UNIVERSIDAD PONTIFICIA COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

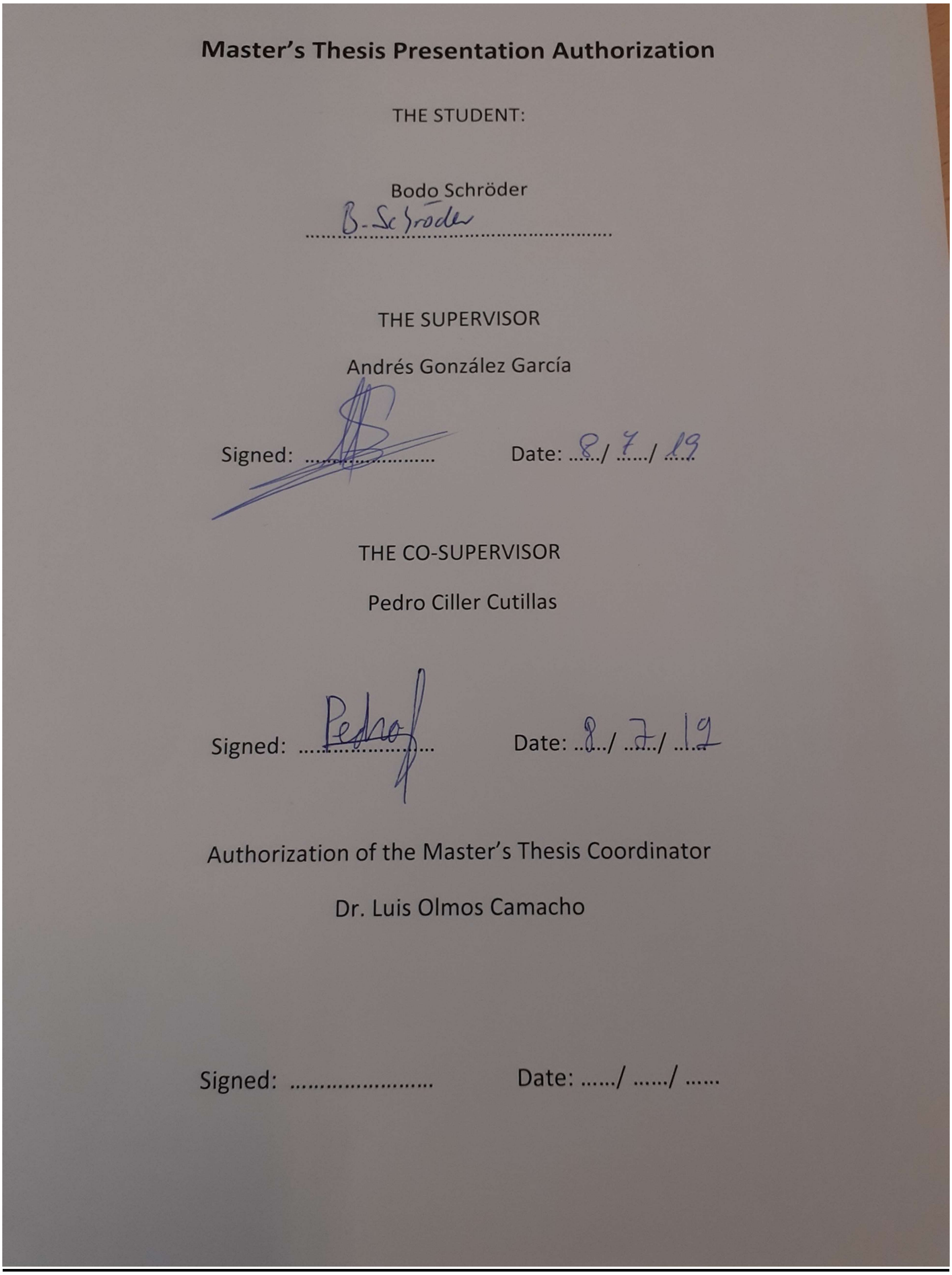
OFFICIAL MASTER'S DEGREE IN THE
ELECTRIC POWER INDUSTRY

Master's Thesis

Improvement of the Reference Electrification Model (REM) through wind power generation

Author: **Bodo Schröder**
Supervisor: **Andrés González García**
Co-Supervisor: **Pedro Ciller Cutillas**

Madrid, 8. July 2019



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Abstract

This master´s thesis contains questions and current challenges in the context of the electrification of rural areas. Within these multiple approaches and diverse strategies are developed and executed by governments, entities and research institutions. Accordingly, the usage of computer models provides certain advantages in order to determine an optimized solution or structuring of the respective designs of the generation and the network. Corresponding to this the extension of the Reference Electrification Model (REM) is the main feature of this work.

The major objective is the implementation of wind power generation into the References Electrification Model to obtain a functional consideration of wind power within the generation design. Initially, the status quo of rural electrification and the Reference Electrification Model is carried out in order to provide a sufficient overview of the topic. Furthermore, determinants of wind energy and the corresponding technical equipment and components are investigated and evaluated. In addition, the behaviour of wind speeds and the main influencing factors are analysed to receive their level of importance with respect to the purpose of obtaining a suitable methodology for the implementation.

The research questions are orientated towards the derivation of representation and preparation of wind data, as well as the development of a suitable wind generators catalogue and the framework conditioning for implementation methods properties.

