University of Flensburg

Doctoral Thesis

renpass
Renewable Energy Pathways Simulation System
-
Open Source as an approach to meet challenges in energy modeling

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Executive Summary

0.1 Problem

Today's energy systems are undergoing fundamental changes. Due to environmental problems, limitations and distribution challenges of fossil fuels as well as the risks of nuclear power, the process of transformation to a low carbon energy system based on renewable sources is ongoing. This thesis refers mainly to the European and, in particular, to the German electricity system, since rapid energy system changes occurred in the context of the so-called "Energiewende" within recent years.

With the transformation of power generation capacities and the entire structure transmission systems, new challenges arise due to the fluctuating nature of wind and solar power. These account for most of the renewable electricity potential in Europe. With a rising need for flexibility, both on the demand and the supply side, the traditional concept of base and peak load power plants is being phased out.

Interactions of grid infrastructure, renewable power generation and storage requirements are highly complex. Analyses of their interplay require computer models in high spatial and temporal resolution. Over the past decade, several model approaches have been elaborated aiming to identify least-cost infrastructures of renewable electricity systems and optimize the operation on an hourly basis. Nowadays, a wealth of models for simulating or optimizing Europe's and Germany's renewable electricity systems exist.

Energy, and especially, electricity system modeling is accepted as an important tool to answer research questions or advice policy makers and investment decisions. However with the increasing relevance of modeling results for policy decisions and the increasing public awareness, challenges are becoming apparent. Credibility has decreased due to significant differences in model outcomes and a lack of traceability. The loss of comparability does not allow proper evaluation of differing results from various models. In order to increase acceptance of modeling results as well as the quality of the modeling approach, transparency in all stages of the process is fundamental. Scientific standards require reproducibility of modeling results which implies the documentation of input data and model structure.

In other scientific fields, transparency and credibility problems are addressed by using Open Data Standards and Open Source Software. Although some Open Source development can be observed in the field of energy modeling, transparency of data and code is far from being common standard. In fact, most energy models are not published.

This work puts forward the following hypothesis:

Introducing an Open Data and Open source approach into energy modeling practice in science and society is a condition to overcome key challenges in energy modeling.

Today, it is already possible to implement a full scale model, including functions and data, and deliver comparable results fulfilling the scientific principles of transparency and reproducibility.

0.2 renpass

0.2.1 Scope

For understanding and analyzing challenges and opportunities of transparent models, an electricity system model according to Open Data and Open Source principles was developed at the Centre for Sustainable Energy Systems (CSES) at the University of Flensburg by the author and Gesine Bökenkamp. Within the scope of this thesis, the development of renpass (Renewable Pathways Simulation System) is described, while Bökenkamp (2015) covers the hydro system part.

In its basic version as developed in the context of this thesis, renpass covers the electricity sector of Germany, Norway, all their neighboring countries, as well as all countries surrounding the Baltic Sea. Figure 1 illustrates the available regional resolution. Each country except Germany is defined as one region. Within Germany, regional borders are chosen according to potential grid bottlenecks. The red lines indicate connections between regions.

0.2.2 Functionality

Figure 2 illustrates the basic functionality of renpass. The installed capacities and development pathways of the different power generation sources have to be set exogenously by the user for the period to be analyzed. For each time step, the production of the

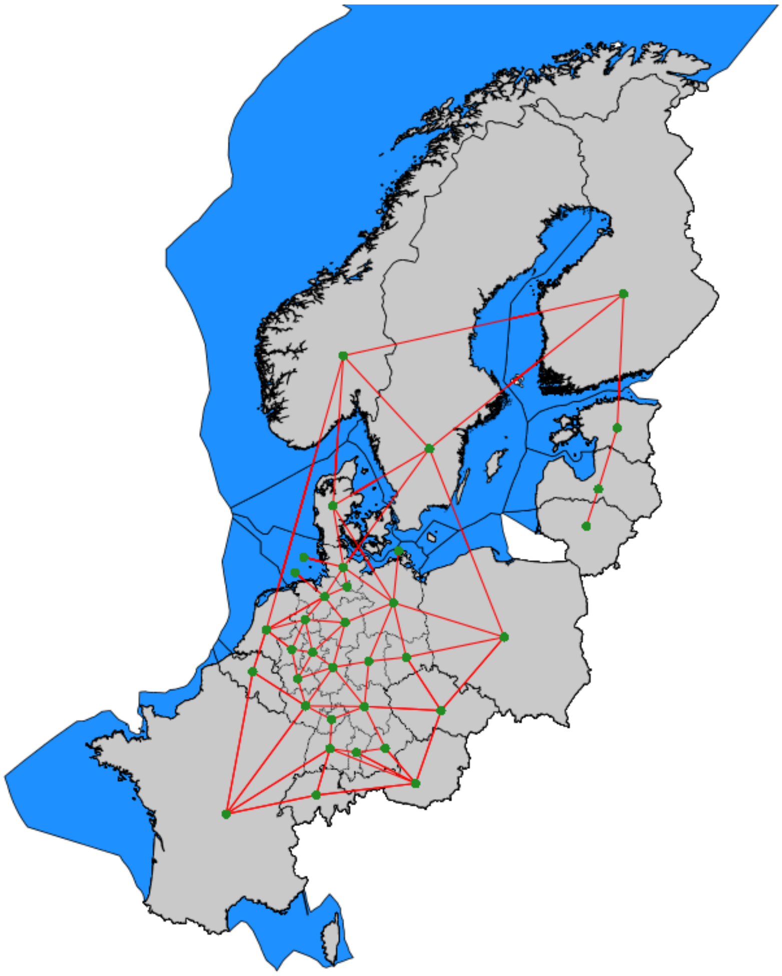

Figure 1: Regions in renpass and summarized grid connections between regions. Source: own image based on ENTSO-E (2012b); GADM (2012); VLIZ (2012)

variable renewable energy sources [VRE], namely wind, solar and run-of-river electricity is subtracted from the demand. The remaining residual load is then supplied by the least expensive combination of the controllable production plants, storage units and grid transmission potential. The utilization of controllable capacity in renpass is based on regional dispatch within each grid region, followed by a balancing between the regions within the grid capacity limits. Once the regional dispatch has been done in each region, information about region price, excess electricity and storage possibilities is provided per region and fed into the exchange algorithm. This heuristic approach finds a robust least-cost solution for each time step within the limits of the given infrastructure. Excess electricity is stored within the available capacity of storage utilities. Regions with uncovered demand are assigned a high scarcity price highlighting their import requirement within the overall system.

renpass provides an optimization of the operational and the transmission processes but it does not optimize the overall system configuration as investment decisions are not included in the algorithm. Instead, they have to be set as scenario assumptions. Referring to grid and transport concerns, it can be classified as a transshipment model.

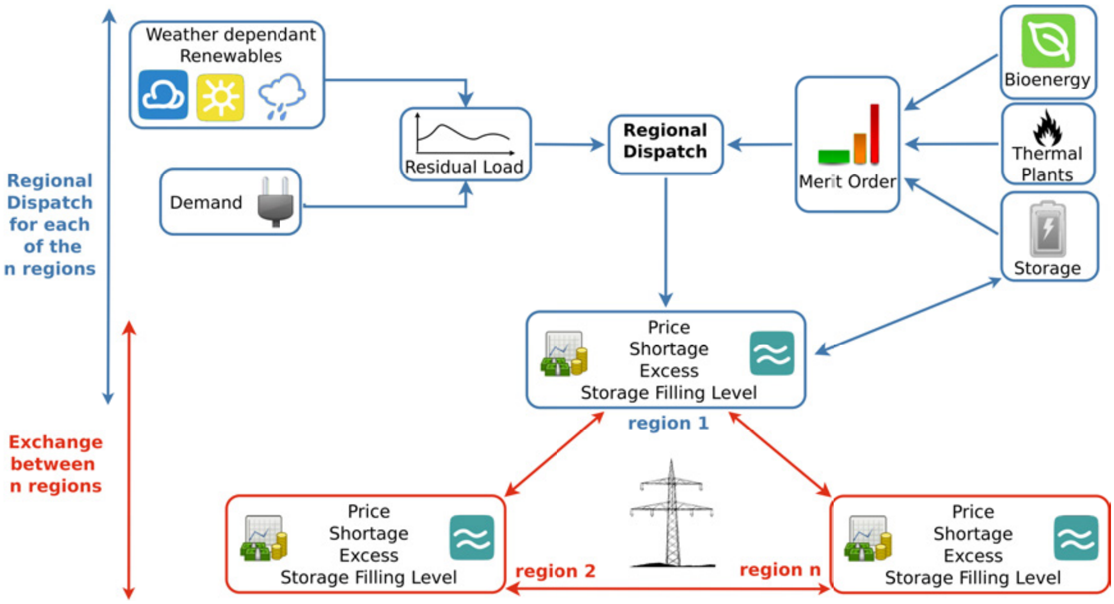

FIGURE 2: Schematic diagram of the regional dispatch and the exchange in renpass. Source: own illustration, icons from Open Icon Library and EnergyMap

0.2.3 Application

All components of the model including manual, databases, code files and functions can be downloaded from `renpass.eu`. renpass is published under the GNU GPL 3 license (FSF, 2007). According to this copyleft license, anyone can use renpass, adjust it to their needs, and has to use the same license to distribute variations.

renpass can be used on computers running on Linux, Windows or Mac operating system. All code is written in the programming language R. The R-package RMySQL is required for the direct data queries to the MySQL database.

Exclusively openly available data is utilized for renpass including time series, parameter and register of the areas meteorological data, power plants, storage utilities and transmission grid. All data is spatially referenced to the renpass regions. Climatological time series are kindly provided by the Helmholtz Center Geesthacht (Geyer and Rockel, 2013). Thanks to the European Network of Transmission System Operators for Electricity (ENTSO-E) some data on grid, installed capacities and demand are available for Europe. Although energy data availability has increased within the last few years, poor quality and incomplete data sets are still a major constraint on energy modeling and hinders rapid improvement. Especially power plant registers and parameters, grid infrastructure and load data in a spatial resolution higher than per country level are not openly available.

To start an hourly simulation in renpass, various scenario settings for year of weather time series, renewable and fossil installations, resource prices, grid and storage infrastructure have to be selected or additionally included in the pathways database. The regional resolution can be chosen, too. The effort of choosing and readjusting input parameters should not be underestimated, since the model's results can misinform, if the assumptions are not consistent and plausible.

Once a simulation is started, the program sequence shown in Figure 3 proceeds. All boxes with double side lines stand for underlying subroutines. Blue framed boxes indicate which routines are repeated in each time step. Clusters of code are indicated in colors.

The output of the model is a log-file, plots and a result database with various time series per region. The automatic plots provide a first insight in the energy balance, coverage of demand, utilization of power plants, prices and grid utilization. The results, as well as some of the plots, are referenced spatially to the regions.

0.2.4 Collaborative Software Development

During the development phase of the renpass version described in this thesis, the model was utilized in several contexts. The high number of users who became co-developers and the wide range of applications at a relatively early stage of development revealed several bugs and some of renpass' shortcomings. Thus, the model's nature of being an open and transparent approach improved its quality and robustness considerably. Experience gained in collaborative software development led to the implementation of the version control software git for collaborative code development, bug fixing, version control and model extensions. The latter have to pass a testing procedure including ten test scenarios before being integrated into a new model version.

0.3 Conclusion

By developing renpass, it was shown that an electricity system model nowadays can rely exclusively on Open Data and Open Source Software. However, there still exist significant barriers.

First, poor data quality and the low availability of spatially referenced power plant and grid infrastructure data jeopardize robust results. This problem could be addressed by

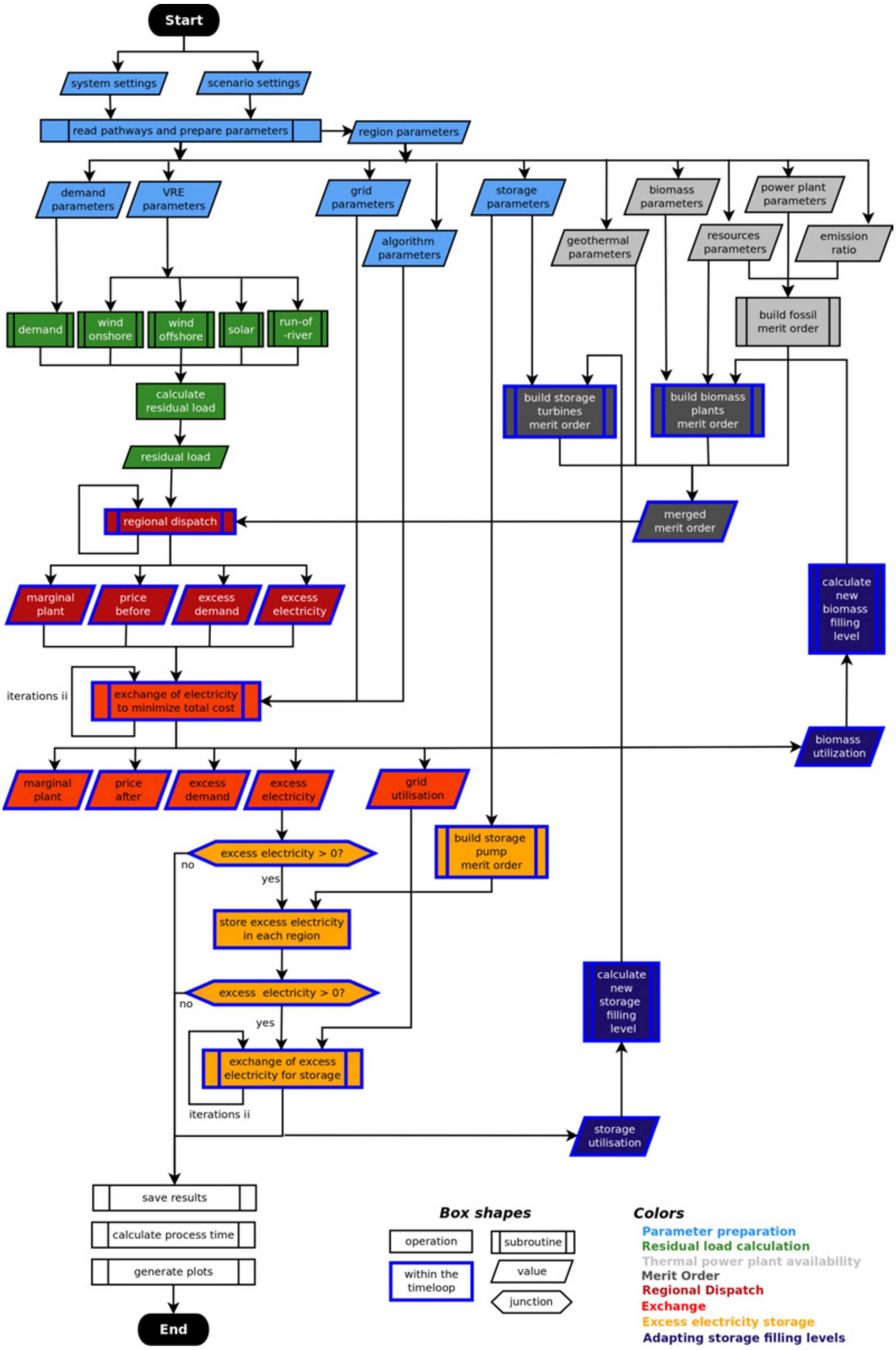

FIGURE 3: Program Flowchart of renpass core, the frame code of the model. Clusters of processing are indicated in colors. The shapes of the boxes indicate operations, underlying subroutines, values or junctions. Blue framed boxes are within the time loop.

establishing an Open Energy Data library at national and European level. Once set up, all important data for energy system modeling could be cooperatively maintained, improved and kept up-to-date. The resources and time gained as a result could be used to develop further modeling scope and methods. A database including reference data sets is the first step towards multi-model approaches. The aim is to compare the outcome of different models addressing the same question. This increases the robustness of modeling outcome.

The second main barrier to build fully transparent and traceable energy models is the complexity of the energy system and the resulting complexity of the models themselves. Utilizing Open Data and Open Source standards is a precondition for transparent communication of the results. But due to its complexity, an energy model is not automatically transparent and traceable even if all data and source code are provided. Structuring a model in clusters with clear interface definitions accompanied by detailed documentation of data input and model structure facilitates the readability and applicability for users other than the programmer themselves. Agreeing on basic standards of data and model documentation, as well as interface definition could increase the compatibility of model parts from different authors.

Furthermore, research and development in the field of model result communication is essential. Such models can be helpful tools to work out interrelations between different components of energy systems. However, the model output has to be translated in a way that users and recipients understand the dependencies between the input and the outcome of the model. Result sensitivities to input parameters should be the focus when communicating and translating model results.

Energy model quality can be increased by applying the described structural changes. Such progress can build the basis for addressing more dimensions of energy systems than their techno-economic characteristics. Several models have demonstrated over the past decade, that 100 % renewable electricity systems in Europe are feasible from a techno-economic point of view. Along with the ongoing transformation, questions about societal and ecological dimension of the various possible pathways arise. Furthermore, the level of resilience of energy pathways regarding changes to techno-economic circumstances plays an increasingly important role. Further research on modeling methodologies is required to evaluate energy pathways that also fulfill ecological, societal requirements and are characterized by a high level of resilience.

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Abbreviations

AC	**A**lternating **C**urrent
BNetzA	**B**undes **Netz** **A**gentur (Federal Network Agency)
BSH	**B**undesamt für **S**eeschifffahrt und **H**ydrogrohie (Federal Maritime and Hydrographic Agency)
COSMO-CLM	**CO**nsortium for **S**mall-scale **MO**delling in **CL**imate
CSES	**C**entre for **S**ustainable **E**nergy **S**ystems
DC	**D**irect **C**urrent
DWD	**D**eutscher **W**etter **D**ienst (German Meteorological Service)
EEG	**E**reneuerbare **E**nergien **G**esetz (German Renewable Energy Act)
EEZ	**E**xclusive **E**conomic **Z**ones
ENTSO-E	**E**uropean **N**etwork of **T**ransmission **S**ystem **O**perators for **E**lectricity
EnWG	**En**ergie **W**irtschafts **G**esetz (German Energy Industry Act)
FINO	**F**orschungsplattformen **I**n **N**ord- und **O**stsee (Research Platforms in North and Baltic Sea)
GADM	database of **G**lobal **ADM**inistrative Areas
GAMS	**G**eneral **A**lgebraic **M**odeling **S**ystem
HVAC	**High** **V**oltage **A**lternating **C**urrent
HVDC	**High** **V**oltage **D**irect **C**urrent
NEP	**N**etz **E**ntwicklungs **P**lan (Grid Development Plan)
NTC	**N**et **T**ransfer **C**apacity
renpass	**r**enewable **en**energy **pa**thways **s**imulation **s**ystem
TSO	**T**ransmission **S**ystem **O**perator
UBA	**U**mwelt **B**undes **A**mt (German Federal Environment Agency)
VRE	**V**aribale **R**enewable **E**nergy
WEC	**W**orld **E**nergy **C**ouncil

Symbols

a	age	$years$
aux	auxiliary power requirement	
E	energy	MWh
C	installed capacity	MW
C_{grid}	transfer capacity	MW
c_{mar}	marginal costs	$€/MWh$
c_{var}	other variable costs	$€/MWh$
dpr	dispatch region	
e_{CO_2}	CO_2 emission factor of consumed fuel	tCO_2/GJ
ee	excess electricity	MW
$f_{security}$	factor to account for n-1 security	
I	current	A
idx	index	
ii	number of iterations	
ed	excess demand	MW
P	electrical power	MW
p	electricity price	$€/MWh$
p_{CO_2}	CO_2 emission price	$€/t$
p_{fuel}	fuel price	$€/GJ$
p_{sc}	scarcity price	$€/MWh$
rl	residual load	MW
sc_{bio}	biomass scarcity factor	
upl	unused part load of marginal power plant	MW
t	time step	
U	voltage	kV

v	wind speed	m/s
y_{sc}	scenario year	
z_0	roughness length	m
η	efficiency	

Chapter 1

Question Formulation

1.1 Energy Pathways - Changes in Energy Supply

Our energy system is undergoing a fundamental transition. Reasons and motivations to change the old system based on fossil fuels are manifold. Since the beginning of the relatively short period of fossil fuel consumption, warnings about the finiteness of resources such as oil, coal, gas and uranium have appeared. Forecasts about the remaining amount vary widely, but it is evident that there will be an end.

Another striking reason for moving away from fossils is climate change. Limiting climate change to two degree demands a reduction of global greenhouse gas emissions by roughly 50% by 2050 as compared to greenhouse gas emissions in 2000 (IPCC, 2007, p.39, Table TS.2). According to §3 of the United Nations Framework Convention on Climate Change, this will require a reduction of the greenhouse gas emissions of industrialized countries by 80 to 95% by 2050 (IPCC, 2007, p.776, Box 13.7). Taking into account that the energy sector is one of the main contributors to greenhouse gas emissions and easier to reform than, for example, agriculture, this sector will have to undergo a transition to an energy system without greenhouse gas emissions. Within the energy sector, it will be easiest to switch for electricity.

In the field of electricity, not only are coal, gas and oil no options, but nuclear power too is not viable for future energy systems: Uranium does not produce particularly that high emissions during use, but life cycle studies like Sovacool (2008) and Lenzen (2008) show that climate emissions occur during the process of extracting the resource. Another

reason to avoid nuclear power in electricity system pathways is the risk of uncontrollable nuclear accidents and problems concerning waste disposal and uranium mining.
The very few examples of newly built nuclear power plants IAEA (2013) reveal another argument for phasing out of this technology: the financial aspect. With rising fossil fuel prices, alternatives are becoming more and more attractive. Fossil fuels are not that well distributed, thus export dependency is another reason for change.

Summing up, there are diverse reasons for transforming the energy system: emissions, finiteness of resources and its inequality in the distribution resulting in security of supply issues. The worldwide rising energy demand strengthens all arguments for the need to transform the energy system. Since every energy generating technology has environmental impacts, the rising demand makes obvious that a transformation has to go beyond just shifting to other sources and technologies.
Thus, the transition consists of consuming less energy (sufficiency), using the energy more efficiently and generating the remaining need of energy with a diversity of low environmental impact technologies. There is always a danger of new technologies only providing additive generation in the short run. That is why the long-term transformation to 100% fossil free energy systems is the focus. Only then, and in combination with sufficiency and efficiency, can it lower the negative impacts of todays energy system.

Energy technologies that do not consume resources during generation are called renewable energy. The IPCC Special Report on Renewable Energy (IPCC, 2011) categorizes these technologies as an important climate change mitigation option. According to this report, “RE [Renewable Energy] is any form of energy from solar, geophysical or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use” (IPCC, 2011, p.38, 1.2.1).
CO_2 neutrality, or rather reduction to the point of zero net climate emissions is one impulse for change and an important aim, but there are more reasons for the usage of renewable energy instead of fossil fuels. To name just a few: saving resources for other purposes, reducing import dependency, diversifying energy sources which leads to a more resilient system. Furthermore, since renewable energies converters tend to arise in smaller entities than conventional ones, energy system transformation is also a chance to democratize energy supply.

For quite a while, according to the International Energy Agency (IEA), there was no alternative to the fossil based energy system. When renewable energy sources started to become more popular, it was common understanding that they could never supply more than a minor share.

Although there have been suggestions as early as 1975 that nationwide 100% renewable energy systems are possible (Sørensen, 1975; Lovins, 1977), in the first phase of 100% renewable publications, those were rather general outlines to demonstrate that this is possible at all (Hohmeyer and Bohm, 2014, p.4). These general attempts were followed by more detailed calculations of renewable potential being able to supply the demand in every hour of a year. One of the first 100% renewable studies with an hourly resolution was published in 2006 by Czisch (2006).

(Hohmeyer and Bohm, 2014, p.6) describe a change of view around 2010. A range of studies with detailed data and hourly resolution from different institutions showed with different methods the same result: National energy systems, as well as the European, could be supplied with renewable energy to 100%. The fact that these studies were made by different stakeholders in society, for example research institutions (FVEE, 2010), state organizations such as the German Federal Environmental Agency (Klaus et al., 2010) and the German Advisory Council on the Environment (SRU, 2011) as well as from companies (PWC, 2010), shows how well established and settled this idea already is in large parts of the society. As the German background of the named sources shows, this holds especially true for Germany, but this idea starts to settle on a European level and in other European countries as well.

The question is no longer, whether a 100% renewable energy system is possible, but rather, how it should pan out. The discussion shifted to the question as to which pathway to pursue. The term energy pathway already implies that there is a whole map of potential energy futures to pursue and even if there are some fixed points about the aim (no fossils, no emissions), there are huge differences in destinations with respect to total installed capacities, technological and geographical distribution and need for infrastructure, like grid and storage possibilities. Even if the target could be agreed upon, multiple pathways may lead to it. Due to huge uncertainty about developments decades in the future, important questions address the danger of lock-in effects of different pathways.

To conclude, the common goal of a 100% renewable energy system opens up more questions about the energy pathways a society wishes to pursue. The aspects under which different energy pathways should be scrutinized are those pushing away from the current, established system and desired ones of future energy systems. Some important aspects are:

- → Resource consumption
- → Land usage
- → Emissions
- → Impact on biodiversity
- → Health impacts
- → Effects on climate change
- → Operating efficiency
- → Economic efficiency
- → Security of supply

Each change of system involves additional effort and negative impact for some of the target dimensions. If the resource consumption for the transformation and the new system exceed the advantages, this is not a good pathway to pursue. Future energy pathways have to be weighed against the old system, but also against each other. All forms of energy generation have financial, ecological and societal impact, use land and consume resources.

Although it is a difficult task, the societal process of transformation offers diverse possibilities. It not only involves a change of sources but also of system, since ownership, consumer and producer roles may change. It is not only a question of technical and economic feasibility, since it has many dimensions, the pathway is constructed step by step in a participatory societal discourse involving different stakeholders. Widespread knowledge, communication and information about options and their impact is one crucial question. Tools for the information flow and research possibilities form a fundamental basis for such a discourse.

1.2 Modeling Energy Pathways

Due to the complexity of energy and especially electricity systems, the assistance of computer models is required to gain knowledge about the interactions and impact of its components. Shaping energy systems in technical and in economic aspects has been an important field of research, especially since the liberalization of energy markets. Energy system computer models are tools to answer various questions concerning the infrastructure and operation of plants, grids, storage and demand. Political as well as investment decisions are quite often taken on the basis of knowledge gained from modeling.
Many institutes and companies have built different kinds of energy models. There has always been the problem of complexity and variety of input parameters. A lot of decisions on the input side have to be taken before processing the simulation or optimization of a model. The outcome of models is usually a range of results rather than merely a single number. It depends heavily on the decisions of input parameters and on the functionality of the model. A computer model can never contain all the aspects and consider all relevant parameters, but improvement can be made by communicating modeling results. Constructive and open dealing with non-knowledge is crucial. This implies showing exactly what was fed into the model, how it was calculated, what could not be considered, what are the weaknesses and the sensitivities of the model are, and which input parameters led to which changes.

Complete transparency is a possibility to overcome these problems and for the longer term increase the quality of models. That means all data and source code are open and traceable. The necessity to be completely open to scrutiny is especially true for energy models looking far into the future, since the range of structural designs of systems is vast.
The complexity of energy systems is increasing, as is the number of people involved and the number of stakeholders providing knowledge in this field. Since the number of tools available for collaborative working and knowledge sharing has increased thanks to the development of Open Source software and easy access to affordable computing power, more people are participating in modeling processes. It will be inevitable to strive for transparency and diversification of modeling approaches, in order to maintain the quality of energy modeling research.

By contrast, when working with energy models, it is quite common that only results are published, which does not comply with the scientific principles of reproducibility. There are already many fields and projects in which principles of Open Data and Open Source software have improved the robustness of the outcomes. It would appear that, in energy modeling, there are still obstacles to Open Data and Open Source approaches, although both could help to improve the quality and reliability of modeling results.

1.3 Contribution

This work puts forward the following hypothesis:

Introducing an Open Data and Open Source approach into energy modeling practice in science and society is a condition to overcome key challenges in energy modeling.

Today, it is already possible to implement a full scale model, including functions and data, and deliver comparable results fulfilling the scientific principles of transparency and reproducibility.

With reference to this, this thesis discusses the state and key challenges of energy modeling and opportunities of Open Data and Open Source approaches (Chapter 2). The structure of the development of the Open Source electricity system model renpass is described in Chapter 3. Chapter 4 contains a description of Open Data utilized for the model. Application examples of renpass and its mode of distribution is the subject of Chapter 5.
This thesis can only provide a small insight into the application of renpass itself. The user manual provides further practical guidance (Wiese et al., 2013).
Chapter 6 covers further developments of renpass and trends of Open Source energy system models from an organizational, technical and economic point of view. Chapter 7 provides a discussion whether Open Source can be an approach to regain quality of energy modeling and if so, which obstacles have to be overcome.

renpass is a joint project with contributions from different PhD and master thesis projects. This thesis describes the basic structure as well as the Open Source idea of renpass. Gesine Bökenkamp is the other main author of the model renpass. Her work contains the detailed model of the Norwegian and German hydro electricity system within renpass (Bökenkamp, 2015).

Chapter 2

Energy Modeling and Open Source

2.1 Energy Modeling

2.1.1 Need for Energy Models

As outlined in Chapter 1, climate issues, fossil resource scarcity, refraining from nuclear power and diversification of sources and technologies for a higher resilience trigger the transformation of energy systems. The fluctuating nature of part of the renewable technologies as well as the trend to smaller entities of power generation and higher technological diversification increase the need for software to model those systems. The need, for but also the variety of energy models has probably never been bigger.

Energy systems consist of complex structures of interconnected parts. Especially electricity systems need a high level of coordination since demand and supply of all components connected to the system have to match in each moment of time. It is hardly possible to answer questions about parts of energy systems without looking at the whole system and its interactions. For example, storage requirements cannot be addressed without taking into account both demand and different feed-in sources at a high spatial and temporal resolution.
The complexity of modeling increases along with structural changes of energy systems. The more interconnection as well as interactions between different technologies, markets and sectors (electricity, heat and mobility) should be modeled, the higher are the requirements on energy models.

In Europe and especially in Germany, a culture of long-term energy scenario thinking and backcasting has emerged during the last years. This trend of using energy models as tools for decision makers in the field of energy and infrastructure planning has accelerated with progress of computer technologies: The possibilities to process large amounts of data, decrease in prices for computational power and advancement in optimization algorithms expand the group of persons and institutions that can contribute to energy modeling.

Investment decisions as well as energy policy rely on energy modeling output. Especially an influence on long-term energy pathway decisions and target setting can be observed.

2.1.2 Existing Energy Models

There exists a wealth of advanced energy models for all kinds of model utilizations from company in-house purposes to the science field (Mai et al., 2013).
For the scientific field of energy modeling, Connolly et al. (2010) provide a review of different computer tools that can be used to analyze the integration of renewable energy. Potential assessment and integration of renewable energy have become a key issue in energy planning (Connolly et al., 2010, p.1060). With their analysis on 68 tools, Connolly et al. (2010, p.1077) illustrate the variety of models and come to the conclusion that depending on the problem that should be solved different tools can be chosen, the perception of 'the' ideal tool has to be altered and point out that the model choice depends on the investigation focus (Connolly et al., 2010, p.1059). Thus, there are energy tools available to support the transition from fossil-fuel to a renewable energy world.

Owed to the dynamic development of energy models, the taxonomy is rather confusing and unclear.
Ventosa et al. (2005) describe three major trends in electricity market models: optimization, equilibrium and simulation models.
Pina et al. (2011) suggest two categories of models: The first group represents models to assess long-term transitions processes in energy systems and their economic and technical implications. They operate on large time scales and regions, mostly covering more sectors of the energy system and thus require a high aggregation of sectoral details. The second group is more on an operational basis and works with a higher resolution in time and space, but thus also with shorter time spans and smaller areas. Those rather focus on specific technology changes in infrastructure and installed capacities of generation

plants.

Haller (2012, p.15) suggests to extend those two categories by a third group of hybrid models, combining short-term system and dynamics and transmission requirements with long-term investment aspects and proposes the model LIMES as a representative of the hybrid models, a long term inter-temporal optimization framework (Haller, 2012, p.18).

Schaber (2014) illustrates a clear approach of model classification whilst remaining the multi-characteristics of energy and power models (see Figure 2.1). On the x-axis, the temporal resolution of models is shown, ranging from decades (long-term development) to seconds (system operation). On the y-axis, the spatial resolution ranging from world, continents, countries, regions, cities to houses. By classifying several models within the graph, three classes emerge: intertemporal, hybrid and operational models. Their temporal and spatial resolution overlaps. Based on this approach, features of the URSB-EU and URSB-D model, that Schaber (2014) presents, are classed on those two axes, which is very helpful for an insight in model description. Additional model features like market dynamics and uncertainty would require an additional dimension (see Figure 2.2).

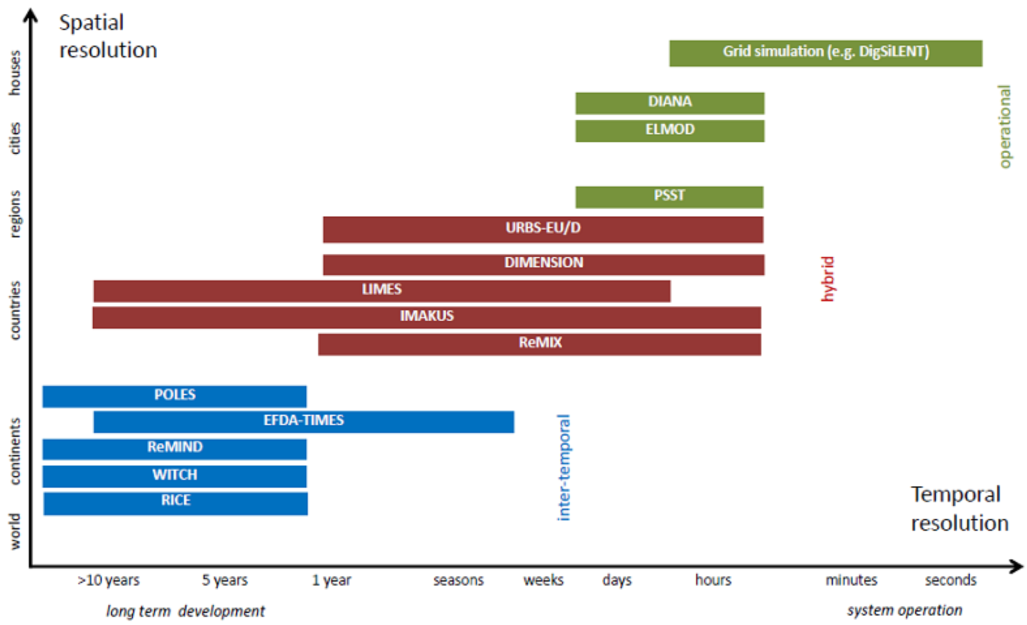


FIGURE 2.1: Classification of model features for energy and power systems models after Haller (2012) and Schaber (2014)

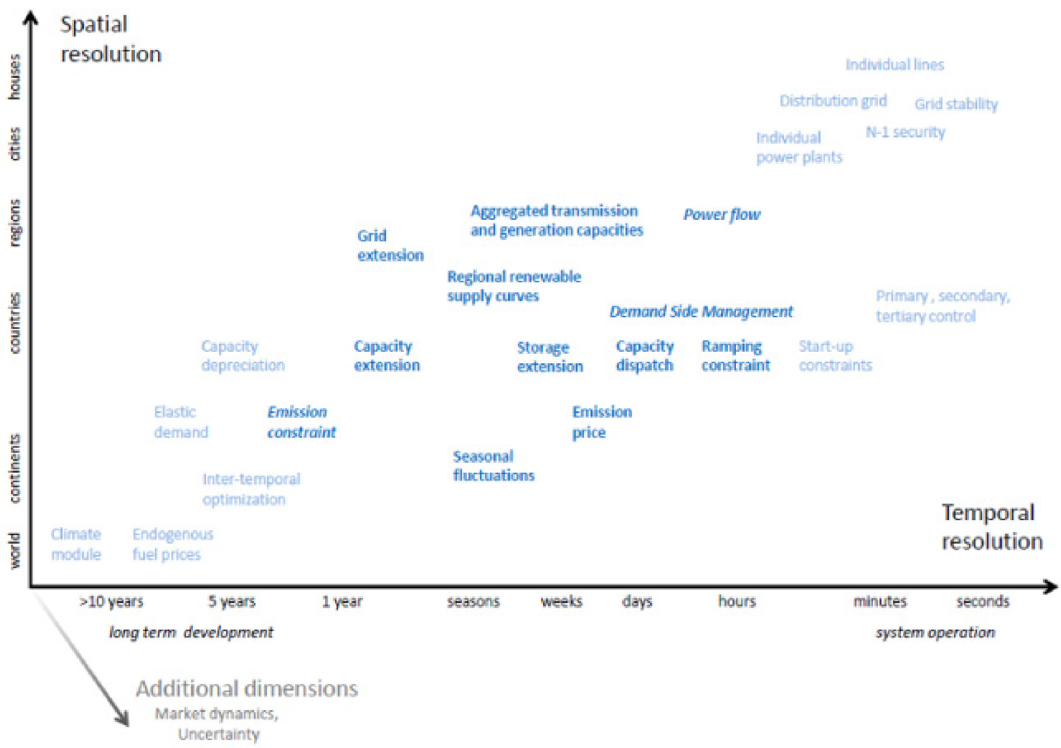


FIGURE 2.2: Classification of model features for energy and power system models after Haller (2012) including model features of URBS-EU and URBS-D after Schaber (2014)

As described, there are different approaches to energy model classifications and the categories vary. Concluding from different approaches, the following characteristics have been identified as a good starting point for understanding and describing an energy model:

→ covered time

→ temporal resolution

→ covered regional/area

→ spatial resolution

→ covered sectors

→ considering existing infrastructure

→ assessment of renewable potential

→ installed capacities, grid, storage optimized or scenario setting

Although outlining these characteristics of a models help to understand possible applications, they do not lead to a clear classification and demarcation of energy models. The number of models rises fast and changes in the energy system make new approaches necessary. Whenever generally accepted classifications evolve, new approaches that do not fit in the existing categories emerge.
Thus, for describing and classifying renpass, the list of indicators above will be used in Chapter 3. Key characteristics are that it is an electricity system simulation model for long-term planning with optimization elements for operation. It has a high spatial and temporal resolution.

