interface for an infrastructural planning tool has been identified. The [R]E 24/7 methodology seeks to find the best possible combination between high resolution input and output, data availability and data volume on one hand, and largest possible scope and transferability to various world regions and network conditions on the other hand. Thus energy models with high technical, regional and temporal resolution are most suitable.

The analysis of seven grid models with different purposes and therefore different methodologies lead to a categorization according to their characteristics:

- *Transmission Grid Models* for infrastructural planning (RWTH11-201240); (van Hulle 200943); (Tröster et.al. 2011<sup>51</sup>)
- *GIS Cluster Models* for the optimal distribution of power generation (Scholz 2012<sup>38</sup>)
- *Economic Models* to calculate trade-off between network expansion and non-network expansion related measures (Langham 2011<sup>63</sup>)
- *Distribution Grid Models* for infrastructural planning (DENA 2012<sup>71</sup>); (Gwisdorf et.al. 2010<sup>72</sup>)

In order to combine the modeling of transmission and distribution grids in an interconnected system, a new methodology to simulate the required three-dimensions was necessary. The combination of the grid node and cluster methodology allows simulation of electricity flows throughout a network with different voltage levels, but has the disadvantage that relatively large amounts of data for a region are required. The grid node methodology was chosen for the simulation of the upper voltage levels, while the cluster methodology is intended to reflect the distribution network level.

The merit order of power generation capacities is reflected with a dispatch order function which can be changed in each cluster. Usually decentralized solar and wind capacities will be dispatched ahead of capacities from higher voltage levels in the [R]E 24/7 model, but a prioritization of solar and wind capacities from higher voltages ahead of dispatch capacities from lower voltage levels is also possible.

Multiple simulations with original input data of a case calculated with the EN model have been carried out to compare EN outputs with those of [R]E 24/7 in order to calibrate the model and to test mathematical correctness of results. The comparison leads to a deviation of +/- 1% for the demand curves and +/- 5% for solar and wind generation curves which indicate a correct simulation of both load flows. Dispatch capacities however deviate also with equal dispatch order assumptions by +/- 3%.

To conclude, the [R]E 24/7 model can re-calculate EN results that are mathematically correct within an error of +/-5%. If generation capacities are further distributed and bottom-up dispatch order is used the deviations can increase to +/- 15% and more. Furthermore a comparison of a power grid analysis for multiple grid nodes or entire

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countries with the different model architectures of EN and [R]E 24/7 will lead with a high probability to divergent results which might not allow a direct comparison due to methodological differences.

The EN model concentrates all demands and supply into one grid node while [R]E 24/7 distributes the same data over 21 clusters – each with its own dispatch order, power generation capacities and demand curves. Thus the [R]E 24/7 model leads to 21 different residual loads for each EN grid node even when the overall annual demand and supply structure is identical. Therefore only minor variations of assumptions for clusters lead to significantly different results.

In addition, the demarcation problem documented in chapter 8 leads to different simulation results as well. The EN model simulates a meshed system in which power can flow over neighboring grid nodes back into the analyzed region (loop-flows), while the [R]E 24/7 model defines clear boundaries. In addition, the load flows in clear defined cascades top-down or vice versa and therefore possible loop flows are not recognized.

### ***Economic Calculation Module***

The economic calculation module of the [R]E 24/7 model is connected to the physical flow simulation and cannot be separated which causes high data volumes. Specific generation costs for all technologies and each grid level can be calculated to analyze average hourly supply costs for various cases. The analysis of average supply costs by voltage level has been tested and model results of various simulations indicate reliable functioning. When the assumed capacity utilization factor is based on cost calculations for dispatch power plants, low utilization shares for dispatch power plants lead to cost-spikes of a factor of 20 and higher, above the average generation costs, which increases the calculated dispatch costs. These cost-spikes have a great influence on the entire system cost analysis and may significantly add up across all grid levels. However this assumption is not in the focus, but to test and verify the mathematical correctness of [R]E 24/7 results is.

Thus a careful evaluation of simulation results is required as possible high dispatch costs may only rarely occur throughout the entire year. To calculate costs for required grid expansion parallel to the system cost analysis is not effective as the assumed high costs will lead to further cost-spikes which could be mistaken as dispatch costs. In order to make the analysis more transparent the calculation for required investments in new power lines should take place after the overall system costs analysis is completed.

### ***Has Bottom-Up Grid Modeling Advantages Over Top-Down Modeling?***

The assumption of this thesis was that bottom-up models for 100% RE grids have advantages over top-down models, because possible bottlenecks in power grid systems can be allocated to the voltage level in which they appear. While increasing shares of solar photovoltaic system are mainly connected to distribution grids and therefore possible measures for a better integration can be simulated close to the generation capacity, onshore and offshore wind capacities connected to medium and



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high voltage transmission are also rapidly increasing. Thus a bottom-up optimization might not necessarily lead to the best use of all available renewable power capacities.

Calculations with different settings of bottom-up and top-down priorities are documented in Chapter 8. Results indicate that when high shares of solar pv are connected to the distribution grid and high shares of onshore and offshore wind are connected to the transmission grid, a strict bottom-up optimization would lead to a greater utilization of dispatch or storage capacities from lower voltage levels. Thus available wind capacities would not be used sufficiently.

An advantage of bottom-up modeling, however, is the analysis of individual clusters. These can be calculated with a great level of technical detail with different supply concepts and/or changing load profiles, both in terms of the load flow and required grid capacities as well as with different economic assumptions. The [R]E 24/7 allows the separate calculation of individual clusters.

The chosen software MESAP/PlaNet has never been used to model electricity grids and the high time resolution of one hour in combination with load flow calculation with a high possibility of reverse flows made it necessary to develop new mathematical functions and use multi-level sub-processes such as the *Dispatch* process and the *Power Flow Manager* process.

Programming the model required the progression of various new processes, sub-processes, external and internal commodities needed to simulated power grids. All parts of the model, especially those required for grid simulations with all necessary parameters have been constantly accompanied with test runs to verify the mathematical correctness of the model results.

To conclude, the model has been successfully programed as outlined in the thesis with commercially available software. A new three-dimensional methodology has been developed on the basis of a combination of two existing grid analysis methodologies and model results have been verified.

### *Strength*

The [R]E 24/7 model can be applied for different regions. The topographical concept documented in chapter 6 makes it possible to calculate different regions and adopt other voltages for power lines without changing the model architecture. The great level of technical details and the possibility to add new technology processes represents an advantage of the model. In combination with the standardized data input concept documented in chapter 7 parameters can both be collected and uploaded quickly.

Clearly defined regions such as cities, communities or islands can be simulated with the model developed for this thesis. The economic calculation module delivers specific hourly average supply costs which allow detailed cost calculations for specific clusters or specific voltage levels. In addition the cost module allows detailed simulations for the financial flow across all voltage levels and enables the modeler to include external and/or political costs as well.

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### **Bridging the Gap Between Energy- and Grid Models:**

Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

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The implemented standard reports, an interface between the SQL database and Excel, allows a quick evaluation and visualization of all modeling results. All figures of [R]E 24/7 model outputs in chapter 8 and 9 are based on these standard reports and a reliable and fast reproduction of this visualization with changed assumptions is possible.

### ***Weaknesses***

The [R]E 24/7 model has been programmed to reflect a great level of technical details across all voltage levels. The advantage of a detailed technological simulation in three dimensions – across all voltage levels – also turns out to be a disadvantage. The large number of input values – 18,000 for the entire [R]E 24/7 model – leads to a high number of variables which made an optimization process impractical. The lack of an optimization function represents one of the main weaknesses of the model.

The economic calculation module is based on the physical flow calculation and cannot be separated. This leads to very large data volumes and therefore extensive calculation times. This is a weakness of the program as economic calculations of a whole year are not possible without mainframes. A time series longer than two months is not possible because data volumes would exceed the data limit of SQL as well as those of average personal computer.

Furthermore pure grid node models which simulate meshed power systems reflect load flows in large scale interconnected transmission systems better than combined grid node and cluster models. The high data volume of the [R]E 24/7 does not allow the simulation of large regions with multiple grid nodes.

Finally the economic calculation of negative electricity flows, from low voltage level towards high voltage levels, is not possible as negative costs would occur which represents an additional weakness of the program.

### ***Further Research Needs***

In order to calibrate and verify the model further, comparisons with other model outputs which use different methodologies, as well as the re-calculation of specific documented events in distribution and transmission grids are required. Especially the simulation of load flows across several voltage levels and grid nodes with real power grid data is needed to further evaluate the three-dimensional grid-node cluster methodology developed for this thesis. The empirical comparison of grid simulation programs categorized in grid-node, cluster and hybrid models is required in order to further evaluate the strengths and weaknesses of various grid simulation methodologies.

The influence of cluster sizes and chosen grid node positions on calculation results requires further research. The interaction of neighboring low voltage clusters, which are connected to a wider network within a meshed grid node system, should be further explored in order to adopt a simulation algorithm for the new developed methodology.

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It possible to create interfaces between measured data from smart meters, distributed generation and wind turbines and the programmed [R]E 24/7 model with MESAP/PlaNet. Uploading measured data further supports additional calibration work to verify and expand the model. By transferring [R]E 24/7 from a laptop to a mainframe a further expansion from a single TA to multiple TA would enable the calculation of large regions e.g. Germany.

Development of an optimization algorithm connected to the model while keeping the three-dimensional grid simulation methodology eliminates the main weakness and expands application areas for [R]E 24/7. Furthermore a GIS based mapping tool in combination with the standard report tool would improve visualization and evaluation options.