The electricity output due to wind power generation underlays certain challenges in this context. The unpredictability and the volatility of the wind speeds values aggravate the development of an appropriate representation to obtain adequate input data for the wind power generation. Additionally, the high influence of local conditions and their impact on the wind speed profiles intensify these challenges.

To cope with these difficulties the thesis contains an investigation of several representation methods and a corresponding evaluation. Regarding the Reference Electrification Model enhancements and the improvement procedures are characterized by coordination and introduction of the current existing characteristics and a corresponding derivation of the adaptations of the model to achieve the goals set.

The developed enhancements were tested in the framework of a case study in order to analyse and evaluate the functioning of these improvements. The new generation designs provided by the model produced causal solutions. The obtained results were promising and meet their objectives.

Summary

This master´s thesis is about the improvement of the Reference Electrification Model (REM) through the implementation of wind power generation as part of the electrification of rural areas.

The first chapter expounds introductory components, which contain the justification of the topic and various general aspects of the frame. In this regard, it gives the classification of the context of the electrification of rural areas, explains the importance of this activity and derives the relevance of the topic.

Referring to the condition of the lack of universal access to electricity of a significant part of the world's population, this maintains profound meaning. To cope with the previous, this issue is on the agenda of current research efforts and various public institutions.

The relevance of electrification and universal access is justified by the multitude of positive effects that possibly result from their execution. In this regard, this work refers to various scientific papers, that describe a variety of positive effects on electrification expansion in developing countries and the population of rural areas. The importance of relevant influencing respective determinants is analysed and evaluated.

Moreover, the potential extension possibilities of the utilization of computer models were explained, subjected to the purpose of obtaining an optimal network and generation design structuring. In addition, the significance of including wind power generation and the favourability of certain grid modes architectures are explained. The brief clarification of the Reference Electrification Model points out a first impression of the capability of this model. The chapter closes with the establishing of an overview of further motivations, the general objectives and the research questions of the thesis, that should be achieved and answered during the development process of the work.

The purpose of the second chapter is to introduce the framework of rural electrification within its actual varieties. This provides an initial overview and the possibility to understand the major conditions and issues of this topic. A detailed description within a state of the art regarding the current status of rural electrification projects worldwide points out the development of different generation and network design approaches. These different technologies used, are analysed and evaluated to provide diverse outcomes and advantages for rural electrification. The data´s origin and essential information are gathered and withdrawn from a multitude of different research papers from projects around the world.

This evaluation contains projects that are subjected to the high diversity of the local conditions and significant differences within its potential generation resources, which allows a wide covering of many aspects and occurrence forms of local conditions. Amongst others, technologies as wind, diesel, solar, hydro, biomass and several combinations of these within hybrid-systems are investigated and the main determinants explored.

Another component of the state of the art is a precise overview and description of the most relevant available computer models used in this context. Their introduction and their processing are explained in detail to enable the understanding of the general operative methodology. This overview includes a separation into the rural electrification, generation sizing, network design, and other tools. For each of these categories, their specialties and respective representatives are expounded.

In Addition, this chapter provides a detailed explanation of the Reference Electrification Model and introduces the working framework of the model. The description also includes the key components: general purposes, the input data, the structure, the output and the current architecture of the model. Whereby, the input data is obtained within their different factors regarding the demand, costs data, weather conditions, and the generation catalogue. The structuring part contains the five major processes of REM, which are represented due to the data processing, the micro grid design, the clustering, the final design, and the post-processing and the reporting. Additionally, the different models' modes, the regional and the local one, are identified, and the differences demonstrated. Finally, the output components and the architecture of REM are introduced. The latter includes the structuring within the micrograids the generation design is based on.

The third chapter introduces the properties of the wind generally. How it is developed within the earth air layers and which are the main driving forces. Followed by the potential advantages and drawbacks of the utilization of wind power generation for producing electricity within hybrid-micro-grids.

The investigation of the main influencing parameters and most important determinants of the wind speed is essential to derive implementation strategies for wind power generation from this withdrawn knowledge. The explanation of the high impact on wind speed by local conditions is provided in detailed resolutions. Especially in the context of small-scale wind power generation, the importance of these determinants corresponds to the highest significance. Regarding this, the processing of the parameters is analysed, and the impact evaluated.

The investigation of adequate representation methods of the wind speed profiles and properties is an important issue to understand and handle the influence of the wind's determinants. The gathering and description of stochastic and probabilistic methods are brought to point out certain possibilities to prepare and obtain the essential wind data. The methods would be useful to deal with the uncertainty and volatility of the wind's behaviour.

Additionally, the unavailability of trustful wind data, especially in rural areas, often leads to major challenges of evaluating locations regarding their usable wind potential. Therefore, this thesis included several different inter- and extrapolation methods to deal with this issue. These methods are review and evaluated. Finally, the conversion of wind energy into electric energy is introduced by mathematical formulations and explained in appropriate depth. This forms the foundation for the power output calculation of the subsequent modelling.

Chapter 4 contains the main part of the thesis and provides the necessary adaptation to implement the wind power generation into the model. The touching parts of REM are described in their current processing method in high resolution to enable an understanding of the relevant parts of the model. These understanding of the processing is essential to be able to follow the expanding of the model through the developed enhancement to achieve the thesis objectives.