The National Renewable Energy Laboratory (NREL) analyses the variety of models in a decision maker's guide to evaluate energy scenarios, modeling and assumptions. They conclude that one has to be aware that "[w]hile there exists a wealth of advanced model, data, and energy scenario options, important questions remain about how to effectively apply these tools to help plan for an uncertain future" (Mai et al., 2013, p.7). Although energy models are very advanced today, there are some problems arising in the fields of transparency, interpretation, bias and data availability.

A prominent example that illustrates the transparency problem of models is the process of identifying low carbon energy pathways for the EU Energy Roadmap. The model PRIMES for energy scenario calculation played a central role in the Commissions work on the Roadmap (European Commission, 2011a, p.16). Although different scenarios were calculated, all results were based on one tool. The Advisory Group on the Energy Roadmap called attention on the sensitivity of results especially with regart to technology-cost, discount rate and fossil fuel price assumptions. Although assumptions were published, the property rights of the model remained at the National University of Athens, so that the results were not reproducible and not open to scrutiny of independent researchers. The Advisory Group criticized that this reduces the credibility of the model results and thus the whole Roadmap (European Commission, 2011a, p.18).
Following the Advisory Group's recommendations, a roof study was carried out to compare results of different models in the framework of the Energy modeling Forum (EMF). Knopf et al. (2013) document the verification of the EU Energy Roadmap by a comparison of 13 models. They state that "the single-model approach leaves several unanswered questions, particularly in terms of the modeling methodology, uncertainties related to input assumptions, and lack of transparency"[p.2] and come to the conclusion that "a

multi-model perspective is valuable for formulating robust and effective energy and climate policies“[p.3].
Despite differences across the models, they all agree that the long-term 80% reduction until 2050 aim can be achieved. Estimating the contribution of different options for greenhouse gas emission mitigation, there is a high degree of conformity between the models. The reduction of energy intensity plays a key role in the mitigation strategies. Concerning the costs, model results diverge. Especially for costs after 2040, the results vary considerably (Knopf et al., 2013, p.32ff).

The EU Energy Roadmap process is just one example where problems of private single-model approaches were discussed publically. Models can assist to identify trends, but the results are always ranges, no absolute numbers and heavily depend on scenario assumptions. Lack of transparency can lead to misinterpretation of results. Especially when it comes to costs, model result lie in a wide range. Recipients of advice based on modeling need to understand the dependencies between input and outcome of energy models and that the characteristics of a model already partially determines its output.

In conclusion, although there exists a wealth of energy models, there are many unsolved problems which lower their ability to serve as reliable tools in energy pathway decisions.

2.1.3 Key Challenges

The National Renewable Energy Laboratory advises to evaluate energy scenarios. ”One must maintain a spirit of humility about predictions, particularly when asked to look decades into the future.“ (Mai et al., 2013, p.7). A common misunderstanding between modelers and recipients of their results is that energy modeling can predict the future. Modeling the energy future can assist in revealing effects of different energy planning and pathway decisions. However some challenges have to be coped with to keep modeling quality high.

Communication of modeling results is one central key challenge in energy modeling. Results can only be interpreted with care when the interpreter is fully aware of influencing factors, strengths and weaknesses of the model. Not only the input assumptions have a major impact on the outcome, but also to the calculation framework and the optimization algorithm define the outcome. Moreover, recipients of advice by model output often expect one result, but models can only provide a range of results and show tendencies. As Mai et al. (2013, p.9) summarizes, "[w]hat modelers consider "results" and what decision makers deem useful information may not overlap."

Decentralized structures are more difficult to model. On average, renewable energy sources are based on smaller units than fossil thermal power plants. In common fossils energy systems in Europe, power plants of the size of several 100 MW feed into the high and highest voltage grids from where electricity is distributed to the customers. Nowadays, feed-in on the level of the distribution network increases.

In Germany, already today, feed-in from the distribution grid level has reached dimensions that reverse power flows are a common challenge network operators have to deal with. The monitoring report 2013 of the German Federal Network Agency (BNetzA) confirms an increase in decentralized power generation (BNetzA, 2013c, p.8).

These changes in system structure have to be represented in modeling of future energy systems. Spatial informations are a key element to be able to answer arising new questions. The placement of variable renewable energy (VRE) as well as their feed-in depend on site-specific meteorological conditions. Grid restrictions play are major role in questions about security of supply. Those cannot be tracked by models without the spatial information of feed-in and demand and considering capacity of the connection lines.

Fluctuation and flexibility are characteristics of future energy systems. Not only the geographic but also the temporal resolution in modeling needs to increase with higher shares of renewable energies. In many future scenarios, wind and solar power form the main share of electricity generation. These VREs depend on weather conditions. Their fluctuating nature causes requirements on the flexibility of other components of the energy system.

For example ramp-up and especially warm-up times after a cold start of fossil power plants increase in importance. The questions which components are flexible enough so that they altogether can match the task of matching demand and supply cannot be investigated without going on a high temporal resolution. Flexibility is a key quality, that has to be reflected in modeling.

It was common practice for energy scenarios to calculate the yearly feed-in sum of all technologies [TWh] in a huge area like a country and see if they do meet the yearly sum of demand in the same area [TWh]. This aggregation does not provide any information on the coincidence of supply and demand.

High resolution data As described, higher spatial and temporal resolution in modeling is necessary. This implies the challenge of processing huge amounts of data. There is a trade-off between temporal and geographic resolution and computing time of the model. The question is to which extent higher resolution and thus more detailed results justify higher time and work effort. The data resolution has a significant effect on the questions that can be answered. For example, if feed-in and demand in is not modeled location-based, no conclusions about grid restrictions can be drawn. Good documentation about the resolution of input data and its effect on the results is essential.

Technological co-evolution and uncertainty become important dimensions of energy modeling. Not only technical development but technological co-evolution needs to be addressed when fundamental changes in energy systems happen. Questions on the cluster of technologies that work well together and about system designs of systems require new modeling approaches.
Another ongoing challenge for energy models is to address uncertainty within the model. A model cannot represent everything but one has to be aware of this incompleteness. An attempt to improve this is to distinguish characterizable unknowns from issues beyond these borders. From other modeling sectors like especially the financial sector, there are tools available to address those unknown factors in models (Mai et al., 2013, p.8). Approaches to deal with uncertainty for energy modeling need to be developed further.

Objectivity is another key challenge of modeling. Mai et al. (2013, p.9) state that accidentally or purposefully, all models incorporate bias. A requirement on scientific models is objectivity and reproducibility of the results. Due to the plethora of assumptions and input parameters that have to be chosen for energy modeling but influence the results, this requisition is difficult to fulfill and kept track of.

Openness to scrutiny has always been a requirement on energy models but increases in importance. On the one hand this complies with the need for participation possibilities. On the on the other hand software can never be without mistakes. The more open a model is and the more people find bugs the better the model gets. It is a challenge to document everything in a way it can be understood. There are no standards for code and data documentation yet. Another barrier for this openness is quite often the anxiety of the programmer of being convicted of wrong calculations, which excludes models from a rapid process of improvement.

In summary , key challenges for energy models are the diversification of technologies, flexibility options as well as spatial and temporal resolution. Additional tasks for models are to cope with non-knowledge and new aspects of technological co-evolution. The consequent increase in complexity intensifies the need for openness to scrutiny and awareness of bias. A major key challenge is the communication of modeling results.
Principles and operation of Open Science, Open Data, and Open Source will be analyzed in this thesis with respect to their contribution to tackle those key challenges of energy modeling. Open Data and Open Source in general are described in Section 2.2. Models already using Open Source software are described in the subsequent Section 2.3.

2.2 Data and Software in Science

2.2.1 Open Data

Science can be described as collecting, analyzing, publishing, reanalyzing critiquing and reusing data (Molloy, 2011). Data is fundamental for scientific progress.

The first World Data Center system was established in preparation for the International Geophysical Year of 1957–1958 (BASC, 2008). Geographical data has a long history of being shared, since this field heavenly depends on data from all over the world. With increasing possibilities of computers such as storing huge amounts of data, this development continued further.
The Committee on Scientific Accomplishments of Earth Observations from Space states about their 50-years experience of using earth data from satellites that a basic infrastructure requirement to advance science is access to Open Data. "Only when academic, government, and commercial scientists are given liberal access to the data, and when a sufficient number of scientists are trained in the effective use of these data, will the analysis tools mature to the benefit of all parties“ (BASC, 2008, p.6).

The need for full and open exchange of scientific data has also been expressed by the Committee on Geophysical and Environmental Data of the US National Research Council (CGED, 1995). They point out that ”The pressing need to understand and monitor the environment has made it more important than ever for scientists to have increased access to relevant data, information, and products“ (CGED, 1995).

The idea and its active promoting dates back to 1950s (Wikipedia, 2014b) while the rise of the Internet has enlarged the possibilities and efficiency to exchange data significantly while costs and time to get data lowered.

In some fields as climate science, there is a common understanding that science can only proceed if worldwide data is made available freely. No single institution, company or country alone could gather and process enough data to feed worldwide models.

In other fields the idea of publishing data is not as widespread. There are multiple barriers to sharing data: fear of losing control, pressure of capitalizing the results of research or just poor formatting. Today many research institutions withhold information since they want to capitalize their findings. The overall scientific advancement is slowed down by that and total research costs rise. As Molloy (2011), a member of the Open Knowledge foundation, expresses it “The more data is made openly available in a useful manner, the greater the level of transparency and reproducibility and hence the more efficient the scientific process becomes, to the benefit of society”(Molloy, 2011).
John Wilbanks, vice president of science of Creative Commons analyzes the irony that ”right at the historical moment when we have the technologies to permit worldwide availability and distributed process of scientific data, broadening collaboration and accelerating the pace and depth of discovery.....we are busy locking up that data and preventing the use of correspondingly advanced technologies on knowledge.“(Wikipedia, 2014a).

There are developments from governments to increase public access to high value data, also in Germany. The site `govdata.de` was launched as a test page in 2013 to become a repository for all information the government collects. The site publishes any data that is not private or subject to restrictions for national security reasons.

In the field of renewable energy, collaborative efforts are made to provide more data about renewable energy resources. Under the roof of the International Renewable Energy

Agency [IRENA], the Global Atlas Initiative compiles a collaborative Internet-based Geographic Information System (GIS) providing information on the potential of renewable energy resources (IRENA, 2013, p.2). The initiative consists of countries and technical partner supporting the idea. The database uses open standards (IRENA, 2014). With the objective to enable involving additional contributors in the future, standards are defined to ensure transparency on the tools and methods used by the Global Atlas (Menard and Getman, 2012, p.2).

As this atlas shows, some parts of energy data forge ahead to Open Data. Due to the fact that renewables are mostly connected to meteorological input, it benefits from the Open Data behavior of climate data. Other data needed for energy modeling like power plant registers and grid installations are rarely published openly. Open Data utilized in renpass will be described in Chapter 3.

2.2.2 Scientific Software

In almost every field of science, huge amounts of data need to be analyzed. Software to process and illustrate the data has become an essential tool and is required in most disciplines. The extensive use is a danger to the reproducibility of research. It is hardly ever done to publish data, source code and parametrization of all software used.
The Yale Law School Round Table on Data and Code Sharing formulated a set of steps how not to hamper progress due to the researchers' inability to independently reproduce or verify published results. Barnes (2013) suggests to apply the following five principles. According to him, they are necessary to reflect that twenty-first century science is not possible without software.

→ **Code:** All source code written specifically to process data for a published paper must be available to the reviewers and readers of the paper.

→ **Copyright:** The copyright ownership and license of any released source code must be clearly stated.

→ **Citation:** Researchers who use or adapt science source code in their research must credit the code's creators in resulting publications.

→ **Credit:** Software contributions must be included in systems of scientific assessment, credit, and recognition.

→ **Curation:** Source code must remain available, linked to related materials, for the useful lifetime of the publication.

2.2.3 Open Source Software

The idea of Open Source is broader than merely accessing to the source code. The development model of Open Source implies free access to the design or blueprint of a product as well as universal redistribution of original or modified versions by anyone. Referring to Open Source software, the Open Source Initiative states in their mission: "Open source is a development method for software that harnesses the power of distributed peer review and transparency of process. The promise of open source is better quality, higher reliability, more flexibility, lower cost, and an end to predatory vendor lock-in." (Open Source Initiative, 2013a, Mission).

The complete definition of Open Source Software implies ten points describing its free distribution, how it is kept open, no discrimination and that the redistribution has to be under the same circumstances (Open Source Initiative, 2013b). Open Source only works if there is a nexus of trust among the widespread users and co-developers. For that purpose, one of the most important activities of the Open Source community is maintaining this definition and Open Source Licenses that comply with this definition.

Open Source Licenses allow software to be used freely, modified, and shared. There are some widely accepted and used ones. The quality and practicality is assured by a review process among the community (Open Source Initiative, 2013c). The different licenses exactly define the rights and duties of users and developers. They are designed to guarantee the freedom to share and change all versions of a program and to make sure it remains free software for all its users. If changed copies of the software are distributed, the distributor has to make sure that the recipients can also get the source code and that they are informed about their rights.

One very popular license is the GNU GPL license, under which **renpass**, the model described in this thesis is published as well. The GNU General Public License is a free, copyleft license for software and other kinds of works and the latest one is version 3 which was agreed on by the Free Software Foundation on 29^{th} of June 2007 (FSF, 2007).

In this thesis, the term Open Source Software will be used. It differs from Free Software. Open Source became associated with ideas and arguments based on practical values such as making or having powerful, reliable software. Free software rather refers to a social movement and addresses the freedom rights. Thus the term Open Source is attributing to a different philosophy than free software: Open Source Software considers the philosophy of improving software continuously and claims that proprietary software is an inferior solution.

2.3 Open Source Energy Models

2.3.1 Existing Open Source Energy Models

There are several energy models that partly comply with Open Source principles. Several models can be downloaded for free. Table 2.1 provides a list of some prominent ones, without claiming to be comprehensive.

Tool	Description of a typical application
RETScreen	renewable analysis for electricity/heat in any size system
HOMER	techno-economic optimization for stand-alone systems
BCHP Screening Tool	assesses combined heat and power in buildings
EnergyPLAN	user friendly analysis of national energy-systems
Invert	simulates promotion schemes for renewable energy
ORCED	simulates regional electricity-dispatch
ENPEP-BALANCE	market-based energy-system tool
COMPOSE	techno-economic single-project assessments
SIVAEL	electricity and district heating sector tool
MiniCAM	simulates long-term, large-scale global changes
STREAM	overview of national energy-systems to create scenarios

Table 2.1: Energy models available for download for free. Based on information from Connolly et al. (2010, Table 1 and Table 2, p. 1061f)

Those models are available for download for free but they just comply with the aspect of being used free of charge. Other important aspects of Open Source Software like the availability of the source code and the possibility to modify and redistribute modified versions are not fulfilled.

An obstacle that often hinders free usage and access to the source code, even if the creators of the program agree to the idea of full transparency, is the utilization of a

proprietary solver or proprietary programs. Especially optimization models often use tools like the General Algebraic Modeling System (GAMS), for which each user has to hold a license.
One prominent example for that is Balmorel, a Danish energy model which is developed and distributed under Open Source ideas, since the developers state that the process of questions for discussion and decision making is best supported if the model is fully transparent (Ravn, 2013). The wealth of projects that have been done with the help of Balmorel confirms the advantages of its Open Source character. Unfortunately, there is one obstacle that restricts the group of possible users: Balmorel is coded in GAMS, thus you need to buy a GAMS license before being able to use Balmorel (Ravn, 2011). Nevertheless, the focus on open communication and transparency of Balmorel since the original project financed by the Danish Energy Research Program in 2001, has leveraged the impact and model reach.

Like in this case, the solver is the quite often the crucial element hindering energy models to be fully Open Source. However, there are several Open Source solvers. A very powerful one for large-scale linear programming is the GNU Linear Programming Kit (GLPK) (Makhorin, 2013).

One energy model called OSeMOSYS [Open Source Energy Modeling System] (Howells et al., 2011) is written in GNU Mathprog, a mathematical programming language which includes a free linear programming solver. It is now linked to LEAP, which is a Long Time Energy Planing Tool (Heaps and Howells, 2013).
Another Open Source electricity model is Genesys of the RWTH Aachen (Bussar et al., 2014). It is programmed in C++, freely available including source code and focuses on the dimensioning of installed capacity. Since the weather data is not Open Data, normalized feed-in time series of VREs are provided to the users. Those are scaled depending on the installed capacities of VREs (Wolf, 2013).

Although some Open Source development can be detected in the field of energy modeling, the vast majority does not comply with principles of Open Data and Open Source. Transparency on data and code is far from being a standard as most energy models are not published. Building an energy model according to Open Data and Open Source principles offers the possibility to identify barriers to building Open Source models.

2.3.2 Short classification of the renpass model

The development of the Open Source model renpass [Renewable Energy Pathways Simulation System] for the techno-economic simulation of the German and European electricity system is supposed to be made available to the general public to scrutinize the assumptions and results of the planning process for the German Energiewende, the transition to a 100 % renewable electricity supply. The Open Source energy model has the goal to fulfill the requirements of full transparency and the possibility to simulate 100% renewable energy target systems as well as today's system and all stages of the system transition on a high regional and time resolution.

renpass was developed at the Centre for Sustainable Energy Systems (CSES) at the University of Flensburg. It is a model of operation optimization, no systemic overall optimization of system configuration. That means, investments are not included. Referring to grid and transport concerns it can be classified as a transshipment model.
renpass was first developed for the simulation of the electricity supply in Germany and Norway. The Norwegian electricity system with its highly developed hydro electricity system is modeled in detail since it is the focus of the work of Gesine Bökenkamp (Bökenkamp, 2015). renpass was then extended to all countries surrounding the Baltic Sea as well as to other countries adjacent to Germany. The idea of the model is further described in Wiese et al. (2014) and the application in the manual of renpass (Wiese et al., 2013).

Chapter 3

renpass Model Description

3.1 Overview

3.1.1 License and Software

renpass will be published under the GNU GPL 3 (FSF, 2007) license. According to this license, everybody can use renpass, adjust it to their needs, and has to use the same license for distributing variations. The license itself is important to keep renpass open. General remarks about Open Source Licenses can be found in Section 2.2.3. GNU GPL3 has been chosen since it matches the development objectives of renpass, is widely spread and will continue to be used by the Open Source community. Furthermore, this license is compatible with the software used.

The following software is required for the application of renpass:

→ MySQL - database

→ R - programming language

→ RMySQL - package for the connection between the MySQL database and the R program

R-package developers are free to use whichever license they prefer and GNU GPL 3 is one possible option for R or associated software, such as packages (r project, 2013).
MySQL can be utilized under the GNU GPL3 license when developing and distributing

Open Source applications (MySQL AB, 2006).

renpass requires the installation of these programs. In addition to all the general guidance published on the internet, assistance is provided in the renpass R and MySQL installation manual (Wiese et al., 2013).

At the beginning of the development of renpass, QuantumGIS was used to process geographical data. Since R now provides a growing functionality of geographic packages, geographical functions to plot and prepare input data are now done in R, too.

In conclusion, all software utilized for renpass is Open Source Software, publicly available and usable under the copyleft license GNU GPL3.

3.1.2 Code Design

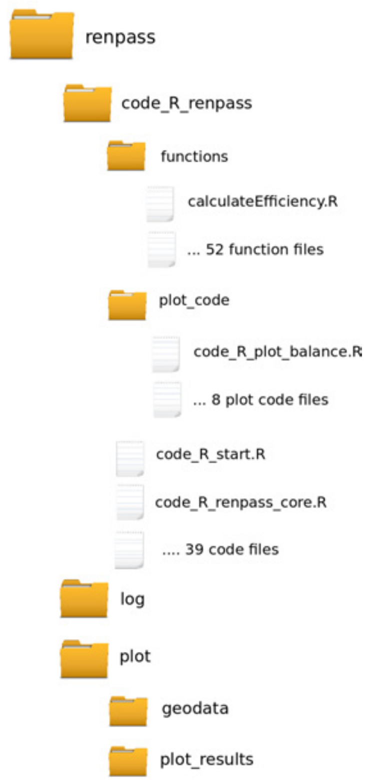


FIGURE 3.1: Folder structure. Icons from gettyicons.com, graphicsfuel.com

Functions and Subroutines The core of the model is the code processing the data, simulating and writing the results back into the database. It is written in the programming language R and organized in 39 files. Figure 3.1 illustrates the folder and file structure. Since the R language is organized in functions, 52 functions were defined for renpass. They are stored in the folder `/renpass/code_R_renpass/functions`.

They can be distinguished from code files containing more than just one function by the file name: functions are named with camelCasing and subroutine code files are named `code_R_...` and stored directly in the main folder.

Code is commented and all functions contain a standardized header with the input and the output of the function. This is the prearrangement in preparation for publishing renpass as an R-package. The code itself is further described in the manual (Wiese, 2013).

Core Code renpass code development is an ongoing process. The version of renpass described in this thesis dates from April 2014 and is published together with this thesis. In this version of the model, there is no graphical user interface to use the model, but renpass can be started by running the code file `code_R_start_renpass`.
When utilizing renpass for the first time, some path and other computer settings have to be made and saved before starting the model.
For a scenario run, the `scenario_nr` has to be specified. This number identifies one scenario for which assumptions and parameters are stored in the database. The `scenario_nr` can address predefined or user-defined scenarios. After choosing the scenario number, renpass is put into operation by sourcing the start code. From this point, everything is automatized.
During the start code execution, the next piece of code of renpass is sourced: `code_R_renpass_core`. All subroutine pieces of code are sourced from here. A user or co-developer can gain an overview of the order of the pieces of code: The structure and sequence of all subroutines of the whole model as well as the time and exchange loops are commented and visible in this code file. All code files are executed at this top level, hence ensuring that it is easier understandable for all users and co-developers.

Another possibility to gain an insight into the program sequence is the flow chart. Figure 3.2 shows the overview flowchart. All boxes with double lines at the sides stand for underlying subroutines. Blue framed boxes indicate which routines are repeated in each time step. Cluster of code are indicated in colors:

→ Parameter preparation (light blue)

→ Residual load calculation (green)

→ Thermal power plant availability (light gray)

→ Merit Order (dark gray)

→ Regional Dispatch (dark red)

→ Exchange (orange)

→ Excess electricity storage (light orange)

→ Adapting storage filling levels (dark blue)

Various result parameters are saved in the result database at different points of the process. This is illustrated in Figure 5.4.

3.1.3 Functionality

Figure 3.3 illustrates the basic functionality of renpass. Installed capacities and expansion pathways of the different energy sources are set exogenously for the period to be analyzed. It is an operational optimization and does not provide systemic overall optimization of system configuration. For each time step, the production of the VREs, namely wind, solar and run-of-river electricity is subtracted from the demand.
The so-called residual load is then supplied by the least expensive combination of the fully controllable production plants, storage units and grid utilization. The utilization of controllable capacity in renpass is based on regional dispatch within each grid region, followed by a balancing between the regions within the grid capacity limits. The latter is illustrated in Figure 3.4: once the regional dispatch has been done in each region, information about region price, excess electricity and storage possibilities is provided per region and fed into the exchange algorithm. All interconnected regions are involved in the exchange.

The following clusters of the renpass process are explained in detail: Residual Load (3.2), Merit Order (3.3), Regional Dispatch (3.4), Exchange (3.5) and Storage (3.6).

3.2 Residual Load

3.2.1 Concept

Variable renewable energies (VREs) are electricity sources, whose feed-in depend directly on meteorological conditions, namely solar, wind and run-of-river. Since negligibly small variable costs arise by using them, the marginal costs of VRE are set to zero. In the merit-order-concept, power plant capacity with the lowest marginal costs is used first to supply the demand.
Using wind, solar, and run-of-river whenever it is offered is a model decision taken in renpass. It reflects the operation mode of VRE today. Due to the absence of fuel costs, it is likely that VRE will be the first in line to supply demand in the future, too. Thus, in

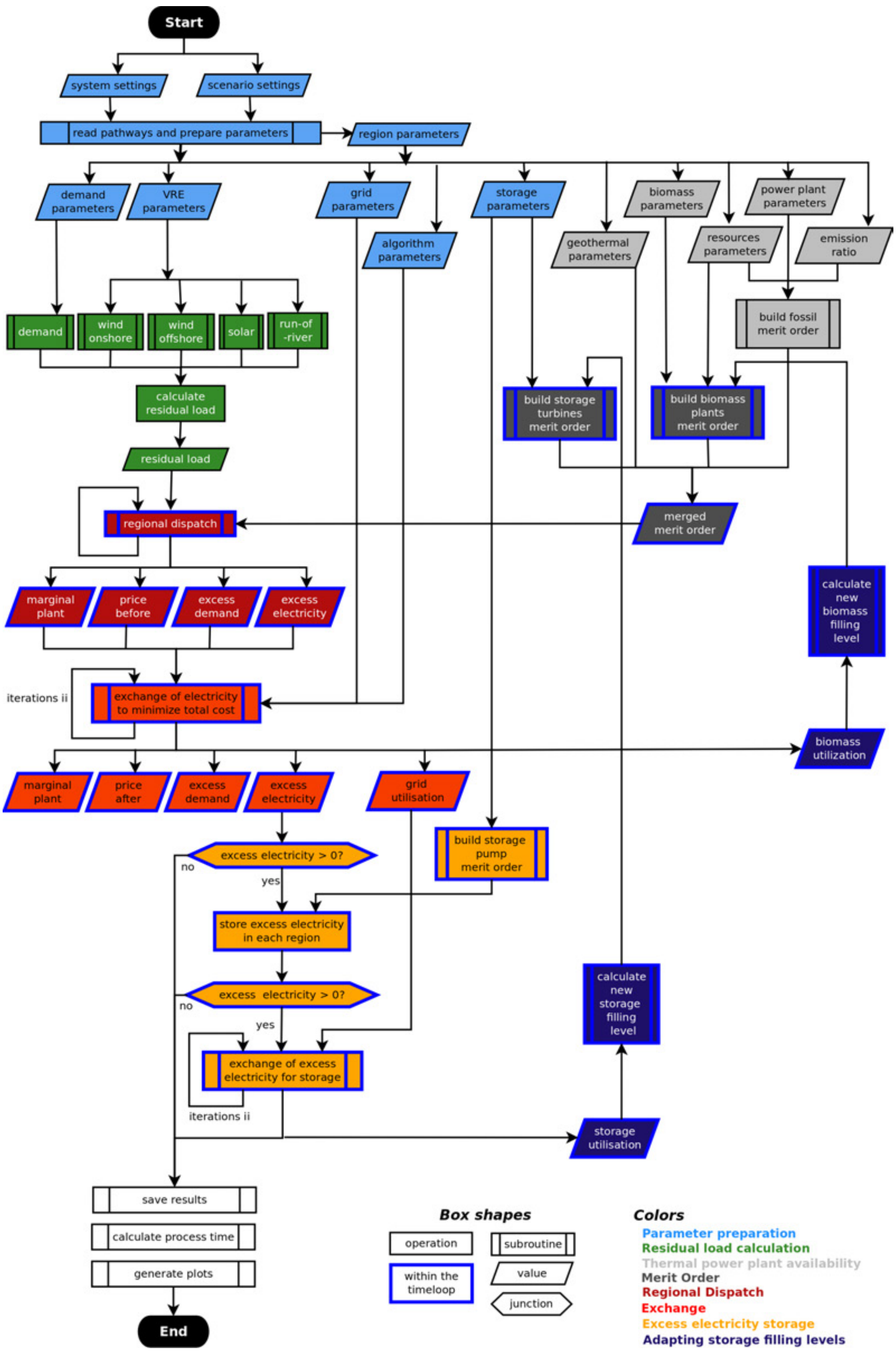


FIGURE 3.2: Program Flowchart of renpass core, the frame code of the model. Clusters of processing are indicated in colors. The shapes of the boxes indicate operations, underlying subroutines, values or junctions. Blue framed boxes are within the time loop.

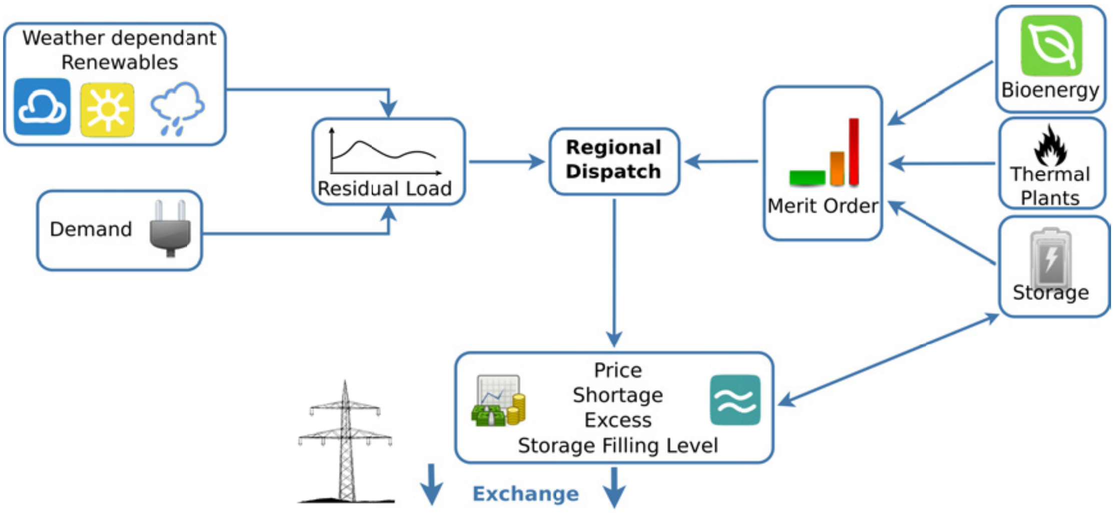


FIGURE 3.3: Schematic diagram of the regional dispatch in renpass. Source: own illustration, icons from Open Icon Library and EnergyMap (Tomi Engels)

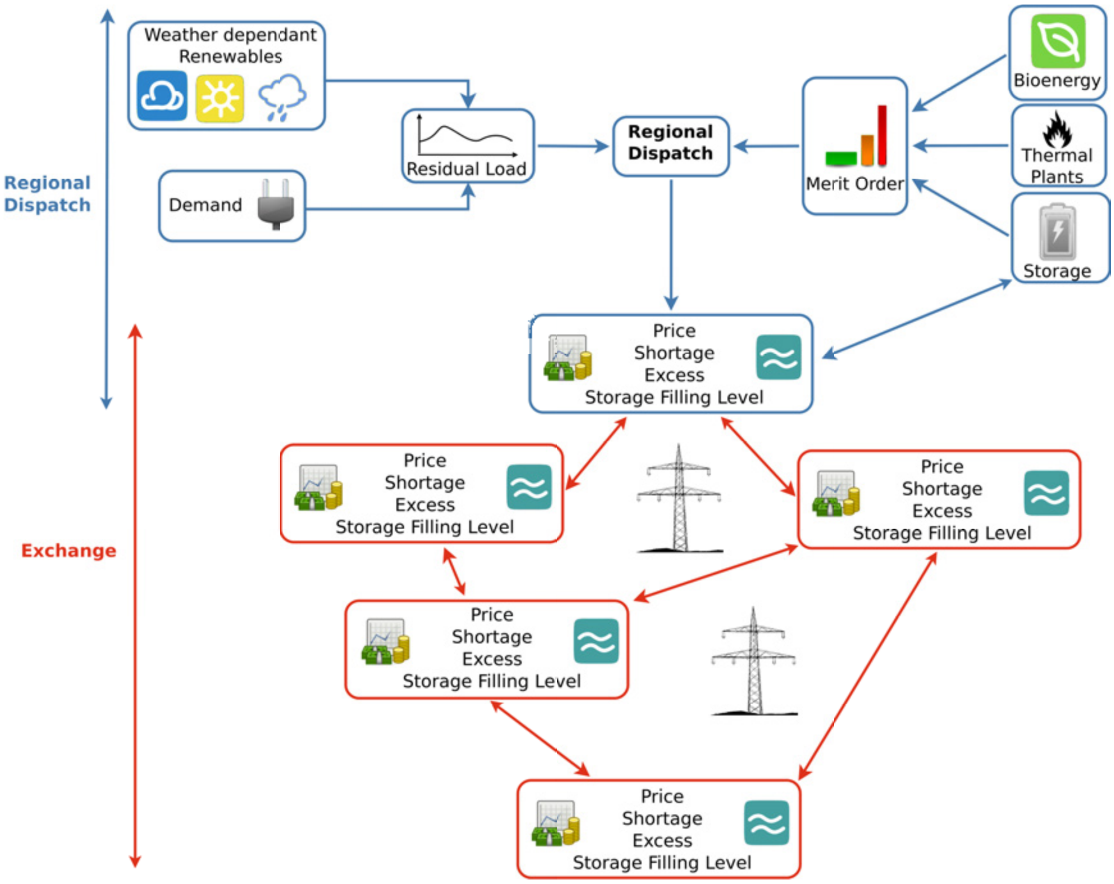


FIGURE 3.4: Schematic diagram of the regional dispatch and the exchange in renpass. Source: own illustration, icons from Open Icon Library and EnergyMap (Tomi Engels)

renpass, demand for each time step per region is read from the database; wind, solar and run-of-river electricity generation is calculated, and then the so-called must-run feed-in is subtracted from the demand for each region and each time step. The result is called residual load.

Since weather data and available feed-in and demand do not depend on the previous time step, the whole matrix of residual load in each region and each time step can be calculated for the whole simulation period before the time loop starts processing.

3.2.2 Demand

Data source for the demand are hourly time series per country, which are described further in Section 4.5. For Germany, a higher regional resolution of demand time series is required due to the region resolution in the version of renpass described in this thesis. Hourly demand time series are divided between the subregions by fixed factors, which are provided in the renpass table `demand_distribution`. Those factors were calculated on the basis of different load situations and the maximal load in each German subregion. This could be improved with regional demand time series, but these are not available yet.

Changes in demand for scenario calculations can be done proportionally, the chosen increase or decrease in demand is applied to each hourly value. The structure of demand is kept the same as the demand data of the basis year. Structural demand changes would be an important extension to cover questions about the non-simultaneity of demand peaks. Additional demand time series could be loaded into the renpass database for this purpose.

The output of the demand calculation is a matrix with regions in columns and time steps in rows.

Demand data utilized does not include power plants for industrial self-supply which are also not included on the supply side (see also Section 4.5 and Section 4.9).

3.2.3 Wind Onshore

The feed-in matrix per region and time step is calculated for the whole year based on wind speed and roughness raster data, wind power plant performance curves and installed capacity per region. The following steps are carried out:

→ Check if each region has at least one raster point. The wind speed data for the database version described in this thesis fulfill this requirement, but in case of model extensions (additional weather years or additional regions), this check is required.

→ Assignment of installed capacity to raster points. This installed capacity per region is distributed equally between the raster points within the respective regions.

→ Calculation of wind speed at hub height (Formula 3.1).

→ Calculation of power output per raster point (Formula 3.2), based on performance curve illustrated in Figure 4.7.

→ Aggregation of the power output per region

→ If the time unit for the whole scenario run should be 15 minutes, the hourly values of demand are interpolated since no quarterly demand values are available.

$$v(z) = v_r * \frac{ln(\frac{z}{z_0})}{ln(\frac{z_r}{z_0})} \tag{3.1}$$

v	m/s	wind speed
v_r	m/s	wind speed at reference height
z_0	m	roughness at reference height
z	m	hub height
z_r	m	reference height of measured wind speed

$$P(C_w, v_z) = f_{pc}(v_z) * C_w \tag{3.2}$$

P	MW_{output}	electrical power output
C_w	$MW_{installed}$	installed capacity of wind power
f_{pc}		function of the normalized wind power curve
v_z	m/s	wind speed at hub height

The result of the wind onshore subroutine which is passed on to the following calculations is a matrix of wind feed-in [MW] with columns indicating regions and rows referring to time steps.

3.2.4 Wind Offshore

The calculation of offshore wind feed-in is analogous to onshore wind, except for the utilized performance curve, the hub height (90 m for offshore, 80 m for onshore) and the roughness length. For offshore, a standard value of 0.0002 m is utilized for surface roughness length.

A more detailed calculation of wind feed-in based on different and more detailed power curves also for weak wind turbines within renpass was done by Bons (2014). This is described further in Section 5.5.3.

3.2.5 Solar

Diffuse and direct solar radiation on the surface $[W/m^2]$ is stored in two hourly radiation time series for each weather data raster point in the weather data base (see also Section 4.4). In the current solar code of renpass, diffuse and direct radiation are summed per raster point, hence representing global radiation.

The installed capacity of solar plants per region is distributed equally to the raster data points available for any specific region. In the solar feed-in calculation, incident global solar radiation is multiplied by a factor reflecting the proportion of radiation that can be transformed to electricity feed-in [MW]. The feed-in factor of 0.9 was determined based on a comparison of modeled and real solar feed-in in 2010 in Germany. This assumes that 90 % of the mean global radiation onto PV-converters for each region are converted into electricity.

A more detailed calculation of solar feed-in requires the inclination and slope of solar panels as additional scenario parameters. This is not included in the standard version of renpass, but for an in-depth solar feed-in calculation, a solar extension can be utilized, which was coded in a master thesis (Höfken, 2012). For that purpose, diffuse and direct radiation are saved as separate values in the weather database of renpass.

3.2.6 Run-of-river

Run-of-river plants are modeled individually and in detail for Germany and Norway and with a constant feed-in for other countries.