### **Bridging the Gap Between Energy- and Grid Models:**

Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

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## **ANNEX**

A1.1: Input Sheets – Transfer ENERGYNAUTICS

Copy from Sheet "EN Summary for Transfer" with NO LINKS in order to copy it into the "Inputsheet Master-1 year"																				
NUR DK02 = TZ1 und DE03 = TZ2 - REST ausgeblendet																				
Installed Cap		Total Installed capacity per grid knot in [MW]																		
Gas	DE03 = TZ2	467																		
Gas	DK02 = TZ1	1.044																		
Coal	DE03 = TZ2	132																		
Coal	DK02 = TZ1	0																		
Nuclear	DE03 = TZ2	0																		
Nuclear	DK02 = TZ1	0																		
Biomass	DE03 = TZ2	401																		
Biomass	DK02 = TZ1	376																		
CSP	DE03 = TZ2	0																		
CSP	DK02 = TZ1	0																		
Geothermal	DE03 = TZ2	0																		
Geothermal	DK02 = TZ1	0																		
Ocean	DE03 = TZ2	0																		
Ocean	DK02 = TZ1	0																		
Hydro run-of-river	DE03 = TZ2	0																		
Hydro run-of-river	DK02 = TZ1	0																		
Hydro storage	DE03 = TZ2	187																		
Hydro storage	DK02 = TZ1	0																		
Levelized per UNIT installed capacity (Wind Generation in [MW/h] geteilt durch installed capacity in [MW]) => CALCULATED IN THE ORIGINAL SHEET not on this sheet!		1.1.30 0:00	1.1.30 1:00	1.1.30 2:00	1.1.30 3:00	1.1.30 4:00	1.1.30 5:00	1.1.30 6:00	1.1.30 7:00	1.1.30 8:00	1.1.30 9:00	1.1.30 10:00	1.1.30 11:00	1.1.30 12:00	1.1.30 13:00	1.1.30 14:00	1.1.30 15:00	1.1.30 16:00		
Wind Onshore	DE03 = TZ2	4396,18	0,66	0,66	0,66	0,66	0,66	0,66	0,66	0,66	0,62	0,57	0,53	0,49	0,47	0,46	0,45	0,43		
Wind Onshore	DK02 = TZ1	2141,54	0,89	0,88	0,88	0,87	0,86	0,86	0,85	0,84	0,83	0,82	0,80	0,84	0,78	0,76	0,74	0,72		
Wind Offshore	DE03 = TZ2	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		
Wind Offshore	DK02 = TZ1	2004,95	0,56	0,57	0,57	0,58	0,58	0,58	0,59	0,60	0,60	0,61	0,61	0,64	0,59	0,58	0,56	0,53		
Photovoltaics	DE03 = TZ2	3668,21	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		
Photovoltaics	DK02 = TZ1	372,52	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,01	0,02	0,05	0,03	0,01	0,00	0,00		
Max load																				
Energyconsumption	Unit MW	DE02	DE03 = TZ2	DE04	DE05	DK02 = TZ1														
E in MWh		0	0	0	0	0														
Full load hours		0	0	0	0	0														
Mfn		149	2.563	316	46	644														
Average		255	4.379	540	78	1.169														
Max		352	6.048	745	107	1.844														
total in MWh/a		2.235.773	38.362.855	4.728.648	681.249	10.236.173														
Time		01.01.2030 00:00	01.01.2030 01:00	01.01.2030 02:00	01.01.2030 03:00	01.01.2030 04:00	01.01.2030 05:00	01.01.2030 06:00	01.01.2030 07:00	01.01.2030 08:00	01.01.2030 09:00	01.01.2030 10:00	01.01.2030 11:00	01.01.2030 12:00	01.01.2030 13:00	01.01.2030 14:00	01.01.2030 15:00	01.01.2030 16:00		
Total 5 Knots	Unit MW/h	5666	5475	5241	5034	4909	4756	4509	4540	4612	4854	5176	5489	5609	5536	5491	5515	5797		
Demand	DE02	221	213	204	196	191	184	171	171	174	185	197	211	216	213	211	211	218		
Demand	DE03	3784	3656	3500	3363	3282	3159	2932	2934	2983	3167	3383	3621	3711	3662	3622	3615	3740		
Demand	DE04	466	451	431	415	405	389	361	362	368	390	417	446	457	451	446	446	461		
Demand	DE05	67	65	62	60	58	56	52	52	53	56	64	66	65	64	64	64	66		
Demand	DK02	1128	1090	1043	1001	973	967	992	1021	1035	1055	1119	1147	1158	1144	1147	1179	1311		
Demand in MW/h >>>		01.01.2030 00:00	01.01.2030 01:00	01.01.2030 02:00	01.01.2030 03:00	01.01.2030 04:00	01.01.2030 05:00	01.01.2030 06:00	01.01.2030 07:00	01.01.2030 08:00	01.01.2030 09:00	01.01.2030 10:00	01.01.2030 11:00	01.01.2030 12:00	01.01.2030 13:00	01.01.2030 14:00	01.01.2030 15:00	01.01.2030 16:00		
Demand	DE02	1.000	220.530	213.094	203.996	195.998	191.281	184.105	170.877	170.974	173.827	184.583	197.177	211.025	216.267	213.409	211.092	210.664	217.987	
Demand	DE03		3.784.032	3.656.407	3.500.297	3.363.053	3.282.118	3.158.989	2.932.024	2.933.680	2.982.644	3.167.196	3.381.297	3.620.908	3.710.844	3.661.807	3.622.060	3.614.715	3.740.366	
Demand	DE04		466.420	450.693	431.451	414.534	404.558	389.380	361.405	361.600	367.644	390.392	417.028	446.317	457.403	451.358	446.459	445.554	461.042	
Demand	DE05		67.196	64.931	62.158	59.721	58.284	56.097	52.067	52.096	52.966	56.243	60.080	64.300	65.897	65.026	64.321	64.190	66.422	
Demand	DK02		1.127.701	1.089.825	1.043.072	1.001.053	972.646	967.024	992.472	1.021.175	1.035.378	1.055.500	1.118.528	1.146.935	1.158.180	1.144.272	1.146.639	1.179.485	1.311.163	
A) Von dem Gesamt-Demand nehmen ich einen Prozentanteil der in HH-SH je für die Industrie und für den Handel gebraucht wird. Die Economic Activity ist dan jeweils "1"																				
B) Den restl. Demand pro Stunde wird geteilt durch die Einwohner-Zahl von SH + HH... und das gibt das Profil pro Person.																				
C) Dann teile ich die Einwohner je nach Region auf und trage die jeweilige Einwohnerzahl in das Smart Demand Sheet ein - und verbinde mit dem in A + B erzeugten (3 unterschiedlichen - Industrie, Handel und Privat) Profilen																				
A) Industry Profiles (TA)		Demand in GW/h		Share from Minimum Load																
		Time	01.01.2030 00:00	01.01.2030 01:00	01.01.2030 02:00	01.01.2030 03:00	01.01.2030 04:00	01.01.2030 05:00	01.01.2030 06:00	01.01.2030 07:00	01.01.2030 08:00	01.01.2030 09:00	01.01.2030 10:00	01.01.2030 11:00	01.01.2030 12:00	01.01.2030 13:00	01.01.2030 14:00	01.01.2030 15:00	01.01.2030 16:00	
		DE02																		
		DE03 = TZ02	0%	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	
		DE04																		
		DE05	0%	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	0,00000	
DK02 = TZ1																				
A) Industry Profiles (TZ)		Demand in MW/h		Share from Minimum Load																
		Time	01.01.2030 00:00	01.01.2030 01:00	01.01.2030 02:00	01.01.2030 03:00	01.01.2030 04:00	01.01.2030 05:00	01.01.2030 06:00	01.01.2030 07:00	01.01.2030 08:00	01.01.2030 09:00	01.01.2030 10:00	01.01.2030 11:00	01.01.2030 12:00	01.01.2030 13:00	01.01.2030 14:00	01.01.2030 15:00	01.01.2030 16:00	
		DE03 = TZ02	33%	1261,33	1218,80	1166,77	1121,02	1094,04	1053,00	977,34	977,89	994,21	1055,73	1127,76	1206,97	1236,95	1220,60	1207,35	1204,91	1246,79
		DE04																		
		DE05	33%	375,90	363,28	347,69	333,68	324,22	322,34	330,82	340,39	345,13	351,83	372,84	382,31	386,06	381,42	382,21	394,16	437,05
DK02 = TZ1																				
B) Business Profiles (DA)		Demand in MW/h		Total DA = Share from Total Demand (=baseline!) -> DA1, DA2, DA3, DA4 share from total DA Demand (!!!) NOT share from Minimum Demand -> so it is a subdivision!!!																
		Time	01.01.2030 00:00	01.01.2030 01:00	01.01.2030 02:00	01.01.2030 03:00	01.01.2030 04:00	01.01.2030 05:00	01.01.2030 06:00	01.01.2030 07:00	01.01.2030 08:00	01.01.2030 09:00	01.01.2030 10:00	01.01.2030 11:00	01.01.2030 12:00	01.01.2030 13:00	01.01.2030 14:00	01.01.2030 15:00	01.01.2030 16:00	
		DE02																		
		DE03 = TZ02/DA (total)	33%	1261,334009	1218,802299	1166,765761	1121,017771	1094,039418	1052,995838	977,3412399	977,893288	994,2147115	1055,720077	1127,762559	1206,969267	1236,947882	1220,602456	1207,353301	1204,905887	1246,788744
		TZ 2 / DA 1	25%	315,3335022	304,7005748	291,6914402	280,2544427	273,5098545	263,2489956	244,33531	244,473322	248,5536779	263,9330152	281,9405898	309,2369704	305,150614	301,8383252	301,2262718	311,697185	319,697185
		TZ 2 / DA 2	25%	315,3335022	304,7005748	291,6914402	280,2544427	273,5098545	263,2489956	244,33531	244,473322	248,5536779	263,9330152	281,9405898	309,2369704	305,150614	301,8383252	301,2262718	311,697185	319,697185
		TZ 2 / DA 3	25%	315,3335022	304,7005748	291,6914402	280,2544427	273,5098545	263,2489956	244,33531	244,473322	248,5536779	263,9330152	281,9405898	309,2369704	305,150614	301,8383252	301,2262718	311,697185	319,697185
		TZ 2 / DA 4	25%	315,3335022	304,7005748	291,6914402	280,2544427	273,5098545	263,2489956	244,33531	244,473322	248,5536779	263,9330152	281,9405898	309,2369704	305,150614	301,8383252	301,2262718	311,697185	319,697185
		CHECK with DE03-TZ02	100%	1261,334009	1218,802299	1166,765761	1121,017771	1094,039418	1052,995838	977,3412399	977,893288	994,2147115	1055,720077	1127,762559	1206,969267	1236,947882	1220,602456	1207,353301	1204,905887	1246,788744
DE04																				
TZ 1																				
DK02 = TZ01		33%	375,9003878	363,2750271	347,6905074	333,6843379	324,2151374	322,3412404	330,8239046	340,3915608	345,1260711	351,8332939	372,8426832	382,3117037	386,0598577	381,4229881	382,2130681	393,1616231	437,0544787	
		TZ 1 / DA 1	25%	93,97509694	90,81875677	86,92264936	83,42108448	80,5883101	82,70597616	85,0978902	86,28151776	87,95832348	93,2106708	95,7792594	96,51496443	95,35599577	95,5326703	98,29040577	109,2636917	109,2636917
		TZ 1 / DA 2	25%	93,97509694	90,81875677	86,92264936	83,42108448	80,5883101	82,70597616	85,0978902	86,28151776	87,95832348	93,2106708	95,7792594	96,51496443	95,35599577	95,5326703	98,29040577	109,2636917	109,2636917
		TZ 1 / DA 3	25%	93,97509694	90,81875677	86,92264936	83,42108448	80,5883101	82,70597616	85,0978902	86,28151776	87,95832348	93,2106708	95,7792594	96,51496443	95,35599577	95,5326703	98,29040577	109,2636917	109,2636917
		TZ 1 / DA 4	25%	93,97509694	90,81875677	86,92264936	83,42108448	80,5883101	82,70597616	85,0978902	86,28151776	87,95832348	93,2106708	95,7792594	96,51496443	95,35599577	95,5326703	98,29040577	109,2636917	109,2636917
		CHECK with DK02-TZ1	100%	375,9003878	363,2750271	347,6905074	333,6843379	324,2151374	322,3412404	330,8239046	340,3915608	345,1260711	351,8332939	372,8426832	382,3117037	386,0598577	381,4229881	382,2130681	393,1616231	437,0544787
G) Households Profiles (DA)		Demand in kW/h		Total DA = Share from Demand (TZ1+TZ2+DA)																
		Time	01.01.2030 00:00	01.01.2030 01:00	01.01.2030 02:00	01.01.2030 03:00	01.01.2030 04:00	01.01.2030 05:00	01.01.2030 06:00	01.01.2030 07:00	01.01.2030 08:00	01.01.2030 09:00	01.01.2030 10:00	01.01.2030 11:00	01.01.2030 12:00	01.01.2030 13:00	01.01.2030 14:00	01.01.2030 15:00	01.01.2030 16:00	
		DE02																		
		DE03 = TZ02/DA (Total)	kW/h	1.261.334	1.218.802	1.166.766	1.121.018	1.094.039	1.052.996	977.341	977.893	994.215	1.055.732	1.127.762	1.206.969	1.236.948	1.220.602	1.207.353	1.204.905	1.246.789
		Check Calculated Demand - total	MW	3.784	3.656	3.500	3.36													

Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

Smart Technical Input Sheet							
FERTIG AUSSER SIEHE UNTEN - NUR EINHEITEN NOCH NICHT VERLINKT!							
Power generation							
No		Process	Inputs which are the same in all clusters	With Meteo-Data Input	PV/Wind Generation Data		
1,00		PV Optimal / Power plant	Efficiency	0,16	1,00		
			Load factor	0,13	1,00		
			Technical lifetime		8760,00		
2,00		PV East-West	Efficiency	0,16	1,00		
			Load factor	0,13	1,00		
			Technical lifetime		8760,00		
3,00		PV-Storage	Efficiency	0,14	1,00		
			Load factor	0,13	1,00		
			Technical lifetime		8760,00		
4,00		CSP	Efficiency	0,23	1,00		
			Load factor	0,20	1,00		
			Technical lifetime		8760,00		
5,00		(Onshore) Wind	Efficiency	0,45	1,00		
			Load factor	0,25	1,00		
			Technical lifetime		8760,00		
6,00		Offshore Wind	Efficiency	0,45	1,00		
			Load factor	0,40	1,00		
			Technical lifetime		8760,00		
7,00		Wind Storage	Efficiency	0,43	1,00		
			Load factor		1,00		
			Technical lifetime		8760,00		
No		Process	Inputs which are the same in all clusters	Unit	Value		
8,00		Hydro Power Plant	Fuel efficiency		1,00		
			Technical lifetime		8760,00		
9,00		Bio Energy Power Plant	Fuel efficiency	0,38			
			Technical lifetime		8760,00		
10,00		Gas Power Plant	Fuel efficiency	0,51			
			Technical lifetime		8760,00		
11,00		Coal Power Plant	Fuel efficiency	0,34			
			Technical lifetime		8760,00		
12,00		Lignite Power Plant	Fuel efficiency	0,34			
			Technical lifetime		8760,00		
13,00		Nuclear Power Plant	Fuel efficiency	0,33			
			Technical lifetime		8760,00		
Grid And Storage							
			all values indicative!!				
No		Process	Inputs which are the same in all clusters	Unit	Value		
		Power Flow manager	Efficiency		0,99		
			Technical lifetime		8760,00		
		balance POS	Efficiency		0,98		
			Technical lifetime		8760,00		
		balance NEG	Efficiency		0,97		
			Technical lifetime		8760,00		
		Transformer/Connect	Efficiency		1,00		
			Technical lifetime		8760,00		
		Storage Load	Efficiency	0,95			
			Technical lifetime		8760,00		
		Storage Manager	Efficiency	0,94			
			Technical lifetime		8760,00		
Load							
No		Process	Attribute	Unit	Value		
		DZ 1 DZ 2 DZ 3 DZ 4	Single Flat [A]	Installed Capacity	kWh/h		
		DZ 1 DZ 2 DZ 3 DZ 4	Family Flat [B]	Installed Capacity	kWh/h		
		DZ 1 DZ 2 DZ 3 DZ 4	Townhouse [C]	Installed Capacity	kWh/h		
		DZ 1 DZ 2 DZ 3 DZ 4	Familyhouse [D]	Installed Capacity	kWh/h		

### A1.3: Input Sheets – Smart Demand

Input all Demands - TA					DEMAND				Legend:											
Attribute	Commodity	Einheit	Hypothese	TA 1					Input Data fields - connected to Import sheet											
Quantity of flow	Economic Activity (220kV)	Industry	#BEZUG!	REF	1.00					1.00	Connected to Import-Sheet									
Sub-Total Annual Demand in [TWh/a]: Industry	8760.00	Intensity	#BEZUG!	Profile						0.50	Calculated Values									
Sub-Total Annual Demand in [TWh/a]: TZ 1 - TZ2										2000.00	Data Input									
Total Annual Demand in [TWh/a]: TA1 - ONLY FOR INFORMATION - NO INPUT DATA					0.000					Population	legend for fields									
TA 1																				
Input all Demands - TZ					TZ 1	TZ 2														
Attribute	Commodity	Einheit	Hypothese	TZ 1	TZ 2															
Quantity of flow	Economic Activity	Industry	head/h	REF	1.00	1.00														
Sub-Total Annual Demand in [GWh/a]: Industry		Intensity	#BEZUG!	Profile																
Sub-Total Annual Demand in [GWh/a]: DA 1 - DA 4																				
Total Annual Demand in [GWh/a]: TZ1, TZ2 ORIGINAL DATA ENERGNATYICS - ONLY FOR INFORMATION - NO INPUT DATA					10.236	38.363														
TA 1											TZ 1 Schleswig Holstein				TZ 2 Hamburg					
Input all Demands - DA					DA1	DA2	DA 3	DA 4	DA1	DA2	DA 3	DA 4								
Quantity of flow	Economic Activity	Business	head/h	REF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00								
Sub-Total Annual Demand in [MWh/a]: Business		Intensity	#BEZUG!	Profile																
Sub-Total Annual Demand in [MWh/a]: DZ 1 - DZ4																				
Total Annual Demand in [MWh/a]: DA1,DA2; DA3, DA4 - ONLY FOR INFORMATION - NO INPUT DATA																				
											TZ 1 Schleswig Holstein									
					DA 1 (SH South)				DA 2 (SH WEST)				DA 3 (SH NORTH)				DA 4 (SH EAST)			
Input all Demands - DZ					DZ 1	DZ 2	DZ 3	DZ 4	DZ 1	DZ 2	DZ 3	DZ 4	DZ 1	DZ 2	DZ 3	DZ 4	DZ 1	DZ 2	DZ 3	DZ 4
Quantity of commodity	Population	Housing	head/h	REF	175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000	175.000
Quantity of commodity	Population	Business	head/h	REF	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Quantity of commodity	Population	Farms	head/h	REF	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Market share	Population	Single Flat [A]	[1]	REF	0.20	0.20	0.20	0.20	0.15	0.15	0.15	0.15	0.25	0.25	0.25	0.25	0.10	0.10	0.10	0.10
Average Demand for Profile - Multiplier in [kWh/a]	1000.00	Single Flat [A]	1.00	Profile																
Market share	Population	Family Flat [B]	[1]	REF	0.15	0.15	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.15	0.15	0.15	0.25	0.25	0.25	0.25
Average Demand for Profile - Multiplier in [kWh/a]	2500.00	Family Flat [B]	2.50	Profile																
Market share	Population	Townhouse [C]	[1]	REF	0.15	0.15	0.15	0.15	0.25	0.25	0.25	0.25								
Average Demand for Profile - Multiplier in [kWh/a]	3250.00	Townhouse [C]	3.25	Profile																
Market share - REST	Population	Familyhouse [D]	Rest		0.50	0.50	0.50	0.50	0.40	0.40	0.40	0.40	0.60	0.60	0.60	0.60	0.65	0.65	0.65	0.65
Average Demand for Profile - Multiplier in [kWh/a]	4000.00	Familyhouse [D]	4.00	Profile																
Market share	Population	Office [G0]	[1]	REF	0.10	0.15	0.20	0.15	0.10	0.15	0.20	0.15	0.10	0.15	0.20	0.15	0.10	0.15	0.20	0.15
Average Demand for Profile - Multiplier in [kWh/a]	40000.00	Office [G0]	40.00	Profile																
Market share	Population	Office [G1]	[1]	REF	0.20	0.15	0.20	0.15	0.20	0.15	0.20	0.15	0.20	0.15	0.20	0.15	0.20	0.15	0.20	0.15
Average Demand for Profile - Multiplier in [kWh/a]	150000.00	Office [G1]	150.00	Profile																
Market share	Population	Restaurant [G2]	[1]	REF	0.15	0.20	0.15	0.15	0.15	0.20	0.15	0.15	0.15	0.20	0.15	0.15	0.15	0.20	0.15	0.15
Average Demand for Profile - Multiplier in [kWh/a]	75000.00	Restaurant [G2]	75.00	Profile																
Market share	Population	Shop [G4]	[1]	REF	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15
Average Demand for Profile - Multiplier in [kWh/a]	50000.00	Shop [G4]	50.00	Profile																
Market share	Population	Backery [G5]	[1]	REF	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Average Demand for Profile - Multiplier in [kWh/a]	250000.00	Backery [G5]	250.00	Profile																
Market share	Population	Entertainment [G6]	[1]	REF	0.15	0.20	0.15	0.25	0.15	0.20	0.15	0.25	0.15	0.20	0.15	0.25	0.15	0.20	0.15	0.25
Average Demand for Profile - Multiplier in [kWh/a]	100000.00	Entertainment [G6]	100.00	Profile																
Market share - REST	Population	24 h Service [G3]	Rest		0.25	0.10	0.15	0.10	0.25	0.10	0.15	0.10	0.25	0.10	0.15	0.10	0.25	0.10	0.15	0.10
Average Demand for Profile - Multiplier in [kWh/a]	35000.00	24 h Service [G3]	35.00	Profile																
Market share	Population	Veg. Farms [L0]	[1]	REF	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Average Demand for Profile - Multiplier in [kWh/a]	200000.00	Veg. Farms [L0]	200.00	Profile																
Market share	Population	Diary Farms [L1]	[1]	REF	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Average Demand for Profile - Multiplier in [kWh/a]	300000.00	Diary Farms [L1]	300.00	Profile																
Market share - REST	Population	General Farms [L2]	Rest		0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Average Demand for Profile - Multiplier in [kWh/a]	400000.00	General Farms [L2]	400.00	Profile																
Total Market Share: Housing					0.50	0.50	0.50	0.50	0.60	0.60	0.60	0.60	0.40	0.40	0.40	0.40	0.35	0.35	0.35	0.35
Total Market Share: Business					0.75	0.90	0.85	0.90	0.75	0.90	0.85	0.90	0.75	0.90	0.85	0.90	0.75	0.90	0.85	0.90
Total Market Share: Farms					0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Sub-Total Annual Demand in [MWh/a]: Housing																				
Sub-Total Annual Demand in [MWh/a]: Business																				
Sub-Total Annual Demand in [MWh/a]: Farms																				
Total Annual Demand in [MWh/a]: DZ1,DZ2; DZ3, DZ4 - ONLY FOR INFORMATION - NO INPUT DATA																				
											TZ 2 Hamburg									
					DA 1 - HH - HARBURG (South)				DA 2 - HH (Zentrum) WEST				DA 3 HH - PI (NORTH)				DA 4 HH - EAST			
Input all Demands - DZ					DZ 1	DZ 2	DZ 3	DZ 4	DZ 1	DZ 2	DZ 3	DZ 4	DZ 1	DZ 2	DZ 3	DZ 4	DZ 1	DZ 2	DZ 3	DZ 4
Quantity of commodity	Population	Housing	head/h	REF	112.500	112.500	112.500	112.500	112.500	112.500	112.500	112.500	112.500	112.500	112.500	112.500	112.500	112.500	112.500	112.500
Quantity of commodity	Population	Business	head/h	REF	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Quantity of commodity	Population	Farms	head/h	REF	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Market share	Population	Single Flat [A]	[1]	REF	0.20	0.20	0.20	0.20	0.15	0.15	0.15	0.15	0.25	0.25	0.25	0.25	0.10	0.10	0.10	0.10
Average Demand for Profile - Multiplier in [kWh/a]	1000.00	Single Flat [A]	1.00																	
Market share	Population	Family Flat [B]	[1]	REF	0.25	0.25	0.25	0.25	0.15	0.15	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.15	0.15	0.15
Average Demand for Profile - Multiplier in [kWh/a]	2500.00	Family Flat [B]	2.50																	
Market share	Population	Townhouse [C]	[1]	REF	0.20	0.20	0.20	0.20	0.15	0.15	0.15	0.15	0.25	0.25	0.25	0.25	0.20	0.20	0.20	0.20
Average Demand for Profile - Multiplier in [kWh/a]	3250.00	Townhouse [C]	3.25																	
Market share - REST	Population	Familyhouse [D]	Rest		0.35	0.35	0.35	0.35	0.55	0.55	0.55	0.55	0.30	0.30	0.30	0.30	0.55	0.55	0.55	0.55
Average Demand for Profile - Multiplier in [kWh/a]	4000.00	Familyhouse [D]	4.00																	
Market share	Population	Office [G0]	[1]	REF	0.10	0.15	0.20	0.15	0.10	0.15	0.20	0.15	0.10	0.15	0.20	0.15	0.10	0.15	0.20	0.15
Average Demand for Profile - Multiplier in [kWh/a]	40000.00	Office [G0]	40.00																	
Market share	Population	Office [G1]	[1]	REF	0.20	0.15	0.20	0.15	0.20	0.15	0.20	0.15	0.20	0.15	0.20	0.15	0.20	0.15	0.20	0.15
Average Demand for Profile - Multiplier in [kWh/a]	150000.00	Office [G1]	150.00																	
Market share	Population	Restaurant [G2]	[1]	REF	0.15	0.20	0.15	0.15	0.15	0.20	0.15	0.15	0.15	0.20	0.15	0.15	0.15	0.20	0.15	0.15
Average Demand for Profile - Multiplier in [kWh/a]	75000.00	Restaurant [G2]	75.00																	
Market share	Population	Shop [G4]	[1]	REF	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15	0.10	0.15
Average Demand for Profile - Multiplier in [kWh/a]	50000.00	Shop [G4]	50.00																	
Market share	Population	Backery [G5]	[1]	REF	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Average Demand for Profile - Multiplier in [kWh/a]	250000.00	Backery [G5]	250.00																	
Market share	Population	Entertainment [G6]	[1]	REF	0.15	0.20	0.15	0.25	0.15	0.20	0.15	0.25	0.15	0.20	0.15	0.25	0.15	0.20	0.15	0.25
Average Demand for Profile - Multiplier in [kWh/a]	100000.00	Entertainment [G6]	100.00																	
Market share - REST	Population	24 h Service [G3]	Rest		0.25	0.10	0.15	0.10	0.25	0.10	0.15	0.10	0.25	0.10	0.15	0.10	0.25	0.10	0.15	0.10
Average Demand for Profile - Multiplier in [kWh/a]	35000.00	24 h Service [G3]	35.00																	
Market share	Population	Veg. Farms [L0]	[1]	REF	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Average Demand for Profile - Multiplier in [kWh/a]	200000.00	Veg. Farms [L0]	200.00																	
Market share	Population	Diary Farms [L1]	[1]	REF	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Average Demand for Profile - Multiplier in [kWh/a]	300000.00	Diary Farms [L1]	300.00																	
Market share - REST	Population	General Farms [L2]	Rest		0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Average Demand for Profile - Multiplier in [kWh/a]	400000.00	General Farms [L2]	400.00																	
Total Market Share: Housing					0.65	0.65	0.65	0.65	0.45	0.45	0.45	0.45	0.70	0.70	0.70	0.70	0.45	0.45	0.45	0.45
Total Market Share: Business																				