The key components are the generation catalogue, the REM architecture, the dispatch, the generation sizing, and the optimization procedure. The generation catalogue contains the different generators the generation design is based on. The explanation is done in high precision of details and corresponding parameters and correlated assumptions are described extensively. This is executed within the current REM structure and regarding the adapted one.

The architecture of the REM is introduced within its occurrence form. In order to adapt the structure for the implementation of wind power generation several alternative architectures are discussed regarding their advantages and disadvantages for the system. Afterward the final solution is derived, and the chosen composition is evaluated and explained to enable the generation of new designs.

Followed by the description of the dispatch strategy and the generation sizing and the optimization method. This includes the master-slave problem and the search methods as main parts.

The generation sizing of the REM is divided into two separated problems. The base problem of the mini-grid generation design is the determination of the optimal generation design and dispatch for local consumers. The objective is to find an optimal solution based on the available above-mentioned generation catalogue with respect to the technical and economic cost parameters, the individual or aggregated demand patterns and some pre-selected strategies for dispatching for every demand’s location. For small systems and a low number of different micro-grids, this determination is done quickly. In the case of large-scale or even whole countries, these procedures are potentially unfeasible regarding the computational effort. In order to solve this issue, the REM produces a selection of optimal solutions for micro-grids with a certain number of demand points and stores them into a look-up table. The look-up table contains the cost-optimal or quasi-cost-optimal generation design for this specific micro-grid size, whereas each consumer type is reflected by an axis and each micro-grid size of the corresponding consumer by a point on the axis. [1] For the determination of the total system, the REM uses an interpolation method that estimates the design based in the next two similar pre-determined optimal solutions or points on the axis above and below the current one, regarding the number of inhabitants within this micro-grid. [2] In order to consider economies of scale, which should result in a reduction of costs while the increase of the micro-grid size the look-up table gets adapted, if necessary, to obtain a strict cost decrease. [3]

The superordinate problem deals with the final design of the whole system. Subjected to the results from the network optimization of the underlying RNM and a clustering process of micro-grids. REM provides the optimal solution of the total networks distribution regarding the different optimal pre-determined micro-grid modes as stand-alone, mini-grid systems and the grid-extension. [4] Further explanations and the working mechanism of the optimization method is explained in the detail within the thesis. But the key points of the search method are based on a modification of the Hooke-Jeeves and a trisection algorithm.

Finally, chapter 4 is closed with the development of potential enhancements for futures works.

Chapter 5 contains the execution of the case study, to evaluate the obtained results from the development of the model enhancements. The case is introduced within its input parameters regarding the location, the demand patterns, the number of consumers, the existing grid structures and the wind conditions in the observed region. Afterward different scenarios are defined and described to evaluate the model's performance and the generation designs under different conditions.

The second part of the fifth chapter is the analysis of the case studies results. These are appraised regarding different costs types, generation compositions, and their corresponding dispatches. Lastly, the final designs reaction subjected to the model's adaptations is analysed briefly.

Chapter 6 contains the conclusion of the thesis and the general evaluation related to the achievement of the objectives and the answering of the research questions.

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[1] (Li V. , 2016, p. 22)

[2] (Laboratory, 2018, p. 13)

[3] (Li V. , 2016, p. 22)

[4] (Laboratory, 2018, p. 13)

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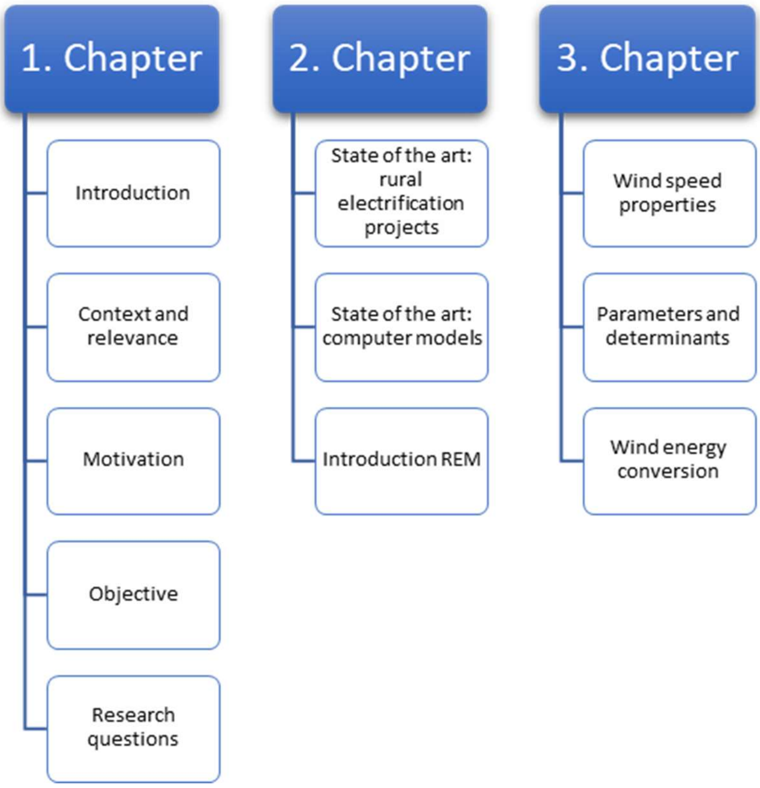