In **Norway**, run-of-river plants are part of the country's complex hydro system. Its electricity production is simulated for each time step based on the installed capacity [MW], the inflow [million m^3] and the corresponding energy value [MWh]. Water flows influence downstream connected reservoirs, for example, the utilization of a run-of-river plant increases the filling level of the next downstream reservoir, which influences the price of a hydro plant or raises the feed-in of a downstream power plant in the next time step.
Water output from run-of-river plants is derived from their operation. Their water output influences connected downstream plants or reservoirs. The impact of hydro and storage plant utilization on the operation of run-of-river plants is not included in renpass. Since run-of-river plants are fed by a natural river, a minimum flow has to be guaranteed. Thus, even if the river is utilized by a hydro storage plant upstream of the run-of-river plant, its influence is considered to be quite low.

In **Germany**, run-of-river plants are assigned to level meters of rivers. Measurements are available for 40 level meters in the vicinity of plants. The assignment of plants to level meters is made according to river and geographic proximity. The shape of the production curve is based on the measurements. The height of the production curve (sum of feed-in per year) is based on the installed capacity and the weather year. The utilization factors depend on the chosen weather years. They are the same for all countries except Norway. The production of the single plants is then aggregated for the dispatch regions.

In contrast to Norwegian and German run-of-river feed-in, a constant feed-in during the whole simulation period is utilized for **other countries**. The feed-in depends on the installed capacity and the chosen weather year. A utilization factor depending on the weather conditions of the weather year is multiplied by the installed capacity of run-of-river plants in the respective region. The utilization factor for the low precipitation weather year 2010 is 0.45, for the high precipitation year 1998 0.65 and 0.55 for the mean one in 2003. Those values are derived from production data of run-of-river plants which have been published by the Federal Statistical Office of Germany (Destatis). This is described further in Bökenkamp (2015).

Data sources for installed capacity and inflow are described in Section 4.7 and Section 4.8. Run-of-river feed-in is treated as must-run like wind and solar.

3.3 Merit Order

3.3.1 Concept

The merit order principle involves sorting all available power plants in the order of their marginal costs while indicating their available capacity. This sequence builds the basis for the choice of power plants in the dispatch: The required capacity to meet demand is called from the cheapest power plants. In the described version of renpass, the unit commitment does not consider possible unavailability due to warm-up times after a cold start. Ramping during operation is considered to play no major role in the temporal resolution of the model.

In renpass, VRE is thus must-run and does not appear in the merit order. All other power plants, geothermal, biomass, fossil and the turbines of storage power plants are listed in a merit order. They are all merged into one merit order per region, but the way marginal costs are derived differs. Marginal costs in renpass reflect either real marginal costs due to short term utilization costs or opportunity costs.
In the following sections, first plants with a constant merit order during the simulation period are described. These are geothermal (Section 3.3.2) and fossil power plants (Section 3.3.3). Thereafter, the merit order contribution which is adapted to reservoir filling levels in each time step is described: biomass (see Section 3.3.4), hydro turbines (see Section 3.3.5) and turbines of other storage plants (see Section 3.3.6).

3.3.2 Geothermal Plants

In renpass, geothermal electricity has priority dispatch status respective to the residual load. This means that if, in a region and a time step, the feed-in of VRE is lower than the demand and geothermal power plants have available capacity, it is utilized before other dispatchable power plants. By being used first, geothermal plants reduce the proportion of electricity that has to be supplied by power plants with higher marginal costs. This priority status is achieved by setting the geothermal price very low. The standard value in renpass is 0.1 €/MWh.
This method is chosen due to the special role of geothermal energy. It does not depend on meteorological conditions like must-run feed-in and is thus dispatchable, but no resource

is combusted. Although the heat from the earth declines by using its energy, resource consumption takes place across a long time frame and its scarcity is not priced, unlike other resources.

The output of the geothermal code is a merit order of the geothermal power plants which will be merged with the main merit order of all dispatchable power plants. The installed capacity per region and utilization factor for the chosen geothermal scenario are provided by `geothermal_pathway` table in the pathways database. The total installed capacity per region is multiplied by the utilization factor, whose standard value is 0.9. This corresponds to an availability of 90 % of geothermal capacity installed during the simulation period.

3.3.3 Fossil Power Plants

A fossil power plant sub-merit order is set up for each region. In contrast to biomass and storage turbines, their marginal costs are not adapted in each time step, but their capacity is offered at the same marginal costs during the simulation period. The following input data and scenario assumptions provide information for setting up the fossil merit order:

→ `thermal_pp_register`: power plant register including fuel, type, age, region

→ `thermal_pp_scenario`: scenario assumptions on installed capacity per region, fuel, type and lifetime

→ `thermal_pp_parameter`: parameters of efficiency and auxiliary power requirements per type-fuel combination

→ `resources_scenario`: prices for resources: lignite, hard coal, gas, biomass, CO_2

→ `emission_parameter`: fuel emission ratios

If scenario assumptions define a fossil free scenario, no fossil merit order is calculated accordingly. In all other cases, the following steps are executed for each region.

Setup of power plant fleet: Status quo of installed capacities per fuel and type per region is provided in the database. For Germany, a detailed power plant register can be retrieved. It is a scenario choice as to whether the power plant fleet should be restricted in terms of its installed capacity or lifetime.
In the latter case, power plants older than the chosen lifetime are not taken into account for the merit order. No additional power plants are taken into account.
If the installed capacity for the scenario year is provided as a scenario assumption, this can be chosen for each power plant type (e.g. gas turbine, coal fired steam turbine, gas combined cycle etc.). To fit the predefined amount, either oldest power plants are sorted out or new blocks of an average size are added. The start-up years assigned to the additional blocks are evenly distributed between this year and the scenario year. This is important since efficiency and thus the marginal costs depend on the age of the plant. The last power plant added is reduced in capacity to fit exactly the chosen sum of installed capacity of this fuel and type.

Adaption to availability: Based on the report 'Analysis of the unavailabilities of thermal power plants 2002 - 2011' published by VGB PowerTech (VGB, 2012), a general availability of thermal power plants of 85 % is applied. This means that only 85 % of the installed capacity defined in the thermal power plant scenario is available. This includes planned revisions, outages and reserve for system services as described by the German TSOs (2012a, p.6f).

Assignment of technical parameters: Auxiliary power requirements, gross efficiency and emission rates are assigned to the power plant fleet according to their type and fuel.

Efficiency determination: Based on age, type and fuel, the efficiency is calculated for each of the power plants according to Formula 3.3. Reference values for efficiency (η_{gross}) and auxiliary power requirement (aux) are given per type-fuel combination. If the start up year of the power plant is unknown, the average age of all its type of plants is applied. An efficiency improvement factor $\Delta\eta$ of 0.003 per year due to technical improvement is utilized.

$$\eta_{net}(a) = \eta_{gross} - aux + ((y_{sc} - y_r) - a) * \Delta\eta \tag{3.3}$$

η_{net}		net efficiency
η_{gross}		gross efficiency of reference power plant in the reference year
aux		required auxiliary power of the power plant type in the reference year
y_{sc}		scenario year
y_r		reference year for η_{gross} and aux. Standard year: 1980
a	$years$	age of power plant
$\Delta\eta$	$\frac{1}{year}$	change factor of efficiency per year. Standard value: 0.003

Marginal cost calculation: Based on fixed costs, variable costs, emission rates and prices for fuel and emissions, marginal costs for each power plant are calculated based on Formula 3.4. A higher efficiency implies less fuel required and thus, lower costs for emissions and fuel consumption.

For nuclear power plants, marginal costs are not derived in the same way, but are set to 10.8 €/MWh. This value is taken from a study that was carried out on behalf of the German Federal Ministry of Economic Affairs and Employment (BMWI, 2010, p.44).

The information passed on to the next calculation step consists of one fossil merit order per region. Power plants are ordered according to their marginal costs. For each of them, power plant number for identification, available capacity [MW], marginal costs [€/MWh] and CO_2 emissions [tCO_2/MWh] are provided.

$$c_{mar} = \frac{1}{\eta_{net}} * 3.6 * p_{fuel} + \frac{1}{\eta_{net}} * 3.6 * e_{CO_2} * p_{CO_2} + c_{var} \tag{3.4}$$

c_{mar}	$€/MWh$	marginal costs
η_{net}		net efficiency
p_{fuel}	$€/GJ$	fuel price
p_{CO_2}	$€/tCO_2$	CO_2 emission price
e_{CO_2}	tCO_2/GJ	CO_2 emission factor of consumed fuel
c_{var}	$€/MWh$	other variable costs of the respective power plant type

3.3.4 Biomass Plants

Biomass as an electricity source plays a special role within the range of renewable energy. It is not weather dependent like wind, solar, run-of-river and the resource is consumed during the process of energy generation. Since there are competing claims for its utilization such as for mobility and food, the resource is limited. Although biomass plants are dispatchable to a certain degree, their operation is restricted not only by the installed capacity [MW] but also by the available amount of biomass [GWh] provided for electricity generation.
The amount of biomass available and the installed capacity have to be determined as scenario parameters for each region across the whole year. renpass currently does not differentiate between biomass plant technology and the kinds of biomass utilized.

Unlike for fossil power plants, the marginal costs of biomass plants are adapted in each time step of the calculation depending on the level of biomass available. The starting value of marginal costs is calculated in the same way as for fossil power plants according to Formula 3.4. The costs for emission certificates are included in the marginal costs of biomass power plants if an emission rate factor higher than zero is inserted in the emission parameters table.
Biomass plants offer their full capacity for the resulting marginal costs in the first time step of the calculation period. In the following time steps, the marginal costs of biomass power plants depend on the availability of biomass. This is determined by the amount of biomass available and the filling level of the biomass that is left.
Prior to the temporal stepwise calculation, how much biomass per region and time step would be utilized if the total available amount of biomass is used evenly during the year is calculated. If the amount of biomass [GWh] per year were evenly distributed for each time step of the year, biomass would always be offered at the average marginal cost, which was calculated for the first time step. If more has already been used, the scarcity of biomass increases the price. If less is used, the price falls.
To keep track of spare biomass, a biomass filling level matrix per region and time step is initialized, which is adjusted during each time step depending of the operation of the biomass plants. The installed capacity per region is the maximal capacity offered.

Formula 3.5 illustrates the marginal price calculation method for biomass plants. The cost rises proportionally to the gap an above-average usage has caused. A scarcity factor

is introduced which determines the price increase depending on scarcity. The higher the scarcity factor, the higher the marginal costs, the further back biomass plants are placed in the merit order.
Determining the biomass scarcity factor is crucial for an efficient usage of the available biomass throughout the year. The standard scarcity factor in the code is set to 100, but this can be changed in the code. In the next version of renpass, the scarcity factor should be a scenario parameter setting since it has a major influence on biomass plant operation.

$$
\begin{aligned}
&if(E_{bio}(t) \leq E_{bio_r}(t))\{ \\
&\qquad c_{mar}(t) = c_{mar_a} * \frac{(1 + (E_{bio_r}(t) - E_{bio}(t))}{E_{bio_r}(t) * sc_{bio}} \\
&\}else\{ \\
&\qquad c_{mar}(t) = c_{mar_a} * \frac{E_{bio_r}(t)}{E_{bio}(t)}\}
\end{aligned}
\tag{3.5}
$$

$E_{bio}(t)$	MWh	amount of biomass available in time step t
$E_{bio_r}(t)$	MWh	reference amount of biomass available in time step t in case of evenly distributed usage
$c_{mar}(t)$	€$/MW$	marginal costs of biomass in time step t
c_{mar_a}	€$/MW$	average marginal costs of biomass
sc_{bio}		biomass scarcity factor. Standard value: 100

Figure 3.5 illustrates the effect of the scarcity factor on the price pattern of biomass. Red dashed lines illustrate the average biomass price if the amount of biomass left compared to the average value is 100%. This price decreases if more than the average amount is left. This does not depend on the scarcity factor, as shown by the line on the left-hand side of the figure. The colored lines indicate the price development according to different scarcity factors from -1 to 100. With a scarcity factor higher than 1, marginal costs rise with an above-average use of the resource.

As described, biomass power plants offer their capacity in the merit order. Their operation is determined within the dispatch. At the end of each time step, biomass filling levels are adjusted depending on the operation. The scale of biomass filling level deduction depends on the usage of biomass in the previous time step. Due to the adjusted

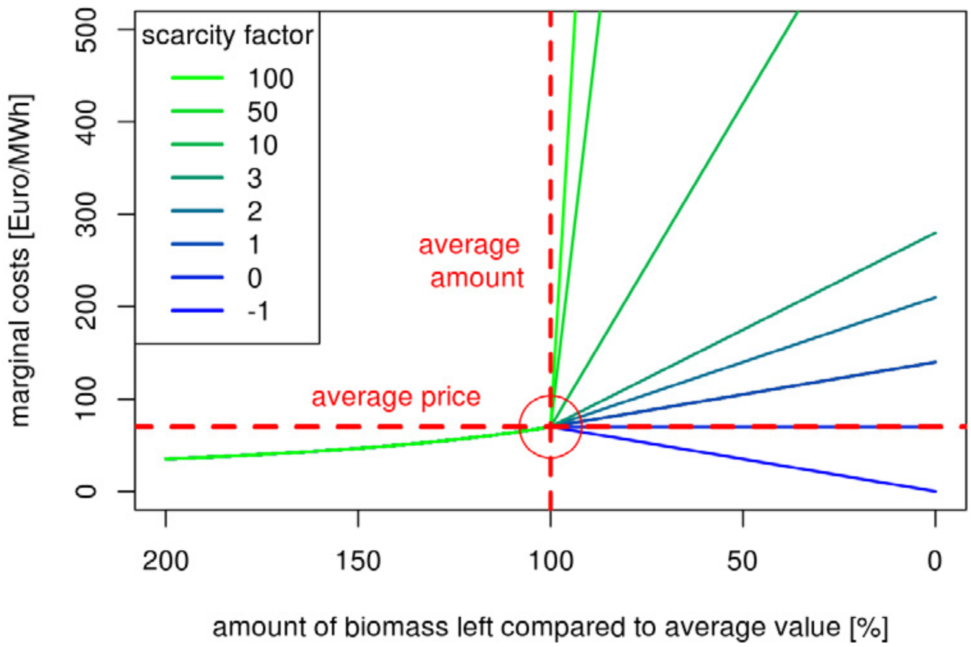


FIGURE 3.5: Effect of different scarcity factors on the marginal costs of biomass depending on the relative filling levels of the resource. Red dashed lines indicate average marginal costs in case of evenly distributed usage during the simulation period.

filling level, the price can be adapted consequently. Thus after dispatch and exchange in each time step, the price for biomass plants is determined again for each region. The biomass filling level cannot become negative. If there is no biomass left, the available capacity of biomass is set to zero.

3.3.5 Hydro Turbines

The production side of hydro plants is integrated into the dispatch via merit order, too. Although no resource prices determine their marginal costs, there is an opportunity value for the electricity stored in the storage medium. The price depends on the filling level of upstream as well as downstream reservoirs, expected inflow and expectations concerning the development of electricity prices.

In renpass, for hydro turbines, a method of ranking was utilized based on an opportunity price concept. The set framework is that they are more expensive than must-run capacity, but cheaper than energy technologies consuming fuels. An overall reasonable utilization of the hydro resource especially in a connected complex hydro system such as in Norway was the basis for the rules. The development of that concept for renpass is described in detail in Bökenkamp (2015, Chapter 4). Water volume and inflow at specific locations determine the marginal costs for hydro power plants. The resulting merit order of hydro turbines is merged into the merit order of each region.

3.3.6 Turbines of Storage Plants

The performance of turbines of other storage plants is determined by storage capacity, the turbines' installed capacity and their efficiency. They are modeled as one generic plant per region. Storage plants are separated into turbine and pump components. The production operation is restricted by the filling levels of the storage reservoir. The marginal costs which determine the order of utilization for storage turbines depend on the filling level of the reservoir which is updated in every time step. The higher the filling level, the lower the marginal costs. Turbines with other storage characteristics are represented in an aggregated way in the version of renpass described.

3.3.7 Summary

Geothermal, fossil, biomass, hydro turbine and storage turbine merit orders are merged into one merit order per region. The sorting by marginal costs reflects the order of utilization. The merit order contains information about available capacity, kind of fuel, marginal costs and CO_2-intensity for each power plant. Geothermal and fossil power plants maintain their offer for the whole year, biomass, hydro and other storage turbine merit orders change in each time step since their price and available capacity depends on their usage, namely their filling level.
Table 3.1 shows an example of a merit order list for two dispatch regions. Geothermal plants with their very low price are usually used first.

3.4 Regional Dispatch

Before the dispatch starts, several result matrices are initialized to keep track of prices before and after power exchange between regions, the development of residual load, CO_2-emissions and storage behavior pattern per region.

'1'				
pp_nr	C	c_{mar}	CO_2	*fuel*
	MW	$€/MWh$	t/MWh	
9999	2690.00	3.25	0.00	biomass
1	299.20	38.43	1.14	lignite
259	85.80	41.64	0.29	gas
...	...	...	...	...
...				
'4'				
pp_nr	C	c_{mar}	CO_2	*fuel*
	MW	$€/MWh$	t/MWh	
7777	121.50	0.10	0.00	geothermal
9999	1474.00	3.25	0.00	biomass
357	297.50	41.64	0.29	gas
232	55.20	42.37	0.30	gas
103	735.00	43.31	0.76	hard_coal
102	714.00	43.31	0.76	hard_coal
287	105.40	43.70	0.31	gas
...	...	...	...	...
80	0.58	52.33	0.00	hydro
24	45.00	59.56	0.00	hydro
...	...	...	...	...
136	20.40	85.55	0.66	oil
...				
'6'				
256	60	5.00	0.00	hydro
270	13	5.00	0.00	hydro
...	...	...	...	...
678	1.50	17.99	0.00	hydro
417	54.50	22.02	0.00	hydro
...	...	...	...	...

TABLE 3.1: Excerpt of the Merit Order of the first time step in test scenario 3. Some power plants of dispatch region 1 (north-western Germany), dispatch region 4 (south-western Germany) and dispatch region 5 (Norway).

3.4.1 Merit Order and Residual Load Matching

Dispatch is a term used for matching load and merit order in a least-cost way. Economic dispatch can be defined as "the operation of generation facilities to produce energy at the lowest cost to reliably serve consumers, recognizing any operational limits of generation and transmission facilities" (US Government, 2005, Sec. 1234 (b)).

In the flowchart of renpass shown in Figure 3.2, the regional dispatch is indicated in dark red. It is repeated in each time step (as outlined by the blue frame around the box in the flowchart). The subroutine of matching the residual load and the merit order is completed for each region. The output variables for each region are the index of the marginal power plant, resulting price [€/MWh], the amount of excess electricity [MW] and excess demand [MW]. In the underlying code, the dispatch is called marginal function and is described in the following section.

3.4.2 Marginal Function

Because it determines the dispatch, the marginal function entitled `marginalIndex` is one of the key elements of renpass.

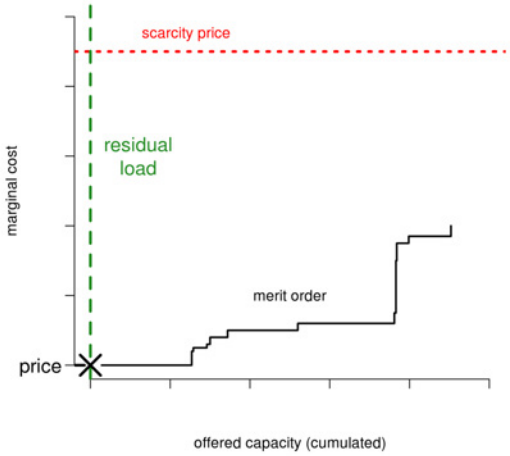
`marginalIndex` input:

rl	MW	residual load
$\vec{C}_{cum}$	MW	vector of cumulated available capacity of dispatchable plants
$\vec{c}_{mar}$	$€/MW$	vector of marginal cost
p_{sc}	$€/MWh$	scarcity price

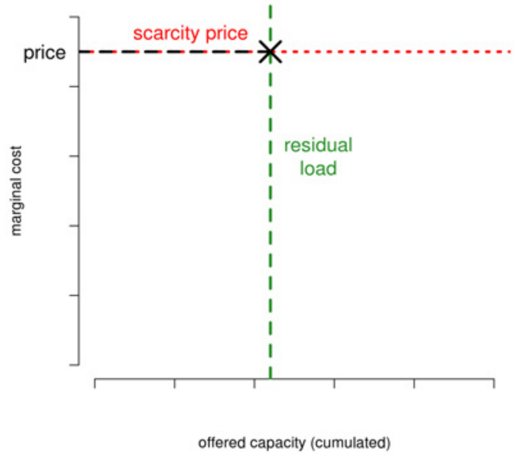
`marginalIndex` output:

idx		index of marginal power plant
p	$€/MWh$	electricity price
ee	MW	excess electricity
ed	MW	excess demand
upl	MW	unused part load of marginal power plant

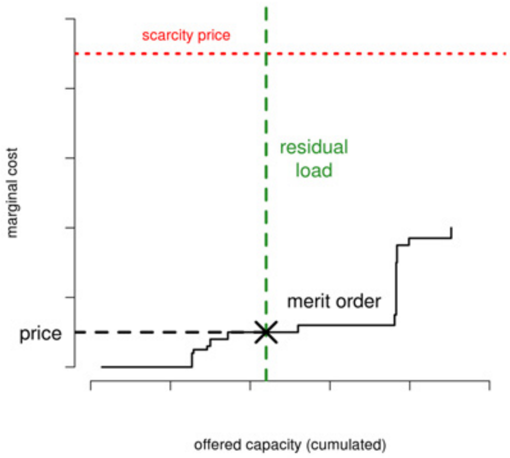
Figure 3.6 illustrates the dispatch schematically in four different cases (A,B,C,D). Offered capacity is illustrated on the x-axis, marginal costs on the y-axis. Residual load is indicated by a dashed green line, scarcity price level by a dashed red line and the merit order curve is shown in black. Here, the scarcity price is defined as the highest possible price. If demand cannot be met in a region, the scarcity price p_sc is assigned to this region to show there is a need for electricity to be imported.



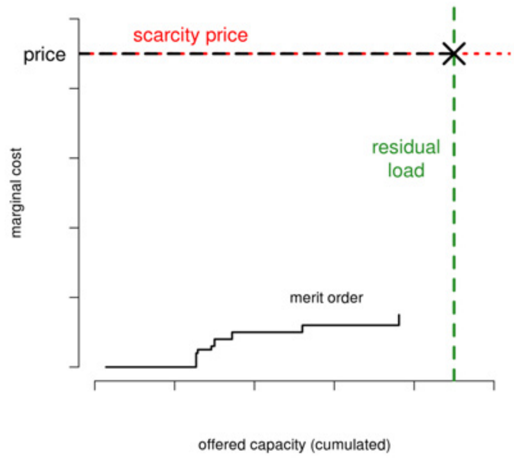
(A) residual load not positive



(B) no dispatchable capacity



(C) residual load met by dispatchable capacity



(D) residual load exceeds dispatchable capacity

FIGURE 3.6: Schematic illustration of the price finding mechanism of the marginal function in four different cases. Source: own image

(A) Residual load is negative because feed-in of VRE exceeds the demand. In renpass, this results in a price of zero.

$$
\begin{aligned}
rl \leq 0 \Rightarrow \quad idx &= 0 \\
p &= 0 \\
ee &= rl \\
ed &= 0 \\
upl &= 0
\end{aligned}
$$

(B) There are no dispatchable power plants to supply the residual load. The resulting price is the scarcity price.

$$
\begin{aligned}
rl &> 0 \\
\vec{C}_{cum} &= 0 \\
&\Rightarrow \quad \begin{aligned} idx &= 0 \\ p &= p_{sc} \\ ee &= 0 \\ ed &= rl \\ upl &= 0 \end{aligned}
\end{aligned}
$$

(C) Residual load can be matched by the dispatchable power plants. The intersection point of the vertical residual load line and the merit order curve indicates the marginal power plant. The marginal cost of the last plant needed to supply the residual load sets the price. To match the demand exactly, it may be necessary to operate the marginal power plant in part load.

$$
\begin{aligned}
&0 < rl < max(\vec{C}_{cum}) \\
&\Rightarrow \quad \begin{aligned} idx &= min(which(\vec{C}_{cum} \geq rl)) \\ p &= \vec{c}_{mar}[idx] \\ ee &= 0 \\ ed &= 0 \\ upl &= \vec{C}_{cum}[idx] - rl \end{aligned}
\end{aligned}
$$

(D) Dispatchable capacity is fully used, but the residual load exceeds the available supply. Thus, there is residual load that cannot be supplied, referred to as excess demand.

$$
\begin{aligned}
0 < max(\vec{C}_{cum}) < rl \\
\Rightarrow \quad & idx = length(\vec{C}_{cum}) \\
& p = p_{sc} \\
& ee = 0 \\
& ed = rl - max(\vec{C}_{cum}) \\
& upl = 0
\end{aligned}
$$

In renpass, regional dispatch consists of applying the marginal function to each region. Resulting regional prices are important indicators for the electricity exchange between the regions. They vary between zero and the scarcity price.

3.4.3 Scarcity Price

In the version of renpass described, the scarcity price is set to 1000 €/MWh. This fixed value is significantly higher than all bids in the merit order. When demand cannot be supplied in one region after the regional dispatch, scarcity prices give an important signal for electricity transfer.

In a scenario setting with high shares of VRE capacity and very few dispatchable plants, in which excess demand could often occur, the value of the scarcity price influences the simulation results significantly. The higher the unmet demand, the higher the attractiveness for the optimization exchange algorithm to export to that region, since the target equation is to minimize total short term costs. Total short term costs are residual load multiplied by the price, summed for all regions. This is explained further in Section 3.5.2.

3.5 Exchange

3.5.1 Grid Capacity

Grid capacity between regions is the limiting factor for the amount of electricity that can be shifted between connected dispatch regions. The transfer limit is either defined as capacity [MW] or by the number of circuits and the voltage level [kV]. If capacity values are provided in the scenario settings, these should contain the capacity reduction due to applying the n-1 security criteria.

In renpass, the capacities of transmission grid for 2012 are provided in the `status_quo_2012` scenario in the `grid_scenario` table of the pathways database. Values for lines within Germany are derived from the ENTSO-E grid map (ENTSO-E, 2012b) as described in Section 4.6. Since this map only indicates lines and voltages, the capacity has to be deduced. Based on the number of circuits between regions, voltage and the maximum amperage, the transfer capacity is calculated for AC overhead lines based on Formula 3.6. According to a study by the German Energy Agency (dena), existing overhead lines are usually designed to allow amperage of up to 2720 A and the factor of usable transmission capacity to take the (n-1) security into general consideration is 70 % (dena, 2011, p.289, section 13.2.2.2).

$$C_{grid} = \frac{n * I_{max} * U * \sqrt{3} * f_{security}}{1000} \tag{3.6}$$

C_{grid}	MW	usable transfer capacity between two regions
n		number of circuits between two regions
I_{max}	A	maximum amperage per circuit
U	kV	voltage of the line in kV, in Germany usually 380 kV or 220 kV
f_{n-1}		factor to account for n-1 security. Standard value: 0.7

Grid capacity is summarized for all circuits between each pair of regions. A data frame of maximum capacities for each dispatch region connection is passed to the exchange algorithm. For each connection line, grid losses are defined as a percentage of exchange. The exporting region has to provide this additional amount of energy. Since the exporting region is charged for the grid losses, the additional amount available in the receiving region is less than the electricity leaving the exporting region.

The amount of grid losses is not accounted for in the capacity limit. For example, 1000 MW should be transferred via a connection with a capacity of 1000 MW. For grid losses of 3 % this results in 30 MW grid losses. Thus, 1030 MW are generated in the export region and 1000 MW arrive in the importing region.

The functionality and influence of grid losses is described in Section 3.5.3.

3.5.2 Optimization Algorithm

For each time step, the objective is to shift electricity from regions with low prices, a sign of cheap generation or even excess electricity, to regions with high prices, pointing towards the use of expensive production capacities or even, demand that cannot be met at all. If grid capacities were unlimited, the exchange algorithm would reach price equality in all regions. This exchange has to be calculated for each time step. The exchange problem becomes more complex as more regions are added.
A heuristic algorithm is implemented in renpass, which delivers robust results in a reasonable amount of calculation time. Its objective function is to minimize the total short term costs for the whole area of simulation that are defined as the sum of residual short term costs of all regions (see Formula 3.7). The installation costs of plants and infrastructure are not included in this optimization. The scenario assumptions define installed grid and plant capacities. The optimization part concerns only their least-cost operation.

$$C* = \sum_{dpr=1}^{R} p_{dpr} \cdot rl_{dpr} \tag{3.7}$$

C^*		temporary total electricity costs per region
$dpr \in DPR$	$:= \{r_1, r_2, ..., r_n\}$	dispatch regions
$p \in P$	$:= \{p_1, p_2, ..., p_n\}$	resulting electricity price per region
$rl \in RL$	$:= \{rl_1, rl_2, ..., rl_n\}$	residual load per region

For a specified number of iterations one operation is repeated. This operation involves testing whether a certain electricity transfer between two regions leads to a reduction of the total short term costs. The more regions are involved, and the more grid connections are available, the more iteration steps are required to reach the minimum. Local minimums have to be avoided.

Input values for the `exchangeStandard` function are summarized in Table 3.2.

$\vec{rl}$	residual load	per region
$\vec{C}_{grid}$	grid capacity	per connection
$\vec{idx}$	marginal power plant index	per region
$\vec{p}$	price	per region
$\vec{C}_{cum}$	cumulated available capacity	per plant
$\vec{c}_{mar}$	marginal cost	per plant
$\vec{ee}$	excess electricity	per region
$\vec{ed}$	excess demand	per region
ii	number of the iterations	

Table 3.2: Input values for the exchange algorithm

With this information, for each iteration step, one region and one region connected to the first one via transmission line are chosen randomly. Additionally, a transfer of electricity [MW] is chosen randomly within the limits of the grid capacity. If the total short term costs rise due to executing this exchange, it is rejected and the next iteration step with different regions and transfer capacity is tested. If the total costs are reduced or remain equal, the exchange is realized and all depending values are consequently adjusted.

Specifying a number of iteration loops solving the trade-off between exact results and short processing time is crucial for the model, since the applicability of an energy model depends to a large extent on computation time. To illustrate the algorithm's behavior, the development of total short term costs is laid out.
Figures 3.7 and 3.8 illustrate the total short term costs during the 3000 iteration steps in the first time step of ten test scenarios. For each of the test scenarios, the exchange during the first time step was calculated ten times with the same starting conditions. Thus, the ten black lines in each picture all start at the same total short term costs at iteration step one (left side of the graph). From that iteration step, the total short term costs remain unchanged or decrease from one iteration step to the next according to the algorithm rules, with the objective of lowering total short term costs. Each iteration step implies a random choice of a transfer of electricity between two regions, thus each of the ten iteration runs - each illustrated by a black line - differ. Red dots indicate discarded exchange operations.

In all test scenarios, the total short term costs converge to a lower cost level, which can be considered a robust result. The red dots indicate total short term cost values for

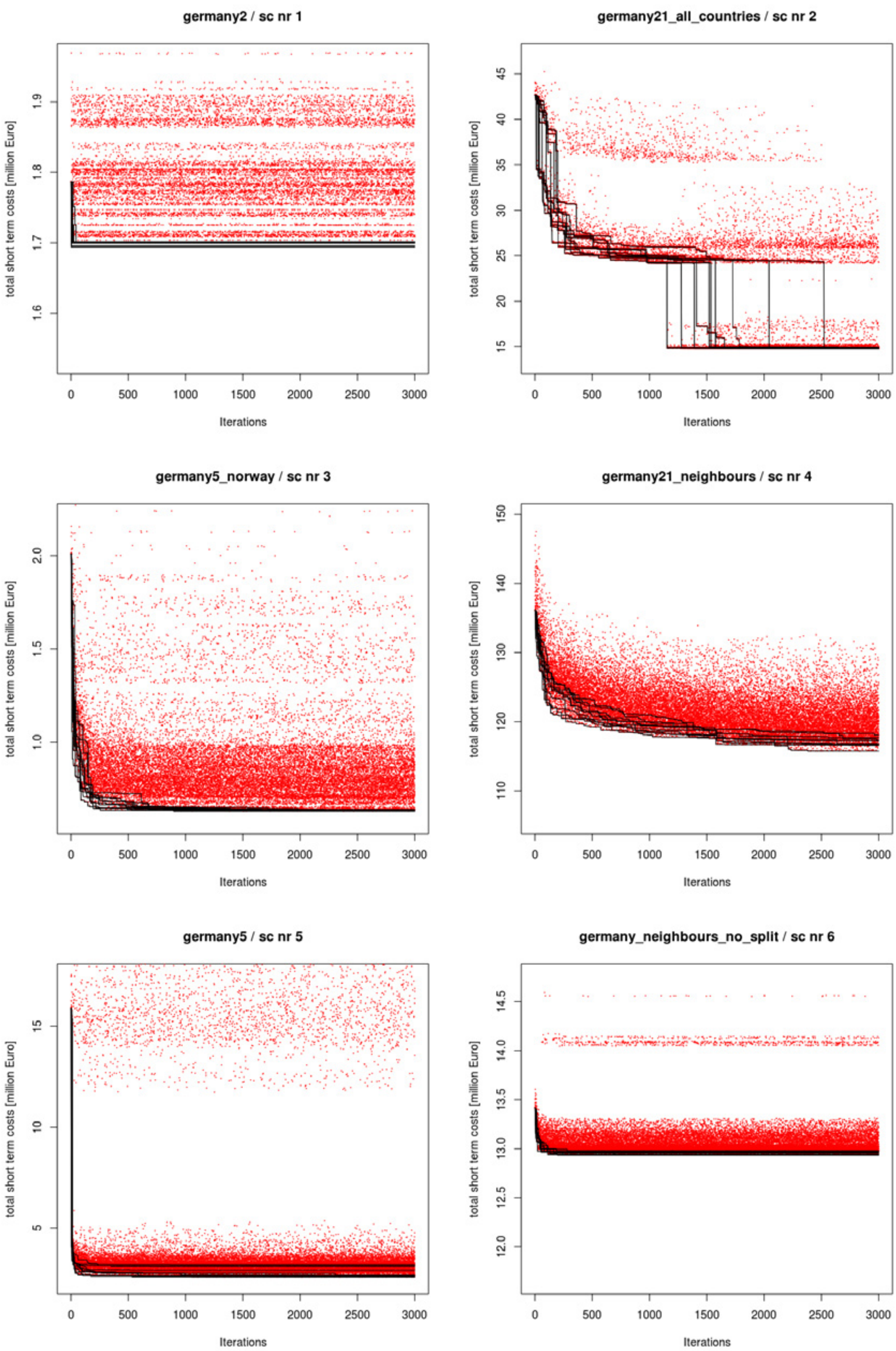


FIGURE 3.7: Heuristic exchange iteration with 3000 steps (x-axis) for the first time step of test scenario 1 - 6. Repeated ten times (black lines) with the same starting value converging to minimal total short time cost (y-axis). The optimal solution in not always reached within 3000 iteration steps, but a robust solution is. Red dots indicate discarded exchange operations. Headings indicate the regions' division and the number of the test scenario. Source: own images

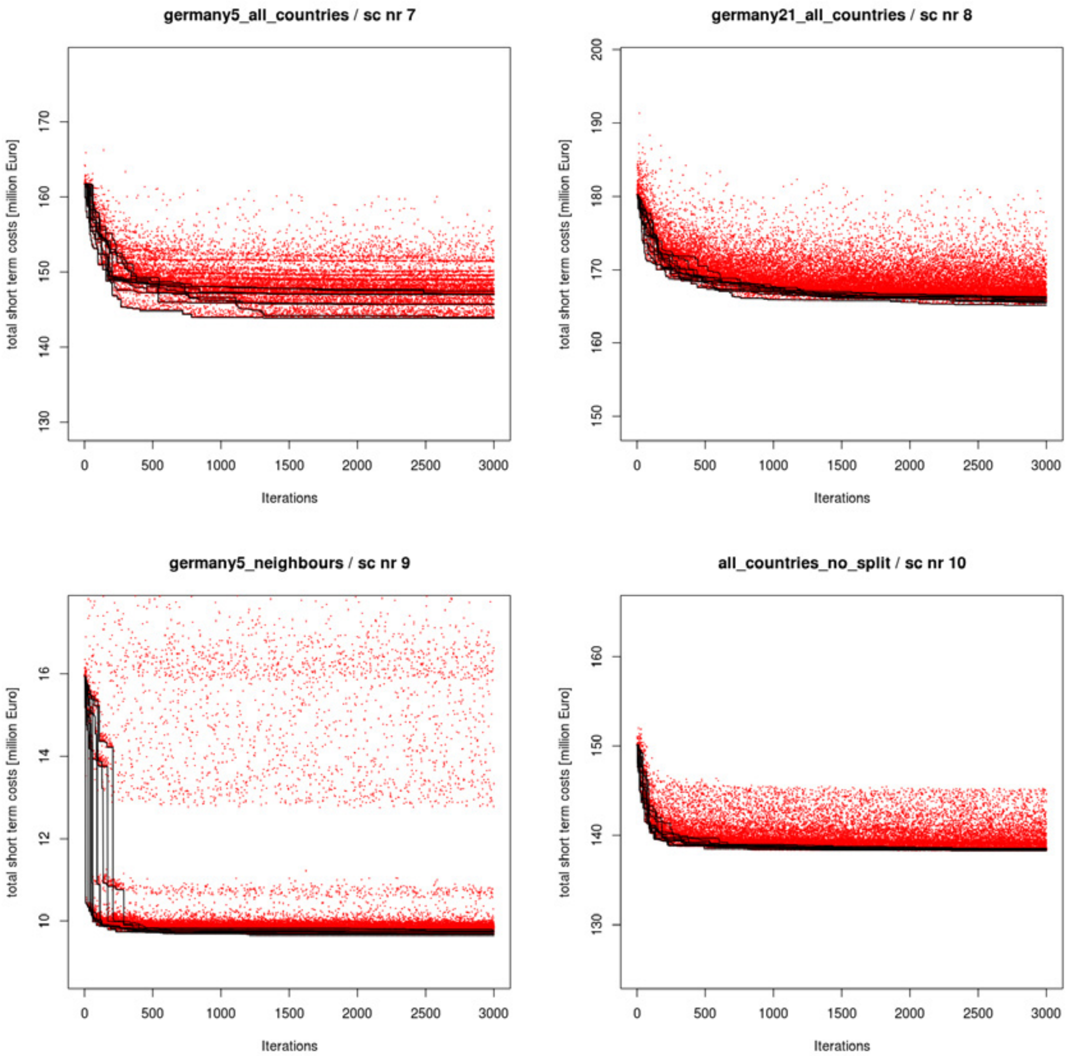


Figure 3.8: Heuristic exchange iteration with 3000 steps (x-axis) for the first time step of test scenario 7 - 10. Repeated ten times (black lines) with the same starting value converging to minimal total short time cost (y-axis). The optimal solution in not always reached within 3000 iteration steps, but a robust solution is. Red dots indicate discarded exchange operations. Headings indicate the regions' division and the number of the test scenario. Source: own images

transfer steps that were tested but rejected, since they led to cost increases. The fact that they are all above the black lines demonstrates it is a functioning algorithm.
More regions and a greater amount of available transfer capacity increases the number of iteration steps required to reach the lowest total short term costs. It is likely that the number of power plants in the merit order influences the optimization process.