	Max Load DK02 [MW/h]	Share from total Demand	Population / Economic Activity => head/h	DA Shares [SUB DIVISION OF total DA)	Share DA 01	Share DA 02	Share DA 03	Share DA 04
Industry 400kW for TZ 1	0	0%	1	Business	25,0%	25,0%	25,0%	25,0%
Industry TZ 1	615	33%	1					
Business DA (total)	615	33%	1					
Demand DZ (total)	615	33%	2.800.000	Max Load In [MW]				
Total Demand				DA	DA 1 / DZ 1	DA 2 / DZ 1	DA 3 / DZ 1	DA 4 / DZ 1
EV-input	1.844			DA Population Share	6,25%	6,25%	6,25%	6,25%
Total Check	1.844	100%	2.800.000	Max Load In [MW]	DA 1 / DZ 2	DA 2 / DZ 2	DA 3 / DZ 2	DA 4 / DZ 2
				DA Population	175.000	175.000	175.000	175.000
				DA Population Share	DA 1 / DZ 2	DA 2 / DZ 2	DA 3 / DZ 2	DA 4 / DZ 2
				Max Load In [MW]	6,25%	6,25%	6,25%	6,25%
				DA Population	175.000	175.000	175.000	175.000
				DA Population Share	DA 1 / DZ 3	DA 2 / DZ 3	DA 3 / DZ 3	DA 4 / DZ 3
				Max Load In [MW]	6,25%	6,25%	6,25%	6,25%
				DA Population	175000	175000	175000	175000
				DA Population Share	DA1/DZ 4	DA2/DZ 4	DA3/DZ 4	DA4/DZ 4
				Max Load In [MW]	6,25%	6,25%	6,25%	6,25%
				DA Population	175000	175000	175000	175000

DK 02 = TZ 1  
Schleswig Holstein  
(TA Industry XX% SH + XX% HH)

Total System in [MW]								
7.992								
Demand								
	Max Load DE03 [MW/h]	Share from total Demand	Multipler per Grid level head/h	DA Shares	Share DA 01	Share DA 02	Share DA 03	Share DA 04
Industry A00-V for TZ 2	0,00	0%	1	Business	25,0%	25,0%	25,0%	25,0%
Industry TZ 2	2015,94	33%	1	DA MW				
Business DA (total)	2015,94	33%	1	Business				
Demand DZ (total)	2015,94	33%	1.800.000	Max Load in [MW]				
Total Demand	6.048			DA	DA 1 / DZ 1	DA 2 / DZ 1	DA 3 / DZ 1	DA 4 / DZ 1
EN-input	6.048			Max Load in Share	6,25%	6,25%	6,25%	6,25%
Total Check	6.048	100%	1.800.000	DA Population	112 500	112 500	112 500	112 500
for Grid-input				DA 1 / DZ 2	DA 2 / DZ 2	DA 3 / DZ 2	DA 4 / DZ 2	
				DA Population Share	6,25%	6,25%	6,25%	6,25%
				Max Load in [MW]	112 500	112 500	112 500	112 500
				DA Population	DA 1 / DZ 3	DA 2 / DZ 3	DA 3 / DZ 3	DA 4 / DZ 3
				DA Population Share	6,25%	6,25%	6,25%	6,25%
				Max Load in [MW]	112 500	112 500	112 500	112 500
				DA Population	DA1 / DZ 4	DA2 / DZ 4	DA3 / DZ 4	DA4 / DZ 4
				DA Population Share	6,25%	6,25%	6,25%	6,25%
				Max Load in [MW]	112 500	112 500	112 500	112 500
				DA Population				