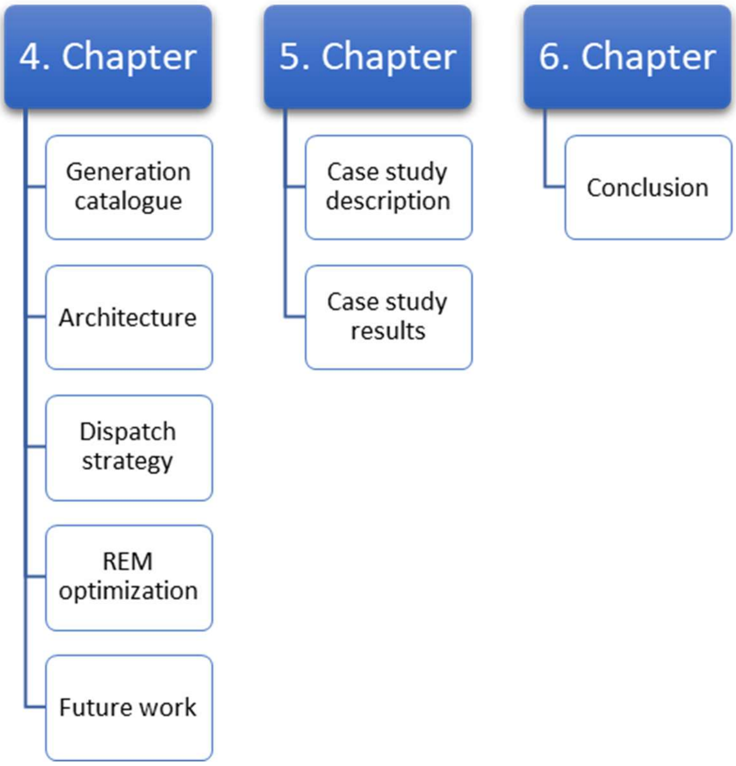

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1. Introduction

Today's societies of the industrialized nations are exclusively and extraordinary depending on the use of energy in its different appearance forms. Almost all activities and processes in our lives are highly related to energy consumption. They also, lead to wealth, prosperity, development and security of the nations. The foregoing everyday life without energy is inconceivable. Energy is the essential base for the industry but furthermore a requirement for human needs. Several generations of researchers pointed out that there is a strong correlation between the development of a country and the penetration of energy access. [5] There is a global trend of the economic ascent of the third world and developing countries with a massive need for energy. The strong strive to electrify their environment leads to adapt to the western standards of living. This processing contains several challenges and problems. Therefore, the interest and attention of electrification proposals and solutions are high.

The first chapter of this thesis introduces the necessity of energy in its occurrence form electricity and presents the relevance, actual context, and status of rural electrification. Furthermore, the motivation and the research questions of the thesis are explained in detail. The context will be justified through the importance of wind power generation and the usage of computer models to develop proposals and supporting techniques to achieve the above-mentioned solutions.

1.1 Context classification

The International Energy Agency (IEA) provides different scenarios of energy and electricity development for the future timeframe until 2040. Each of these scenarios predicts an increase in worldwide total demand.

As a prediction base, the International Energy Agency defines three different scenarios to analyze the scope and the reach of the results of the variations in the policies and the strength of an impact on economics, society, and environment.

The first is the New Policies Scenario, which is considering the actual policies that are implemented or announced related to the Paris Agreement targets of the different countries worldwide until 2040. This scenario provides a view on a possible development opportunity that is realistic to take place in the energy sector if the planned policies are implemented as presaged. But it is not considering certain technology developments or policy changes that happened beneath this timeframe. [6]

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[5] (Hirsh & Koomey, 2015, p. 72)

[6] ((IEA), 2016, p. 33)

The Current Policies Scenario considers, in contrast to the above-mentioned scenario, only policies, and measures that have been implemented until 2016. Correspondingly, this scenario outlines a situation, where the world community doesn't follow the purposes of the agreed climate goals. Therefore, it serves an outcome, that occurs because of the non-persisting of further development of climate policy targets. [7]

The 450 Scenario objectives aim for the limitation of the average global temperature increase until 2100 by 2 degrees Celsius related to the pre-industrial levels. Therefore, this scenario is considering the heavy use of renewable technologies, CO2 emission reduction, and energy efficiency. This scenario provides a treatment towards advanced future climate development policies. [8]

The New Policies Scenario forecasts an electricity demand with an annual growth about 2%, which is equal to a 2/3 (~33%) general increase of demand, compared to the actual demand level until 2040. The current Policies Scenario is assuming 2,3% and the 450 Scenario 1,5% raise in electric demand per year until 2040. [9]

The biggest electricity consuming countries will be Asia (China, Southeast Asia, and India), whose proportion of global demand will be between 42% and 64% depending on the different scenarios. [9]

Also, the generation technology mix is very diverse in each scenario. The shares of renewable generation lay between 29% in the Current Scenario up to 58% in the 450 Scenario until 2040. In contrast to this, the emitted CO2 emissions are related to the amount of installed renewables energy technologies. [10] [11]

We can conclude that the actual development of the energy and electricity sector underlay a general growth; the assumed scenarios are incidentally in this context. Therefore, actual problems and challenges regarding the electricity in general and, the provision of universal access to electricity will be increasing in the future.

1.2 Topic relevance

One important condition is to verify the relevance of rural electrification. In the actual research environment, this topic is prevalent and approaching a short debate about their relevance, regarding the benefits and possible side effects.