For test scenarios one, two, five, six, nine and ten, the iteration loop could stop earlier, since no significant improvement is made from a certain iteration step level. The iterations in other scenarios like four, seven and eight do not come to an optimal result.

These seem to reach a local minimum.
3000 iteration steps seems to be an applicable standard number, since all test scenarios containing different region divisions reach a robust result. For detailed calculation and new region divisions, adjusting the number of iterations is recommended.

In addition to the heuristic optimization algorithm, an approach based on the algorithm method of simulated annealing was proposed by Hilpert (2012). This can generate more precise results, but has to be fine-tuned in detail. For the basic version of renpass, the more robust heuristic algorithm has been applied. For more specific research, where exact results are crucial and when knowledgeable about setting algorithm parameters, the simulated annealing algorithm should be applied.

3.5.3 Grid Losses and their Effect on the Exchange

Transferring electricity via transmission lines causes losses of energy to the electricity system. These transmission grid losses have to be accounted for and generated additionally. By "charging" transfers of electricity with grid losses, more electricity has to be provided in the exporting region. This increases the load and hence, eventually, the price in the exporting region. If the additional costs caused by the transfer are higher than its benefit, the transfer is not executed despite the price differences between region. In this way, grid losses influence the exchange algorithm to use electricity or storage possibilities provided locally first, which also reflects the physics of electrical flow. For each connection line, grid losses can be defined by specifying a percentage value, indicating the share of electricity flowing through this line that has to be generated additionally due to grid losses. The standard value is 3 % in the current version of renpass. This includes all grid losses from producer to consumer.

Since region sizes differ and thus, so do the distances and the grid losses of connections, a more precise method was added. If the length of a connection line, the kind of current and the voltage are specified, renpass estimates the proportion of grid losses based on those values. Calculation method and utilized parameters can be found in the function `gridLossFromDistance`.

During the iteration steps of the optimization algorithm (see Section 3.5.2), electricity is shifted back and forth, but no grid losses should be accounted for in each iteration step. Only the net transfer flow has to be charged with grid losses. During the random iteration, the grid losses are corrected for each iteration step. The function `gridLoss` fulfills this task.

In conclusion, the additional electricity required to cover the grid losses also has to be provided by the exporting region. This creates a tendency to use local sources first. By implementing the additional costs of transfer into exchange decisions via grid loss, the total short term costs of the system are reduced.

3.6 Excess Electricity Storage

Figure 3.9 shows how storage is implemented in the code. It is an excerpt from the main flowchart in Figure 3.2.

3.6.1 Regional Storage

Electricity is stored first in storage capacities, which does not induce grid usage. The regions to which excess electricity has been assigned after the exchange are not necessarily the regions in which this excess VRE feed-in has been generated. This is due to the fact that excess electricity is shifted during the heuristic exchange algorithm: VRE electricity may not be required in any of the regions to cover residual load, or it may not be able to reach regions with remaining residual load due to grid restrictions. In this case, this excess electricity appears randomly in one of the regions at the end of the iteration steps of the exchange algorithm.

Nevertheless, electricity storage facilities in the regions where excess electricity is located after exchange are used first to save transport capacity and electricity required additionally due to grid losses. The order in which storage plants are used depends on their storage capability. Only electricity at marginal price zero is used for storage, thus dispatchable power plants do not generate electricity for storage.

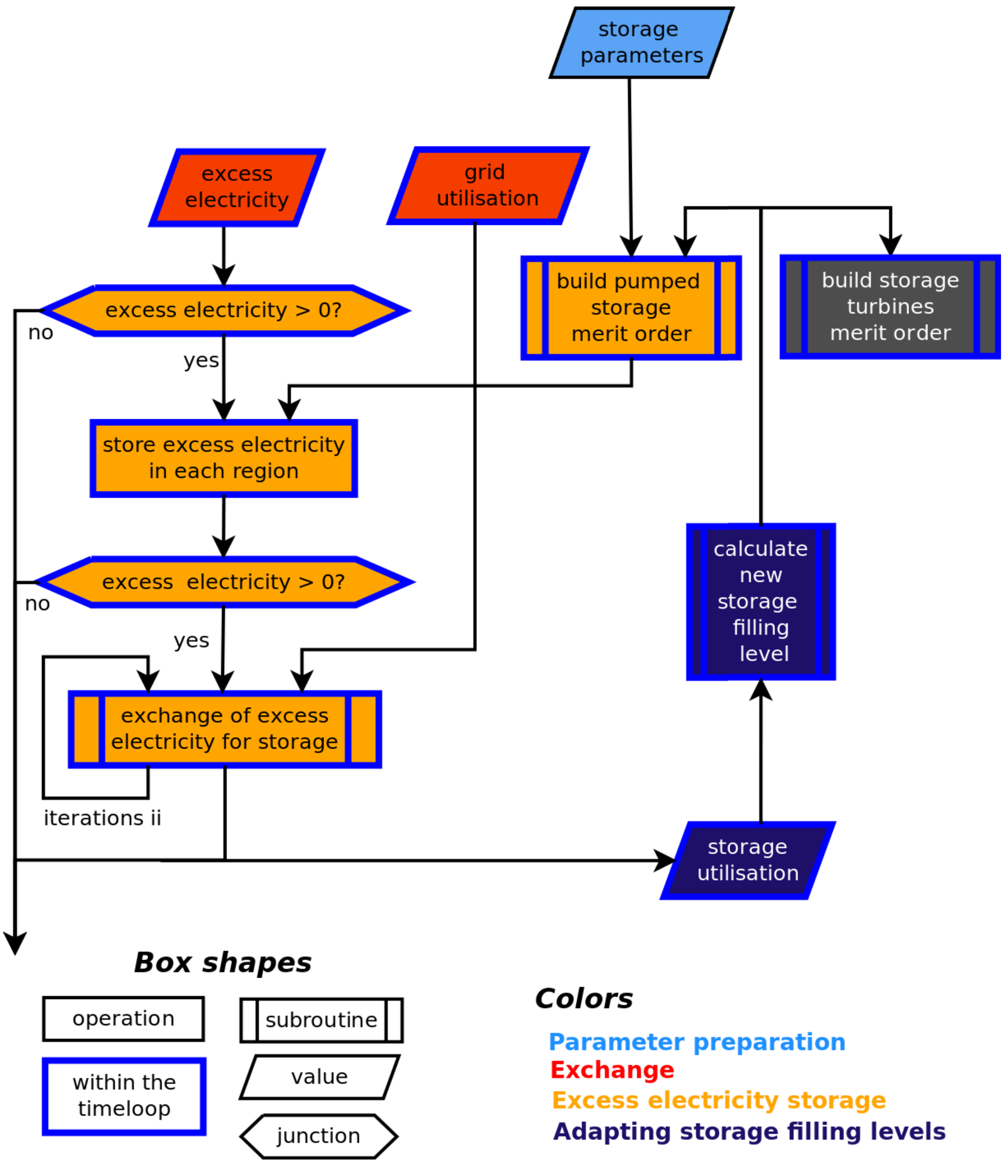


FIGURE 3.9: Flow chart excerpt: Code structure of the storage cluster of renpass

3.6.2 Exchange for Storage

VRE must-run electricity that even exceeds storage capacities in the region is transferred to storage capacities in other regions respecting the restriction of remaining grid capacity. Since the distribution of excess energy is similar to the exchange algorithm problem, a simplified version is utilized for finding an near-optimal distribution of excess electricity to storage capacities. Due to its rules, it is likely that the algorithm will first accommodate excess electricity in neighboring regions, if storage capacity is available. The storage exchange algorithm has to fulfill the task of not shifting around excess electricity senselessly. This would create additional electricity requirements due to grid losses and consequently reduce of excess electricity without storing it.

Similarly to the main exchange algorithm, the following setup is chosen in each iteration step:

→ one region containing storage capacity

→ one neighboring region with excess electricity

→ capacity to be transferred

The capacity is chosen randomly within the limits of excess electricity and grid restrictions, taking into account the grid capacity already utilized in the first exchange step. The shifted amount could be bigger than the storage capacity in the specific region since it is possible that the region is utilized to transfer excess electricity to the next region.

In the simplified exchange algorithm for combining excess electricity and storage capacities the shift is done in every case. The selection criteria of exchange regions and amount are defined more narrowly in the storage exchange since only regions with storage capacities and those with excess electricity can be chosen. With the aim of keeping the calculation time within manageable time frames, several stop criteria are implemented which may take effect before the maximal amount of iterations is reached:

→ no storage possibilities left - as much excess electricity as possible is stored

→ no excess electricity left

→ excess electricity in all regions - no storage possibilities left

A pump merit order defines which storage pumps are used first. The order depends on the filling levels of the reservoirs. Pumps which low filling level upper reservoirs should be used first. This is described in detail in Bökenkamp (2015, Chapter 4).

Should there still be excess electricity left after the storage exchange algorithm, fluctuating renewable plants causing excess electricity have to be curtailed. In the modeling of renpass, a shut-down priority remains undefined, thus no decision is taken as to which plant or technology has to be shut down first. The sum of excess electricity per time step is stored in the result database. High values of excess electricity could indicate an excess of installed capacity, a lack of transmission capacity or a lack of storage capacity.

3.6.3 Filling Level Adaption

At the end of each time step, the filling levels of hydro and other storage plants as well as the biomass filling levels are updated depending on the energy generated and the production pumping operations. This is an important input for the next time step since the marginal cost of biomass and storage depends on the filling levels, and thus, has an effect on the merit order.

For biomass plants, the biomass available for the whole year for each region is reduced by the amount that was used for electricity production in the time step.

For hydro storage plants, the production, storage of electricity and inflow have to be taken into account. Power generation and pumping are converted to water volume. In combination with inflow and efflux from run-of-river plants, this determines the new filling levels and is calculated for each reservoir. If there is more inflow than a reservoir can capture, this amount is spillage and therefore lost to the system. The total amount of spillage per time step is saved in the simulation's log-file.

Filling levels of other storage reservoirs are increased or reduced accordingly. Unlike hydro storage plants, they do not have natural inflow, the adaption of their filling levels only depends on generation, storage and efficiency.

3.7 Summary of Load and Generation Balancing

In summary, the sequence of dispatch in each time step is defined in renpass as follows:

1. Regional VRE must-run: wind onshore and offshore, solar, run-of-river
2. Regional dispatchable plants by merit order in the same region
   → Geothermal: very low marginal cost
   → Biomass: marginal cost depends on the filling level of biomass and the mean biomass resource price
   → Storage turbines: marginal cost depends on filling level reservoirs and inflow
   → Nuclear power plants: fixed marginal cost

→ Fossil thermal power plants: marginal cost depends on the resource price, CO_2-price and power plant parameters such as efficiency

3. Excess VRE from other regions

4. Merit order of cheaper dispatchable plants from other regions

5. Shifting excess electricity to other time steps by storing excess electricity regionally

6. Shifting excess electricity to other time steps in other regions by exchanging excess electricity

7. Curtailing must-run feed-in in case of excess electricity and full storage

In renpass, the balancing of supply and demand follows the idea of supplying with the given infrastructure in the cheapest way from a macroeconomic point of view. renpass applies the principle of merit order and dispatch via merit order as it is the case in today's electricity markets across Europe. In contrast to today's market rules, the dispatch and formation of prices is done at a regional level first. This is followed by an exchange between the regions within the limits of grid capacity. Regional prices reflect the value of energy at a specific location when it is delivered, including the transmission congestion costs.

renpass can be used to simulate 100% renewable energy target systems, today's system and all stages of the transition at a high regional and time resolution. As it is a simulation tool, besides the code functionality, the input data and scenario assumptions are pivotal in determining the outcomes of the model.

Chapter 4

Data

In order to achieve full transparency, traceability and the reproducibility of an electricity model, the software, but also the data has to be open, and sources, as well as data processing has to be well-documented.

Especially in the field of energy, data is part of commercial competition. Power plant registers are traded commercially. Providing grid data is partly rejected on grounds of national security. Nevertheless, over the past few years the availability of Open Data concerning energy supply has increased. Legislation over the last decade has had an increasing tendency to request data availability from grid system operators and energy companies.

At European level, the European Network of Transmission System Operators for Electricity (ENTSO-E) pursues an agenda of making grid data available (`www.entsoe.eu`). In the field of renewable energy data, the Directive 2009/28/EC on Renewable Energy induces better data availability: Article 24 requires the European Commission to establish an online public Transparency Platform. Another step towards transparency was taken by the EU Framework Programme for Research & Innovation (Horizon 2020), which demands open access when publishing results financed by the aforementioned program (European Commission, 2014, p.26).

In Germany, improvement of data availability in the field of energy started as renewables began to make up a larger share: Due to the German Renewable Energy Act (EEG), an installation register as well as feed-in time series of wind and solar have to be provided by the Transmission System Operators (TSOs). The draft amendment of the EEG

2014 addresses data quality problems and develops the transparency duties of renewable plants further (EEG, 2014, p.174).
The availability of electricity system data has improved in Germany thanks to the Grid Development Plan (NEP) process. The growing problems related to acceptance of grid extensions have revealed the need for transparency in the planning process of electricity grid extensions. If stakeholders affected by infrastructure measures are not informed about the background and reasons, this can lead to delays and higher costs. The German Bundestag commissioned the TSOs to compile a Grid Development Plan (NEP) every year starting in 2012, with the German Energy Industry Act (EnWG) § 12a-d building its legal basis (German TSOs, 2012b, p.14). This resulted in a participatory process of electricity and grid system modeling. As public consultations were done on scenario assumptions and results, the underlying data for the scenario calculations had to be published. During that process, the Federal Network Agency (BNetzA) published a register of German power plants with more than 10 MW of installed capacity, a starting point for the provision of power plant data.

Changes in the EnWG §12 obligate the TSOs to publish data about the electrical balance. Striking differences in data interpretation and definition of vertical load between the TSOs have since become obvious as a result (German TSOs, 2012a).

Although data availability has increased over the past few years, data remains a considerable constraint to energy, especially Open Source energy modeling and hinders rapid improvement and the comparability of different models.

In this chapter, the structure and sources of input data in renpass are described. Since only Open Data is used, this gives a first insight into the availability of open energy data in Europe.

4.1 Input Data and Scenario Assumptions

The delimitation of fixed input data and scenario assumptions in energy transformation modeling is not straightforward.

Some parameters such as physical constants do not change and are not controversial. Technical parameters, for example the efficiency of different power plant types are

relatively uncontroversial for state-of-the-art values, but assumptions on technological progress vary widely and their determination can be biased.
Economic parameters such as, for instance, cost developments of fuel prices or installation costs are partly a consequence of energy pathway decisions. Their uncertainty increases with time and are highly controversial. In least-cost optimization models, they are decisive and varying them influences the outcome to a large extent.
Environmental costs are integrated in energy modeling only if they have already been given a price due to existing regulations such as with the CO_2-emission trading scheme. Other external costs such as land use or loss of biodiversity have not been yet integrated in the input side of energy system models due to a lack of methods.
Social parameters, including acceptance, are seldom integrated in electricity system models on the input side since there are almost no methods developed so far for translating them into model feed-in.

Input data is controversial in more than one dimension. The different dimensions of data/scenario assumptions and their related problems are clustered in Figure 4.1. Different input parameters are ordered according to the variety of potential future development (x-axis) and their uncertainty in quantification for modeling purposes (y-axis). A further developed categorization could include additional dimensions, such as the influence of the parameter on the output (indicated in gray on the z-axis). The controversy of the input variables increases with the distance to the zero point. The categorization does not claim to be complete but should be regarded as a first attempt to provide an illustration of the input data controversy problem.

For renpass, a difficult decision as to where to draw the line between input data and scenario assumptions had to be taken. Input data is not adapted in each scenario run. It is stored in the `weather` and the `renpass` database and is, in part, only visible in the code. Although sources of the data are documented in the model description, the influence on the model results is not as obvious to the user as the scenario assumptions are.
Scenario assumptions have to be defined by the user every time a scenario is to be calculated.
The challenge is to ease the trade-off between the model's transparency and its usability. The more parameters are preset as fixed input data, the easier the handling is, since fewer conscious decisions have to be taken by the user, but the less aware the user is on

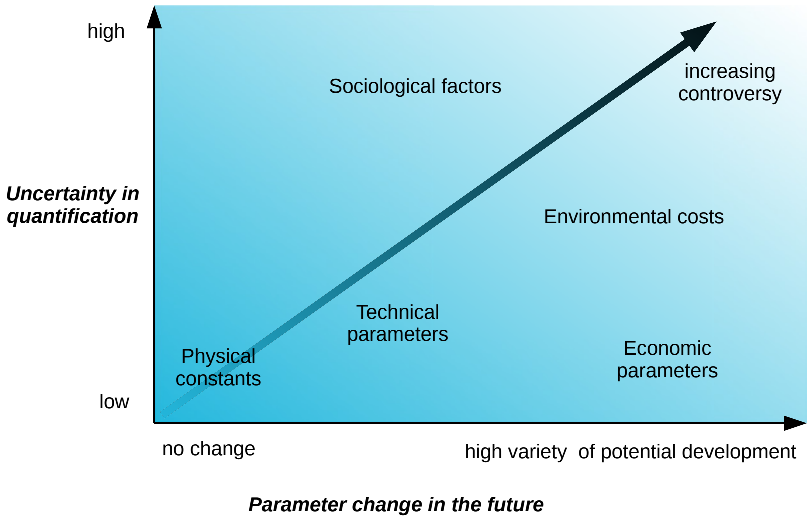


FIGURE 4.1: Controversy dimensions of clusters of input data to energy models. Source: own illustration

influences of the input on the results. If all parameters have to be chosen each time, the model would not be practical.

In the following section, the input data of renpass is described, scenario assumption setting is described in Chapter 5.

4.2 Database Structure

renpass contains four databases: `pathways`, `weather`, `renpass` and `results`. The scenario database `pathways` can be decided upon and compiled by the user (see Section 5.2). In the `result` database, the output of the simulation is saved in various tables (see Section 5.4.1).

Input data is stored in the `weather` and the `renpass` databases. Although this data can also be adapted, these tables are not part of the usual scenario setting. These input data tables and their sources are described in the following sections.

Table 4.1 displays the tables in the input databases of the basic renpass version. Tables are clustered into the following categories:

→ weather

→ demand

→ power plants

→ storage

There are three different table categories:

→ time series

→ parameter

→ register

cluster	**time series**	**parameter**	**register**
weather	solar diffuse solar direct wind offshore wind onshore		solar raster wind offshore raster wind onshore raster weather station ror run-of-river
demand	demand	distribution	
power plant		thermal pp emission	thermal pp
storage	storage flow	storage inflow field no.	storage reservoirs reservoir turbine upper reservoir turbine lower

Table 4.1: Tables of input databases weather and renpass grouped by cluster and category

Grid infrastructure is represented in the scenario settings rather than in the input tables. Since existing grid infrastructure is taken into account in most scenario settings, a `status_quo_2012` scenario is provided in the `pathways` database. It is described in Section 4.6.

4.3 Geography

Almost all electricity-related data is bound to geographical information. High resolution geographical data is therefore essential for electricity modeling. In renpass, geographical information is not processed in the final simulation but is required for the assignment of weather data, installed capacity, grid capacity between regions and for the illustration of results.

The area of renpass in the version described in this thesis covers Germany and all its neighboring countries, as well as Norway and all countries surrounding the Baltic Sea, except Russia. The area is illustrated in Figure 4.2. The grid capacity between regions is summarized per connection, as indicated by the red lines.

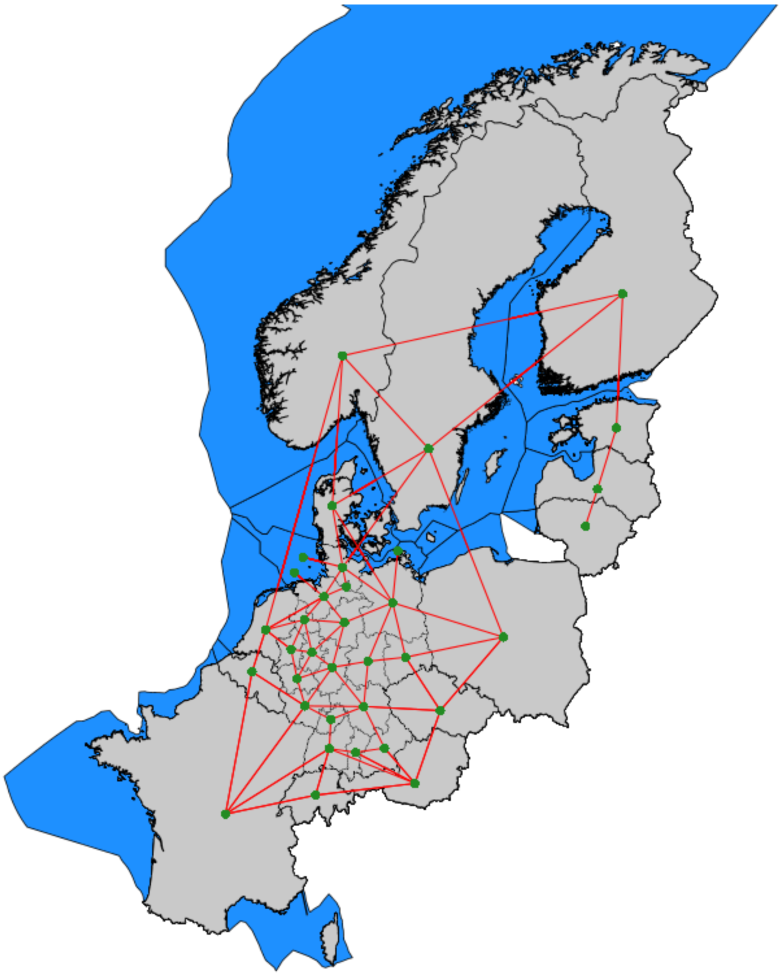


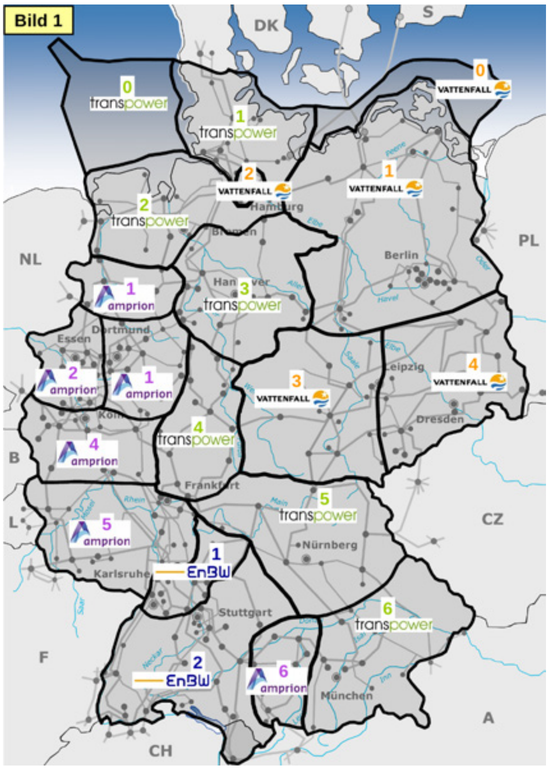
FIGURE 4.2: Regions in renpass and connections between regions. Source: own image based on ENTSO-E (2012b); GADM (2012); VLIZ (2012)

The country shape files and the district shape file of Germany are taken from the database of Global Administrative Areas (GADM, 2012). The spatial data files they provide are freely available for academic and other non-commercial use. Redistribution or commercial use is not allowed without prior permission. Spatial data on the maritime areas of the countries is provided on a homepage developed and maintained by the Flanders Marine Institute (VLIZ, 2012). The countries' Exclusive Economic Zones (EEZ) have been chosen as input data for potential offshore wind areas.

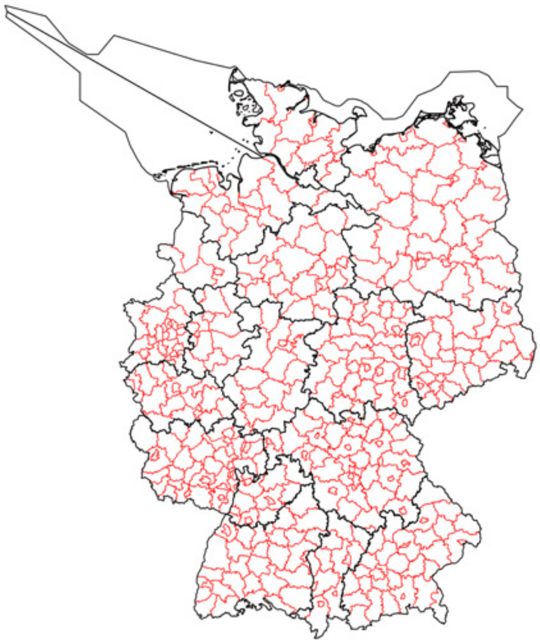
The processing of the geographical data was mainly done in R using additional R-packages for spatial data processing: ncdf, sp, ggplot2, splancs, geosphere, maptools. The geo-reference system used is WGS84.

In renpass, Germany's spatial resolution is higher than for the other countries. As it can be seen in Figure 4.2, Germany consists of 18 onshore and three offshore regions. The breakdown into regions follows potential grid bottlenecks and administrative boundaries between districts. The regions are an aggregation of districts. Although administrative boundaries are not relevant for grid infrastructure, they are useful for other information such as population and gross domestic product (GDP) (VGRdl, 2012). Which districts were aggregated to a renpass region was decided on the basis of grid infrastructure. To be able to detect grid bottlenecks, regions have to chosen in a way that these potential capacity shortages appear between, rather than within regions.
The German TSOs have published a map (German TSOs, 2009) of electricity flows within Germany. On the one hand, the regions are aligned with the control zones, on the other hand, with grid bottlenecks. These regions were also applied in the grid study on the integration of renewable energy (dena, 2011) (see Figure 4.3 (A)). Since there is no geographical information available about these regions, the map was used to derive renpass regions. It was layered on the district region map of Germany (see Figure 4.3 (B)). Red lines indicate district boundaries, black lines indicate the derived German subregions.

An ID with five characters has been assigned to each region. Subregions in Germany have been assigned the numbers 11001 - 11021 (Figure 4.4). The list includes three offshore regions: the Baltic Sea is one region (11019) and the North Sea is divided according to the clusters defined by the offshore plan for the North Sea (BSH, 2013). 11020 consists of the north-eastern part of the German EEZ. The plan is for it to be connected to



(A) TSO Region model



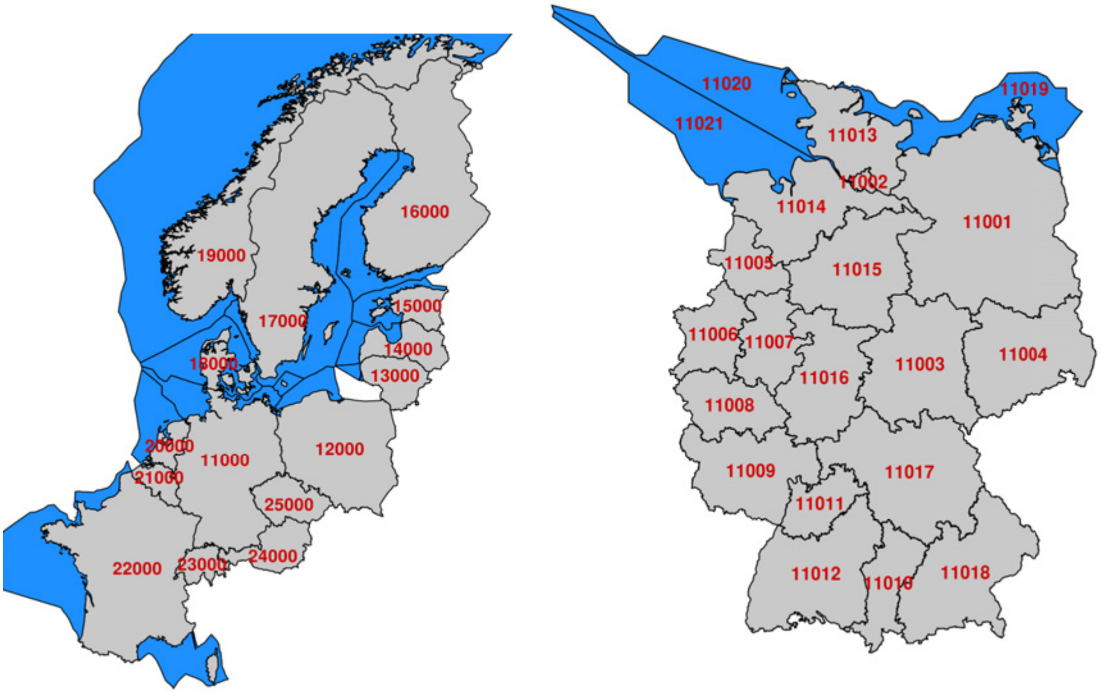
(B) renpass regions (black) derived from districts (red)

FIGURE 4.3: The subregions of Germany in renpass are aggregations of districts. The rough approximation lines of the region model of the TSOs (A) were the basis for the decision as to how to aggregate districts to regions for renpass (B). District boundaries from GADM Version 2.0 January 2012 do not include new district boundaries for Saxony-Anhalt. Sources: German TSOs (2009) ,GADM (2012),VLIZ (2012),OpenGeoDB (2013), own editing

the grid of Schleswig-Holstein (11013). Region 11021 contains the south-western part of the German EEZ, connected to the coast of Lower Saxony (11014). Additional grid connections can be added in the grid scenario assumptions.

All other countries are modeled as one region each in the basic version of renpass. A further division into sub-regions would require grid infrastructure and spatial power plant data.

In order to assign installed capacities of renewable energy plants to the renpass regions, the OpenGeo dataset (OpenGeoDB, 2013) was used . This freely available dataset, maintained by volunteers provides information on postal code, administrative units and coordinates.



(A) Region IDs of country regions (B) Region IDs of German subregions

FIGURE 4.4: renpass country regions (A) and Germans subregions (B) with region IDs. Sources: GADM (2012),VLIZ (2012),OpenGeoDB (2013), own editing.

4.4 Meteorology

Whenever fluctuating renewables are part of a model approach, weather data is required. In renpass, wind speed, solar radiation and inflow data with a high regional and temporal resolution is utilized.

Common approaches are to either use computed re-analysis raster data or measured time series. Both data types involve advantages and disadvantages.

The German Meteorological Service provides free access to about 70 German weather stations for measured hourly onshore wind speed times series (DWD, 2013). The data quality and time span of availability differ significantly between stations.

Offshore wind measurements in the German seas are collected at three Research Platforms in the North and Baltic Seas (FINO) and are provided by the Federal Maritime and Hydrographic Agency (BSH, 2012). One time series for the Baltic Sea and two wind speed time series of different heights for the North Sea are available. For reliable estimates of offshore wind feed-in, more spatially distributed wind time series would be required, otherwise the variability of feed-in may be rather overestimated.

In summary, the availability of measured time series is not sufficient for robust wind feed-in calculations, especially for offshore wind.

Re-analysis raster data has the advantage of having a higher geographical density of available time series and does not have data gaps. Furthermore, climate science is a research field with a long history of cooperating and worldwide data sharing. Since renpass depends on Open Data, this approach was pursued.
The so-called `coastDat-2_COSMO-CLM` data set is an extensive data set of historic climate raster data on an hourly basis, based on climate model COSMO-CLM. Applications of the climate model are described in Weisse et al. (2008). Geyer and Rockel (2013) made various climatological time series available for the area shown in Figure 4.5. The `coastDat-2_COSMO-CLM` data set is further described in Geyer (2014).

longitude	*W*	050.125 °	*E*	051.125 °	→ 234 raster data points
latitude	*N*	30.125 °	*N*	79.875 °	→ 228 raster data points

For renpass weather data, the available raster points were intersected with the EEZ (VLIZ, 2012, version 7) and the land area (GADM, 2012) of the regions in renpass. For Norway, the offshore area was cut 60 nm north of the northernmost point of the Norwegian mainland at 72.17 °C N, since it is not very likely that there will be offshore wind farms around the icy and sparcely inhabited area around Svalbard.
The result is stored in the `weather` database in the form of raster point registers and time series for wind speed, roughness and solar radiation.

In order to save storage space and processing time, only every third row and every third column of the available raster points is utilized in renpass. Figure 4.6 illustrates all renpass weather data points.

Wind speed data is provided for 10 m above sea level. Offshore, the roughness is assumed to be 0.0002. This value was determined by Bohm (2014) on basis of wind speed measurements at different heights of the three FINO-stations in the Baltic and North Seas.
For Lithuania, an additional raster point was chosen since no raster point of the third

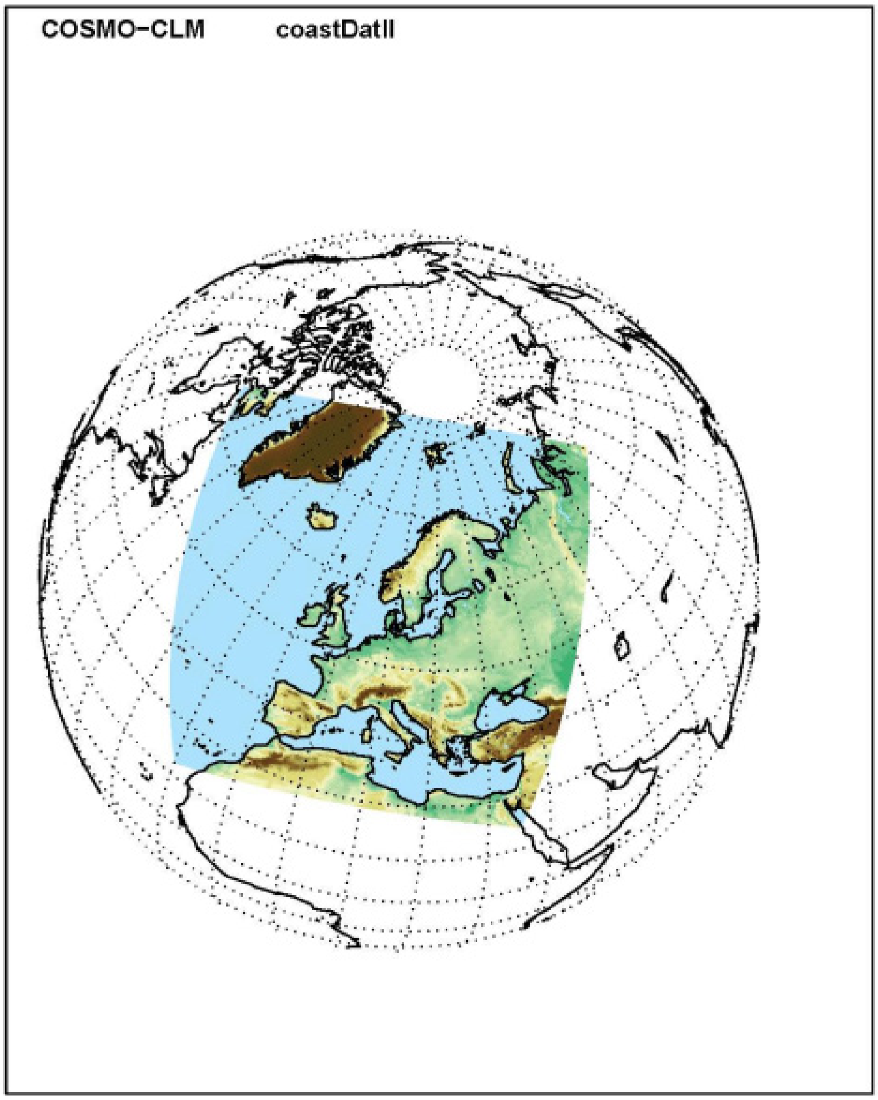


FIGURE 4.5: Area of available raster data coastDat-2 based on the Climate Model COSMO-CLM according to Geyer and Rockel (2013)

row and third column is located in the offshore area of Lithuania and the country does have offshore wind potential.

For the calculation of onshore wind speed at wind turbine hub height, the roughness raster data of the `coastDat-2_COSMO-CLM` dataset is utilized. Roughness data is also provided per hour. Due to ice cover and vegetation roughness, values change slightly during the year. For renpass it is estimated to be accurate enough to utilize one roughness value per raster point. The roughness from the data set varies significantly between locations and ranges between 0.0000109 and 9.999999.