DE 03 = TZ 2  
Hamburg

DE 03 = TZ 2  
Hamburg

A1.4: Input Sheets – Smart Grid

Grid TA				TA 1	Nicht verlinkt!	GRID	Legend:
Votage Level in[kV]: Available amount of lines:				400,00 10			
Maximum flow	400kV (DS)	balance 400kV NEG	TW/h/h	0,00			Input Data fields - connected to Import sheet
Installed Capacity	400 kV	Power Flowmanager	GW/h/h	14,36			Connected to Profiles via multiplier
Grid Limit	400kV (DS)	balance 400kV NEG	TW/h/h	0,00			0,50 Calculated values -> for a better overview only
Grid Limit	400kV (DS)	balance 400kV POS	TW/h/h	0,00			2000,00 Data Input
Installed Capacity	New Grid 220kV	balance 400kV NEG	GW/h/h	0,00			Population legend for fields
Installed Capacity	New Grid 220kV	balance 400kV POS	GW/h/h	14,36			
Installed Capacity	220/110kV (DS)	Transformer 400-110kV	GW/h/h	14,36			
Installed Capacity	220kV	Connect 220/110kV	GW/h/h	14,36			
Total Annual Demand in [TWh/a]: TA1 - ONLY FOR INFORMATION - NO INPUT DATA				0,00			
Average load (8760h/a) in [MW]				0,00			
Secured costumer capacity: (linked with Techn Overview + Smart Demand) in [MW]				100,00			
TA 1				TZ 1	TZ 2	Check demand input	
Votage Level in[kV]: Avaliable amount of lines:				220,00 7	110,00 14		
Maximum flow	110kV (DS)	balance 110kV NEG	GW/h/h	0,00	0,00		
Installed Capacity	New Grid 110kV	balance 110kV NEG	GW/h/h	1,54	1,54		
Installed Capacity	New Grid 110kV	balance 110kV POS	GW/h/h	1,54	1,54		
Installed Capacity	220/110kV	Power Flow Manager	GW/h/h	1,54	1,54		
Maximum flow	Electricity 110kV POS	Power Flow Manager	GW/h/h	1,54	1,54		
Grid Limit	Electricity 110kV NEG	balance 110kV NEG	GW/h/h	0,00	0,00		
Maximum flow	110kV (DS)	balance 110kV NEG	GW/h/h	0,00	0,00		
Maximum flow	220/110kV (DS)	balance 110kV NEG	GW/h/h	0,00	0,00		
Grid Limit	Electricity 110kV POS	balance 110kV POS	GW/h/h	1,54	1,54		
Installed Capacity	220/110kV (DS)	Transformer 110-10kV	GW/h/h	1,54	1,54		
Total Annual Demand in [GWh/a]: TZ1; TZ2 ORIGINAL DATA ENERGYNAUTICS - ONLY FOR INFORMATION - NO INF				10236,17	38362,86		
Average load (8760h/a) in [MW]				1168,51	4379,32		
Secured costumer capacity: (linked with Techn Overview + Smart Demand) in [MW]				5,00	5,00		
TA 1				TZ 1			
Grid DA				DA1	DA2	DA 3	DA 4
Votage Level in[kV]: Avaliable amount of lines:				20,00 2	20,00 2	20,00 2	20,00 3
Maximum flow	10kV (DS)	balance 10kV NEG	MWh/h	0,00	0,00	0,00	0,00
Grid Limit	Electricity 10kV NEG	balance 10kV NEG	MWh/h	0,00	0,00	0,00	0,00
Grid Limit	Electricity 10kV POS	balance 110kV POS	MWh/h	40,00	40,00	40,00	60,00
Installed Capacity	New Grid 10kV	balance 10kV NEG	MWh/h	1,00	1,00	1,00	1,00
Installed Capacity	New Grid 10kV	balance 110kV POS	MWh/h	1,00	1,00	1,00	1,00
Installed Capacity	20/10 kV	Power Flow Manager	MWh/h	40,00	40,00	40,00	60,00
Installed Capacity	10kV (DS)	Transformator 10kV-0,38k	MWh/h	40,00	40,00	40,00	60,00
Maximum flow	20/10kV (DS)	balance 10kV NEG	MWh/h	0,00	0,00	0,00	0,00
Maximum flow	Electricity 10kV POS	Power Flow Manager	MWh/h	40,00	40,00	40,00	60,00
Total Annual Demand in [MWh/a]: DA1;DA2; DA3; DA4 - ONLY FOR INFORMATION - NO INPUT DATA				0,00	0,00	0,00	0,00
Average load (8760h/a) in [MW]				0,00	0,00	0,00	0,00
Secured costumer capacity: (linked with Techn Overview + Smart Demand) in [MW]				1500,00	1,50	1,50	1,50
				TZ 1			
Grid DZ				DA 1			
Votage Level in[kV]: Cable Capacity Factor				DZ 1 0,40	DZ 2 0,40	DZ 3 0,40	DZ 4 0,40
Maximum flow = Secured customer capacity * Cable Capacity Factor	380V (DS)	balance 380V NEG	kWh/h	0,00	0,00	0,00	0,00
Maximum flow	380V (DS)	balance 380V POS	kWh/h	245.123	245.123	245.123	245.123
Installed Capacity	New Grid 380V	balance 380 V POS	kWh/h	1,00	1,00	1,00	1,00
Installed Capacity	New Grid 380V	balance 380 V NEG	kWh/h	1,00	1,00	1,00	1,00
Maximum flow	Electricity 380V POS	Power Flow Manager	kWh/h	245.123	245.123	245.123	245.123
Installed Capacity	380V	Power Flow Manager	kWh/h	1,00	1,00	1,00	1,00
Grid Limit	Electricity 380V NEG	balance 380V NEG	kWh/h	0,00	0,00	0,00	0,00
Grid Limit	Electricity 380V POS	balance 380 V POS	kWh/h	245.123	245.123	245.123	245.123
Total Annual Demand in [MWh/a]: DZ1;DZ2; DZ3; DZ4 - ONLY FOR INFORMATION - NO INPUT DATA				0,00	0,00	0,00	0,00
Average load (8760h/a) in [MW]				0,00	0,00	0,00	0,00
Secured costumer capacity (calculated via linked parameter) in [MW]= "Techn Overview" [ installed capacity from customer] * "Smart Demand [Population]				350,18	350,18	350,18	350,18
				TZ 2			
Grid DZ				DA 2			
Votage Level in[kV]: Cable Capacity Factor				DZ 1 0,40	DZ 2 0,40	DZ 3 0,40	DZ 4 0,40
Maximum flow	380V (DS)	balance 380V NEG	kWh/h	0,00	0,00	0,00	0,00
Installed Capacity	New Grid 380V	balance 380 V POS	kWh/h	1,00	1,00	1,00	1,00
Installed Capacity	New Grid 380V	balance 380 V NEG	kWh/h	1,00	1,00	1,00	1,00
Maximum flow	Electricity 380V POS	Power Flow Manager	kWh/h	157.623	157.623	157.623	157.623
Installed Capacity	380V	Power Flow Manager	kWh/h	1,00	1,00	1,00	1,00
Grid Limit	Electricity 380V NEG	balance 380V NEG	kWh/h	0,00	0,00	0,00	0,00
Grid Limit	Electricity 380V POS	balance 380 V POS	kWh/h	157.623	157.623	157.623	157.623
Total Annual Demand in [MWh/a]: DZ1;DZ2; DZ3; DZ4 - ONLY FOR INFORMATION - NO INPUT DATA				0,00	0,00	0,00	0,00
Average load (8760h/a) in [MW]				0,00	0,00	0,00	0,00
Secured costumer capacity (calculated via linked parameter) in [MW]= "Techn Overview" [ installed capacity from customer] * "Smart Demand [Population]				225,18	225,18	225,18	225,18
				TZ 3			
Grid DZ				DA 3			
Votage Level in[kV]: Cable Capacity Factor				DZ 1 0,40	DZ 2 0,40	DZ 3 0,40	DZ 4 0,40
Maximum flow	380V (DS)	balance 380V NEG	kWh/h	0,00	0,00	0,00	0,00
Installed Capacity	New Grid 380V	balance 380 V POS	kWh/h	1,00	1,00	1,00	1,00
Installed Capacity	New Grid 380V	balance 380 V NEG	kWh/h	1,00	1,00	1,00	1,00
Maximum flow	Electricity 380V POS	Power Flow Manager	kWh/h	157.623	157.623	157.623	157.623
Installed Capacity	380V	Power Flow Manager	kWh/h	1,00	1,00	1,00	1,00
Grid Limit	Electricity 380V NEG	balance 380V NEG	kWh/h	0,00	0,00	0,00	0,00
Grid Limit	Electricity 380V POS	balance 380 V POS	kWh/h	157.623	157.623	157.623	157.623
Total Annual Demand in [MWh/a]: DZ1;DZ2; DZ3; DZ4 - ONLY FOR INFORMATION - NO INPUT DATA				0,00	0,00	0,00	0,00
Average load (8760h/a) in [MW]				0,00	0,00	0,00	0,00
Secured costumer capacity (calculated via linked parameter) in [MW]= "Techn Overview" [ installed capacity from customer] * "Smart Demand [Population]				225,18	225,18	225,18	225,18
				TZ 4			
Grid DZ				DA 4			
Votage Level in[kV]: Cable Capacity Factor				DZ 1 0,40	DZ 2 0,40	DZ 3 0,40	DZ 4 0,40
Maximum flow	380V (DS)	balance 380V NEG	kWh/h	0,00	0,00	0,00	0,00
Installed Capacity	New Grid 380V	balance 380 V POS	kWh/h	1,00	1,00	1,00	1,00
Installed Capacity	New Grid 380V	balance 380 V NEG	kWh/h	1,00	1,00	1,00	1,00
Maximum flow	Electricity 380V POS	Power Flow Manager	kWh/h	157.623	157.623	157.623	157.623
Installed Capacity	380V	Power Flow Manager	kWh/h	1,00	1,00	1,00	1,00
Grid Limit	Electricity 380V NEG	balance 380V NEG	kWh/h	0,00	0,00	0,00	0,00
Grid Limit	Electricity 380V POS	balance 380 V POS	kWh/h	157.623	157.623	157.623	157.623
Total Annual Demand in [MWh/a]: DZ1;DZ2; DZ3; DZ4 - ONLY FOR INFORMATION - NO INPUT DATA				0,00	0,00	0,00	0,00
Average load (8760h/a) in [MW]				0,00	0,00	0,00	0,00
Secured costumer capacity (calculated via linked parameter) in [MW]= "Techn Overview" [ installed capacity from customer] * "Smart Demand [Population]				225,18	225,18	225,18	225,18





A1.5: Input Sheets – Smart Generation

Capacities - Power Generation - TA

AttributeCommodityEinheitHypothese

Maximum flowElectricity 220kV POSHydro PP (400kV)GW/hREF0,00

Installed CapacityElectricity 220kV POSHydro PP (400kV)MW/hREF0,00

Maximum flowElectricity 220kV POSBio PP (400kV)GW/hREF0,00

Installed CapacityElectricity 220kV POSBio PP (400kV)MW/hREF0,00

Maximum flowElectricity 220kV POSGas PP (400kV)GW/hREF0,00

Installed CapacityElectricity 220kV POSGas PP (400kV)MW/hREF0,00

Maximum flowElectricity 220kV POSCoal PP (400kV)GW/hREF0,13

Installed CapacityElectricity 220kV POSCoal PP (400kV)MW/hREF131,72

Maximum flowElectricity 220kV POSLignite PP (400kV)GW/hREF0,00

Installed CapacityElectricity 220kV POSLignite PP (400kV)MW/hREF0,00

Maximum flowElectricity 220kV POSNuclear PP (400kV)GW/hREF0,00

Installed CapacityElectricity 220kV POSNuclear PP (400kV)MW/hREF0,00

Maximum flow400kV (DS)balance 400kV NEG TW/hREF

Installed Capacity (LINKED with Transfer Wind + Solar)

Solar Power PlantkWREF0,00

CSP - StoragekWREF0,00

Onshore WindkWREF0,00

Offshore WindkWREF0

Onshore Wind - StoragekWREF0,00

Total Installed Capacity in [MW]

131,72

Secured costumer capacity: (linked with Techn Overview + Smart Demand) in [MW]

100,00

Installed Capacities + Max Flow - Power Generation - TZ

AttributeCommodityEinheitHypothese

Installed CapacityHydro Power (110kV)Hydro PP 110kVGW/hREF0,000,00

Maximum flowElectricity 110kV POSHydro PP 110kVGW/hREF0,000,00

Installed CapacityGasGas PP 110kVGW/hREF0,340,15

Maximum flowElectricity 110kV POSGas PP 110kVGW/hREF0,340,15

Installed CapacityBio energyBio PP 110kVGW/hREF0,120,13

Maximum flowElectricity 110kV POSBio PP 110kVGW/hREF0,120,13

Installed Capacity (LINKED with Transfer Wind + Solar)

Solar Power PlantkWREF122930,461210510,94

Solar - StoragekWREF0,000,00

Onshore WindkWREF706.7081.450.738

Onshore Wind - StoragekWREF0,000,00

Total Installed Capacity in [MW]

1298,162947,81

Secured costumer capacity: (linked with Techn Overview + Smart Demand) in [MW]

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Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