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[7] ((IEA), 2016, p. 34)
[8] ((IEA), 2016, p. 35)
[9] ((IEA), 2016, p. 246)
[10] ((IEA), 2016, p. 249)
[11] ((IEA), 2016, p. 250)

Besides the challenge of universal electricity access some additional aspects of rural electrification regarding regulatory, economic and consumer-related issues occur. And the importance of using computer techniques to provide more sophisticated mechanisms for solving existing difficulties. Furthermore, we introduce the Reference Electrification Model, that is the main subject of these Master´s thesis and finally, a magnitude, wind power generation could provide, to improve and generate additional value to rural electrification.

The Member States of the United Nations defined and adopted in 2015 the Agenda for Sustainable Development until 2030. One of the 17 Sustainable Development Goals was Goal 7, to ensure the availability of affordable, reliable and modern energy for the global population. This includes universal access to electricity. Even though the population with electricity access increase from 2000 to 2016 up to 87%, the amount of people without electricity is still high. Furthermore, most of the remaining population around 87% of the global access deficit is based in rural areas often found in Southern Asia and Sub-Saharan Africa. [12]

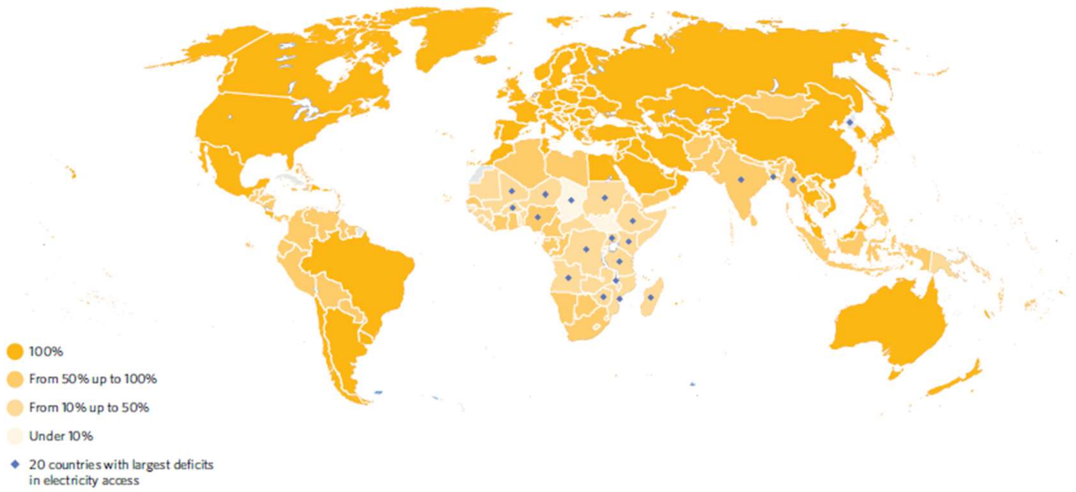

Figure 1: Overview of current electrification level [12]

These rural zones suffer from a high level of energy poverty and are usually sparsely populated. The area of these regions is large and the distances to the nearest urbanized zones are quite high. Therefore, the connection to the existing electric grid would be extremely cost intensive and economically not feasible. [13]

Related to the Sustainable Development Goal 7 and the fact that mostly rural lack of electricity access, their electrification is an important approach to reach this goal. Hence the rural electrification possibilities should be lighted up more clearly.

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[12] (Nations, 2018, p. 23)
[13] ((IEA), 2016, p. 419)

To overcome the challenge of non-economic access to the grid infrastructure, the above-mentioned approach includes the opportunity of usage of the off-grid or stand-alone network structures, which will be explained in more detail later. Furthermore, the sparse areas usually have an abundant renewable energy potential, that provides alternative generating opportunities. Renewable technologies such as wind power, solar PV, solar thermal, biomass or hydro can be easily combined within the rural electrification technologies and gain certain synergies such as lower costs and a more ecological universal access.

Besides the pure achievement of access to electricity, there are great numbers of further implications related to wealth and education of the deprived population related to this. As shown in the work from M. Kanagewa and T. Nakata the access to electricity has an impact on socio-economic factors such as health, education, economy. [14]

Additionally, S. Khandker, D. Barnes and H. Samad show in their study similar results as mentioned above. They show in a case study regarding Bangladesh that total incomes raise up to 30% due to electrification. Also, they confirm the significant lengthening of absolved years in school and the related study time; therefore, an important driver for additional education. [15]

These presented research papers show only two case examples, but, even if the results are not a general proof of the possible positive influences of rural electrification, they bought some important facts about individual potential improvements on certain cases. This indicates, that dealing precisely with this topic is mandatory to provide the desired outcome.

The rural electrification procedure is persistent and coupled with an assorted number of different determinants. Following a brief selection of them and related concepts for this thesis.