Lindenberg (2011) describes the quality of wind onshore raster data of the `coastDat-2_`

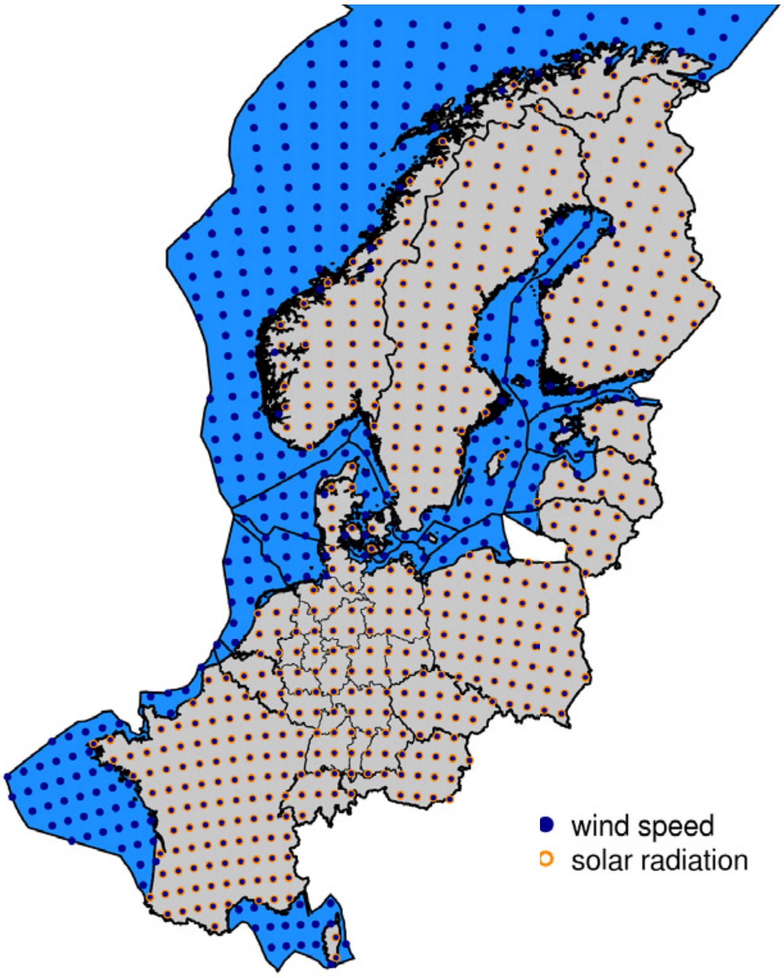


FIGURE 4.6: Weather raster data points wind speed offshore/onshore and solar radiation onshore. Source: own illustration based on Geyer and Rockel (2013); GADM (2012); OpenGeoDB (2013); VLIZ (2012)

`COSMO-CLM` dataset. One finding was that a data grid with a lower resolution does not have a high influence on the modeling quality. For calibration in renpass, the real wind feed-in 2012 in Germany was compared to the calculated feed-in based on the installation numbers at the end of 2012 and the wind and roughness raster data of 2012. With the help of calibration, wind speed as well as roughness data is considered to be very much applicable for the simulation of wind power feed-in in the basic version of renpass. The approach and methods in detail are described in detail in Section 4.10.2.

The solar radiation data utilized in renpass consists of two hourly time series from the `coastDat-2_COSMO-CLM` data set: Diffuse and direct radiation on the surface $[W/m^2]$. The solar raster data points are the same as the wind onshore data points.

Weather Years. By varying the meteorologic years in scenarios of renpass, the influence of different weather conditions can be examined. Thus, different weather years can be chosen from the `weather` database. The COSMOS-CLM dataset covers the period from 1948 to 2012. Each weather year in the database includes 4,563,960 additional wind speed values onshore, 2,811,960 offshore and 9,127,920 solar values. A limitation of five data years makes the basic version of renpass more user-friendly.
1998, 2003 and 2010 were chosen due to their wide range of weather patterns with respect to wind, solar and hydro inflow. These years differ significantly in terms of weather pattern as summarized in Table 4.2.
In addition to those three years, wind speed and solar radiation data sets for 2011 and 2012 are stored in the database since they are required to calibrate the solar and wind electricity feed-in calculated using the weather data.

year	**wind speed**	**solar radiation**	**hydro inflow**
1998	high	medium	high
2003	medium	high	medium
2010	low	high	low

TABLE 4.2: Classification of selectable weather years in renpass

For the version of renpass described, precipitation data is taken from a different climate model data set. Precipitation and inflow data sources are described in Section 4.8.

Other potential sources for re-analysis climate data sets based on satellite data are the World Meteorological Organization (WMO), the National Renewable Energy Laboratory (NREL) and the European Centre for Medium-Range Weather Forecasts (ECMWF).

4.5 Demand

Electricity demand time series in renpass are derived from hourly load values provided by ENTSO-E (2012a) for each European country. Load in this case is defined as *"the hourly average active power absorbed by all installations connected to the transmission network or to the distribution network. [...] It is the power consumed by the network including (+) the network losses but excluding (-) the consumption for pumped storage*

and excluding (-) the consumption of generating auxiliaries" (ENTSO-E, 2010, p.1).
The hourly load values are the average values of the 60 minutes load preceding the hour. Some industrial power stations for self-supply and grids operating parallel to public supply, for example railways in some countries, are not included in these figures. The representativity of demand data accounts for 80 to 100% of the total national demand across countries.
Taking Germany as an example, the load values cover 91% of the whole electricity demand across the country ENTSO-E (2010, p.4). The rest is covered by the industry's own production and railways supply which are not fed into the public grid.
In renpass, neither the production side nor the demand side of the industry's own production are included in the input data. Demand time series for 2010 provided in the table `demand_timeseries` in the `renpass` database represent demand per country excluding industry self-supply. What is included and excluded per country is described further in ENTSO-E (2010).

For Germany, the demand time series is required in a higher resolution than at a national level. One time series for each of the 18 onshore subregions needs to be derived for renpass.

Load time series are provided by the German TSOs for each of the four control areas but this data is not utilized for renpass since data quality is low and methods differ for the determination of the load time series (German TSOs, 2012a, p.13ff). However, due to the German Grid Development Plan, the coordination of definitions and documentation is improving.

For the basic version of renpass, the aggregated time series from ENTSO-E is distributed to the 18 regions by distribution factors. Those distribution factors for the demand of German subregions are derived from the region model for electricity transfer published by the German Transmission System Operators (German TSOs, 2009). As described in Section 4.3 and Section 4.6 the division to 18 regions is based on this publication, too. Load values for each of these regions are provided in the following situations (German TSOs, 2009, Picture 3-6):

→ strong wind / low load

→ strong wind / high load

→ weak wind / low load

→ weak wind / high load

The distribution coefficients for the regions were derived from the load values of the four situations. This method was also applied in dena (2011, p.259f).

Since this is a rather rough estimation for regional demand time series, three other parameters were examined for their applicability as factors for load distribution: number of inhabitants, land area and GDP. Those values are available at a district level from the Federal Statistical Office of Germany (VGRdl, 2012). Since renpass' dispatch regions are district aggregations, inhabitants, land area and GDP values per region can easily be derived from this data.

The four different distribution factors were compared by applying them to real data regional time series: For the four control areas, demand time series are available. Thus, the four different country demand distribution methods were applied to them. Distribution factors derived from the four load situations led to the best results. They are therefore used in renpass and provided in the `demand_distribution` table in the `renpass` database. As soon as reliable load data is available in higher resolution, this should be amended.

4.6 Grid

Grid infrastructure is part of the scenario assumptions. Nevertheless, information about the status quo of grid infrastructure is crucial. Since investment cycles of extra-high voltage lines exceed forty years, grid scenarios will be based on today's grid infrastructure. For the `status_quo_2012` grid scenario, information on number of circuits, voltage level [kV] and current type [AC or DC] of extra-high voltage lines (>=220kV) were based on the ENTSO-E grid map (ENTSO-E, 2012b). The number of circuits is indicated by shape and voltage level by color. How the grid capacity is derived from these values and how the n-1 criteria (safety margin) is accounted for constitutes part of the methodology and thus described in Section 3.5.1.
Initiatives and projects to increase grid data availability are emerging, but ENTSO-E is considered to be the most reliable source of information so far.

The available capacity between countries is published by ENTSO-E as Net Transfer Capacity (NTC) (ENTSO-E, 2011). NTC values constitute the maximum foreseen magnitudes of exchange programs that can be operated between two areas respecting the n-1 security conditions of the involved areas, taking into account the uncertainties on the assumptions of NTC assessment (ENTSO-E, 2011). These values are provided in MW. Transparency on how the NTC values are derived, increases. A NTC definition can be found in Amprion (2014); 50Hertz (2014); transpower (2009); TransnetBW (2014). A comparison between calculations based on the capacities obtained by the circuit and ENTSO-E NTC values reveals that the latter are significantly lower. This is due to the fact that for the NTC-values, loads and power plants in neighboring countries are taken into account. A load balance cannot be calculated for just two regions, but only multilaterally.
NTC values are utilized for inter-country connections in renpass. If the value differs depending on the direction of the flow direction, the higher value is employed for both directions.

For grid scenario assumptions, the ETNSO-E System Outlook and Adequacy Forecast Reports (ENTSO-E, 2013) are valuable sources of information for the development of NTC values. Information on grid infrastructure planning within Germany and to neighboring countries can be found in BNetzA (2013a, p.85). Grid capacity values for 2024 and 2034 in this source are the ones utilized in the scenario framework 2013 of the German Grid Development Plan 2014, authorized by the BNetzA.

4.7 Renewable Energy Plants Register

Information about already installed capacities and distribution of renewable energy plants is important for the creation of scenarios, since renewable scenarios will not be completely independent of existing installations. Furthermore, information on today's distribution of installed capacities can be a useful indicator to extrapolate the distribution of installed capacities between regions.

The European status quo for 2012 is derived from ENTSO-E (2014). Since this source has aggregated the installed wind energy capacity, the offshore share is taken from EWEA (2013, p.13).

In Germany, although the number of renewable plants is huge, the data availability is much better than for fossil power plants. The TSOs have the obligation to publish a register of all plants remunerated under the EEG mechanism. With the objective to provide an easier access to renewable plant data and to point to possible improvements in data provision, the German Section of the International Solar Energy Society (DGS) merges and verifies the registers of the TSOs and distributes the result as a csv-file of all renewable electricity plants except large hydro for free download on their website (DGS, 2013). The `status_quo_2012` renewable scenario in renpass is based on the downloaded register of February 2013. Information concerning which versions of the register are used is the actual status can be found in the manual of renpass (Wiese, 2013).

4.8 Run-of-River, Water Inflow and Hydro Storage Plants

For the compilation of run-of-river plants, several sources were used. Installed capacities of German run-of-river plants which are under the EEG are also derived from DGS (2013). Older and larger hydro plants are not included in this register since they do not operate under the EEG. Installed capacities of run-of-river plants per region were mainly derived from a study by Fichtner on behalf of the German Federal Ministry of Economic Affairs and Employment (BMWI, 2003). For German run-of-river plants, the average capacity utilization is determined by the selected weather year. Inflow data from 40 level meters in German rivers are selected from the German hydrological yearbook of the year 2006. Run-of-river plants are assigned to nearby level meters from the same river system. For each power plant, the flow curve is transformed in a way that maximum production corresponds to the plant's installed capacity, the minimum is zero and the capacity utilization amounts to the value determined by the selected weather year. The production of the plants is then aggregated to form run-of-river feed-in for every dispatch region. Data on German hydro storage plants was collected from the different plant operators.

Water inflow and hydro plants are modeled with a very high resolution for Norway. The Norwegian University of Science and Technology and SINTEF Energy Research kindly provided data on historical hydro inflow to storage reservoirs (NTNU and SINTEF, 2010). Inflow data for the main solar and wind year data (1998/2003/2010) were not openly available. Instead, inflow time series for the years 1969, 1979 and 1990 are utilized. The inflow pattern of those years is similar to 1998, 2003 and 2010. Data about reservoirs, run-of-river and hydro plants in Norway is based on the Norwegian Water Resources and Energy Directorate (Norges Vassdrags- og Energidirektorat, 2010). Hydro power plant data includes information on the total annual inflow and energy yield per cubic meter for each plant. The inflow curve is scaled to represent the inflow for each plant that can be converted to electricity generation with the energy yield. The generation level of each time step is restricted by the plants' installed capacity.

For countries other than Germany and Norway, the run-of-river production is not modeled with individual plants, but as aggregated facilities per country. The European status quo of installed run-of-river capacity in 2012 is based on ENTSO-E (2014). The seize of the plants is the basis for differentiation between run-of-river and hydro storage plants. All plants up to 50 MW are assigned to run-of-river capacity. Run-of-river production for these countries is modeled as being constant. The utilization of the assumed capacity and thus the level of production is determined by the selected weather year and varies between 0.45 and 0.65. The status quo data 2012 for hydro storage plants is based on ENTSO-E (2014): Hydro plants larger than 50 MW are taken as hydro storage plants.

For a more detailed explanation of the hydro part of renpass, see Bökenkamp (2015).

4.9 Fossil Power Plants Register

The register of German thermal power plants in renpass (`thermal_pp_register`) is based on BNetzA (2013b), which includes types and parameters of existing power plants in Germany with an installed capacity of more than 10 MW installed capacity. In addition to this publicly available list, research institutes can apply for further data used for simulations for the Grid Development Plan. It is not allowed to disseminate this data any further.

For other countries other than Germany, no fossil power plant registers are provided in the `renpass` database. Although open datasets on power plants in Europe are under development, they are not considered complete enough to be used in simulations yet. Thus, in the version of renpass described, installed capacities per fuel and country are stored in the `pathways` database as `status_quo_2012` scenario. The values are derived from the Yearly Statistics & Adequacy Retrospect 2012 provided by ENTSO-E (2014).

Since there is no information about the type of plants, lignite and hard coal fired power plants are assigned to the type steam turbine, oil to gas turbine and the installed capacity of natural gas fired power plants was divided equally between gas turbine and combined cycle. Since there is no information about the age distribution of the plants, the start year is distributed evenly between today and the scenario year.
Other sources for power plant capacity are EC Energy (2012), EC Energy (2013) and EIA (2014) but those only provide aggregated numbers for fossil fuel plant capacities. Information regarding estimated future capacity can taken from the ENTSO-E System Outlook and Adequacy Forecast Reports (ENTSO-E, 2013).

4.10 Technical Parameters and Emission Factors

4.10.1 Power Plant Parameters

Power plants are modeled individually in renpass, but power plant parameters such as auxiliary consumption, average efficiency, variable and fixed costs are provided in the table `thermal_pp_parameter` clustered by fuel-type combinations.
Efficiency values are provided for power plants that started operation in 1980. The efficiency value is modified by 0.3 percentage points for each year difference between when an individual power plant actually started operation and 1980. More recent power plants have a higher efficiency. This is described in depth in Section 3.3.3.

The parameters of fossil power plants (efficiency, auxiliary power) are taken from Grimm (2007, Table 4.1, p.47). Efficiency for lignite power plants is based on dena (2008, p.54). For nuclear power plants, the marginal costs are set to 10.8 €/MWh, which is taken from a study commissioned by the German Federal Ministry of Economic Affairs and Employment (BMWI, 2010, p.44). The parameters are summarized in Table 4.3.

Emission factors in renpass indicate the amount of CO_2 emitted per GJ of fuel consumed. They are derived from a list on emission factors and carbon contents provided by the German Emissions Trading Authority (DEHSt) at the Federal Environment Agency (UBA) (DEHSt, 2004). Table 4.4 shows the emission factors applied in renpass.

type of plant in plant register	*fuel*	c_{var} variable costs $€/MWh$	η_{gross} gross efficiency %	*aux* own consumption as share of efficiency %
steam turbine	uranium	10.80		
steam turbine	hard coal	1.00	42	7
combined cycle	gas	0.70	58	1.7
gas turbine	gas	0.50	40	0.75
steam turbine	lignite	1.00	37	7
gas turbine	oil	0.50	40	0.75
steam turbine	refuse	30.00		
internal combustion	gas	0.50	40	0.75
steam turbine	gas	1.00	42	0.75
internal combustion	oil	0.50	40	0.75
steam turbine	oil	1.00	42	7
combined cycle	oil	0.70	58	1.7
internal combustion	biomass	0.5	40	0.5

TABLE 4.3: Thermal power plant parameters

fuel	e_{CO_2} $kgCO_2/GJfuel$
lignite	100
hard coal	95
oil	76
natural gas	56
refuse	54
uranium	0
biomass	0

TABLE 4.4: Emission factors of different fuel resources

4.10.2 Wind Performance Curve

Figure 4.7 shows three different power performance curves of wind power plants normalized to a rated power of 1 MW. They are stored in the table `wind_pp_parameter`. If more detailed wind power curves are needed, they can easily be added to this table.

In the basic version of renpass, for onshore power plants, an aggregated performance curves of three 3 MW plants of manufacturers with large market shares is utilized (light blue line in Figure 4.7).

For offshore power plants, the performance curves of three 5 MW plants, namely Siemens SWT-3,6, Vestas 112 and REpower M5 are combined, which results in the dark blue line in Figure 4.7.

The computation of the performance curves is the work of Bons (2014).

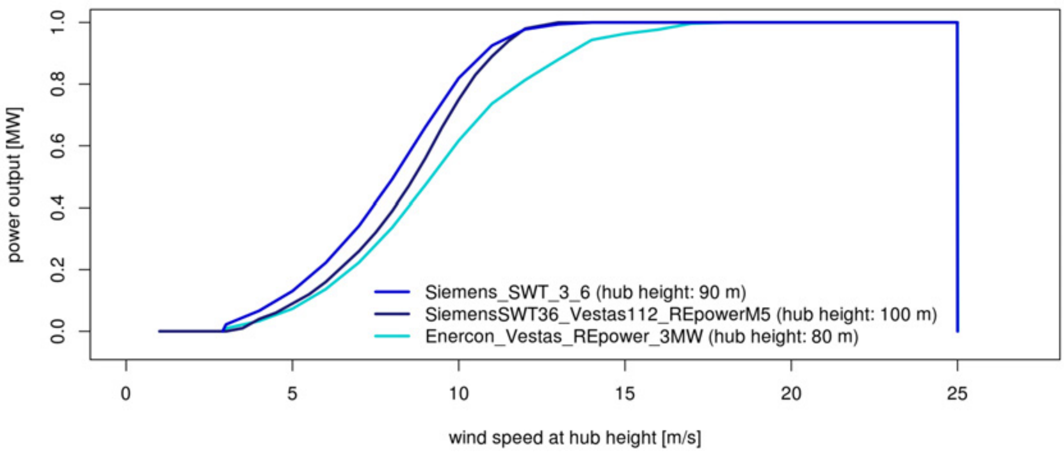


FIGURE 4.7: Performance curves of wind power plants stored in the renpass database, normalized to a rated power of 1 MW. For wind onshore, the joint 3 MW (turquoise) and for offshore, the joint 5 MW (dark blue) performance curve is utilized. Source: illustration based on Bons (2014)

To calibrate the wind feed-in calculation, time series of real feed-in from wind power in 2012 in Germany are compared to the calculated feed-in. Calculated feed-in is based on the wind speed and roughness data described earlier (see Section 4.4) and installed wind capacity at end of 2012. The total feed-in of wind power in Germany accounted for 46 TWh in 2012. The installed capacity of wind onshore power amounted to 31.3 GW. The wind onshore code of renpass resulted in 63.1 TWh. Two main reasons were identified for this overestimation: the availability restriction and very high values for roughness lengths in the raw data.

The average roughness length for all raster points is 0.69 m. Since locations with small roughness lengths are usually chosen for wind turbines, it is assumed that roughness lengths of wind power plant locations will, in reality, be lower.

According to Pfaffel et al. (2012, p.48), modern wind energy power plants have an availability of 95 to 99 %. For older plants the availability is lower.

For calibration, two measures are introduced. First, the height of the initial wind speed, which amounts to 10 m was increased to 15 m to compensate for smaller roughness values. Secondly, a correction factor of 0.8 was implemented which already includes the availability factor. With these two elements of calibration, the simulated feed-in amounts to 46.6 TWh for 2012.

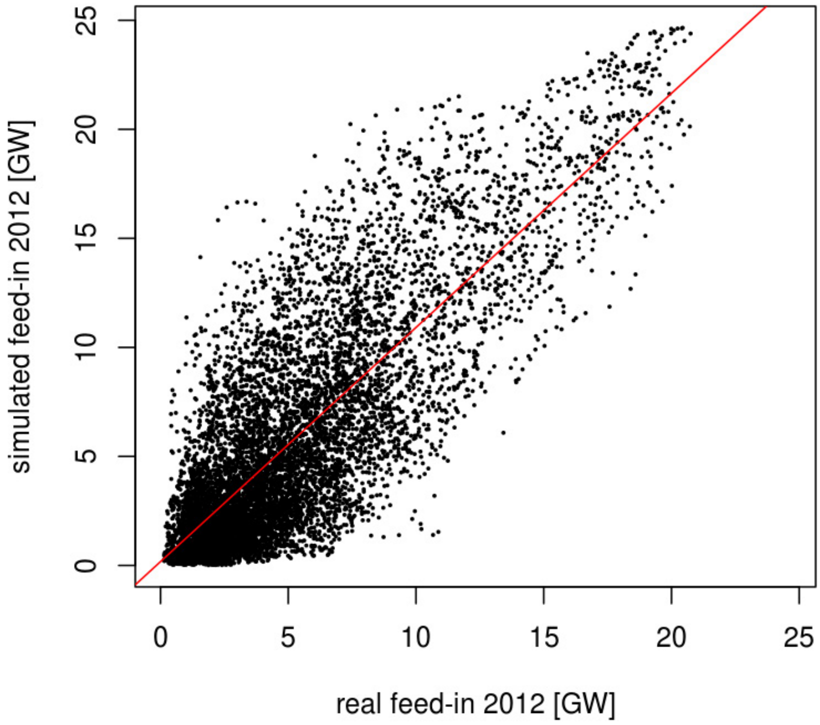


FIGURE 4.8: Calibration of onshore wind power curve in renpass compared to real and simulated feed-in. Regression line in red. Source: own image

The scatter plot (Figure 4.8) and duration curves (Figure 4.9) illustrate the resulting adapted wind feed-in compared to real time series for 2012. The red regression line and the duration curves highlight the remaining overestimation of feed-in at high wind speeds. It is assumed that this is due to the fact that power curves with a cut out wind speed of 25 m/s are utilized in the renpass wind code, which does not represent existing wind turbines. The simplified power curve approach does not take into account older plants. However, it can be assumed that the wind power plant fleet will be closer to the utilized wind power curves. Thus, for scenario calculation more than a few years in the future, these state-of-the-art power curves are more suitable than historical ones.

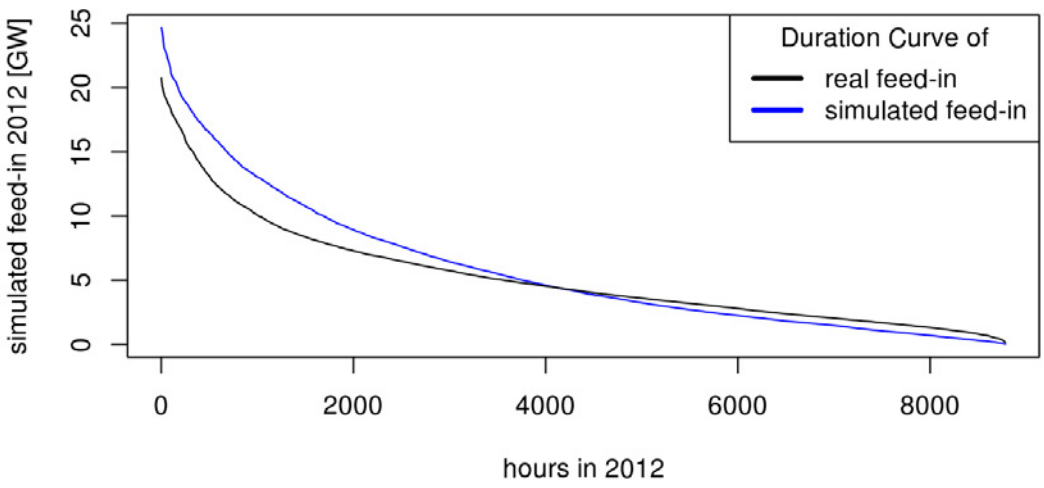


FIGURE 4.9: Calibration of onshore wind power curve in renpass compared to real and simulated feed-in: duration curve. Source: own image

Bons (2014) refined the wind feed-in calculation by introducing a database of power plant curves in renpass. A classification was done based on the year of construction with the specific plant distribution. For each year and region, a different power plant curve was aggregated and utilized to calculate of the wind feed-in. Furthermore, in low wind speed areas, power curves of specific low-wind turbines were introduced. This extension is not implemented in the basic version of renpass.

For offshore power plants an availability factor of 0.9 is applied to account for outages. In a simulation test with weather data from 2010, this led to 4127 full load hours of offshore wind plants. This is considered to be in the right order of magnitude.

Refinement of the wind feed-in calculation is under preparation: Bohm (2014) is developing a simulation of the wind energy feed-in on the same weather database as used in renpass. This tool works at a district level resolution and takes into account different hub heights and power curves of all major wind plant types. Its output, detailed wind feed-in time series, will be connected to renpass by a soft link.

4.11 Open Data Availability

The availability of data is still a constraint to high resolution energy modeling. A lot of data on climate, power plants and infrastructure exists and huge amounts can be stored and processed due to rapid developments in the field of computer technology. But often this data is proprietary, sorted poorly and much work preparing and pre-processing the data is done again and again in parallel isolation. In the worst cases, the availability of data even determines research directions. This can be improved by collaboration based on publicly financed data information portals on national and European level, maintained and improved by contributions from its users.

Important data for energy modeling:

→ Meteorological time series for wind speed, solar radiation, precipitation, temperature

→ Grid infrastructure including spatial information and transfer capacities

→ Power Plant register including location and grid connection

→ Technical parameter of power plants such as efficiency and ramping times

→ Load time series at different grid levels on a regional basis

Concerning the time series, the standard resolution of weather and demand data should be 15 minutes. In energy systems with increasing shares of VRE, power plant characteristics like ramping times is becoming increasingly important and the contribution of flexibility options can only be evaluated properly in models with a high temporal resolution.

Chapter 5

renpass Application

Applying an energy simulation model requires the calculation of more than one scenario to answer a question. The model gains in significance by enabling the comparison of the outcomes of different scenario settings.

This chapter addresses the process of a simulation run with renpass:

→ Input: decision on assumptions (Section 5.2)

→ Processing: running the model (Section 5.3)

→ Verification: plausibility check of the results (Section 5.4)

Thereafter, some renpass application examples and their contribution to the model development will be described (Section 5.5). The common practice of extension implementation by different users and co-developers is explained in Section 5.6.

Section 5.7 gives an account of a general scenario setting approach for a long-term pathway simulation which is drawn from previous modeling experience with renpass. To conclude, Section 5.8 summarizes the scope of renpass, including the limits, strengths and weaknesses of the model. Additionally, this section presents renpass' mode of distribution.

5.1 Requirements

renpass can be applied on computers running on Linux, Windows or Mac operating systems. All code is written in R and data, assumptions and results are stored in a MySQL database. The R-package RMySQL is needed for the direct data queries. Thus, for running renpass, the following software is required:

→ MySQL - database (`http://www.mysql.com/`)

→ R - programming language (`http://cran.r-project.org/`)

→ RMySQL - package for the connection to the database (`http://cran.r-project.org/web/packages/RMySQL/index.html`)

→ *optional*: maptools, lattice, colorRamps - additional R-packages. These are required if spatial plots should be included in the renpass result visualization.

The model itself consists of four databases:

→ weather

→ renpass

→ pathways

→ results

and three folders:

→ `code_R_renpass` with all code files and functions

→ `plot` which includes the shape files (geospatial data format) of the available regions

→ `log` which is where log-files keeping track of the simulations will be kept.

All renpass components can be downloaded from `renpass.eu`. A manual on the installation of the software required on the user's computer assists in setting-up renpass (Wiese et al., 2013). A second manual (Wiese, 2013) describes in detail the practical application of renpass, as well as the background to the data and its functionality.

5.2 Input

In a simulation, the choice of a consistent input is an important part of the analysis. The effort involved in choosing input parameters should not be underestimated. Optimization models are quite often restricted to just a few user-defined assumptions, while the other assumptions are hidden as input parameters within the model setting. As Ventosa et al. (2005, p.905) state, the advantage of a simulation approach lies in the flexibility that allows for a wide range of purposes, however this freedom requires the assumptions to be consciously chosen and justified. Model results can misinform if the assumptions chosen are not consistent or plausible.

5.2.1 Pathways Database

The renpass input parameter setting is organized in the database `pathways`. Predefined scenarios or combinations of development paths can be chosen. Scenarios and sub-scenarios are identified by their scenario names (= *primary key*). Additionally, each of the sub-scenarios and its parameters can be defined by the user. Figure 5.1 gives an overview of all scenario parameters, sub-scenarios and their attributes.

The starting point for setting a new scenario is table `1_scenario_parameter`. Figure 5.2 gives an impression of what manually inserting a new line in this table looks like. It includes many choices some of which are simplified by having standard settings or drop-down menus. Standard choices can provide a solid basis for the first calculation of a new reference scenario, but can also be adapted. The `scenario_nr` is the primary key in the table and serves as the identification number for the scenario calculation.
Instead of inserting each new scenario manually via the graphical user interface phpMyAdmin, there are different ways to import data as csv or sql. Scenarios can also be generated and pre-processed in R and written into the database via RMySQL-connection. The data sources and the existing scenarios in the pathways database of renpass are described in the manual (Wiese, 2013).

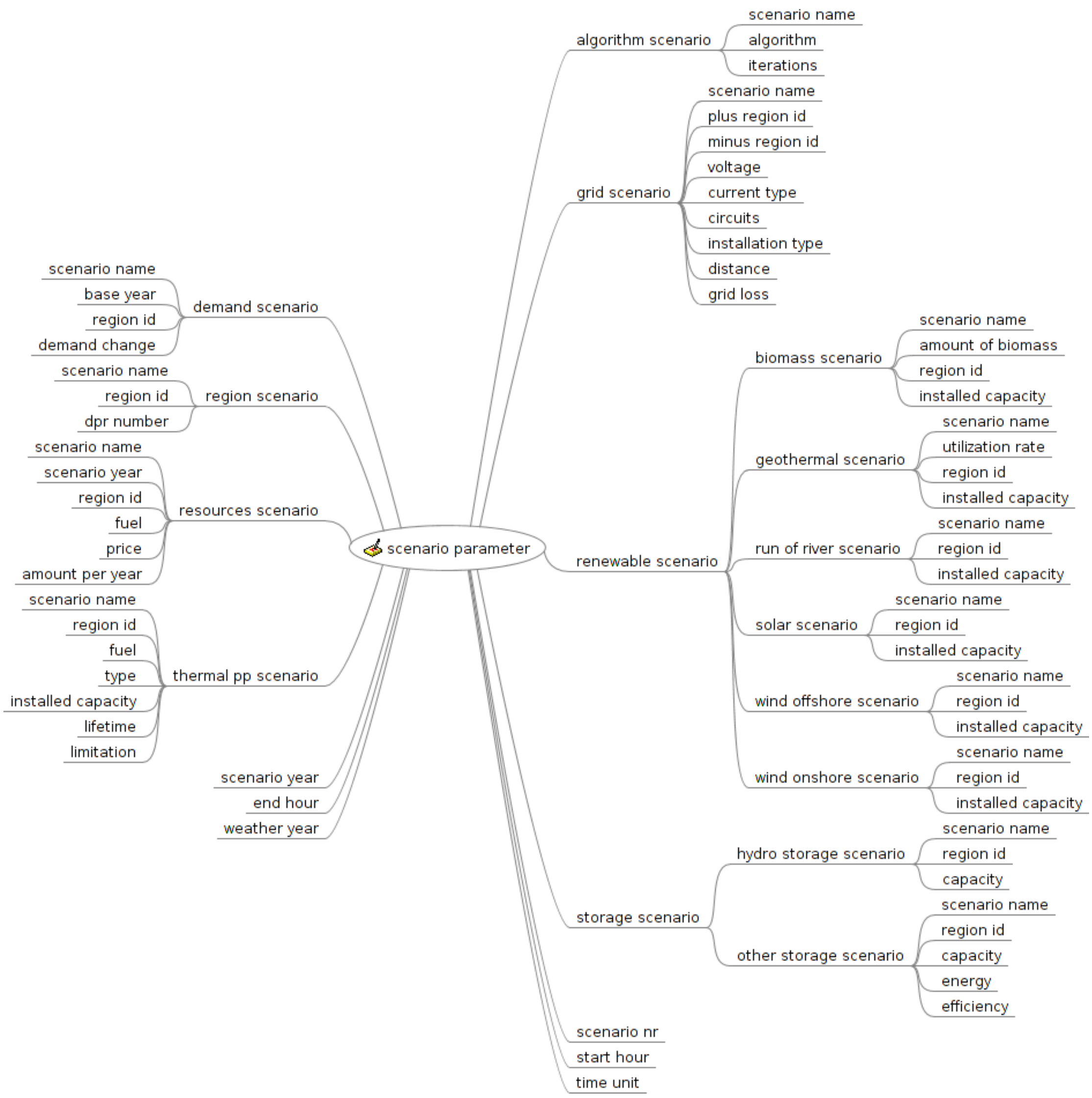


FIGURE 5.1: Sub-scenarios and attributes of all pathways tables. Source: own illustration

5.2.2 Area and Region Choice

The resolution of regions determines which grid bottlenecks can be tracked and can be chosen by the `region_scenario`. The choice of area and the region breakdown is crucial for the definition of sub-scenarios on installed capacities and other parameters as the required resolution of these settings differs according to the `region_scenario`.

. For example, if no region division within Germany is defined, the whole country is modeled as one region without internal grid constraints. In this case, installed capacities and other input parameters can be provided as nationwide aggregations. It would be enough to determine the sum of installed wind capacity in Germany as, for instance,

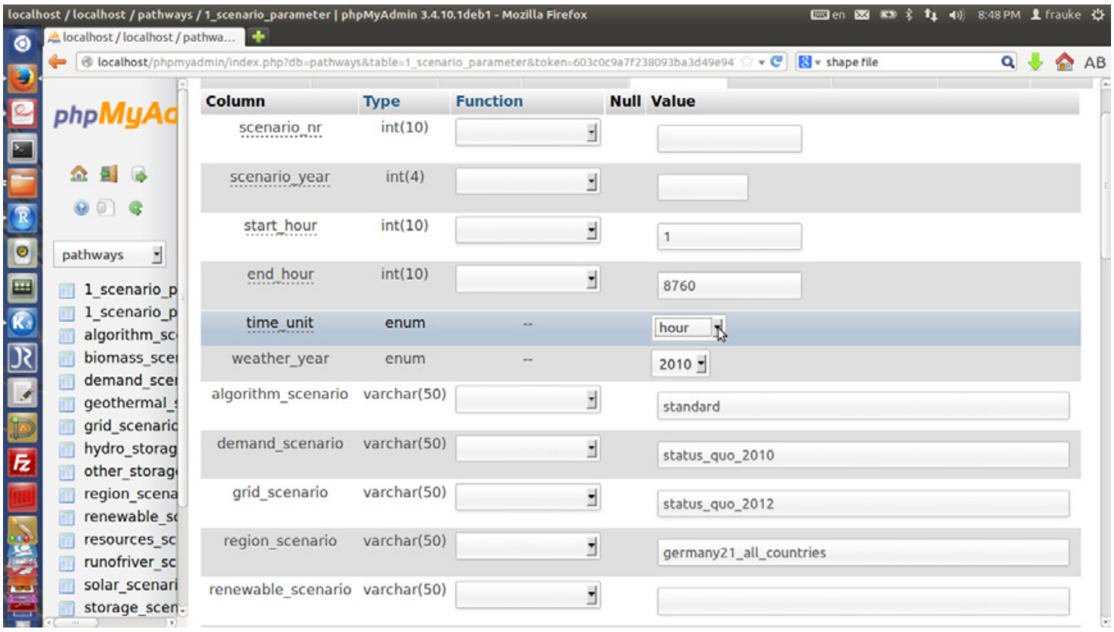


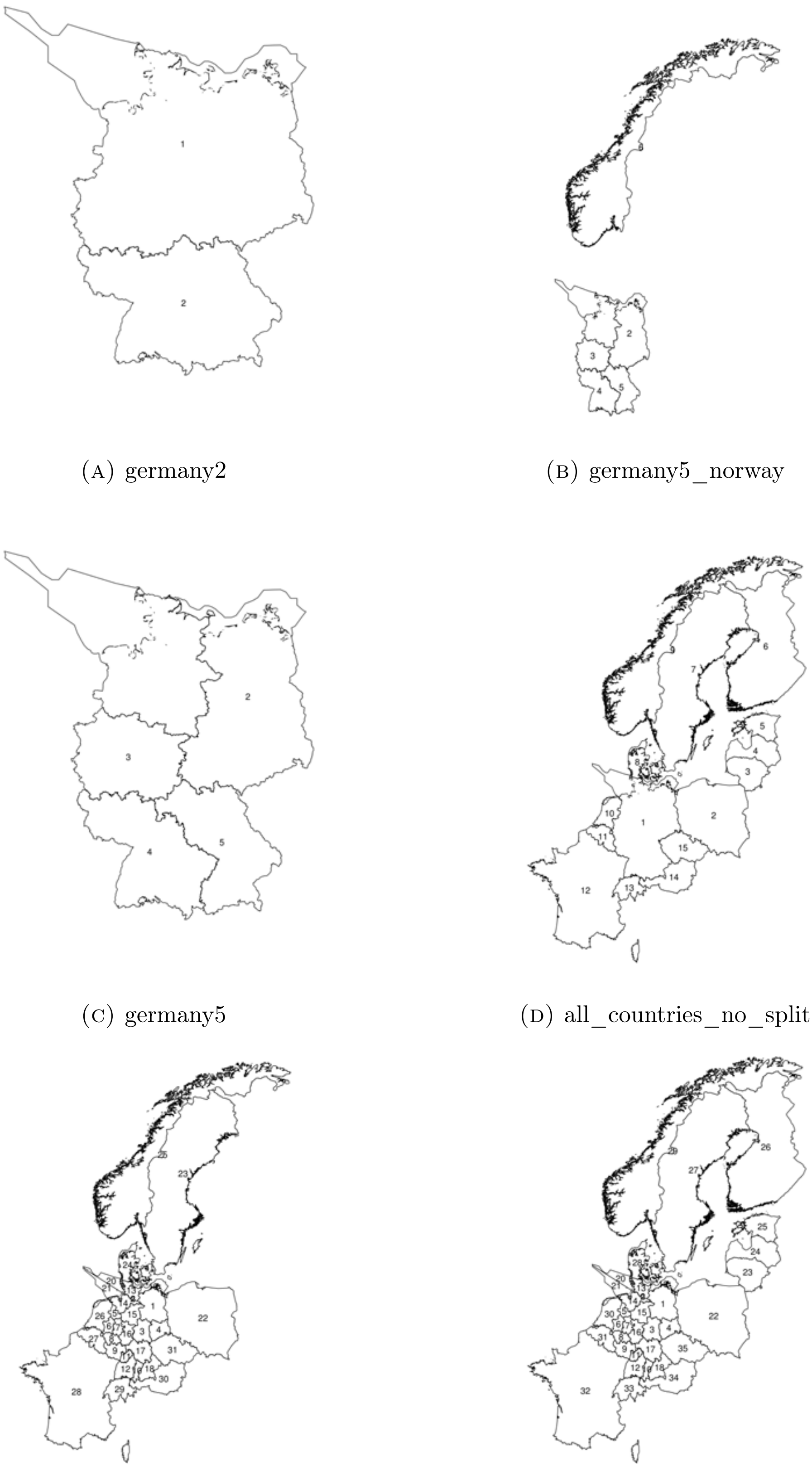
FIGURE 5.2: Screenshot of choosing new scenario settings manually

40 GW. If Germany is modeled in 21 regions, all settings have to be provided for all regions. In this case, the user has to decide upon the geographic distribution of the 40 GW across Germany.