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###	Storage																																							
###																<div>Legend:</div> <div><div>Input Data fields - connected to Import sheet</div><div>Connected to Profiles via multiplier</div><div>0.50 Calculated values -&gt; for a better overview only</div><div>2000,00 Data Input</div><div>Population legend for fields</div></div>																								
###	Attribute	Commodity	400kV		TA 1																																			
###	Maximale Speicherlade- und -entladerate	Storage 220kV	Dispatch 400kV	GWh/h	REF	0,00	Assumption: Equal to Installed capacity																																	
###	Obere Speichergrenze	Storage 220kV	Dispatch 400kV	GWh/h	REF	1,00	Assumption= Equal to Initial Storage Capacity																																	
###	Installed Capacity	Storage Load Input 400kV	Dispatch 400kV	GWh/h		0,00	Linked to Solar + Wind Storage																																	
###	Installed Capacity	Storage (4000kV)	Dispatch 400kV	GWh/h		0,00	Linked to Storage load Input																																	
###	Storage efficiency	Storage 220kV	Dispatch 400kV	[1]	REF	0,95	Linked to Techn Overview																																	
###	Initial storage quantity	Storage 220kV	Dispatch 400kV	GWh/h	REF	1,00	Assumption capacity X 10																																	
###	Maximum flow	Electricity 220kV POS	Storage Manager 400kV	GWh/h	REF	0,00	Linked to Storage load Input																																	
###						TA 1																																		
###						110kV					REF		TZ 1		TZ 2																									
###	Maximale Speicherlade- und -entladerate	Storage (110kV)	Dispatch 110kV	GWh/h	REF	0,00									Assumption: Equal to Installed capacity																									
###	Obere Speichergrenze	Storage (110kV)	Dispatch 110kV	GWh/h	REF	0,00									Assumption= Equal to Initial Storage Capacity																									
###	Storage efficiency	Storage (110kV)	Dispatch 110kV	[1]	REF	0,95									Linked to Techn Overview																									
###	Initial storage quantity	Storage (110kV)	Dispatch 110kV	GWh/h	REF	0,00									Assumption capacity X 10																									
###	Installed Capacity	Storage Load Input 110kV	Dispatch 110kV	GWh/h	REF	0,00									Linked to PV + Wind Storage																									
###	Installed Capacity	Storage (110kV)	Dispatch 110kV	GWh/h	REF	0,00									Linked to Storage load Input																									
###	Maximum flow	Electricity 110kV POS	Storage Manager 110kV	GWh/h	REF	0,00									Linked to Storage load Input																									
###	TA 1																																							
###						TZ 1					TZ 2																													
###						10KV				DA1		DA2		DA 3		DA 4		DA1				DA2		DA 3		DA 4														
###	Maximale Speicherlade- und -entladerate	Storage (10kV)	Dispatch 10kV	GWh/h	REF	0,00																							Assumption: Equal to Installed capacity											
###	Obere Speichergrenze	Storage (10kV)	Dispatch 10kV	GWh/h	REF	0,01																							Assumption= Equal to Initial Storage Capacity											
###	Storage efficiency	Storage (10kV)	Dispatch 10kV	[1]	REF	0,95																							Linked to Techn Overview											
###	Initial storage quantity	Storage (10kV)	Dispatch 10kV	MWh/h	REF	10,00																							Assumption capacity X 10											
###	Installed Capacity	Storage Load Input 10kV	Dispatch 10kV	MWh/h	REF	0,00																							Linked to PV + Wind Storage											
###	Maximum flow	Electricity 10kV POS	Storage Manager 10kV	MWh/h	REF	0,00																							Linked to Storage load Input											
###	Installed Capacity	Storage (10kV)	Dispatch 10kV	MWh/h	REF	0,00																							Linked to Storage load Input											
###																																								
###						TZ 1																																		
###						DA 1				DA 2				DA 3				DA 4																						
###						10KV				DZ 1		DZ 2		DZ 3		DZ 4		DZ 1		DZ 2		DZ 3		DZ 4		DZ 1		DZ 2		DZ 3		DZ 4		kWh/h + GWh/h						
###	Maximale Speicherlade- und -entladerate	Storage 0,4kV	Balance 380V	GWh/h	REF	0,00																									Assumption: Equal to Installed capacity									
###	Obere Speichergrenze	Storage 0,4kV	Balance 380V	GWh/h	REF	20000,00																									Assumption= Equal to Initial Storage Capacity									
###	Storage efficiency	Storage 0,4kV	Balance 380V	[1]	REF	0,95																									Linked to Techn Overview									
###	Initial storage quantity	Storage 0,4kV	Balance 380V	kWh/h	REF	20000,00																									Assumption capacity X 10									
###	Installed Capacity</																																							

### A1.7: Input Sheets – Smart Costs (part 1)

Power generation					
No		Process	Inputs are the same in all clusters	Unit	Value  (connected to colum"M")
		PV Optimal / Power plant	Specific capital costs	€/ (kJ)*h	0,00003472
		PV East-West	Specific capital costs	€/ (kJ)*h	0,00004630
		PV-Storage	Specific capital costs	€/ (kJ)*h	0,00033333
		CSP	Specific capital costs	€/ (kJ)*h	0,00003690
		(Onshore) Wind	Specific capital costs	€/ (kJ)*h	0,00001111
		Offshore Wind	Specific capital costs	€/ (kJ)*h	0,00002083
		Wind Storage	Specific capital costs	€/ (kJ)*h	0,00010417
		Hydro Power Plant (10/20kV)		€/(MWh)*h	11,00
		Hydro Power Plant (110/220kV)	Specific capital costs	€/(GWh)*h	11000,00
		Hydro Power Plant (400kV)		€/(GWh)*h	11000,00
		Bio Energy Power Plant	Specific capital costs	€/ (kJ)*h	0,00001034
		Gas Power Plant	Specific capital costs	€/ (kJ)*h	0,00000661
		Coal Power Plant	Specific capital costs	€/ (kJ)*h	0,00000386
		Lignite Power Plant	Specific capital costs	€/ (kJ)*h	0,00000448
		Nuclear Power Plant	Specific capital costs	€/ (kJ)*h	0,00002083

Definitions:											
Capital Costs: Installation Costs per [kW] / Techn Lifetime [a] (+ costs for interest rates) Xload factor - only for PV and Wind in [h/a] = annual capital costs (NOTE: Units kJ AND kWh - depending on commodity! MESAP will calculate with a LOAD FACTOR - so for the INPUT Value: Installation Costs / Technical Lifetime!										Check	
Installation Costs [€/kW]		Source		Technical Life Time [a]	Input Value [€/kW a]	Conversion factors (1KWh = 3600 kJ; 1 MWh = 1000kWh)	Input Values	Units	[h/a] Example!	[€/kWh]	
2500,00		DLR Energy	[R]evolution 2012	20,00	125,00	3600,00	0,00003472	[€/kJ]	1000,00	0,13	
2500,00		DLR Energy	[R]evolution 2012	20,00	125,00	3600,00	0,00004630	[€/kJ]	750,00	0,17	
6000,00		DLR Energy	[R]evolution 2012	20,00	300,00	3600,00	0,00033333	[€/kJ]	250,00	1,20	
9300,00		DLR Energy	[R]evolution 2012	20,00	465,00	3600,00	0,00003690	[€/kJ]	3500,00	0,13	
1800,00		DLR Energy	[R]evolution 2012	20,00	90,00	3600,00	0,00001111	[€/kJ]	2250,00	0,04	
6000,00		DLR Energy	[R]evolution 2012	20,00	300,00	3600,00	0,00002083	[€/kJ]	4000,00	0,08	
7500,00		DLR Energy	[R]evolution 2012	20,00	375,00	3600,00	0,00010417	[€/kJ]	1000,00	0,38	
3300,00				60,00	55,00	1000,00	11,00	[€/MW]	5000,00	0,01	
3300,00		DLR Energy	[R]evolution 2012	60,00	55,00	1000000,00	11000,00	[€/GW]	5000,00	0,01	
3300,00				60,00	55,00	1000000,00	11000,00	[€/GW]	5000,00	0,01	
3350,00		DLR Energy	[R]evolution 2012	20,00	167,50	3600,00	0,00001034	[€/kJ]	4500,00	0,04	
750,00		DLR Energy	[R]evolution 2012	7,00	107,14	3600,00	0,00000661	[€/kJ]	4500,00	0,02	
1250,00		DLR Energy	[R]evolution 2012	20,00	62,50	3600,00	0,00000386	[€/kJ]	4500,00	0,01	
1450,00		DLR Energy	[R]evolution 2012	20,00	72,50	3600,00	0,00000448	[€/kJ]	4500,00	0,02	
7500,00		DLR Energy	[R]evolution 2012	20,00	375,00	3600,00	0,00002083	[€/kJ]	5000,00	0,08	

Fixed Costs: Annual maintenance costs Costs per kW (in general X% of installation costs) + Installation costs = annual fixed costs (NOTE: MESAP will use the Loadfactors to break costs down to hourly costs!)						Check					
Annual Maintenance Costs [€/kW]		Source		Share of Installation Costs [%] (JUST FOR OVERVIEW!)	Input Value (Maintenance + Installation Costs) [€/kW a]	Conversion factors (1KWh = 3600 kJ; 1 M Wh = 1000kWh)	Input Values (with conversion factor AND LF!)	Units	[h/a] Example!	[€/kWh]	
43,00		DLR Energy	[R]evolution 2012	0,02	168,00	3600,00	0,00004667	[€/kJ]	1000,00	0,17	
43,00		DLR Energy	[R]evolution 2012	0,02	168,00	3600,00	0,00006222	[€/kJ]	750,00	0,22	
90,00		DLR Energy	[R]evolution 2012	0,02	390,00	3600,00	0,00043333	[€/kJ]	250,00	1,56	
418,50		DLR Energy	[R]evolution 2012	0,05	883,50	3600,00	0,00007012	[€/kJ]	3500,00	0,25	
63,00		DLR Energy	[R]evolution 2012	0,04	153,00	3600,00	0,00001889	[€/kJ]	2250,00	0,07	
228,00		DLR Energy	[R]evolution 2012	0,04	528,00	3600,00	0,00003667	[€/kJ]	4000,00	0,13	
300,00		DLR Energy	[R]evolution 2012	0,04	675,00	3600,00	0,00018750	[€/kJ]	1000,00	0,68	
132,00		DLR Energy	[R]evolution 2012	0,04	187,00	3600,00	1000,00	37,40	[€/MW]	5000,00	0,04
132,00		DLR Energy	[R]evolution 2012	0,04	187,00	1000000,00	37400,00	[€/GW]	5000,00	0,04	
132,00		DLR Energy	[R]evolution 2012	0,04	187,00	1000000,00	37400,00	[€/GW]	5000,00	0,04	
134,00		DLR Energy	[R]evolution 2012	0,04	301,50	3600,00	0,00001861	[€/kJ]	4500,00	0,07	
30,00		DLR Energy	[R]evolution 2012	0,04	137,14	3600,00	0,00000847	[€/kJ]	4500,00	0,03	
50,00		DLR Energy	[R]evolution 2012	0,04	112,50	3600,00	0,00000694	[€/kJ]	4500,00	0,03	
58,00		DLR Energy	[R]evolution 2012	0,04	130,50	3600,00	0,00000806	[€/kJ]	4500,00	0,03	
300,00		DLR Energy	[R]evolution 2012	0,04	675,00	3600,00	0,00018750	[€/kJ]	1000,00	0,68	

below. Specific Variable Costs - hidden

Commodities					
No		Process	Inputs are the same in all clusters Specific cost of commodity	Unit	Value
1,00		Sun		€/ (kJ)	0,00000000
2,00		Sun East-West		€/ (kJ)	0,00000000
3,00		Sun-Storage		€/ (kJ)	0,00000000
4,00		Sun CSP		Wo?	0,00000000
5,00		(Onshore) Wind		€/ (kJ)	0,00000000
6,00		Offshore Wind		€/ (kJ)	0,00000000
7,00		Wind Storage		€/ (kJ)	0,00000000
8,00		Hydro (10/20kV)	10/20kV	€/ (MWh)	0,00000000
		Hydro (110/220kV)	110/220 kV	€/ (GWh)	
		Hydro (400kV)	400 kV	€/ (GWh)	
9,00		Bio Energy		€/ (kJ)	0,00000546
10,00		Gas		€/ (kJ)	0,00000554
11,00		Coal		€/ (kJ)	0,00000236
12,00		Lignite		€/ (kJ)	0,00000060
13,00		Uranium		€/ (kJ)	0,00000070