Consumer preferences

B.R. Entele et al. investigated consumer preferences regarding the connection of Green Electricity Services of rural consumers within a solar PV and micro-hydroelectric generation designs in Ethiopia. They determined that their marginal willingness to pay is highly determined by several attributes as reliability, electricity-related services and the absence of externalities. The willingness to pay is representing the maximum value a consumer is able to pay for a certain service. The consideration of the consumers' willingness to pay and the corresponding influencing attributes could be an important factor of the electrification design planning of rural areas. Especially, because of the high costs of investments and the necessary remuneration

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[14] (Kanagawa & Nakata, 2008, pp. 2026 - 2027)

[15] (Khandker, Barnes, & Samad, 2009, pp. 22 - 23)

schemes. As rural electrification will develop to a commercial business the redeemable amount of money from the consumer will consider in their decision-making processes. [16]

Regulatory

Regarding the difficulties to provide economically feasible access to the electricity networks in rural areas, the regulatory entities and governmental institutions face the challenge to implement the right incentives or business models to stimulate investment-decisions. For the purpose of finance, rural electrification is not only funded with public funds. The institutions developed different remuneration and regulatory scheme to attract private agents to invest in these areas. E. Martiont and K. Reiche analysed within several case studies different regulatory scheme of archiving the above-mentioned purposes. They investigated the PAEPRA Program, that was a reform of the Argentina government within the framework of liberalization of the power sector. They divided the country into two different markets, one mainly related to electricity services in urban areas and the second one for rural off-grid customers. The electricity should be supplied and contracted within private rural concessions, that guaranteed the companies a 15-year lasting monopoly concession contract for a certain area received to the smallest willingness to accept, according to subsidies within auctions. The services were remuneration due to governmental set tariffs. [17]

A Peruvian approach was based under a regulatory framework, that enables small communities to form their own small enterprises with diverse ownership models. The local communities had concessions for their surrounding areas. Whereas the government had the possibility to occur as a financial supporter and partially subsidized the investments and the operation. At the same time, the concessions were limited by governmental regulation. [18]

In Cape Verde, in contrast, the concessions are not linked to a geographical monopoly structure. The concession owner can operate freely within his concession area. A 10-year contract ensures a sufficient timeframe to recover the investments. [19]

Besides the approaches of using a mixture of public incentives and private investments, some governments executed the electrification amongst other strategies by public interventions. Brazil, for instance, connected several parts of the country due to infrastructure investments to provide rural electricity access. [20]

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[16] (Entele, Emodi, Murthy, & Dioha, 2018, p. 1)
[17] (Martinot & Reiche, 2000, pp. 2 - 3)
[18] (Martinot & Reiche, 2000, p. 6)
[19] (Martinot & Reiche, 2000, p. 5)
[20] (Javadi, et al., 2013, p. 406)

Even though the challenges of rural electricity access are similar in most countries regarding the lack of universal access, their approaches are very diverse in strategy and the efficiency of the outcome.

Business

Access to electricity leads to significant improvement in socio-economic terms. The meta-analysis of 50 studies from R. Jimenez estimates an increase in several measured parameters. For instance, the school enrolment raises on average by 7%, the general employment by 25% and the total income by 30%. These improvements depend heavily on the country and the related framework, but their impacts are significant. [21]

Universal access provides the possibility of substituting the former used conventional electric or non-electric energy sources, which is most likely related to savings of expenditures. Therefore, the purchasing power of the local producers and population increase and leads to short-term productivity improvements and long-term economic growth, which implies capital distribution and poverty reduction. [22] The combination of the growing accessible income, due to less expensive fuels and lighting resources, and the economic and human capital are key drivers to stronger economic development. [23]

In addition, the markets of the network and generation technologies are in an early stage and a decrease in costs and an increase in efficiency is expectable. [13] Accordingly, the IEA is predicting a share of 60% of capacity provided by off-grid and stand-alone systems to gain additional universal access until 2040, being 66% of them by renewable generators. Several governments and institutions as the Indian government or the Asia Development Bank issue programs to electrify their region through these technologies. [13] Therefore, the combination of increasing income with decreasing technology prices might accelerate universal access aspirations worldwide. Furthermore, create several business models and enable attainment of the purposes.

Relevant off-grid solutions

Extending the power grid is not always the most effective solution since the unelectrified consumers are mostly distributed sparsely in rural areas where off-grid alternatives are usually less capital intensive. There always is a cost-benefit trade-off subjected to economic terms. The ethical and social objectives of the provision of social welfare and prosperity could often not be solved under pure economic terms. The meaningfulness of rational cost expenditure

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[21] (Jimenez, 2017, p. 3)
[22] (Torero, 2014, pp. 10 - 12)
[23] (Jimenez, 2017, p. 4)

must be considered, in order to guarantee self-carrying capabilities of purchasing power to the local population and continuance in operation and maintenance of the new structures. Therefore, additional infrastructure solutions and variable architectures must be used. A combination of grid extension designs, and the installation of off-grid systems seems to be a rational approach to provide universal access. The different network configurations are introduced in the following.

Wind generation

The implementation of wind, which is the main topic of this thesis, and the use of wind power generation provides some additional value when electrifying rural areas. Besides the possibility of substituting conventional fossil fuel driven generators the utilization of wind expands the configuration possibilities of generation structures. As a result, the performance of rural electrification systems could be increased, and diversified regarding the security of supply, reliability and widen the scale of available technical feasible architectures of generation systems and their adaptation to complex and variable local conditions of rural areas. Further advantages and challenges of wind power generation will be discussed in more detail.