The area in the basic version of renpass covers Poland, Lithuania, Latvia, Estonia, Finland, Sweden, Denmark, Norway, the Netherlands, Belgium, Luxembourg, France, Switzerland, Austria, the Czech Republic and Germany. Germany can be divided into up to 21 regions, all other countries constitute one region each.
Some region scenarios are predefined and already included in the table `region_scenario` in the pathways database. Figure 5.3 shows possible region clusters. Further explanation of predefined region scenarios and how to introduce new region scenarios can be found in the renpass manual (Wiese, 2013).

5.2.3 Predefined Scenarios

A key challenge in simulation models is to keep the level of transparency and information about the chosen input and its influence as high as possible while making sure it is not too complex to be practical. Model users have different needs with respect to the depth of self-determined input.
In renpass, this challenge is addressed by having predefined scenarios. The first approach



(A) germany2

(B) germany5_norway

(C) germany5

(D) all_countries_no_split

(E) germany21_neighbors

(F) germany21_all_countries

FIGURE 5.3: Predefined region scenarios. Different country compilations and Germany clustered in 2, 5 or 21 regions. Source: Own illustration, based on shape files from GADM (2012)

was to define one *standard scenario* for installed capacities, resources and grid development. However, experience shows that the wording *'standard scenario'* can lure the user into thinking that by choosing standard scenarios, these would not influence the results significantly.

Here is an example for an analysis aimed at estimating the performance of biomass plants in a 100% renewable electricity system. The parameters of interest, that are varied in the scenario calculations, are the amount of biomass and the distribution of installed capacities. Then, the need for the dispatchability characteristic of biomass plants will differ depending on other flexibility options. Varying the distribution of installed biomass capacities certainly effects whether there is little or much transmission capacity between regions. Furthermore, the distribution of VREs will also influence the operation of biomass plants. Although it is not possible to carry out sensitivity analyses for all parameters, one has to be aware of their potential influence.

In summary, it is impossible to choose unbiased standard sub-scenarios. In renpass, predefined scenarios are mainly status quo scenarios which contain historic figures of installed capacities or clearly defined planed capacities. For example, the grid pathway `status_quo_2012` contains all connections existing in 2012 and the `planned_2015` scenario also includes all the lines already under construction.

Predefined future scenarios have distinctive scenario names that indicate the data source. For example, the renewable scenario `NEP_2024_C` contains the installation figures of the NEP for the year 2024, scenario C (German TSOs, 2013).

5.2.4 Unexpected Influences

As described and illustrated in 4.1, the choice of input parameters is not straightforward. The problem of unrevealed influence does not only concern the pathway choice since major influence on the results is often the result of decisions taken by the programmer beforehand and hidden in the code.

To illustrate this, an example for an unexpected level of influence that appeared during the development of renpass is described in the following paragraph. Within the marginal dispatch function, a region with excess demand is assigned a scarcity price of 1000 €/MWh.

This number does not appear as a scenario setting but is just written in the code. Thus,

no sensitivity analysis was carried out with the scarcity price during scenario runs, although it influences the results considerably. In systems with high shares of VREs and few dispatchable plants, the scarcity price has a major influence on the total costs of a system since it reflects the value of security of supply.
The scarcity price usually reflects the consumer's willingness to pay. In a model in which not all flexibility options are included, the exogenous scarcity price setting is a possibility to reflect the opportunity value of flexibility options. The higher the scarcity price chosen, the more likely it is that flexibility options are profitable. If the results of a simulation reveal that the price in regions equals the scarcity price quite often, this is a sign of excess demand and if it occurs often, of a lack of flexibility options.

The scarcity price is just one example of settings hidden in the code of models that can exert unexpected influence on the results. The challenge is to be transparent on these settings.

5.3 Processing

5.3.1 Start

A renpass simulation is started by running the code file `code_R_start.R`. In this file, the user has to adapt some settings concerning the system software and the path where the folder `renpass` is located on the computer. This folder includes all the code files and functions, log-files and result plots.
The operating system has to be specified for the computer on which the simulation takes place. The operating system is of relevance, since for Windows, the memory limit size hast to be set to the maximum via R code and for Macs, the connection to the MySQL-databases requires a different host, port and socket.
User-dependent settings only have to be done once and only in this file. All other subroutines can then be sourced from the scripts.

The only element that has to be specified for each scenario calculation is the `scenario_nr`. This number identifies the parameters for an individual scenario defined in the database.

5.3.2 Log File

Once the processing has started, it is possible to keep track of the calculation, the log-file is saved for each scenario run in the folder `log`. In this text-file some basic parameters and steps of calculation can be checked. At the end of a simulation run, the total computing time, as well as the time share of the optimization loop and other parts are detailed.
For better traceability and a first insight into the consistency of the calculation, in this version of renpass, the control parameters sum of demand $[TWh]$ and sum of residual load $[TWh]$ for all regions for the whole calculation time are saved. By checking them, the user may recognize at an early calculation stage that something essential is wrong and that computing time can be saved.

5.3.3 Computing Time

renpass' computing time for one scenario depends on the power of the machine it is running on, utilized exchange algorithm and iteration steps, area and number of regions, time unit and time span to be calculated, as well as region exchange possibilities. The time loop part of the program (blue boxes in flowchart Figure 3.2) accounts for the largest proportion of computing time by far, since it contains the iteration steps of optimization. Calculating on an i5 CPU M 540 kernel with a frequency of 2.53 GHz and a cache of 3072 KB, one year with 8760 time steps for 35 regions takes about 5.6 hours processing time. The optimization part requires 4.9 hours (87.5 %) of total computing time, which corresponds to two seconds per optimization time step. Processing a simulation for two regions instead of 35 regions, while keeping all other conditions unchanged, one time step can be processed in 1.6 seconds on the kernel described.
The processing time per time step is a good indicator to determine whether coding changes harm the speed of the optimization.

With the objective of keeping computing time low, several stop criteria were introduced in the optimization exchange algorithm. Implementing a solver instead of using own programming (described in Section 3.5.2) for the heuristic exchange algorithm would probably increase the speed of the model. There are Open Source solvers for such problems, but, on the one hand, the disadvantage of longer computing time comes with the advantage of knowing the mechanism of the algorithm and being able to modify it easily on the other. The influence of the optimization algorithm on the results is discussed in Section 6.4.

Parallelization within the exchange algorithm was refrained from since iteration steps depend on each other and are interrelated. Many R-packages designed especially for parallelization (Eddelbüttel, 2014) exist, however for this version of renpass, an easier but very effective way of parallelization has been applied: since research carried out with renpass always implies the calculation of various scenarios, the parallel calculation of various scenarios on different kernels of the computer saves at least as much time as internal parallelization would have done. Computing time savings are probably even higher than internal parallel calculation within a scenario since there are no dependencies and thus no waiting time between the scenarios.

5.4 Output and Verification

5.4.1 Results Database

The results that need to be saved from a simulation depend on the type of research question a model ought to address. For renpass, the aim was to obtain information on the operation of energy system components with a high spatial and temporal resolution. Table 5.1 provides an overview of all tables in the `results` database which are filled out during each scenario run.

Figure 5.4 shows at which points, during the simulation, figures are extracted and saved in the associated result table. The flowchart is a summary of the colored code clusters from the flowchart in Figure 3.2. The results within the tables can be linked to the input parameters by the `scenario_nr`.

Some of the fourteen result tables are clarified below:

Electricity production comprises of the amount of electricity produced by dispatchable power plants (geothermal, biomass, thermal, hydro, storage turbines) and the maximal amount of electricity that could be produced by VRE (solar, wind, run-of-river) if transmission and storage infrastructure allows for it. The generation side of all storage plants is included in this table, too.

result table name	unit	per time step	per region	Σ all regions	per technology
demand	MW	x	x		
residual_load_before_exchange	MW	x	x		
electricity_production	MW	x	x		x
co2	ton	x	x		
exchange	MW	x			
exchange_after_storage	MW	x			
excess_vre_after_exchange	MW	x		x	
excess_vre_after_storage	MW	x		x	
price_before_exchange	€/MWh	x	x		
price_after_exchange	€/MWh	x	x		
over_demand	MW	x	x		x
storage_consumption	MW	x	x		x
filling_level_indicator					
filling_level	GWh & $mio\ m^3$	x	x		x

Table 5.1: renpass result tables

Excess electricity of variable renewable generation (excess_vre) is the amount of electricity that cannot be used because there is (a) no demand or storage capacity to absorb it, or (b) there is not enough grid capacity to transport it to demand or to available storage capacities. It is saved at two different code steps in each time step of the simulation: Before storage capacities are used to absorb excess electricity, and afterwards. Of course, after storage, values of excess electricity cannot be higher than before storage. All values are saved as positive values.

`excess_vre_after_exchange` is the electricity generated by VRE that cannot be used either due to a lack of transport capacity or because the demand in the entire simulation area is already satisfied.

`excess_vre_after_storage` is defined as the electricity generated by VRE that cannot be used due to a lack of demand, transport and storage capacity.

The difference between the two values represents the excess electricity absorbed by storage utilities. The results concerning excess electricity are not assigned to a type of VRE, but represent the amount of VRE that have to be curtailed. Excess electricity cannot be clearly assigned or related to a region because it is shifted around during the exchange

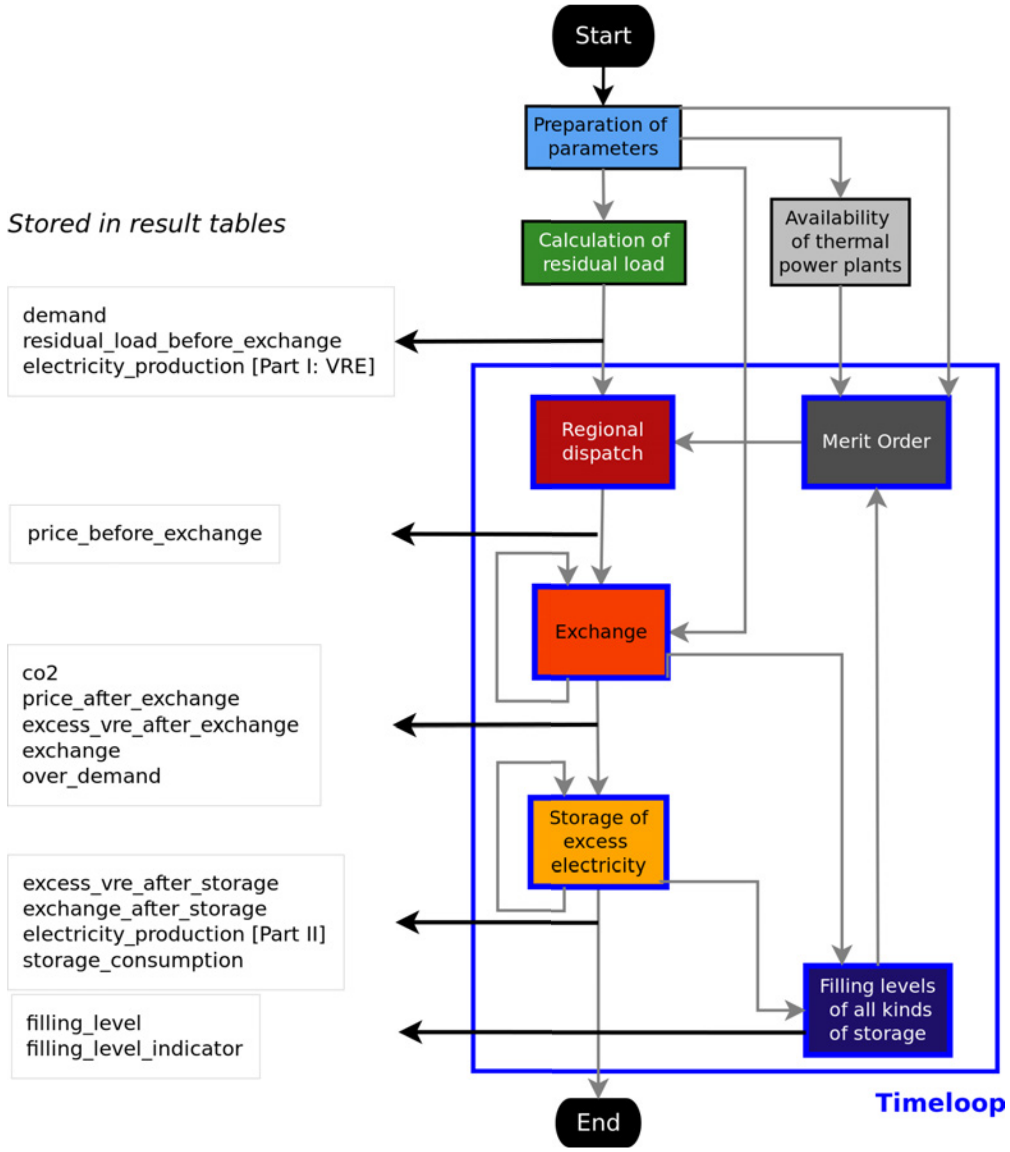


FIGURE 5.4: Overview flowchart of renpass showing at which steps in the simulation result parameters are extracted for the result tables. Source: own illustration.

step the region this electricity is assigned to after the exchange is chosen randomly. Thus, only sums for the whole calculation area are saved.

Prices in renpass are derived from the marginal costs of the marginal power plant in the merit order. For fossil thermal power plants, they reflect short term costs, but for biomass plants and storage utilities they reflect opportunity prices and are indicators to place them in the merit order rather than real prices to cover costs. Thus, especially in scenarios without fossil power plants, prices do not necessarily reflect real costs. Instead, they can be used for comparison between scenarios rather than as absolute values. Prices

are also an indicator of how often the scarcity price appears.
The average `price_before_exchange` of all regions should be higher than the average `price_after_exchange` because during exchange the total short term costs are minimized. Exporting regions can have higher prices after exchange. During storage, the price does not change, since only excess electricity with a price of 0 is stored.

Exchange result tables reflect the usage of the transmission grid. Exchange numbers are stored per connection and time step. Connections are always between two regions which are indicated by `plus_region` and a `minus_region`. The determination of plus and minus region is important to identify the direction of the flow. The leading sign of the numbers in the column `capacity_used` identifies the direction of the flow: If the value is positive, the electricity flows from the `plus_region` to the `minus_region` and vice versa.

Additionally, there are two columns for `grid_loss` in each exchange table. Grid losses of transmitted electricity between two regions are given in absolute $[MW]$ and relative values. They are saved as positive values.
The values in the table `exchange_after_storage` include the capacity usage status of the first exchange step before storage. Thus, the difference between the two exchange tables gives a rough estimation of the amount of electricity transferred due to storage. `exchange` is an additional table and `exchange_after_storage` is the main exchange result table because it states the final transport needs.
It is possible, that for some scenario settings, the exchange numbers in the result tables are higher than the minimum transport needs, since the excess electricity after the exchange step is not necessarily assigned to its region of origin. This is due to the standard heuristic exchange algorithm, which randomly chooses regions for exchange for the defined number of iteration steps. Transferring must-run capacity with marginal costs of zero does neither rise nor lower the total costs, since within the algorithm logic (see also Section 3.5.2), these are calculated as the product of residual load times price. Thus, must-run capacity could be transferred even if it cannot be utilized in the importing region and some of it is used up by grid loss. This described possible inaccuracy in the exchange results is just relevant in scenarios in which renewable energy hast to be shut down. The dimension of the inaccuracy depends on the amount of excess electricity.

Filling levels of storage utilities are summed per region and type in the table `filling_level`. Filling levels are saved in energy values [GWh] and volume [$million\ m^3$ for hydro, not yet defined for other storage mediums] per time step. `filling_level_indicator` contains indicators of the operational pattern of each reservoir during the simulation time. See Bökenkamp (2015) for a more detailed explanation of the filling level result tables.

5.4.2 Plots

Model results are only ever as useful as a user can understand, interpret and communicate its results. Along with summarizing figures, plots offer the possibility to display large amounts of result data in a comprehensible way. For renpass, some automatic result figures are plotted at the end of each simulation run, if the plot output option is chosen in the code settings (in `code_R_start_renpass.R`). These plots give a first impression of the scenario run and can be a starting point for deeper analysis of the results. They can also be used for further comparisons between different scenarios. There is a danger of already transporting a message of interpretation when plotting graphs. One has to be aware of the dependency between interpreting the results and presenting the data.

The merit orders of each region and the aggregated merit order of the whole area for the first and the last time steps are plotted. Although the merit order of fossil power plants does not differ between the time steps, the marginal costs of biomass, hydro, geothermal and storage power plants do change.
Figure 5.5 shows an example of a start merit order for the entire simulation area (test scenario 3). The sequence of the merit order represents the hierarchy in which applications are called to supply the residual load. Thus, its illustration can provide important insights into scenario calculation.

Usage rates are plotted according to the type of utilized energy source. They are aggregated for all regions and are illustrated either as full load hours or, if less than one year is calculated, in percent. The example in Figure 5.6 illustrates the usage rates of all utilized energy sources in test scenario 7 which covers July 2050 in a system without fossil fuels.

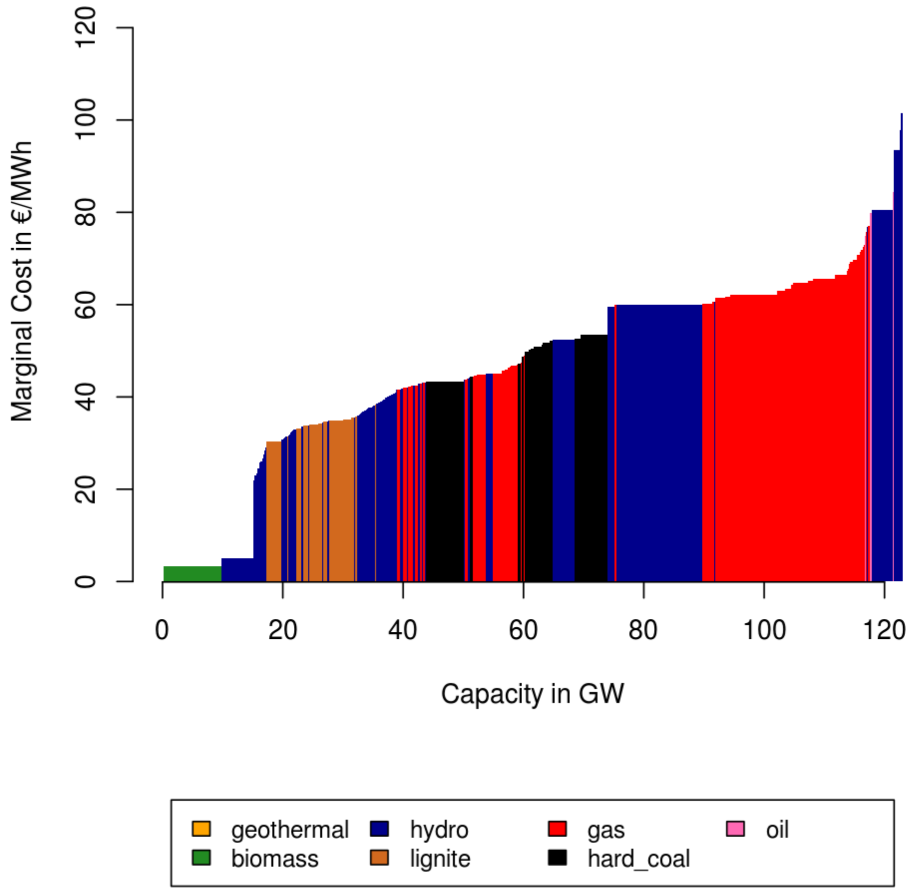


FIGURE 5.5: Example of plot output: Merit Order at the beginning of the timespan to be calculated, dispatchable power plants of the regions Germany and Norway in test scenario 3. Source: own image of renpass.

Electricity balances for all regions are illustrated in two figures. These balances offer a brief impression of a pathway's consistency. The sum of electricity production and excess demand is displayed next to the sum of demand, storage consumption, grid losses and excess electricity, so that the two may be compared. These two sums should be equal, if not, this represents untracked losses or increases in electricity during simulation. To be able to see if they match at a glance, a red line corresponding to the sum to be compared is plotted on the graphs. If the calculated timespan stretches over more than two weeks, additionally to the plots with hourly or 15 minutes resolution, sums of each week are plotted (Example: Figure 5.7).

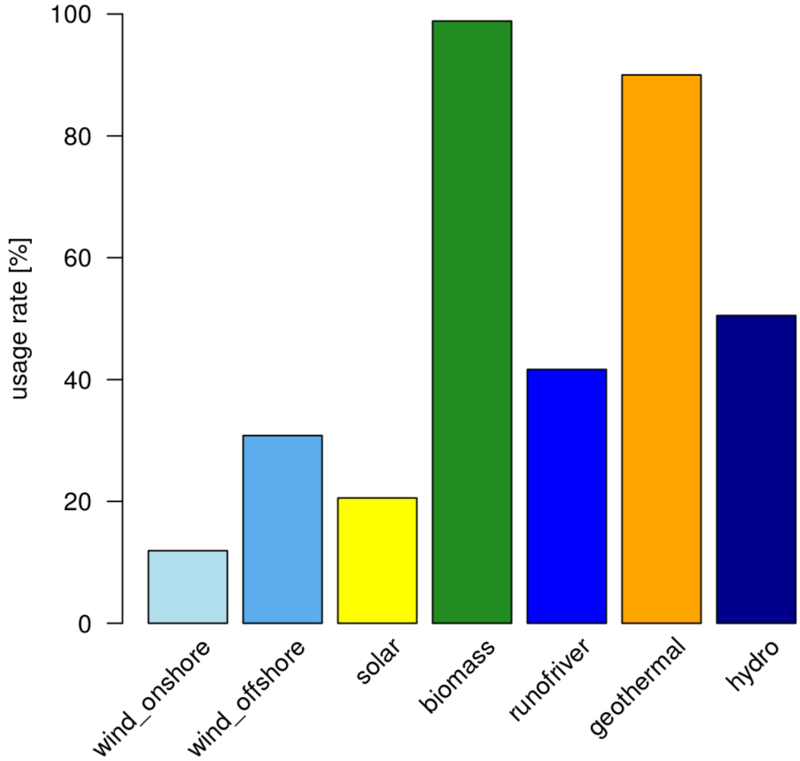
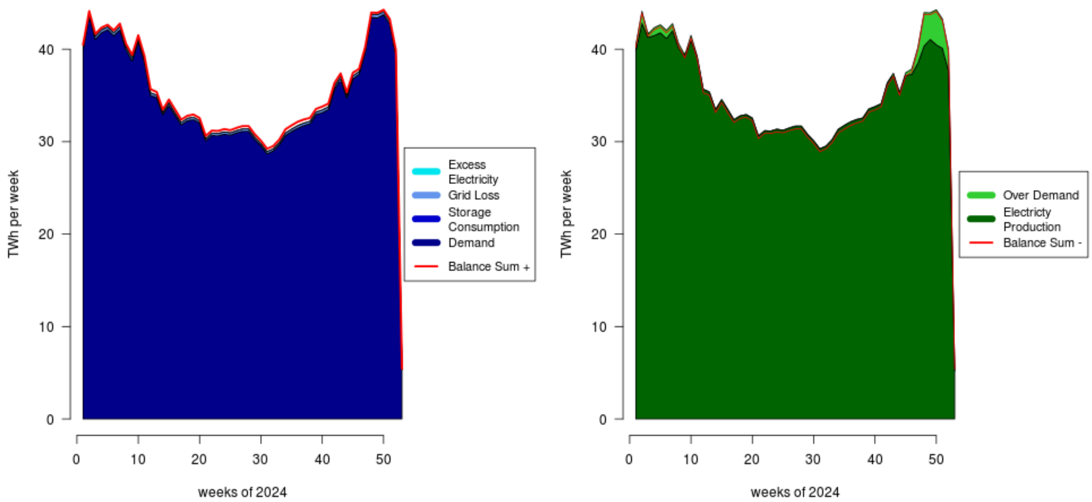


FIGURE 5.6: Example of plot output: Usage rates of utilized energy sources for the whole simulation area in July - Test scenario 7. Source: own image of renpass.



(A) Weekly sums of demand, storage consumption, grid losses and excess electricity

(B) Weekly sums of electricity production and excess demand

FIGURE 5.7: renpass plot output example: Weekly sums of energy balance. Red lines indicate the sum of the respective other balance sum - Test scenario 9. Source: own image of renpass.

Coverage rate of demand is illustrated in a spatial plot to easily grasp whether demand is supplied in all regions during the simulation period. The example in Figure 5.8 shows the second test scenario. Both Switzerland and Finland have a significant lack of supply.

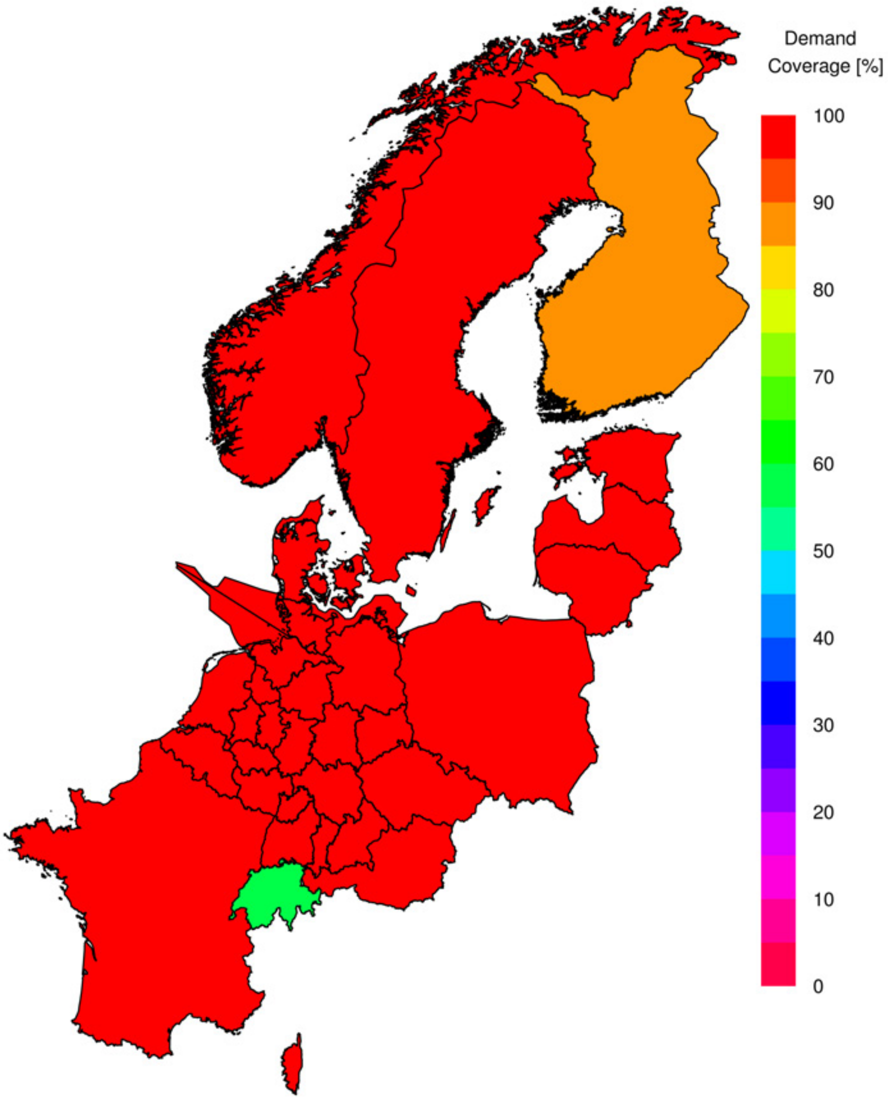
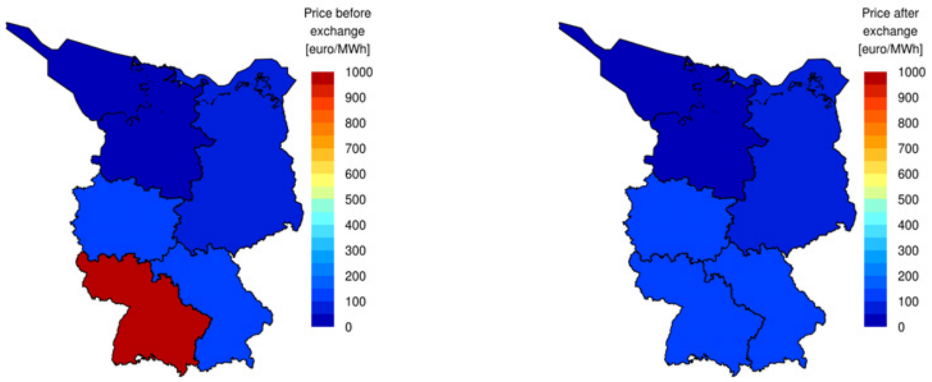


FIGURE 5.8: renpass plot output example: Coverage of demand [%] in different regions, summarized for the calculation period - Test scenario 2. Source: own image of renpass.

Prices can indicate excess electricity ($\Rightarrow$ *price* = 0) and excess demand ($\Rightarrow$ *price* = *scarcity price*). By comparing the price before and after the electricity exchange between regions, it can be checked whether high prices in some regions converge to the price level of neighboring regions by importing electricity. If this is not the case, and price differences still occur after exchange, this points to a lack of transmission capacity. Two spatial price plots are generated at the end of a renpass simulation. The first one presents the average price per region during the simulation period before the exchange, the second one the average price afterwards. As test case five illustrates (see Figure 5.9), transmission lowers prices. The south-western region reveals high excess demand if demand is supplied only by power plants within the same region. Very high prices, indicated in red, reflect that excess demand appears quite often (Figure 5.9 A). The price level in the south-western region decreases considerably after exchange and converges to the price level of the other regions (Figure 5.9 B).



(A) Average price before exchange (B) Average price after exchange

FIGURE 5.9: renpass plot output example: Average prices of test scenario 5. Comparison of prices before and after electricity exchange shows that they converge: The lack of electricity indicated by a high price in southwestern Germany (red) can be countered by importing which lowers the average price in that region. Source: own image of renpass

Grid capacity and usage is illustrated in a spatial plot, too. Absolute capacity is indicated by the width of the arrows between regions. Usage rate of the connections during the simulation period for every connection in both directions is indicated by the color. The thick yellow arrow in Figure 5.10 reflects a stronger utilization from north to south than in the other direction (blue arrow). This plot of test scenario 5 is consistent with the price plots of the same test scenario (Figure 5.9): Electricity is mainly shifted from the northern and the north-eastern region to the south-western region, which indicates need for electricity by high prices.

For spatial plots, the R-package maptools has to be installed and the shape files of the predefined region scenarios have to be provided in the folder `plots\geodata`. In addition,

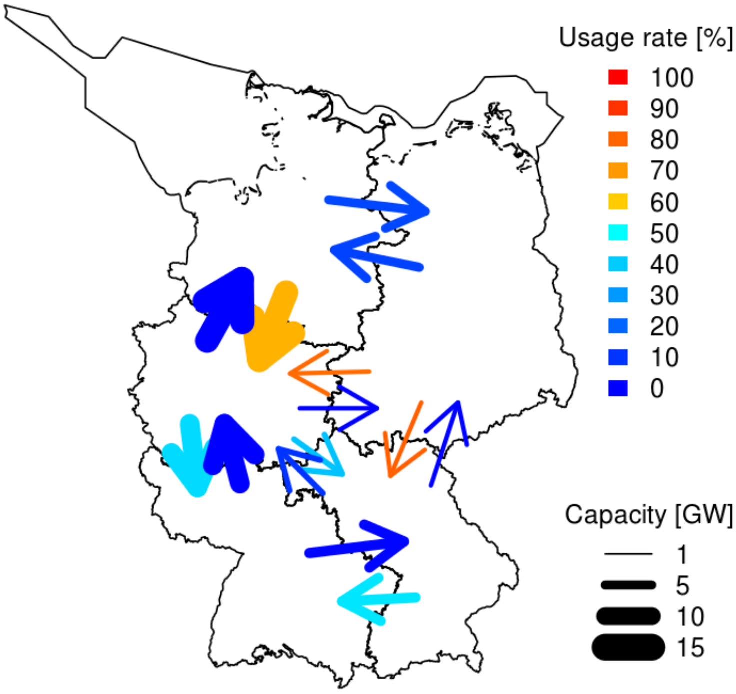


FIGURE 5.10: renpass plot output example: The colors of the arrows reflect the usage rate [*% of grid capacity in the simulation time*] and the capacity of the connections [*GW*] is illustrated by the width of the arrows (Test scenario 5). Source: own image of renpass

the R-packages lattice and colorRamps are required for the renpass spatial plots. To keep renpass usable without these additional requirements too, the spatial plot code is only sourced if it is chosen in the start code file. The user can choose $plot \leftarrow$ "*all*" or $plot \leftarrow$ "*no_spatial*" or $plot \leftarrow$ "*none*".

Spatial plots have the advantage of providing a simple overview of spatial information. Since almost all energy data has a spatial dimension, this offers good opportunities to illustrate and communicate the results.

R is a graphics-rich analysis language and provides a wealth of graphic and spatial packages. R partly replaces GIS programs like QGIS and the increased use of spatial referencing will be one field of advancement for renpass. For a more in-depth discussion on the importance of spatial referencing in energy modeling, see Section 6.2.

5.4.3 Plausibility Check

In this step, the first part of verification and consistency is already recorded while the calculation is running: sums of demand and residual load for the whole timespan and all regions are recorded in the log-file. If residual load exceeds the demand, or is too low to be within a possible range according to the scenario input, the simulation run can be manually stopped by the user. This saves computing time.
Other verification components are the result database and the automatically generated plots. The latter are visualizations of the figures stored in the result tables and should provide a first overview of huge amount of result figures and their interrelations. The following crucial values have been identified as being good first markers and are thus illustrated for a first plausibility check of the result:

→ Full load hours $[h/a]$ or usage rate [%] per energy technology

→ Coverage rate [%] of supplied energy for each region

→ Average prices before and after exchange for each region $[€/MWh]$

→ Merit Order of the first and last time step for each region. x-axis: capacity $[MW]$. y-axis: marginal costs $[€/MWh]$

→ Balance of energy supply for the whole area per time step $[GW]$ and sum per week $[TWh]$:

  → $plus - balance$: Σ(demand, storage consumption, grid losses, excess electricity)

  → $minus - balance$: Σ(electricity production, excess demand)

If there are inconsistent values, this has to be traced back to either calculation mistakes or inconsistent scenario assumptions. The procedure to check if scenario assumptions are consistent is part of the process of finding a reference scenario. This could be supported and simplified by consistency check functions which are not implemented in the basic version of renpass.

5.5 Application Examples

In the development phase of this renpass version, the model was utilized in several contexts. The approach in collaborative Open Source projects of many different people finding bugs in software and models maintains the quality and increases the robustness of the model.

renpass was utilized for applications at a relatively early stage of development since applications by users who are not involved in the development push models forward to stable versions. At a certain development stage, improving the program code and detecting bugs is done more effectively by users and co-developers than by the original developers. The programmers themselves intuitively find their way around problematic parts. Users new to the program are better suited to find those weak spots.

During simulations done with renpass, several bugs, functional restrictions and room for improvement and extensions came to light. In the following section, some exemplary uses during the development phase of renpass and their contribution to the advancement of the model will be described. All of the applications operate in the context of shaping future energy systems.

5.5.1 Sustainable Electricity Systems for the Baltic Sea Region

The aim of a seminar of the master program *Energy and Environmental Management* at the University of Flensburg was to find a 100% renewable electricity scenario for all countries surrounding the Baltic Sea except Russia. A variety of pathways and solutions for a sustainable electricity system were modeled and different scenarios were developed to identify the most important parameters for a secure supply in 2050.
First of all, renewable energy potentials were estimated roughly, then scenarios for the installed power plants and storage utilities, electricity demand and grid capacity of the interconnectors were chosen for Germany, Poland, Lithuania, Latvia, Estonia, Finland, Sweden and Denmark. Various loops of scenario runs and adapting input parameters were executed to find a base scenario that fulfills the aim of supplying the electricity demand of the target region with 100% renewable electricity in 2050 (CSES, 2012). Flexibility of biomass plants and grid capacity were varied and there were some first

attempts to compare costs between the scenarios. The main task was to find at least one consistent and reliable pathway.