Cost of Commodities: For Solar, Wind and Hydro those costs are "0" - for all other power generation technologies these are fuel costs										Check	
Market Price		Unit	Source	Conversion factors (1tonne = 29 GJ; 1GJ = 1000000 kJ)	Value [€/GJ]	Conversion Factor (1GJ = 1000000 kJ)	Input Values [€/kJ]	Efficiency [%]	[€/kWh]		
0,00											
0,00											
0,00											
0,00											
0,00											
0,00											
0,00											
0,00											
0,00											
0,00											
0,00											
7,80		\$/GJ	Energy [R]evolution	1,00	5,46	1000000,00	0,00	0,38	0,03		
7,91		\$/GJ	Energy [R]evolution	1,00	5,54	1000000,00	0,00	0,51	0,03		
99,00		\$/tonne	Energy [R]evolution	29,31	2,36	1000000,00	0,00	0,34	0,01		
25,00		\$/tonne	Energy [R]evolution	29,31	0,60	1000000,00	0,00	0,34	0,00		
1,00		\$/GJ	Energy [R]evolution	1,00	0,70	1000000,00	0,00	0,33	0,00		

A1.8: Input Sheets – Smart Costs (part 2)

Commodities - GRID - there is only ONE commodity each -					Cost of Commodities: <b>NOTE:</b> Grid Costs are calculated via Capital + Fixed Costs for now - it would be an option to use only "Cost of Commodity" and/or "Variable Costs". Current Assumption: <b>Cost of Commodity and Variable Costs = "0"</b>										Check		
		New Grid 0,4kV	Specific cost of commodity	€/kWh	0,00												[€/kWh]
		New Grid 10/20kV	Specific cost of commodity	€/MWh	0,00												
		New Grid 110/220kV	Specific cost of commodity	€/GWh	0,00												
		New Grid 400 kV	Specific cost of commodity	Wo?	0,00												
		400 kV	Specific cost of commodity	Wo?													
		220kV	Specific cost of commodity	€/GWh	0,00												
		110kV	Specific cost of commodity	€/GWh	0,00												
		20/10kV	Specific cost of commodity	€/GWh	0,00												
		10kV	Specific cost of commodity	Wo?	0,00												
		0,4 kV	Specific cost of commodity	€/kWh	0,00												
Grid And Storage					Definitions:										Check		
No		Process	Inputs which are the same in all clusters	Unit	Value	<b>Capital Costs:</b> Installation Costs per [kW] / Techn Lifetime [a] (+ costs for interest rates) = annual capital costs <b>(NOTE:</b> Units kJ AND kWh - depending on commodity! <b>MESAP will calculate with a LOAD FACTOR - so for the INPUT Value: Installation Costs / Technical Lifetime!</b>										Check	
			Specific capital costs	Units ->		Installation Costs [€/kW]	Source	Technical Life Time [a]	Value [€/kW]	Conversion factors (1kWh=3600 kJ; 1MWh=1000kWh)	Input Values	Units	[h/a] <i>Example!</i>	[€/kWh]			
		Power Flow manager	0,4 kV	€/kWh)*h	0,00	0,00		20,00	0,00	1,00	0,00	€/kWh)*h	8760,00	0,00			
		Power Flow manager	10/20 kV	€/MWh)*h	0,00	0,00		20,00	0,00	1000,00	0,00	€/MWh)*h	8760,00	0,00			
		Power Flow manager	110 / 220 kV	€/GWh)*h	0,01	0,00		20,00	0,00	1000000,00	0,01	€/GWh)*h	8760,00	0,00			
		Power Flow manager	400kV	€/GWh)*h	0,01	0,00		20,00	0,00	1000000,00	0,01	€/GWh)*h	8760,00	0,00			
<b>Note:</b> Within the MESAP cost calculation for both processes balance NEGATIVE and balance POSITIV - the NEW GRID commodity has been chosen has "capacity relevant flow". Therefore the three processes "balance POS", "Power Flow Manager" and "Transformer" have cost input values!! But <b>the power flow manager has minor costs - new grid is not a process - its a commodity!</b>																	
		balance POS	0,4 kV	€/kWh)*h	0,00	0,00		20,00	0,00	1,00	0,00	€/kWh)*h	8760,00	0,00			
		balance POS	10/20 kV	€/MWh)*h	0,00	0,00		20,00	0,00	1000,00	0,00	€/MWh)*h	8760,00	0,00			
		balance POS	110 / 220 kV	€/GWh)*h	0,01	0,00		20,00	0,00	1000000,00	0,01	€/GWh)*h	8760,00	0,00			
		balance POS	400kV	€/GWh)*h	0,00	0,00		20,00	0,00	1000000,00	0,00	€/GWh)*h	8760,00	0,00			
		balance NEG	0,4 kV	€/kWh)*h	0,00	0,00		20,00	0,00	1,00	0,00	€/kWh)*h	8760,00	0,00			
		balance NEG	10/20 kV	€/MWh)*h	0,00	0,00		20,00	0,00	1000,00	0,00	€/MWh)*h	8760,00	0,00			
		balance NEG	110 / 220 kV	€/GWh)*h	0,01	0,00		20,00	0,00	1000000,00	0,01	€/GWh)*h	8760,00	0,00			
		balance NEG	400kV	€/GWh)*h	0,01	0,00		20,00	0,00	1000000,00	0,01	€/GWh)*h	8760,00	0,00			
		Transformer	10 -0,4 kV	€/MWh)*h	0,00	0,00		20,00	0,00	1000,00	0,00	€/kWh]	8760,00	0,00			
		Transformer	10/20 kV - 110/220 kV	€/MWh)*h	0,00	0,00		20,00	0,00	1000,00	0,00	€/kWh]	8760,00	0,00			
		Transformer	400kV > 220 kV	€/MWh)*h	0,00	0,00		20,00	0,00	1000,00	0,00	€/kWh]	8760,00	0,00			
		Storage Load	0,4 kV	€/kWh)*h	0,00	0,00		20,00	0,00	1,00	0,00	€/kWh)*h	8760,00	0,00			
		Storage Load	10/20 kV	€/MWh)*h	0,00	0,00		20,00	0,00	1000,00	0,00	€/MWh)*h	8760,00	0,00			
		Storage Load	110 / 220 kV	€/GWh)*h	0,01	0,00		20,00	0,00	1000000,00	0,01	€/GWh)*h	8760,00	0,00			
		Storage Load	400kV	€/GWh)*h	0,01	0,00		20,00	0,00	1000000,00	0,01	€/GWh)*h	8760,00	0,00			
		Storage Manager	0,4 kV	€/kWh)*h	0,00	0,00		20,00	0,00	1,00	0,00	€/kWh)*h	8760,00	0,00			
		Storage Manager	10/20 kV	€/MWh)*h	0,00	0,00		20,00	0,00	1000,00	0,00	€/MWh)*h	8760,00	0,00			
		Storage Manager	110 / 220 kV	€/GWh)*h	0,01	0,00		20,00	0,00	1000000,00	0,01	€/GWh)*h	8760,00	0,00			
		Storage Manager	400kV	€/GWh)*h	0,01	0,00		20,00	0,00	1000000,00	0,01	€/GWh)*h	8760,00	0,00			
No		Process	Inputs which are the same in all clusters	Unit	Value	<b>Fixed Costs:</b> Annual maintenance costs Costs per kW (in general X% of installation costs) + <b>Installation costs</b> = annual fixed costs <b>NOTE:</b> MESAP will use the Loadfactors to break costs down to hourly costs!										Check	
			Specific fixed costs	Units ->		Annual Maintenance Costs [€/kW]	Source	Share of Installation Costs [%] (JUST FOR OVERVIEW)	Input Value [€/kW a]	Conversion factors (1kWh=3600 kJ; 1MWh=1000kWh)	Input Values	Units	[h/a] <i>Example!</i>	[€/kWh]			
		Power Flow manager	0,4 kV	€/kWh)*h/h	0,00	0,00		0,00	0,00	1,00	0,00	€/kWh]	8760,00	0,00			
		Power Flow manager	10/20 kV	€/MWh)*h/h	0,00	0,00		0,00	0,00	1000,00	0,00	€/kWh]	8760,00	0,00			
		Power Flow manager	110 / 220 kV	€/GWh)*h/h	0,01	0,00		0,00	0,00	1000000,00	0,01	€/kWh]	8760,00	0,00			
		Power Flow manager	400kV	€/GWh)*h/h	0,01	0,00		0,00	0,00	1000000,00	0,01	€/kWh]	8760,00	0,00			
		balance POS	0,4 kV	€/kWh)*h/h	0,00	0,00		0,00	0,00	1,00	0,00	€/kWh]	8760,00	0,00			
		balance POS	10/20 kV	€/MWh)*h/h	0,00	0,00		0,00	0,00	1000,00	0,00	€/kWh]	8760,00	0,00			
		balance POS	110 / 220 kV	€/GWh)*h/h	0,01	0,00		0,00	0,00	1000000,00	0,01	€/kWh]	8760,00	0,00			
		balance POS	400kV	€/GWh)*h/h	0,00	0,00		0,00	0,00	1000000,00	0,00	€/kWh]	8760,00	0,00			
		balance NEG	0,4 kV	€/kWh)*h/h	0,00	0,00		0,00	0,00	1,00	0,00	€/kWh]	8760,00	0,00			
		balance NEG	10/20 kV	€/MWh)*h/h	0,00	0,00		0,00	0,00	1000,00	0,00	€/kWh]	8760,00	0,00			
		balance NEG	110 / 220 kV	€/GWh)*h/h	0,01	0,00		0,00	0,00	1000000,00	0,01	€/kWh]	8760,00	0,00			
		balance NEG	400kV	€/GWh)*h/h	0,01	0,00		0,00	0,00	1000000,00	0,01	€/kWh]	8760,00	0,00			
		Transformer	10 -0,4 kV	€/MWh)*h/h	15,41	135,00			135,00	1000,00	15,41	€/kWh]	8760,00	0,02			
		Transformer	10/20 kV - 110/220 kV	€/MWh)*h/h	154,11	135,00			135,00	1000,00	154,11	€/kWh]	8760,00	0,02			
		Transformer	> 220 kV (siehe Bemerkung	€/MWh)*h/h	770,55	135,00			135,00	1000,00	770,55	€/kWh]	8760,00	0,02			
		Storage Load	0,4 kV	€/kWh)*h/h	0,00	0,00		0,00	0,00	1,00	0,00	€/kWh]	8760,00	0,00			
		Storage Load	10/20 kV	€/MWh)*h/h	0,00	0,00		0,00	0,00	1000,00	0,00	€/kWh]	8760,00	0,00			
		Storage Load	110 / 220 kV	€/GWh)*h/h	0,01	0,00		0,00	0,00	1000000,00	0,01	€/kWh]	8760,00	0,00			
		Storage Load	400kV	€/GWh)*h/h	0,01	0,00		0,00	0,00	1000000,00	0,01	€/kWh]	8760,00	0,00			
		Storage Manager	0,4 kV	€/kWh)*h/h	0,00	0,00		0,00	0,00	1,00	0,00	€/kWh]	8760,00	0,00			
		Storage Manager	10/20 kV	€/MWh)*h/h	0,00	0,00		0,00	0,00	1000,00	0,00	€/kWh]	8760,00	0,00			
		Storage Manager	110 / 220 kV	€/GWh)*h/h	0,01	0,00		0,00	0,00	1000000,00	0,01	€/kWh]	8760,00	0,00			
		Storage Manager	400kV	€/GWh)*h/h	0,01	0,00		0,00	0,00	1000000,00	0,01	€/kWh]	8760,00	0,00			





Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

[illegible]

#### A.1.10 Data for Figure 77, 78 and 79 – Part 2

[illegible]

Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

### A.1.10 Data for Figure 77, 78 and 79 – Part 3

[illegible]



#### A.1.10 Data for Figure 77, 78 and 79 – Part 4

[illegible]

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[illegible]

#### A.1.10 Data for Figure 77, 78 and 79 – Part 6

[illegible]

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[illegible]

#### A.1.10 Data for Figure 77, 78 and 79 – Part 8

[illegible]

## Bridging the Gap Between Energy- and Grid Models:

Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

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## A.2 Electricity Demand

For the [R]E 24/7 detailed data analysis about the electricity demand in each cluster and grid level is required for the time resolution e.g. 1 hour steps. This data can either be measured from smart meters, historical information from grid operators or utilities or standard load curves for different customer groups.