Computer models

The high number of influencing factors and the complexity of the present conditions of the locations, constitute a detailed and variable base of the considerable information for the access systems architecture. Furthermore, the wide range of technical network solutions and a variety of generation designs and related costs of fuels and components are enhancing input factors. Additionally, the clear target of achieving universal access under the condition of technical and economic feasibility with, a minimum of environmental and ecological impact produces a problem with a lot of decision variables and parameters. It is necessary to apply optimization techniques to solve these problems. One powerful method is the utilization of computer models, which provide a variety of different approaches in the form of algorithms with diverse objectives and procedures.

The utilization of the computer model to generate an efficient and effective generation and network design could be supportive for public and private agents in order to achieve economic feasibility. The optimal result gives the regulator a tool to estimate the construction cost and strengthen their position within contract negotiations and provides the possibilities to introduce an efficient remuneration scheme. The private agents could provide a low-risk investment-decisions based on the determined design and get further incentives to develop business models and investments due to the decreasing uncertainty regarding the cost's structures and remuneration.

In the forthgoing several optimization techniques are reviewed. The Reference Electrification Model is the chosen tool to fulfil the thesis objective of implementing wind power generation.

Reference Electrification Model (REM)

The Reference Electrification Model provides a minimum-cost electrification solution for a large - scale area. This solution is usually a combination of mini-grids, stand-alone systems, and grid extension designs. The model deals with diverse scales regarding the number of contained individuals and sizes of the considered areas, as it occurs in a local and a regional model mode. In this context, the essential and subjected constraints regarding the technical power system and the user-related constraints are implemented and respected. REM uses heuristic algorithms to obtain a quasi-optimal solution. These algorithms can be adapted to cater to the specific needs of each region. The systems design of generation and network considers several generation technologies and different network components as existing grid extension, off-grid mini-grid, and stand-alone systems. [24]

In the end, it seems as rural electrification could be a powerful tool or mechanism to provide the Sustainable Development Goal 7 issued by the United Nations and as side effects some additional positive feedback on other development indictors. Rural electrification and all tightly related subjects are highly relevant, in particular methods, that provide an optimized approach.

1.3 Motivation

The topic and the framework of this master´s thesis is provided by the Institute for Research in Technology (IIT) from the ICAI School of Engineering at the Comillas Pontifical University in Madrid. The IIT and the MIT work together in the Universal Energy Access Lab. Within this cooperation, several publications and research papers are provided. One major development is the Reference Electrification Model, that was used in cooperation with different public institutions to reduce the lack of electricity access in the above-mentioned areas.

Within the schedule of the Master of the Electric Power Industry Program of the Comillas is mandatory to prepare a master´s thesis in order to complete the graduation. Fortunately, I got the opportunity to write the thesis in cooperation with the IIT in the Universal Energy Access Lab.

The electrification process of rural areas is an important purpose of several public and non-governmental institutions, organizations, and agencies and could provide an increase of

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[24] (Laboratory, 2018, p. 11)

development and wealth in these regions. The improvement and extension or the collection of further knowledge might enhance and accelerate this process.

Besides the fact that this substantive framework conditions of rural electrification highly corresponds to my personal interests the result of this thesis might be useful for further related research and potentially provide some progression of the Reference Electrification Model.

1.4 Objectives

The general objective of the present master´s thesis is the adaptation of the Reference Electrification Model, especially the enhancement due to the implementation of wind power generation.

The goals of the thesis are the following:

1. Elaboration of a state of the art regarding rural electrification and corresponding computer models
2. Development of a generation catalogue that contains wind power generators
3. The adaptation of the generation design procedure of the REM to include wind power generation
4. Verification of the functioning of the implementation of the REM adaptation through the execution of a case study

1.5 Research question

To reach the above-mentioned objectives the thesis addresses these research questions.

1. What are the main determinants of wind speed profiles and how could these be prepared to be utilized as input data for wind power generation?
2. Which technical parameters and components must be contained in a generation catalogue that enables wind power generation? What are the underlaying assumptions for the related optimization process?
3. How could these conditions be formulated?
4. What kind of impact of wind generation would occur in a case study?

The rural electrification is actual and an important topic of several leading research institutes, governmental and non-governmental entities. Related to the Sustainable Development Goal 7, the universal access and thereby rural electrification as one of the major drivers of the electrification of the remaining population. Consequently, this topic has a credible and plausible relevance for further research efforts and could possibly contribute a valuable part of the improvements of universal and the general wealth and life conditions.

2. State of the art

A deeper understanding and the development of a wider knowledge of modelling techniques regarding the rural electrification framework are essential to provide enhancements within this sector. The gathering of respective information and the reviewing on the current state will enable the development of solving approaches to execute the model enhancements. In order to follow this approach, this chapter explains the current status of the worldwide rural electrification development. We begin with a literature review that considers the different technologies. The variety of these technologies enables a flexible and diverse combination of the systems setups and a precise adaptation to the environmental respective circumstances. We also describe the available tools for determining an adequate solution or even optimal ascertainment of the structures of the system. The working and solving methods of the different tools are elucidated and the upcoming advantages and disadvantages nominated. Finally, the Reference Electrification Model (REM) is introduced and explained in further detail. The main goal of this thesis is the partial complementation of REM.

2.1 Rural electrification projects

The approaches to providing rural electrification are quite diverse and several technologies, constructions, and structures are used in the actual literature. Upcoming some examples of the current research applications.