The conclusion was that the Baltic countries can be supplied to 100% with renewable electricity. An important pillar of the identified scenario is the flexibility of biomass plants. In case of very flexible biomass capacities, Scandinavian hydro storage and grid capacities between countries do not have to be extended (CSES, 2012, p.I, Executive Summary). Connections within countries were not looked at. The composition of supply and demand as daily sums over the course of the year 2050 for the whole simulation region is illustrated in Figure 5.11. The important role of flexible biomass as the main flexibility option in this scenario is illustrated by way of example in Figure 5.12. It shows the contribution of biomass and hydro electricity to cover the residual load: The main share of this load not supplied by VRE is covered by biomass.
The role of biomass in this case is much like placeholder for flexibility options in general. Whether biomass plants themselves could play this important role was not examined, since technical aspects such as ramping times and biogas storage possibilities and resource availability were not studied in detail as part of this study.

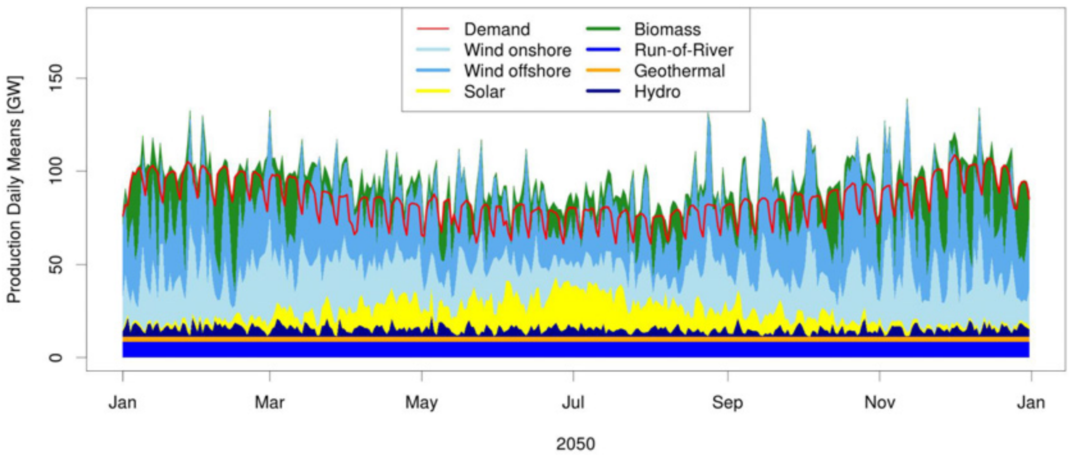


FIGURE 5.11: Example Application: One possible compilation of demand and renewable electricity production in the course of the year 2050 summarized for the whole Baltic Sea region. Source: CSES (2012, p.15, Figure 10)

This application led the way forward to including countries other than Germany and Norway in renpass: All countries around the Baltic Sea were inserted.
Since this application appeared at an early stage of the model, substantial lessons were learned concerning the organizational and structural nature of renpass. Having to fix

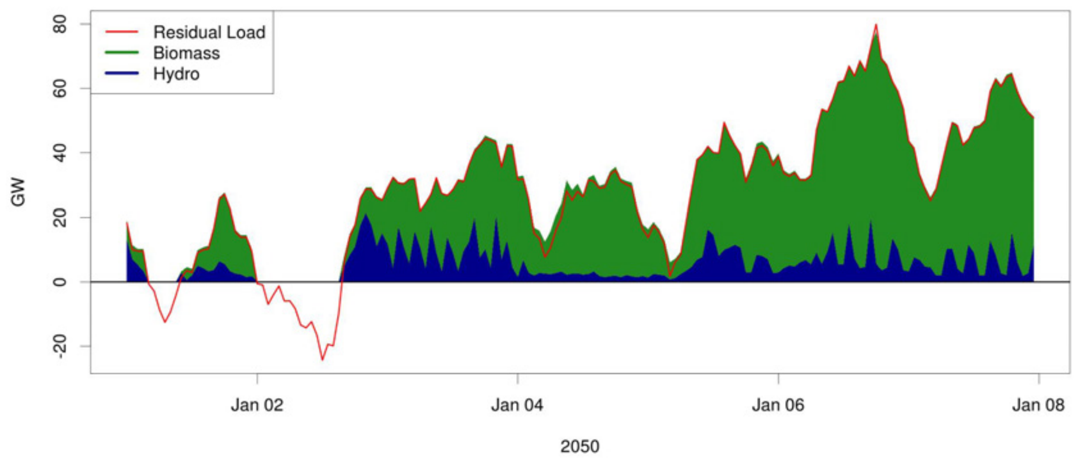


FIGURE 5.12: Example Application: Hydro and biomass electricity feed-in covering the residual load in the Baltic Sea region in January 2050. Source: CSES (2012, p.17, Figure 12)

considerable amounts fo bugs under time constraint led to the use of the version control software git (Chacon, 2009) for code development. This software proved to be of great help for bug fixing, collaborative code development, version control and extension implementation. The experience also led to a reorganization of renpass into function and subroutines that are all sourced from the core code piece `code_R_renpass_core.R`. This new structure brings renpass nearer to a truly modularized design and facilitates understanding for co-developers new to the code. Extending the group of co-developers led to the formulation and implementation of coding and database guidelines (Hilpert, 2013a; Bökenkamp, 2013).

5.5.2 Future Role of Scandinavian Hydro Storage

One feature of renpass is the detailed picture of Norway's hydro system and the price building mechanism in a very high resolution of numerous reservoirs, hydro turbines and pumps and the inflow to this complex Norwegian system. The combination of Scandinavian hydro flexibility, storage possibilities and fluctuating but cheap wind power from Germany was the focus of the work of Gesine Bökenkamp who programmed the "hydro-part" of the renpass model.

The aim of her work was to estimate the beneficial capacity of cable connection between Germany and Norway and extension of pumped storage plants in Norway. Furthermore, the operation of the system and impacts on reservoir filling levels were analyzed. The simulations showed that with the given assumptions cable capacity of 10 GW and additional pumped storage capacity of 10 GW would be beneficial. The revenues and benefits of the installations are most sensitive to the presence of other flexible capacity and the production of renewable electricity in Germany and Norway. The impact on filling levels seems to be moderate. More detail can be found in Bökenkamp (2015).

One of the main lessons learned from this application was the influence of the scarcity price in the simulation of renpass for electricity systems with a high share of fluctuating feed-in. Scenario variations of grid capacity between Scandinavia and Germany and the installed capacity of pumps in Norway were carried out to find the least-cost solution including installation costs. If the scarcity price (the price that is set in a region with excess demand) is very high, a massive extension of capacities will always appear to be the least-cost solution within this framework. This could go as far as having new installations, to be used just a few hours per year, assessed as cost efficient due to the modeling input data.
This experience stresses the need to provide a reasonable scarcity price, or, in other words, a thoroughly defined flexibility option price. In the case of the Norway calculation, no other flexibility option such as demand management, other storage possibilities or other dispatchable power plants were considered since this was not the focus of the investigation. Thus, to reach a realistic approach for the least-cost combination, the scarcity price needs to represent the opportunity price of other possibilities to supply the hours of excess demand. If just one flexibility option is considered (in this case hydro storage), the picture is distorted, hence either different flexibility options need to be included in the modeling or, if this is not possible, at least values in the range of alternative options have to be set as the scarcity price.

5.5.3 Wind Energy in Southern Germany and Resulting Transmission

Within the scope of a master thesis (Bons, 2014), renpass was applied to investigate the impact of additional capacities of wind power plants with performance characteristics adjusted to poorer wind conditions. The simulation covered Germany with 21 regions, Norway, Austria and Switzerland. These neighboring countries were chosen due to their availability of hydro storage. Indeed, the location of storage utilities strongly influences transmission flows in systems with high shares of VRE. Input scenario parameters were derived from the scenario framework of the German Grid Development Plan 2012 (German TSOs, 2011).

The research question was whether wind electricity generation close to consumers allows for a reduction of grid extensions identified by the Grid Development Plan. Bons (2014, p.98) concludes that increased capacity in the southern part of Germany, while reducing offshore wind in the North Sea accordingly, leads to a more evenly distributed usage of the transmission lines connecting southern and northern Germany, but does not result in a reduction of transmission needs.
To interpret the results, one has to be aware that the shift of wind generation capacity from north to south only covered a fraction of the generation/consumption imbalance. In the 2050 scenario with the highest additional wind capacity in southern Germany, only 50 % of the demand can be supplied by regional generation in the south. In northern Germany, four times the local demand is generated.

Figure 5.13 and 5.14 illustrate the usage and installed capacities of AC and DC extra high voltage grid in 2032 in two scenarios differing in the distribution of installed wind capacities. The installed capacity of wind energy in southern Germany in these scenarios adds up to:

→ *Scenario A*: 15.2 GW corresponding to 24 % of installed wind onshore capacity in Germany

→ *Scenario C*: 46.6 GW corresponding to 49 % of installed wind onshore capacity in Germany.

(Bons, 2014, Table 4.10, p.77)

Additional storage capacities in the scenario were mainly located in Norway (hydro storage) and northern Germany (compressed air energy storage). It is important to mention this for the interpretation of the results. The more even distribution of flow hints at the fact that not only the local, but also the temporal convergence has to tackled. Converging production and demand spatially cannot reduce transmission needs, if the demand cannot be met at the right moment. In this case, additional storage or demand management utilities are required locally. This points to the double challenge

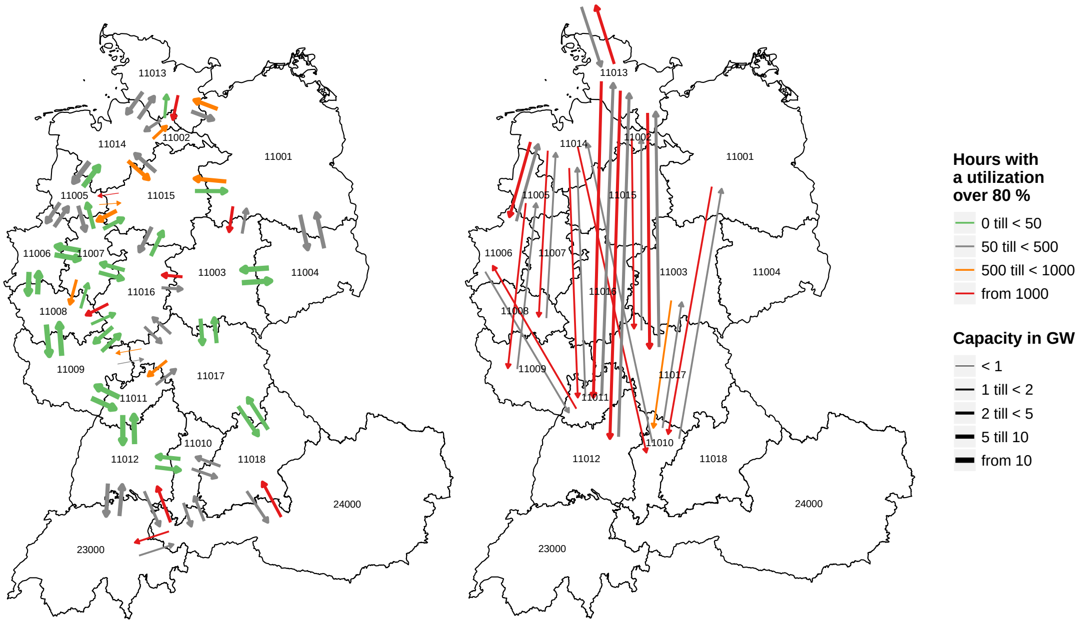


FIGURE 5.13: Usage rate of the transmission lines HVAC (left) and HVDC (right) in 2032. *Scenario A* in this study is based on scenario assumptions of Grid Development Plan Scenario B. Source: (Bons, 2014, p.81, Figure 5.2)

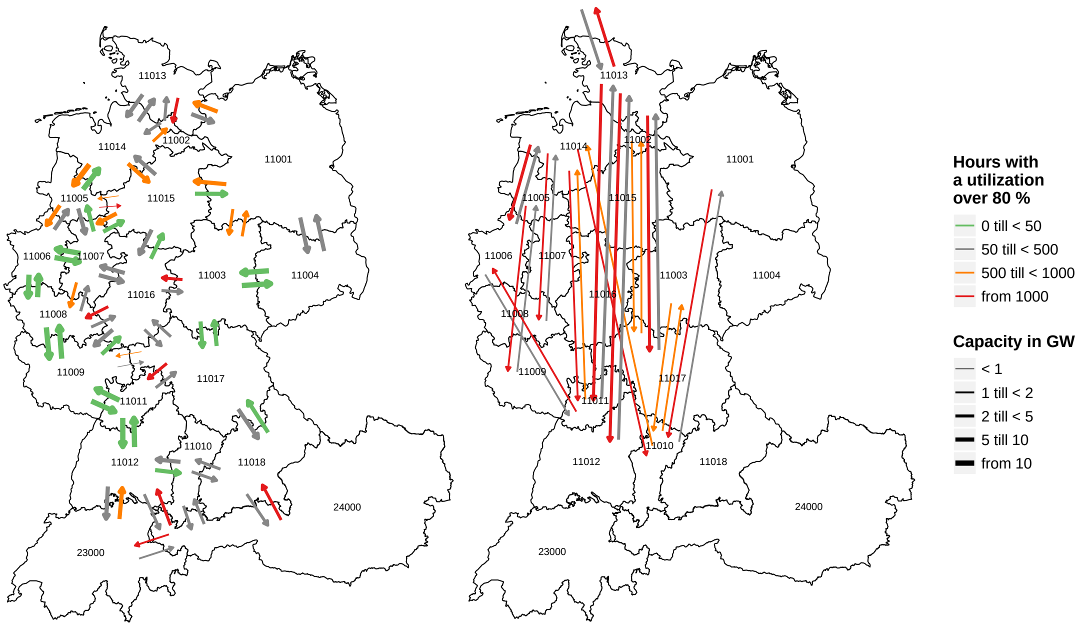


FIGURE 5.14: Usage rate of the transmission lines HVAC (left) and HVDC (right) in the year 2032. *Scenario C* with wind power capacity shifted to the south of Germany. Source: (Bons, 2014, p.89, Figure 5.6(b))

of providing options for temporal and spatial flexibility. This will be discussed further in Section 6.2.

Marian Bons' application led to the implementation of several improvements of the model:

→ Dependence of HVAC transmission lines grid losses on the distance between the regions they connect. HVDC transmission losses depend mainly on the converter losses. This application demonstrated the strong influence of grid losses on the results, and the aforementioned improvements were therefore undertaken.

→ Refined wind energy power curves.

5.5.4 Electricity Price Scenarios

With the objective to investigate the role and financing possibilities of thermal power plants in the German energy system, simulations were carried out by the University of Flensburg for a public utility company. Hourly electricity price time series for the time period between 2014 and 2041 were modeled in renpass based on an average weather year and the resulting feed-in of VRE with increased installed capacities. The scenario assumptions were approximately based on the framework of the German Grid Development Plan (German TSOs, 2013).
Additionally, one variation was calculated: a pathway towards a CO_2-neutral electricity system in 2050. The hourly price time series of the energy-only market were used as basis to estimate capacity payments for thermal power plants in a possible future capacity market. Since prices are extremely sensitive to input parameters, the results of renpass were compared to another electricity model.

The simulation showed a low price level until 2020 due to the assumption of low prices for CO_2 emission certificates. Furthermore, the rising share of VRE leads to low prices. The rise in price level until 2034 is followed by a relatively stable price level until 2050. Duration curves show that hours of very low price levels appear more often, due to rising fluctuating feed-in of VRE, with very low marginal costs (Wingenbach et al., 2013, p.22). Thermal power plant curtailment due to re-dispatch because of grid constraints did not play a major role in the simulations until 2020, since grid bottlenecks mainly occurred in times of low prices when thermal power plants would not be used anyway (Wingenbach et al., 2013, p.26). Assuming today's market mechanisms would be maintained, financing gaps for thermal power plants were identified (Wingenbach et al., 2013, p.25).

Countries with a direct border to Germany were integrated into renpass during this project. Each neighboring country is modeled as one region, thus transmission flows between Germany, other countries and between the 21 inner German regions can be tracked, but no transmission flows within the other countries are considered.
One outcome of this application was an improvement for renpass, namely: the integration of thermal power plant availability. A further lessons learned was the importance of start-up times of power plants due to their thermal characteristics. This cannot be modeled adequately with renpass yet, which is one of the main weaknesses of the model.

5.5.5 100% Renewable Energy System Germany + Neighbors

During a seminar on electricity system modeling with renpass in the winter term 2013/14, as part of the M.Sc. in Energy and Environmental Management winter term 13/14 at the University of Flensburg, the model was used to familiarize students with the complexity of energy system modeling. A simulation of a 100 % renewable electricity system in Germany and its neighboring countries was set up, calculated, verified and analyzed. This application was part of the testing phase of the version of renpass described, and the learning effect on both sides was impressive. The students evolved to becoming co-developers rather than users of the model. Improvements for the code evolving from this application and lessons learned at an organizational level will be described in the following section.

The interpretation of the results was done so that each participant interpreted one result parameter, thus looked from a specific point of view at the results. This focussed evaluation was followed by taking a look at interdependencies between the parameter studied and the other result parameters. The scenario assumptions can be found in CSES (2014). Some of the findings are described below.

Excess electricity in a scenario with 75 % VRE can be reduced by 56.3 % by changing the proportion of onshore wind and solar capacities from 32:68 to 59:41 (Söthe, 2014, p.3). Since the appearance of excess electricity corresponds to solar feed-in, the excess electricity can be lowered by changing the proportion of the main components of VRE onshore wind and solar while keeping the total amount constant (see Figure 5.15).

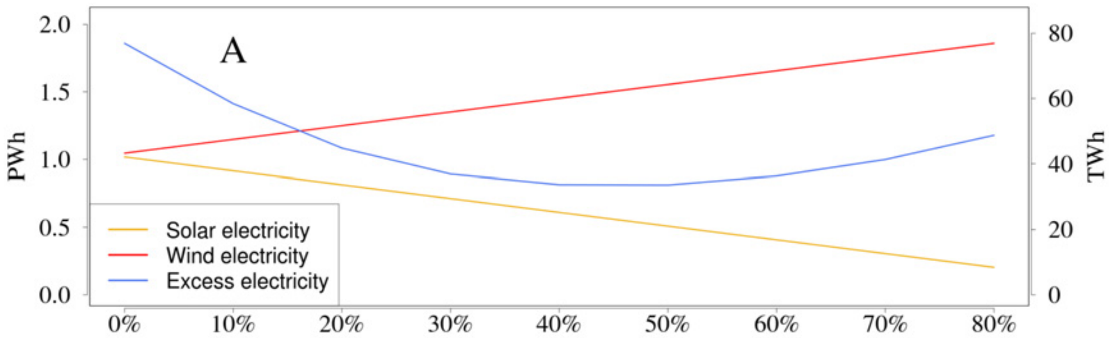


FIGURE 5.15: Excess electricity subject to the proportion of onshore wind and solar. Source: Söthe (2014, Figure 2, p.3)

Böhm (2014) illustrated storage filling levels, utilization and grid utilization in the simulation hour in which the maximal excess electricity occurred (Figure 5.16). This visualization aims to find a reason for a high level of unused electricity in this specific hour. Pumps or grid connections operating at full capacity or full storage reservoirs could explain the appearance of excess electricity. However, all three illustrated potential limiting factors of excess electricity reduction are not at their limits. Böhm (2014) suggests that a lack of water in the lower reservoirs of hydro storage systems could be another possible reason as to why not all excess electricity can be absorbed.

Calculating the levelized costs of energy requires assumptions on installation costs which are described in Wiechers (2014). Mean levelized costs are in the range of 17-30 €cent/kWh (Wiechers, 2014, p.4) with wind and solar being competitive. It was critically noted and emphasized that they depend heavily on learning curves and other insecure parameters (Wiechers, 2014, p.5).

In a simulation, satisfying demand is one of the main indicators for a reliable energy system. The result parameter in renpass to access this information is called excess demand. For the reference scenario in this case, a relatively low amount of demand remained unsatisfied. Variations of grid expansion, energy efficiency and a drop in demand were shown to significantly affect excess demand (Kaldemeyer, 2014, p.2). Figure 5.17 illustrates a high coverage in regions with dispatchable power facilities such as storage and biomass plants. According to the scenario assumptions, Switzerland is not equipped with any of these. Furthermore, the existing Swiss hydro storage utilities were not considered. This

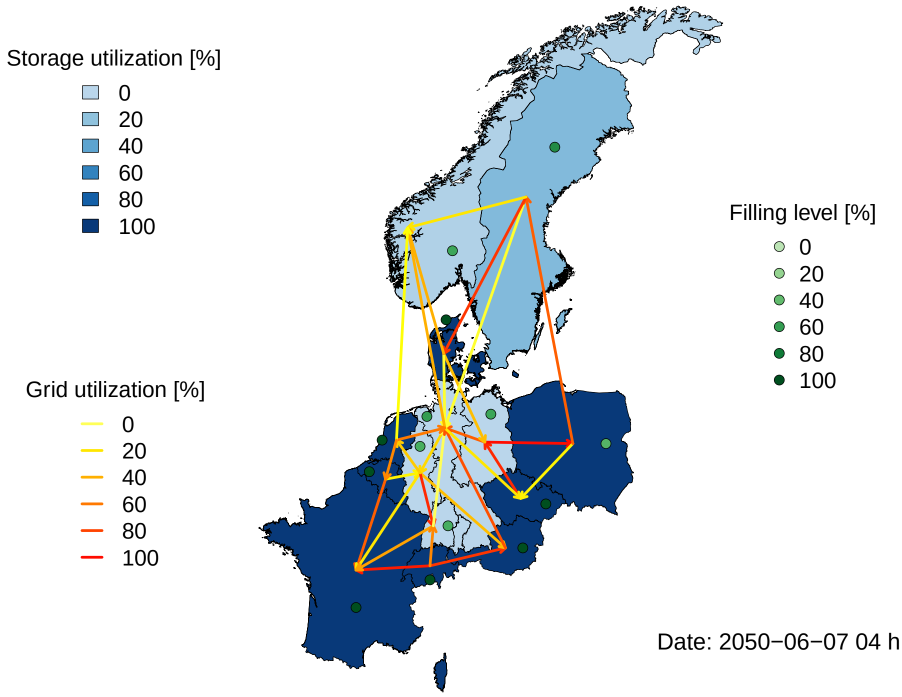


FIGURE 5.16: Storage utilization, grid utilization and filling level in the modeled countries in scenario 16003 during the hour of maximal excess electricity. The storage capacities of countries without pumps are considered as 100% utilized and their reservoirs filled to 100%. Source: Böhm (2014, Figure 2, p.3)

results in a high level of excess demand which increases if the total demand is assumed to rise.

Mitigation of excess demand was attempted by changing the input parameters illustrated in Figure 5.18. The largest potential could be mobilized by a combination of enlarging storage capacities and increasing renewable production capacities. Taking the costs of the options into consideration, according to Kaldemeyer (2014, p.3) the potential offered by a demand reduction is of particular interest due to the comparably low costs.

Concerning the scenario results, the participants summarized: "In conclusion, for a 100% renewable electricity system, all different measures should be linked together in a way that they can complement each other, in order to achieve low total system costs" (Kaldemeyer, 2014, p.3). Furthermore, the composition of the renewable energy mix is of utmost importance on a pathway to a low-carbon electricity system (Söthe, 2014, p.3f).

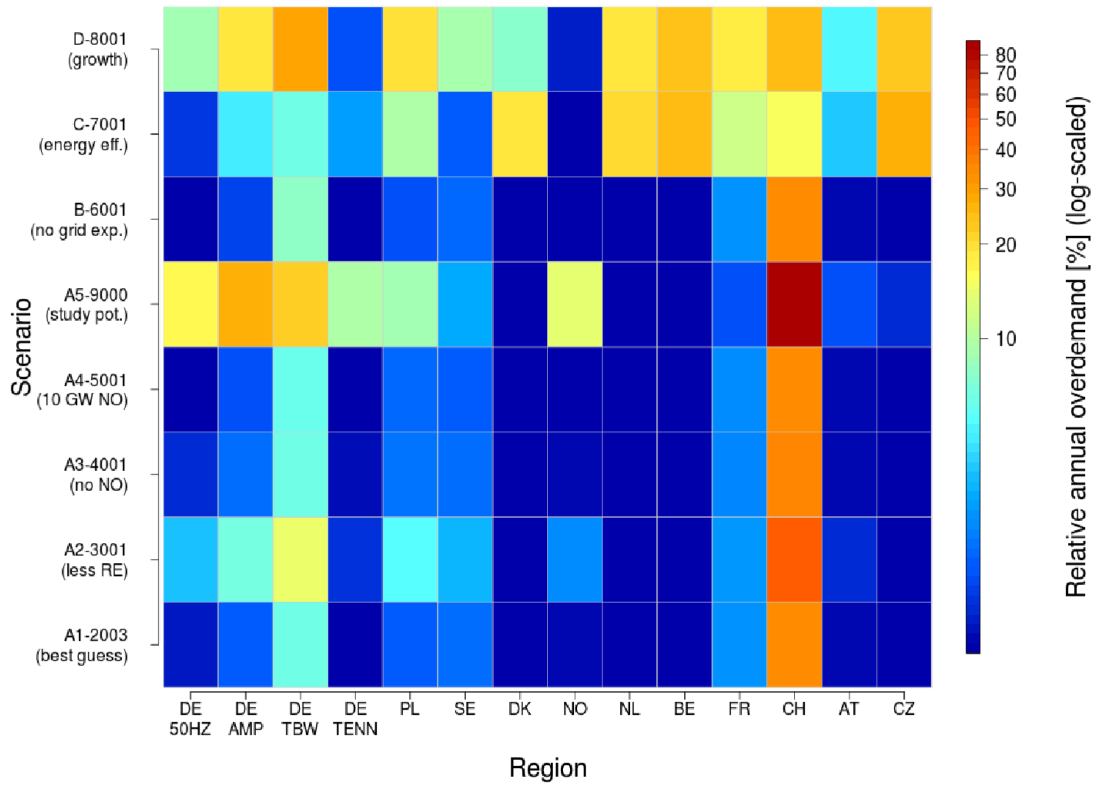


FIGURE 5.17: Relative annual excess demand on a logarithmic scale for all regions. Source: Kaldemeyer (2014, Figure 2.1, p.2)

Improvement potential for the model was revealed especially in the field of biomass plant performance, storage filling levels and pricing in case of excess demand.

By looking at the usage of biomass, it was detected that this resource was being depleted too rapidly throughout the year (Bunke, 2014). To achieve the flexibility role biomass plants should take on to serve the system, a better allocation could be triggered by adopting opportunity prices which reflect that role. Higher marginal costs at the beginning of the simulation would prevent an early exhaustion of the amount of biomass. In combination with a lower scarcity factor, this would limit their use to situations in which biomass plants are needed most urgently, so that it can be used to the benefit of the system.

In renpass, other storage reservoirs than hydro started with a 50% filling level at the beginning of the simulation. Taking a closer look at large power-to-gas storage utilities showed that a high filling level at the beginning of the year is like electricity for free to the system and gets exhausted relatively fast. Thus, this was changed to empty reservoirs as a starting point in the simulation. With this setting, those storage plants

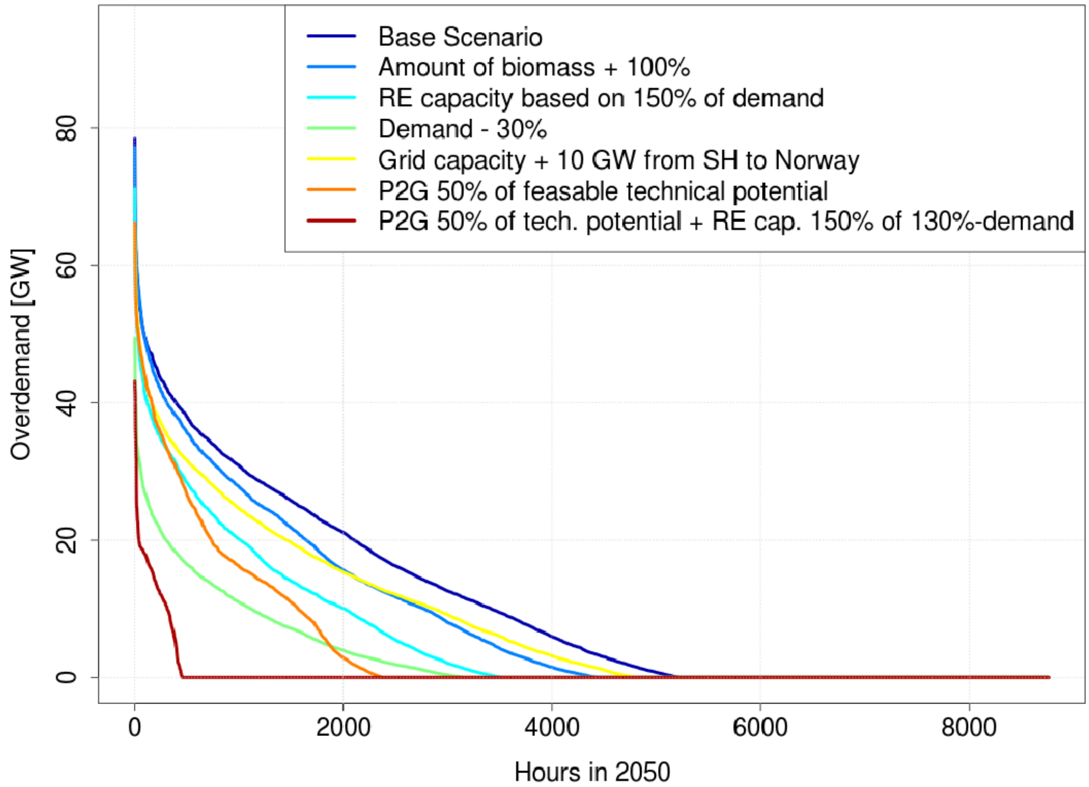


FIGURE 5.18: Parameter influence on the excess demand duration curve in Germany. Source: Kaldemeyer (2014, Figure 3.1, p.3)

can only provide electricity that has been stored within the simulation period. For hydro storage this is treated differently. An exhaustion is prevented by rising prices for hydro plants with low reservoirs. The 69 % starting reservoir filling level corresponds to the long-term average filling level of the Norwegian system. This value is applied to hydro storage reservoirs in other regions as well because for small reservoirs like in Germany this has a minor influence and other mountain areas like Scandinavia are assumed to have similar filling level curve throughout the year.

The case of Switzerland exporting while still having excess demand, revealed an seminal bug: due to a mistake in the marginal dispatch, the price in a region with excess demand was set to zero if there were no dispatchable power plants like biomass, hydro or thermal in that region. This was the case for Switzerland and thus the reason why this region exported zero priced electricity instead of supplying its own demand. The price setting in the case of no dispatchable power plants in a region was subsequently changed to the scarcity price. This prevents a region from exporting electricity while still not covering its own demand.

Lessons were learned at an organizational level and with respect to the procedure of scenario setting. This application underlined the importance of scenario clusters to present results in an understandable way. Although the idea of grouping scenarios turned out to be a helpful approach, sensitivity within these scenario groups should be defined subsequently. This is explained in the study group report: "due to the fact that always more than one parameter had been changed within our different course scenarios, no clear cause and effect relationship could be established from the results." (Kaldemeyer, 2014, p.2f). Thus, additional variations have been calculated. A useful approach which prevailed during this application was to carry out a rough analysis of all scenarios first, followed by a selection of and a closer look at the most striking scenarios.
Furthermore, the influence of data quality was revealed thanks to the case of Switzerland. As mainly EU studies were used for status quo and potential data of renewables, storage and other infrastructure, Switzerland was largely neglected. This led to an extreme shortage in the demand coverage of Switzerland which influenced all the results (see Kummerfeld (2014)). Nevertheless, this mistake revealed the unexpected effect of Switzerland exporting and thus helped to find the excess demand - price bug in renpass.

This application showed that competent users represent the greatest potential for model development: if users are introduced to the calculating methods of renpass, which means using and understanding its basic flowchart (Figure 3.2), fundamental improvement for the model can successively be delivered. As described, several weaknesses and bugs could be revealed and fixed. Thus, this seminar proved the thesis that models improve if more people contribute.

5.5.6 Other Applications

Furthermore, renpass has been applied in the following projects and Master theses:

- → Future role of combined heat and power plants in the German Energy System (Hilpert, 2013b), master thesis
- → Possible effects of electric vehicles on future electricity systems with high shares of fluctuating renewables (Bernhardi, 2014), Master thesis
- → Role of heat pumps and block heat plants as dispatchable users in renpass (Schröter, 2013)

→ Refinement of renpass in the solar feed-in calculation (Höfken, 2012)

→ "Vernetzen", integrating socio-economic indicators in techno-economic electricity system modeling. Project of the Institute of Future Studies and Technology Assessment [IZT] and the University of Flensburg, supported by the socio-ecologic research program of the German Research Ministry (IZT, 2014)

→ A 100% renewable electricity system for Spain and for Portugal

An important lesson learned from the variety of applications and the variety of programming abilities of different users is the need to encapsulate parts of renpass. That implies, for instance, using the residual load part without deeper knowledge of other complex parts such as the hydro system of the model.

5.6 Implementation of Extensions

One of the initial ideas of renpass is its role as a crystallization point for research on different aspects of pathways to renewable electricity supply. The electricity system is so highly connected and its components are so intercorrelated that investigating one aspect always requires an in-depth basis of knowledge about the rest of the system. Synergies can be drawn from building a framework of a modularized energy simulation tool with optimization parts with good possibilities of varying and extending it collaboratively with a large group of users. Preconditions for simple extension implementations are a code based on functions or other clearly definable interfaces, code structure documentation, summaries, a clear database structure and modularization of the code.

There is no fully standardized procedure for the implementation of add-ons, extensions and solving bugs in renpass yet, but a best-practice scheme is emerging from experience already gathered with the model. For collaborative development of the model, database guidelines (Bökenkamp, 2013) and coding guidelines (Hilpert, 2013a) were decided upon. In the following section, the pathway of an extension implementation will be described: definition of the interface (subsection 5.6.1), version control for developing the extension without harming the main version (subsection 5.6.2) and testing procedure (subsection 5.6.3).

5.6.1 Interface Definition

Additional code parts can have different levels of interference with the main model. Whether an extension induces changes in existing subroutines and functions or completely new functions and subroutines are added depends on the characteristics of the extension. All subroutines of the renpass code are sourced from `code_R_renpass_core.R` (described in Section 3.1.2). This facilitates the definition of interfaces which is the basic requirement to combine renpass with parts of other models and to add extensions easily. Clear interfaces define the parameters that have to be handed over.

The following three extension examples differ in levels of interference with the core body of renpass:

Minor interference: New code pieces and functions are added but do not interfere with other subroutines except for being sourced from them. *Example:* implementation of a more detailed wind power curve was done with the new function `powerCurve` which was then sourced in the `code_R_wind_onshore.R` subroutine.

Considerable interference: Changes in existing code pieces and/or functions. *Example:* a change in the way grid losses are calculated caused changes in the function `gridLoss.R` and in the subroutine `code_R_prepare_grid.R`. The better the modularizing, the smaller the effect on other parts of the code will be.

Major interference: Structure of the model is affected. *Example:* integrating flexible demand.

5.6.2 Source Code Management System

New contributions to the main model are developed and tested in an individual branch of the present stable version. For renpass, the distributed revision control and source code management system for software development *git* (available at `http://git-scm.com/`, manual: Chacon (2009)) is utilized.
The master branch can stay untouched until the extension branch has passed the functionality test. Then, it can be merged into the master branch. If the extension is

complex, committing small comprehensible change steps is recommended. Quite often, interferences and dependencies with other code pieces occur. They can be dealt with better if changes are done stepwise.

In the visualization tools of git (e.g. gitg), conflicts of the branch and the master code can be detected. Keeping track of changes by clear commit messages also assists in the documentation of each extension. A visualization example of the version control software is given in Figure 5.19.

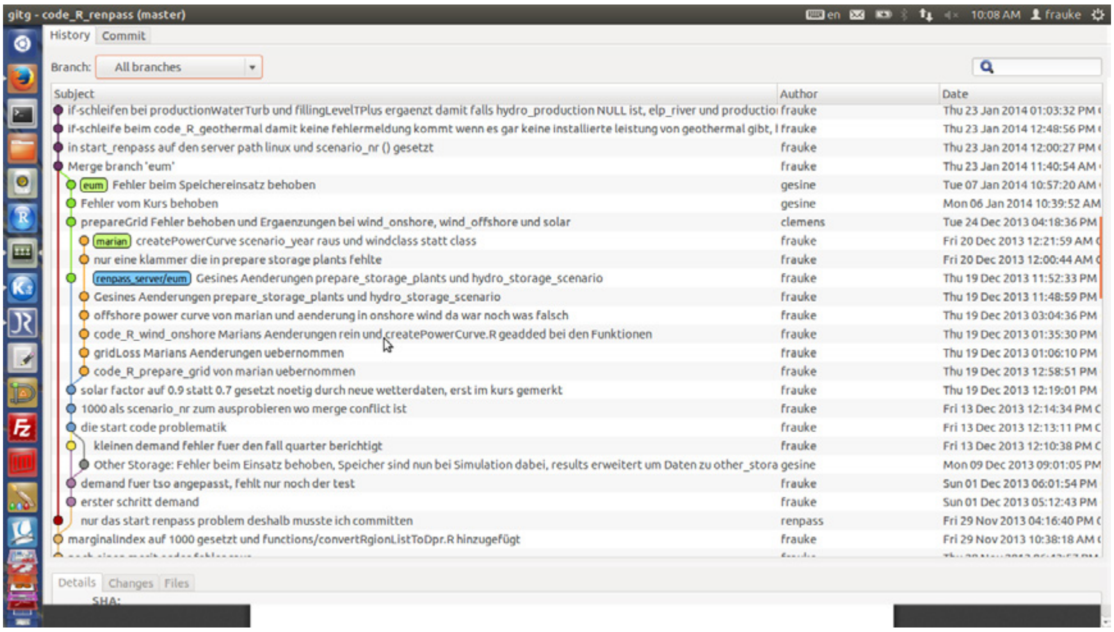


FIGURE 5.19: Part of the renpass code development in different branches with the help of git software. Visualization with gitg.