### A.2.1 Electricity Demand Input via Standard Load Curves

For private costumers, who are connected at the distribution level, and do not have a smart meters which allow the grid operator to measure real time demand data, actual demand data is not available, as such grid operators use standard load curves for demand forecasts. The German Association for Energy and Water Utilities (BDEW 2012- Bundesverband der Energie und Wasserwirtschaft e.V.<sup>124</sup>) developed standard load curves for households and a variety of different businesses.

All demand profiles are calibrated to 15 minute steps and an annual demand of 1000 kWh. A weekly profile contains data for each working day, as well as for Saturday and Sunday. Those weekly profiles are available for winter, summer and the transition period.

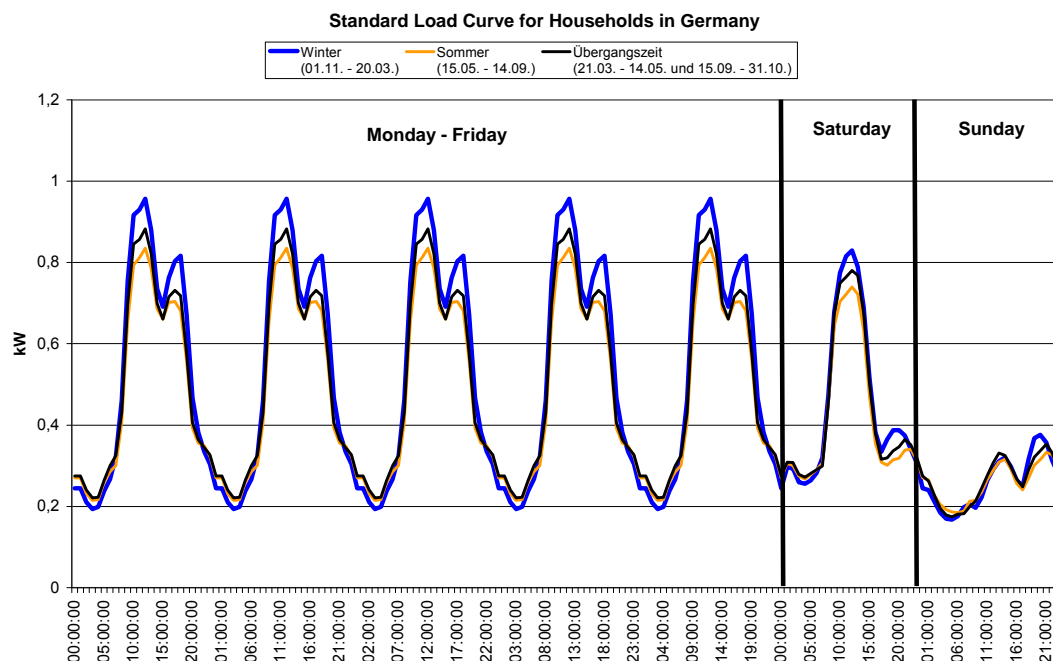


Figure 94: Standard load curves for households in Germany

Figure 94 shows a standard load curve for households in Germany calibrated to an annual demand of 1000 kWh. In case a household has an annual demand of 2500 kWh,

the values of this curve will be multiplied by the factor of 2.5; the shape of the curve however will not change.

While those curves do not reflect the actual demand pattern of a single household, a large number of households add up to the given load curves. Not all German utilities and grid operator use the standard load curves developed by (BDEW 2012), but use profiles based on their regional experiences. However the methodology remains the same. In order to use standard load curve profiles in the [R]E 24/7 model, the time resolution might have to change to 1 hour steps and the data needs to be multiplied by the a factor which represents the average annual demand per household type and the number of households.

### A.2.2 Electricity Demand from Large Scale Consumers

Electricity demand from large scale consumers such industry or railways are connected to the transmission network and their demand is measured from grid operators. No standard load profiles are available, therefore historical data of the overall load profile within the specific voltage level is required. Generally specific demand curves from industry and other large scale consumers vary significantly case by case, and grid operators do not provide any standard load curves, but measure the actual demand of those customers. Therefore the [R]E 24/7 basic RES structure has only one process for demand. The total load curve of this particular grid level cluster is the minimum data requirement in order to undertake the analysis.



## Bridging the Gap Between Energy- and Grid Models:

Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimize the interaction of flexible power generation, smart grids and storage technologies

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## Endnotes

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<sup>1</sup> IPCC-SRREN 2011; Renewable Energy Sources and Climate Change Mitigation; Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press; 32 Avenue of the Americas, New York, NY 10013-2473, USA; ISBN 978-1-107-02340-6, page 799, box 10.1;

<sup>2</sup> Schröder et.al. 2013; Market driven power plant investment perspectives in Europe: Climate Policy and Technology Scenarios until 2050 in the model EMELIE-EYS; December 2013; World Scientific, Climate Change Economics, Vol4, Suppl. 1 (2013),1340007 (22 pages)  
[www.worldscientific.com](http://www.worldscientific.com), page 3;

<sup>3</sup> [http://gridoptics.pnnl.gov/articles/m/o/d/Modeling\\_Simulation\\_and\\_Analysis\\_9a3f.html](http://gridoptics.pnnl.gov/articles/m/o/d/Modeling_Simulation_and_Analysis_9a3f.html);

<sup>4</sup> <http://www.kebmin.dk/en/climate-energy-and-building-policy/denmark/energy-supply-and-efficiency/smart-grid-the-intelligent-1>;

<sup>5</sup> DENA 2012; Dena-Verteilnetz Studie – Ausbau- und Innovationsbedarf der Stromverteilnetze in Deutschland bis 2030; Deutsche Energie Agentur GmbH (DENA), Chausseestraße 128a, 10115 Berlin, Germany, Dezember 2012;

<sup>6</sup> <https://www.entsoe.eu/Pages/default.aspx>;

<sup>7</sup> IPCC-SRREN 2011; Renewable Energy Sources and Climate Change Mitigation; Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press; 32 Avenue of the Americas, New York, NY 10013-2473, USA; ISBN 978-1-107-02340-6, Chapter 1, page 172ff;

<sup>8</sup> IEA 2014, The Power of Transformation – Wind, Sun and the Economics of Flexible Power Systems, February 2014, International Energy Agency, 9, rue de la Fédération, 75739 Paris Cedex 15, France; page 8 – 11;

<sup>9</sup> RWTH 11-2012; „Szenarien für eine langfristige Netzentwicklung“ - Schlussbericht – Aachen, Studie im Auftrag des Bundesministeriums für Wirtschaft und Technologie, November 2012;

<sup>10</sup> Van Hulle 2009; TradeWind – Integrating Wind: Developing Europe’s power market for the large-scale integration of wind power, May 2009; principal author Frans van Hulle; EU project number EIE/06/022/SI2.442659; European Wind Energy Association, Rue d'Arlon 80, B-1040 Brussels, Belgium;

<sup>11</sup> Langham 2011; Langham, E. Dunstan, C. and Mohr, S. (2011). Mapping Network Opportunities for Decentralised Energy: The Dynamic Avoidable Network Cost Evaluation (DANCE) Model, iGrid Working Paper 4.4, Prepared by the Institute for Sustainable Futures, University of Technology Sydney as part of the CSIRO Intelligent Grid Research Program. Sydney, NSW, Australia, May 2011;

<sup>12</sup> Connolly et. al, 2010, September 2009, Elsevier; page 1064, Table 4; “A review of computer tools for analyzing the integration of renewable energy into various energy systems.”;



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<sup>13</sup> Knopf et.al. 2013; Beyond 2020 – Strategies and Costs for Transforming the European Energy system, December 2013, World Scientific, Climate Change Economics, Vol4, Suppl. 1 (2013),1340001 (38 pages) [www.worldscientific.com](http://www.worldscientific.com); page 7ff;

<sup>14</sup> Knopf et.al. 2013; Beyond 2020 – Strategies and Costs for Transforming the European Energy system, December 2013, World Scientific, Climate Change Economics, Vol4, Suppl. 1 (2013),1340001 (38 pages) [www.worldscientific.com](http://www.worldscientific.com); page 9;

<sup>15</sup> Knopf et.al. 2013; Beyond 2020 – Strategies and Costs for Transforming the European Energy system, December 2013, World Scientific, Climate Change Economics, Vol4, Suppl. 1 (2013),1340001 (38 pages) [www.worldscientific.com](http://www.worldscientific.com); page 7;

<sup>16</sup> E.De Cian 2013; European-led climate policy versus global mitigation action: Implication on trade, technology and energy, World Scientific, Climate Change Economics, Vol4, Suppl. 1 (2013),1340002 (28 pages) [www.worldscientific.com](http://www.worldscientific.com), Table 2 page 6;

<sup>17</sup> Schröder et.al.; Market driven power plant investment perspectives in Europe: Climate Policy and Technology Scenarios until 2050 in the model EMELIE-EYS; December 2013; World Scientific, Climate Change Economics, Vol4, Suppl. 1 (2013),1340007 (22 pages) [www.worldscientific.com](http://www.worldscientific.com);

<sup>18</sup> Schröder et.al.; Market driven power plant investment perspectives in Europe: Climate Policy and Technology Scenarios until 2050 in the model EMELIE-EYS; December 2013; World Scientific, Climate Change Economics, Vol4, Suppl. 1 (2013),1340007 (22 pages) [www.worldscientific.com](http://www.worldscientific.com); page 4;

<sup>19</sup> IPCC-SRREN 2011; Renewable Energy Sources and Climate Change Mitigation; Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press; 32 Avenue of the Americas, New York, NY 10013-2473, USA; ISBN 978-1-107-02340-6,, Chapter 10.2.1.1. page 799;

<sup>20</sup> IPCC-SRREN 2011; Renewable Energy Sources and Climate Change Mitigation; Special Report of the Intergovernmental Panel on Climate Change, Cambridge University Press; 32 Avenue of the Americas, New York, NY 10013-2473, USA; ISBN 978-1-107-02340-6,; Chapter 10.2.1.1, page 799;

<sup>21</sup> Medium-Term Renewable Energy Market Report 2014 -- Market Analysis and Forecasts to 2020, 260 pages, ISBN 978-92-64-21821-5, see Executive summary;

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