5.6.3 Testing Procedure

Before integrating an extension into the main version of renpass, a testing procedure has to be completed to make sure that the extension does not destabilize the model. It has to be checked if new database tables comply with the database guidelines (Bökenkamp, 2013) and if new code subroutines and functions comply with the coding guidelines (Hilpert, 2013a).

Ten test scenarios with different scenario and parameter settings covering a range of possible applications of renpass are stored in the `scenario_parameter` table with scenario numbers 1 to 10. For further information on the test scenarios of the actual version of renpass, see the `1_scenario_parameter` table in the `pathways` database.

All test scenarios on the basis of the extended code and/or databases are compulsory, must be processed, and have to run without errors. If this is the case, a consistency verification of the results follows. This verification includes consistent energy balances, usage rates of energy types, coverage ratios, price development and usage of grid capacities. A successful extension and its consequences for the user of the model then have to be documented for the manual before the new version release can take place.

5.7 Strategies for Applying Electricity Simulation Models

In addition to the learning process about the renpass model itself, during its development and application, general problems regarding the simulating of electricity systems were experienced. Approaches to cope with the variety of scenario assumptions in long-term electricity simulations have been deduced from this experience.

5.7.1 Scenario Setting Strategy

To answer questions about future electricity systems with renpass, it is always necessary to compare a range of scenario settings and variations. There is hardly a question for which a single scenario calculation would be of help. Energy system simulation models prove their strengths in broader pictures of differences and interactions. This requires some basic understanding of sensitivities and how to choose scenarios. Although there are many possible approaches to use such a model, the following format has proven beneficial for previous renpass applications.

1. Definition of research question to be answered
2. Identification of the central result parameter(s)
3. Definition of the simulation area, spatial and time resolution: as finely resolved as necessary to answer the research question, but not higher, to save computing time
4. Assumption about major, considerable or minor effects of input parameters on the results
5. Compilation of the reference scenario combined with schemes of scenario clusters

6. Calculation of the reference scenario

7. Plausibility check of input and output with the help of visualization. A first calculation at an early stage of scenario development is very important since it provides insights that can save a lot of time thinking theoretically about scenario settings

8. Adjustment of reference scenario settings. Step 5-7 have to be repeated until a consistent reference scenario is found.

9. Result interpretation of the reference scenario and thereof successive refinement of scenario clusters

10. Definition of additional sensitivity analyses

11. Visualization and interpretation

12. Bug report and suggestions for improvements of the model and its manual

A variety of scenario setting approaches exist, but the following aspect should be accounted for in all energy modeling applications: The importance of the process of readjusting and verifying the assumptions and input parameters cannot be overestimated.

5.7.2 Main Driver Approach

Item four of the scenario approach suggestion (5.7.1) points to a very useful approach to apply simulation models. The strength of simulations models is to reveal which input parameter has the greatest influence on the output parameter of interest. This approach could be called the *Main Driver Approach*. The following example illustrates its structure.

By way of example, the research question considered is: *"How many kilometers of new electricity grid lines have to be built to integrate 50% VRE into the grid in Germany?"*. This question has to be refined further to be able to work on this question with a simulation model. The question could be subdivided into the following questions:

→ Which input parameter is the main driver? Which input parameter variation results in the greatest variation of grid capacity requirement?

→ Which additional input parameters, apart from the main one identified, influence the grid capacity required?

→ Do these parameters increase the need for grid extension if they are increased/decreased?

→ Is there a minimal amount of grid extension that results from the simulation in every case, regardless of input parameters changes?

The assumption is that the following drivers are most relevant: spatial distribution of demand management options, spatial distribution of storage options, decline in demand, VRE location, installed capacities of VRE and connection to neighboring countries. Having found a robust reference scenario, each driver, one after the other, has to be varied in separate simulation runs.
For this example, the amount of additional grid capacity needed in the north/south direction of Germany is chosen as the result parameter to be looked at first. The range in which this number varies can be taken as an indicator of the influence of different drivers. Let us assume that the following ranges are calculated by the simulation runs:

→ Spatial distribution of demand management options:
→ Requires additional $5 - 25\ GW$ grid capacity between northern and southern Germany

→ Spatial distribution of storage options: → $10 - 20\ GW$

→ Decline in demand: → $5 - 10\ GW$

→ Installed capacities and placement of VREs: → $5 - 50\ GW$

→ Connection to neighboring countries: → $5 - 15\ GW$

As seen in the widest range of required grid capacity in the result parameters, the distribution of VREs seems to be the main driver of transmission needs. Based on that, additional scenarios should be calculated: one scenario cluster with the values for the main driver that resulted in the highest need for transfer capacity, one cluster with values for the main driver that resulted in the lowest result and an average one. For those three clusters, again, the drivers identified as having considerable influence (and possibly also the minor ones) are varied. The result is a range of *GW* capacity needed additionally in the north-south direction.

The outcome would be a table that indicates how parameters influence the transfer capacity both in direction and magnitude. If, after a variety of scenario calculations including sensitivity analyses, the range of required new lines lies in the range of $5-50$ *GW* on the north/south direction in each case, those 5 *GW* constitute a no regret option.

It has to be noted that this example is a very simplified one and does not reflect simulation results. It simply aims to clarify the idea of the main driver approach. It is a common procedure in modeling to carry out sensitivity analysis, which means to vary single parameters individually and find out how they affect the results. The main driver approach goes one step further by putting the input-output influence relation at the center of the interpretation of simulations and scenario settings.

5.8 renpass Outlook

This section concludes the renpass application chapter by summarizing the scope of what renpass can be applied for as well as outlining its strengths and weaknesses. Finally, the mode used to make renpass available is described.

5.8.1 Scope, Strengths and Weaknesses

renpass is specialized in simulations of electricity systems with high shares of VREs in high spatial and temporal resolution with a least-cost optimization on the operation of the user-defined electricity infrastructure. Although the Open Source aspect of electricity system models is the focus of this thesis, renpass modeling strengths and weaknesses are briefly mentioned in the following bullet points.

→ Technical flexibility characteristics of thermal power plants like ramping speeds and start-up times are not yet includedf.

→ Modeling of transmission is limited to the transfer capacity of the connection between the regions, no electricity network calculation is done within renpass.

→ Storage technologies other than hydro storage are not classified in detail in renpass.

→ Demand management is not integrated as a flexibility option in the simulation, only the need for it can be derived from the result figures on excess demand.

→ The modularized structure enabling collaborative software development and simplifying extensions has not yet been fully implemented in renpass. This would create more opportunities for intrasectoral modeling, the importance of which is discussed further in Section 6.1.

→ Furthermore, it has to be stressed that the full coverage of demand is not guaranteed in the simulations, but is a result of the user-defined infrastructure. The installed capacities of plants, storage and transmission lines are not optimized automatically within the model, but are scenario settings that have to be done by the user. An additional loop around the whole model could enable the additional feature of installation optimization that guarantees the full coverage of demand, but it would be necessary to reduce the computation time of the basic version of renpass beforehand. Modeling with renpass is time-consuming due to relatively long processing times in the range of hours when simulating a whole year.

→ One of the main strengths of renpass is its flexibility of application. A large number of parameters can be varied and a variety of result parameters may be examined.

→ By varying the spatial resolution and the time span, as well as the temporal resolution, users can adjust the model to their requirements. If a higher resolution of the region distinction does not bring further knowledge gain for the research question, it should not be too high to save processing time and reduce complexity.

→ The resolution of the hydro system in Norway is very high compared to other electricity simulation models.

→ All in all, interdependencies of the numerous influencing parameters of the energy system can be extracted with the help of renpass. Results drawn from modeling with renpass consist mainly of relative rather than absolute numbers.

Finally, the striking strength of renpass is its openness, not being dependent on proprietary software solvers and licenses. This opens doors to improvement and extensions

(Section 5.6) and enables renpass to keep up with and adapt to new energy modeling requirements (Section 6).

5.8.2 Model Publication and Distribution

renpass is published under the following copyleft 2014:

renpass is free software: you can redistribute it and/or modify it under the terms of the GNU General Public License as published by the Free Software Foundation, version 3 of the License, or any later version. renpass is distributed in the hope that it will be useful, but without any warranty; without even the implied warranty of merchantability or fitness for a particular purpose.

More details on the terms of and the complete GNU GPL 3 license can be found in FSF (2007). This license was chosen for renpass because it is widely spread and will be continuously updated by the the Open Source Community. Furthermore, it is compatible with the other Open Source Software employed in renpass.

Databases, code and manuals can be found on `renpass.eu`. Anyone who registers with a valid email address can download the model and run it on any computer.
New versions and extensions of renpass are currently processed on a server at the University for Applied Sciences in Flensburg. The master branch of the version control software is located on this server. After a successful completion of the testing procedure of an extension or improved version, the code and/or database extension is synchronized with the server. New versions are thereafter published on `renpass.eu`.

To facilitate access to the application of the model, the idea is to transfer renpass to an R-package. This would imply further adaptation of the renpass code to the R-package structure, consisting of functions and a standard documentation for each function which is already partly implemented in renpass. The database is distributed additionally.

Chapter 6

Discussion: Energy System Modeling Trends

Following on an energy model overview and current problems of energy modeling issues (Section 2.1), the experience gained from programming the electricity model renpass (Chapter 3/4) and its application (Chapter 5), this chapter summarizes energy modeling trends. It discusses how this refers to the role Open Data and Open Source could play in energy modeling.

Energy modeling has always been a dynamic process, but the profound upcoming changes demand thorough adaptions in the energy modeling world.

Push factors for profound changes in energy modeling are:

→ Moving towards renewable energy systems due to climate change mitigation and phasing out nuclear energy

→ Growing shares of VREs and thus fluctuating feed-in

→ Decreasing number of dispatchable plants

→ Smaller unit size of energy power generators

→ Need for components of spatial and temporal flexibility in the system

→ Convergence of consumer and producer roles

Pull factors for profound changes in energy modeling are:

→ Progress in the field of computer technology: algorithms, computing time, availability and decreasing cost of computing power

→ Data availability in higher temporal and spatial resolution

Developments and trends described in the following section refer to programming structures, the organization of model development, technical and economic characteristics of model objects and data processing. Furthermore, the development of energy modeling is also influenced by a shift in the focus of research questions, different user groups and new ways to communicate results.

Energy system modeling trends in this thesis are mainly derived from the perspective of techno-economic electricity system modeling. Nevertheless, as integrating heat and mobility in models is of major importance, the following section also touches upon general energy modeling trends. Examples are taken mostly from European and German energy models.

6.1 Modularized and Integrated System Approach

Energy system modeling consists of a trade-off between a high level of detail in the components and considering the big picture of the complex energy system these components are embedded in. Not only intersectoral (mobility, heat, electricity), but also interdisciplinary (technical, economic, societal, ecological) interfaces are required if the numerous interdependencies are to be considered. The effort to integrate the big picture in models should not affect the quality of its individual parts negatively. Thus, for good comprehensive research, modularized models with clear interface definitions are needed. A modularized, yet integrated system approach can ease the apparent trade-off between detail and integrity.

6.1.1 Intersectoral Modeling

Growing VRE feed-in requires gearing the electricity, heat and mobility sector more and more. There has been a shift in terminology from *Smart Energy Grids* to *Smart Energy*

Systems, the latter referring to an integrated view on the whole energy system, not just the electricity sector. Research questions about the integration of VREs can only be answered thoroughly by modeling sectors simultaneously.

Taking into account flexibility options provided by the electricity sector can only lead to an overestimation of the costs and problems of a system with high shares of VRE. For example, Connolly et al. (2014) looked at a new 'district heating plus heat savings' scenario for the EU Heat Map which was technically and economically assessed from an energy system's perspective. They came to the conclusion that the goal of reducing primary energy supply and carbon dioxide emission can be achieved at a lower cost (approximately 15% less), if district heating is integrated (Connolly et al., 2014, p.1). Thus, by taking an intersectoral approach, cost reduction potentials can be revealed.

There are already models that integrate different sectors in one model. For example, BALMOREL (Ravn, 2011, 2013) includes, besides different electricity market areas in a high time resolution, detailed CHP- and district heating modeling, as well as the transport sector. District heating and heat demand is GIS-based which complies with another trend described (Section 6.2).

Schaber et al. (2013, p.1) used the GAMS-based model URBS to look at how energy sector coupling, i.e., the interconnection of the power, heat, hydrogen, and natural gas sector, can help to make use of excess electricity from VREs from an economic perspective. They found that the heat sector can absorb parts of excess electricity from VREs which challenges the need for long term electricity storage (Schaber et al., 2013, p.1). According to their findings, transmission extensions can be reduced in the medium term, but are required in the long term to facilitate sector coupling. Thanks to sector coupling, excess electricity from VREs can have an economic value. An illustrative example is the case of generating heat by absorbing excess electricity. Thus, what was excess electricity before, then has the value of the gas saved. In this way, a reduction of the total costs can be revealed thanks to sectoral integration. Costs for flexibility options are estimated to be higher if only the electricity sector is considered.

Another energy system model including sectoral coupling is REMix which was developed at the German Aeronautics and Space Research Centre (DLR) (Scholz, 2012). Supplying the heat demand in each time step with CHP, electric heating, heat pumps etc. is a side constraint for the optimization. Electric cars as a flexibility option are also integrated, as is the conversion of excess electricity to hydrogen for the conventional mobility sector.

In conclusion, energy system models that consider the interconnections of different energy sectors to address their synergies for a stable renewable energy system already exist. So far, resources to build and maintain such comprehensive energy system models can only be found in rather large institutions. The complexity of these models is a barrier for more specialized smaller institutes to contribute to energy modeling progress. Since the diversity of energy models and model approaches improves the overall modeling quality (see Section 6.5.5), ways have to be found to overcome this barrier. An approach is modularization and the definition of interfaces which is explained in Subsection 6.1.3.

6.1.2 Interdisciplinary Modeling

Most energy models that address pathways to low-carbon energy systems cover technical or economic aspects, or both. Ecological dimensions are mostly reduced to greenhouse gas emissions. Other ecological aspects are, if at all, only evaluated additionally to the output side. Ecological aspects such as other emissions or land consumption are seldom integrated in the optimization of the model. If external costs of energy supply were to already be part of the optimization input side, this would open up new prospects to find sustainable energy pathways resilient to additional environmental costs.
The same is true of for societal aspects. Outcomes of techno-economic models are useless if their solutions are highly vulnerable to acceptance problems. For example, if the extension of transfer capacity triggers strong resistance from the residents affected, a least-cost solution from a techno-economic point of view can turn out to be a dead end if it relies strongly on this new infrastructure.

Ongoing scientific research addresses the challenge of an integrated view of our energy system. For example, the project *Vernetzen* (IZT, 2014) is developing an upstream module for renpass, that indicates the delay in extending the electricity infrastructure based on socio-ecologic indicators. Delaying grid extension and the expansion of renewable energy installation causes additional costs to the total costs of the transformation pathway.

Although integrating socio-ecological indicators on the input side of modeling is at an early stage, and methods to express such indicators in modeling language have not yet been defined, this is a promising development. In addition to expert knowledge of single scientific fields, there is an increased need for clearly defined interfaces from techno-economic, ecological and societal disciplines.

6.1.3 Collaborative Modeling

The complexity of models that fulfill requirements of intersectoral and even interdisciplinary integration is often greater than what its users or even programmers can grasp. Furthermore, if a model is only deemed to be functional if it is an intersectoral and interdisciplinary one, only few new model approaches can emerge and energy system modeling remains static. Since the contribution of many different modelers accelerates progress and improves modeling quality, a collaborative modularized modeling approach including precise interface definitions could solve the trade-off of complexity and advancement.

Preconditions for functional modularized models are organizational rules and clear interfaces between the modules with a sound documentation and definition of the variables to be exchanged between the interfaces. The danger of pathway dependency due to different programing languages can be overcome, either by agreeing on one language at the very beginning of modeling or by embedding code files of different languages. In the latter case, clear interface definitions are essential. Furthermore, the solver for optimization should be defined as an exchangeable module in a model. It could influence the results too, but is often hidden in the code.

Collaborative software development is facilitated by using Open Source principles. The higher the transparency of the modules, the better the information flow and the more synergies can be leveraged.

In the field of electricity supply which is highly software dependent, examples of collaborative software development have come to light. For example, six German distribution system operators commissioned a feasibility study on consortial software development for distribution grid operation on the basis of Open Source software. In this study, Heinritz et al. (2013) recommend a collaborative software development. They point out economic advantages as well as the benefit to avoid being dependent on a monopolist software distributor. This study emphasizes opportunities for faster adaption of software to new requirements of the electricity system if collaborative Open Source software is used.

Distributed development of energy models requires clear interface definitions which, in turn, increases the transparency of models, avoids lock-ins and make modeling progress faster. Barriers of entry, which lower the model quality, for new modelers and innovative modeling ideas can be overcome with a modularized but integrated distributed approach. The development of many model pieces from different working groups increases the robustness of the modeling results (see also Section 6.5).

6.2 Spatial Referencing

Almost all energy data is associated with a spatial reference. Many currently arising energy supply questions cannot be answered without the data of power plants, demand, grid and storage being spatially referenced.

6.2.1 Spatial Match of Demand and Supply

Energy supply has always been a transport issue, because resources, generation and consumers are not naturally in the same place. Indeed, electricity supply even implies the need for a grid system. Today, two circumstances increase the challenge of not only matching electricity supply and demand on a time axis, but also matching supply and demand spatially.

First, the rising share of VREs are usually located according to the availability of the source, thus where wind speeds, solar radiation or river flows are best. Second, this is enforced by the regulatory framework of unbundling. At a European level, the internal energy market triggered the separation of the planning concerning where to locate electricity generation on the one hand, and how to transfer it to consumers on the other. This clear separation of the tasks to produce energy and to distribute it also means modeling this spatial problem becomes more important.

6.2.2 Spatial Data and Software Availability

Input data on demand, power plants, storage and transmission needs to be geographically referenced. Only then can issues regarding transport requirements and the value of adapting the locations of power plants to factors other than the quality of the source be investigated in electricity models. This requirement coincides with the increasing availability of data in higher spatial resolution. In terms of costs and computer facilities, collecting, storing and providing geographic data has become easier than ever before.

With growing shares of weather dependent energy sources, climate data is needed for modeling. Climate and meteorologic science have a long history of sharing data openly.

In the field of basic spatial data, at European level, the availability has increased due to the INSPIRE-Directive (Infrastructure for Spatial Information in the European Community) (European Parliament and Council, 2007). This directive aims to make geodata easily accessible online and has made geographical data more easily available, after it was implemented at national level.

An example for increased availability of spatially referenced energy-related data is the Global Solar and Wind Atlas provided by the International Renewable Energy Agency (IRENA, 2013, 2014). renpass uses the hourly time series of wind speed and radiation from the `coastDat-2_COSMO-CLM` climatological data sets (Geyer and Rockel, 2013; Geyer, 2014) which is provided openly for scientific purposes.
Open Street Map `http://www.openstreetmap.org` is another good example for increased availability not only of data, but also of software for spatial modeling. In a PostgreSQL object-relational database geographic objects can be stored allowing location queries to be run in SQL. Such a PostGIS database can be synchronized with the Open Street Map database. For other programming features, too, spatial packages and functions substitute the need for GIS-software in many cases. For example, R has a huge toolbox of packages for geo-referenced calculations.

6.2.3 Visualization of Assumptions and Results

During the development phase of renpass, an increasing number of additional R-packages for spatial plotting were used to visualize scenario assumptions and results. The additional dimension of spatial reference and the information that can be passed on through this mode of presentation facilitates the choice of parameters and the communication of the results. Other programing languages provide similar features and a general tendency to illustrate energy modeling results with spatial reference can be observed.

Gathering and processing spatial data requires quite a lot of manpower. As examples like Open Street Map show, Open Data projects bring together a large contributing community.

6.3 Flexibility

6.3.1 Technical Flexibility

The traditional concept for a secure electricity supply consisted of base load power plants supplying the base load share of electricity demand all year long and peak load power plants filling in the times of additional demand. With growing shares of VREs in the system, this concept is outdated and no longer appropriate. The main task of units that are dispatchable, such as thermal power plants and hydro turbines, is to fill the gaps. Their operation should be more and more driven by residual load instead of load only. Thus, technical characteristics such as ramping times are important qualities of power plants and should be included in models. Otherwise, plants with cheap fuels, but no operational flexibility are assigned important roles in the energy system although they cannot fulfill the gap-filling quality that is required for the system.

6.3.2 Spatial and Temporal Flexibility

Not only at the level of power plant technologies is flexibility required, but also at system level. There is a need for more flexibility to match demand and supply in the temporal and the spatial dimensions. Different flexibility options with regard to costs and their contribution to system stability need to be compared to find pathways to resilient energy systems. Thus, this needs to be represented in models. A precondition for integrating this view into a model's system is the availability of spatially referenced data (see Section 6.2).

Three obvious flexibility options exist:

Extending transmission grid increases the spatial flexibility in a system because the location of demand, supply and storage utilities becomes less restrictive.

On the one hand, **storage utilities** increase the temporal flexibility of the system. The degree of temporal flexibility gained depends on the volume of storage reservoirs and this varies by anything from minutes to seasons. On the other hand, storage facilities put additional stress on spatial flexibility if the storage is not located close to the sources of excess electricity and if the consumers are not geographically close to the electricity stored.

Demand side management can increase the temporal flexibility of a system if the demand is simply shifted to other times, but in this case it is bound locally. The other case is load shedding, which means that demand can be cut in cases of transmission bottlenecks or excess demand. Load shedding/elastic demand can also increase spatial flexibility.

The three system flexibility options described are the most evident ones, but there are more. A diversity of flexibility options increases the security of supply, as well as the robustness and resilience of an energy system (see also Section 6.5).

6.3.3 Flexibility of the Economic Framework

With regard to electricity supply, the financing mechanisms of power plants are manifold these days. There is a growing range of possibilities to regain investment costs and make a profit with energy installations. Feed-in tariffs, regulating power provision, marketing of green or local electricity as well as self-generation are financing possibilities additional to the usual transfers on spot, day-ahead or forward markets.
Compared to earlier times, this development implies chances for new market participants and diverse business models for smaller investors, too, but also increases the complexity. In the transition to low-carbon electricity systems, more changes in the market structure are likely: marginal cost based market structure of European electricity exchanges may need to be adapted or completely replaced in systems with very large shares of VREs *(very low marginal costs)* and storage turbines *(pricing on the basis of opportunity costs)*.

Toolkits for representing the economic flexibility of financing options are needed in electricity market modeling. For long-term energy pathway modeling, different market structures have to be considered. If energy models aim to find out which market framework matches, or even leads to a stable, cheap and sustainable energy system, different economic options have to be representable.

From a social welfare economics view, it becomes important to assess the value of security of supply. To assess the scarcity price is a crucial point to be able to model the value of flexibility options.

6.4 Evolutionary and Swarm Algorithms

The outcome of electricity models that are optimization models or contain optimization parts is influenced by the way the algorithm utilized proceeds. Since computing time is thought to be crucial for the application of models, quite often, the fastest, available solvers for linear or non-linear optimization are applied. A possibility to assess the degree of influence on the results due to the choice of solver is to apply different solvers to the same problem and compare the results. This requires a clear interface at the point in the model where the solver for the optimization is called.

For renpass, the function `exchangeStandard` contains the optimization part of finding the least-cost utilization of an existing electricity infrastructure at a given demand. Eight parameters are the input of this function. The function could be replaced by sourcing a different exchange function. This has not been fully applied and implemented yet, but the ground has been prepared by the defined interface. The optimization part of renpass is rather slow, because it is a heuristic algorithm written by the author in the R language. Nevertheless, the open, rather than black box character of the algorithm helps to understand how local minimums are handled and gives an impression of the sensitivity to the initial situation.

Looking at the bulk of electricity system models that can be used to model 100% renewable systems, two optimization tasks occur primarily. Some models contain both.

→ **Installation optimization:** Find a configuration of generation, storage and transmission with minimal system costs under the premise of either greenhouse gas reduction or certain shares of renewable energy.

→ **Operation optimization:** Minimize operation costs for a certain time frame to meet demand and supply. Side constraints are: available feed-in, storage options and grid infrastructure and capacity restrictions.

For the installation optimization, evolutionary, precise genetic algorithms are starting to be of interest for the energy system modeling world. For example, the Open Source electricity model Genesys from RWTH Aachen uses a combined evolutionary strategy/hierarchical system management approach with low total costs as the positive feature for the optimization of infrastructure (Bussar et al., 2014, p.41).

For the spatial problem of operation optimization, swarm algorithms, another related but differently specialized type of algorithm are promising due to the analogy to possible developments in energy systems. A trend to smaller units in energy systems can already be observed. The role of consumer and producer is becoming blurred and is no longer clearly determined. The importance of communication on the one hand, and of intertwining the small parts of the system without the need for one big control instance on the other hand, is similar to the characteristics of animal swarms. Thus, the idea itself suggests that algorithms adopting the successful collaborative survival behavior of flock animals, as swarm algorithms do, could bring robust results to the complexity of the energy organism.

Limiting the focus to a least-cost solution, which is the framework of many energy models today, drastically curtails the integrated view on energy systems. The qualities of energy systems are not limited to being the cheapest, but characteristics such as resilience will gain in relevance (see Section 6.5). Thus, algorithms suitable for energy system modeling must be able to depict these qualities and to handle the complexity of smaller units. Otherwise, results are misleading and, as it happens today, centralized structures are the models' preferred solutions because modeling abilities of today's algorithms are more suited to such structures.

Optimization algorithms in particular hinder energy models from becoming completely Open Source as the use of proprietary solvers is common, including in freely available models. Scientific reproducibility can only be met with full transparency, including that of the software utilized. It is hardly possible to adapt algorithms for energy modeling when utilizing proprietary solvers.

6.5 Resilience and Diversity

As the vulnerability of energy systems rises, resilience is becoming an important quality for energy systems which has to be taken into account in robust modeling frameworks.

6.5.1 Traditional Approach: Energy Security and Vulnerability

An essential quality for an energy system is its security of supply and a low level of vulnerability. According to the World Energy Council, "vulnerability of an energy system can be measured by its ability to cope with adverse events" (WEC, 2008, p.5). Traditionally, vulnerability, the counterpart of energy security has been looked at in terms of technical failure, accidents and operation errors. However, the multidimensionality of vulnerability is recognized and there are attempts to broaden the set of indicators.

Gnansounou (2008) developed a composite index of energy demand/supply weaknesses as a proxy of energy vulnerability. His indicators are energy intensity, oil and gas import dependency, CO_2 content of primary energy supply, electricity supply weaknesses and non-diversity in transport. Similarly, the World Energy Council defined the different aspects of vulnerability as the primary energy supply risk, the infrastructural risk and the vulnerability of consumption of end-use energy (WEC, 2010, p.3).

Although the perspective has been broaden, this is still a very narrow approach to the complex issue of energy systems' vulnerability. This becomes clear in the measures proposed by the WEC to counter vulnerability: extending the operating life of nuclear power stations is proposed as one measure to decrease vulnerability according to this definition (WEC, 2010, p.4). The nuclear failure in Fukushima has proven that relying on nuclear power exposes a system to vulnerability. Lovins and Lovins (1982) argued back in 1982 that vulnerability to faults is an unintended side effect of highly centralized technologies.

In summary, advanced approaches to assess vulnerability are required. So far, vulnerability is rarely considered when modeling future energy systems and pathways.

6.5.2 New Approaches: Resilience of Energy Systems and Pathways

Resilience can be a seen as a counter to vulnerability (O'Brien and Hope, 2010, p.1). The term resilience is used and defined in a number of fields: ecology, engineering and construction, economics, networks and systems. Broadly, it means "the ability to withstand and adjust to disruptions whilst still retaining function."(O'Brien and Hope, 2010, p.3). A resilient system will use its adaptive capacity to adjust to new conditions in the event of a disturbance in order to persist. A core quality is the ability to learn how to cope and adjust.

Resilience concepts have been mostly developed for ecological systems (Smit and Wandel, 2006, p.283). In an energy system context, O'Brien and Hope (2010, p.4f) propose the following working definition: "A resilient energy exhibits adaptive capacity to cope with and respond to disruptions by minimizing vulnerabilities and exploiting beneficial opportunities through socio-technical co-evolution. It is characterized by the knowledge, skills and learning capacity of stakeholders to use indigenous resources for energy service delivery."

A trend towards the growing vulnerability of energy systems has been recognized by the WEC (2010, p.6). In the momentum of system transformation, vulnerability increases. In the long run, resilient energy systems with a high level of adaptive capacity should be reached. On the one hand, characteristics of renewable energy seem to increase vulnerability due to their fluctuating nature, but on the other hand, they enable a decrease in vulnerability due to the diversity of technologies and small unit sizes.

Stirling (2010) argues that diversity within energy systems builds resilience. Moreover, he has developed a multi-criteria diversity analysis framework for the appraisal of energy portfolios.

A system or pathway that depends mainly on one technology option is highly vulnerable. For example, new ecological and economic aspects are revealed which disqualify a technology which was the main pillar of the low-carbon system. Subsequently, the energy system collapses and other advantages of this technology such being the least-cost option are void. Pathways relying on a diverse range of technologies and flexibility options are inherently more resilient.

In conclusion, resilience and adaptability are important qualities of energy system pathways and should be integrated in energy modeling and discussions on pathway decisions.

6.5.3 Resilience and Least-Cost

The majority of energy models that are used to find 100% renewable energy systems are least-cost optimization models. The focus on least-cost pathways is restrictive. The cost indicator seems to be a figure much more straightforward to define than characteristics such as resilience. However, system cost figures quite often only demonstrate a pretense of precision due to their sensitivity to cost assumptions.

The Special Report on Renewable Energy Sources and Climate Change Mitigation of the IPCC (2011) compares some global scenarios on renewable energy development, including with respect to costs. They point to the fact that input cost assumptions play a major role in determining the scenario mix since cost-optimization energy models use cost assumptions for each technology as one of the main determinants of market expansion or reduction (IPCC, 2011, 10.3.1.1, p.816). These models are therefore vulnerable to the assumptions of learning curves.

In a meta-analysis, Pahle et al. (2012) compare 16 studies for a long-term transformation of energy systems at global, European and national levels with respect to the costs of renewable energy expansion. They state that a comparison of total costs is difficult, because they are not defined in the same way in the different studies. Thus, they only compare the investment costs of renewable technologies. All of the 16 studies rely on learning curves. Learning curves exhibit ranges which are higher for less mature technologies. The statistical relationship of learning by doing is more valid for more modular technologies such as photovoltaics. The development of learning curves is less predictable for wind offshore or CSP (Pahle et al., 2012). The authors criticize that the studies do not consider these learning curve ranges. They come to the conclusion that considering the robustness of pathways for renewable energies would improve the quality of scientific modeling. Consistent and transparent models should take into account the uncertainties and vulnerability to highly assumptive learning curves.

Förster et al. (2012) compare three scenario studies published since 2009 by Greenpeace, Eurelectric and the European Climate Foundation (ECF) with respect to their cost assumptions and outcomes. One of the main findings is that providing data and the methods of applying learning curves is not sufficiently transparent (Förster et al., 2012, p.26 and p.32).

The document explaining and accompanying the EU Energy Roadmap points out that a "[c]omparison of total costs for developing a more sustainable EU energy system by 2050 is hardly possible due to lack of transparency in most scenarios on methodological and data assumptions." (European Commission, 2011b, p.102).

To summarize, the studies and examples mentioned show that least-cost optimization requires a high level of transparency. Additionally, sensitivities have to be considered and quality of resilience should be included in energy pathway scenarios. Some initial approaches to resilience indicators are discussed in the next subsection.

6.5.4 Indicators for Resilience of Energy Systems

To integrate resilience into energy system modeling, indicators are required. An approach to quantify resilience in energy systems has been proposed by Molyneaux et al. (2012). They suggest a resilience index as a composite of seven metrics concerning non-renewable fuel used, generation and distribution efficiency, carbon intensity, diversity, redundant electricity for use in GDP and reliance on imports (Molyneaux et al., 2012, p.18).

A review of their approach, and that of others to address the question of resilience led to the identification of the following indicators. They are ordered according to their expected suitability for use in a model. In other words, indicators that are rather straightforward to model are listed first, and those far from current model methods are last.

→ Diversity of energy supply technologies

→ Availability, distribution and diversity of resources

→ Diversity and distribution of flexibility options such as dispatchable power plants, storage, grid, demand management

→ Possibilities of temporal and spatial decoupling of demand and supply

→ Level of the scarcity price reflecting value of flexibility options and elasticity of the demand curve

→ Changes in the range of results if main driver factors are varied

→ Changes in the range of results if one technology option is removed

→ Stakeholder and ownership diversity

→ Degree of communication possibilities of a system, user interactions with energy capture and use

→ Motivation for the individual stakeholders of the energy system to contribute to the overall system improvement

Dynamic key features concerning learning aptitude, the development of new trajectories and the ability to respond to disruptions and innovations are particularly difficult to model. Nevertheless, as it will be necessary to identify a resilient low-carbon pathway, methods to assess its indicators should be developed further.

6.5.5 Robustness of Energy System Modeling

Regardless of whether an energy model considers the technical, economic or resilience aspects of an energy system, the modeling itself should deliver robust results. It is a similar concept to resilience, but in the field of computer science, the term robustness is used. Robustness is the ability of a computer system to cope with errors during execution or the ability of an algorithm to continue to operate despite abnormalities in input, calculations, etc. (Wikipedia, 2014c). The robustness of the modeling software is an important quality for energy system models and can best be tested with the help of many users and a large variety of applications. In case of Open Source software, there can be more users and users have the possibility to evolve to become co-developers which makes Open Source software more robust than other software.

With respect to energy system models and their task of unfolding the map of energy transformation pathways, the concept of model result robustness can be applied to a multi-model approach. The result verification by a wide range of different models can increase the robustness of the overall modeling results or reveal the range of result figures. An example of where precisely the robustness of a single model's results was criticized was during the development of the EU Energy Roadmap (European Commission, 2011a, p.18). Following the recommendation of the Advisory Group on the Energy Roadmap, this lack of result robustness was then countered by adopting a multi-model approach (Knopf et al., 2013, p.3).

Chapter 7

Conclusions

Implementing of a full scale electricity model to simulate 100% renewable electricity systems based solely on Open Data and Open Source software is possible but there are barriers, especially in the field of data availability.

Although energy data availability has increased over the past few years in Europe and Germany, poor quality and incomplete data remains a major constraint to energy modeling and hinders rapid improvement. Especially power plant registers and parameters, grid infrastructure and load data in a spatial resolution higher than per country are not openly available.

Introducing an Open Data and Open Source approach into energy modeling practice in science and society is a precondition to overcome key challenges in energy modeling and cope with future trends of energy system modeling.
The masses of spatially referenced data in energy modeling requires a widespread, openly organized community of contributors to gather, verify, publish and update all the data required for energy modeling. For energy systems undergoing profound changes, elaborated modeling approaches for flexibility options, diversification of sources and blurred producer and consumer roles are necessary. Open standards in this field facilitate advancement. Synergies can be drawn, and ideas can build upon one another if code is open and well-documented. Bugs, which always occur in models, are detected faster if there are more people checking both code and data. Thus, the outcomes of models whose results can be scrutinized by a wide range of persons are more robust.

As far as model users and result recipients are concerned, a key requirement for progress in modeling energy system transformation is transparency. Using Open Data and Open Source software is a first step to overcome information asymmetry between data/model experts and the recipients of model results in politics and in public sphere. Using open standards is a precondition for the reproducibility of results, but is not sufficient. The model development of renpass illustrates that an energy system model is too complex to be understood by users at first glance, even if all the data and code is accessible. Aside from transparency, the next step to uncover the black box of modeling is good communication of model's complex functionality. In addition to using Open Source, more emphasis and effort has to be made on thorough result interpretation and communication. Reference data sets, documentation standards, model comparisons and calibrations, as well as visualizations that can pass on information in a nutshell are essential steps for models to gain credibility.

Concerning the model development, Open Source does not automatically imply that synergies in model development can be drawn. Additionally to allowing everybody to look into data and code, applying methods for collaborative software development creates new opportunities: Combining different model modules with clearly defined interfaces opens the possibility for programmers to delve into detail in parts of the model. If individuals are not constrained to doing the same development deliberately closed off from one another, the single parts can improve in detail and quality. The complexity of energy models can be defused if they consist of modules which are well-documented and connected by precisely defined interfaces. Collaborative software development has proven useful in other fields. Energy modeling still lacks experience in methods for collaborative development and can benefit from the experience gathered in Open Data and Open Source applications.

Energy models have been successful in showing that it is possible to supply demand with 100% renewable energy from a techno-economic point of view. The new task of those models has now shifted to finding out which pathway to pursue. Decisions on future energy systems will be based on several criteria which include technical, economic, environmental and social considerations. This discussion can be supported by models that are able to spread out the map of transformation of all pathways feasible from a techno-economic point of view. Then, additional criteria of ecological and societal nature can be applied to crystallize the resilient no-regret options from the extensive range of possible pathways. That way, pathway decisions can be derived based on facts that go beyond questions of costs and security of supply.

Several steps can be taken to embark on the necessary journey to energy modeling transparency: important policy measures must provide open energy data and a framework for transparency standards. By agreeing on requirements on the reproducibility of modeling results, the foundation can be laid for a diversity of modeling approaches that fulfill scientific standards. Open and connected models can be of better quality. Openness to scrutiny instead of black box models deliberately developed in a closed-off environment, enhances credibility. Modular development reduces the inertia of existing energy models. To keep up with fast transforming energy systems, models should be updated and re-engineered as part of an ongoing process. This dynamic development could be well managed by a collaborative community working on the basis of Open Data and Open Source.

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