M. Al-Sound and E. Hrayshat investigated the feasibility of wind power generation in five different rural sites in Jordanian with different environmental conditions of each area. They found out that some of the observed areas provide potential locations for the use of wind power generation. The surrounding environmental conditions such as the high availability of space and the open and plain terrain provided good generating conditions. Depending on the analysis the wind profiles of the areas and the distance to the national grid of some locations provide the essential necessities, to operate wind farms in economic and commercial terms to provide rural electricity access. To maintain operation in case of inadequate wind load they recommended a diesel power back-up unit as most feasible. [25]

In addition, S. Salehin, Md. M. Rahmann and A.K.M. S. Islam compared in their study the use of a solar PV – diesel – battery system with a pure diesel system in the northern part of Bangladesh. The present conditions contained a high distance from the national grid and a sufficient radiation amount to economically operate solar PV modules. They stated that the costs of energy of using a PV – diesel – batter system are slightly lower than using pure diesel generation, but the emitted CO2 emissions are significantly lower (~54%). Therefore, the use of this

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[25] (Al-Soud & Hrayshat, 2008, pp. 236 - 237)

hybrid-system is an alternative approach for more ecological energy, which corresponds to Bangladesh’s expansion targets. [26]

S. Linn and A. Ze Ya analyzed the possibility of the usage of a system consisting of solar – wind-diesel – battery hybrid energy system. They analyzed the feasibility of this configuration in a rural off-grid location in the center of Myanmar. Where around 70% of the rural population doesn´t have permanent access to electricity. [27]

Q. Hassan, M. Jaszczur and J. Abdulateef in contrast dealt with a similar system configuration in a rural area in the East of Iraq. This rural area has off-grid properties. These to model areas mainly differ in their environmental conditions, which finally results in different optimal hybrid system configurations related to the total net costs. [28]

While the Myanmar location has a rather uniform radiation distribution between 3 up to 5 kWh/m²/d in the whole year, the distribution of wind was quite diverse. It differs with low values of average monthly wind speed in the winter months around 2 to 4 m/s up to 10 m/s as the peak in the summer. [27]

However, the distribution of the renewable potential of the Iraqi location was another way around. The wind speed distribution is uniform over the whole year with values between 3,5 up to 4,5 m/s, while radiation was alternating. The winter months suffer from a lack of radiation with 3 kWh/ m²/ d. Between March and October, the solar energy profile reaches values within 4,5 to 7,5 kWh/ m²/ d. [29]

As a result of these differences, the systems of Myanmar consider much higher wind power generation in contrast to the Iraqi one. In both cases, a diesel back-up unit in combination with battery storages was necessary to supply electricity continuously during the whole year. The renewable energy generation was too volatile to provide the full year supply. The hybrid structures exceeded the use of pure diesel generation in both countries related to the cost and enabled a cleaner energy provision. [30] [27]

All the above-mentioned approaches have similar weaknesses. The provision of electricity in rural areas is always subjected to certain trade-offs. There is no perfect solution that works for every case. The supply with a diesel generator, that can provide the demand continuously and according to the requirements but has the drawback of high fuel costs and high emissions. Therefore, a substitution with more economical technologies is a major purpose to reduce

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[26] (Salehin, Rahman, & Islam, Techno-Economic Feasibility Study of a Solar PV-Diesel System , 2015, pp. 1220, 1223, 1228)

[27] (Linn & Ya, 2014, Vol. 3, Issue 10, pp. 2172 - 2176)

[28] (Hassan, Jaszczur, & Abdulateef, 2016, pp. 1 - 2)

[29] (Hassan, Jaszczur, & Abdulateef, 2016, p. 3)

[30] (Hassan, Jaszczur, & Abdulateef, 2016, p. 7)

costs and environmental impact. The use of pure wind or solar generation is limited by the intermittent character of these renewable techniques. The continuous supply without a diesel back-up unit or a storage device is currently not possible. Depending on the locational conditions these hybrid solutions could be a more economically efficient solution as seen before. But still, there are cost disadvantages of the production intervals of the diesel generator. The storage of electricity as a back-up in inconvenient conditions for renewable production could theoretically substitute a diesel unit, but this is not economically feasible regarding the relatively high cost and the limited storages capacity of batteries. Therefore, the research community is seeking possibilities to overcome the volatility and uncertainty of the wind and solar energy production within economical limitations.

The Alliance for Rural Electrification investigated an approach that is related to these necessities. Accordingly, the use of a small hydroelectric plant could enforce the previous rural electrification concepts. [31]

In contrast to wind and solar the energy production, with the hydro-generator is less volatile. The inflows of rivers could be almost assumed as constant. Therefore, this technology could almost provide base-load electricity. [32]

The Alliance for Rural Electrification carried out a case study in Colombia within a hydro-solar off-grid system structure. The system was installed within the outflow of a large-scale hydro plant to analyze the base load capability under the 100% availability of hydro production. As a result, it was investigated that the small hydro plant was able to substitute a diesel back-up unit or a battery storage device in this framework. In combination with the solar generation, this off-grid installation was able to provide electricity with 100% renewable technologies. [33]

The above-mentioned study shows that the run-of-river hydro plants might be enabled to substitute back-up diesel units. Even though the 100% availability of the hydro plant is not existing in every possible scenario. The combination with a storage device could be a possible renewable solution even in scarcities from wind and solar generation to provide continues energy. Additionally, as seen in the World Small Hydropower Development Report 2016 the hydro potential is spread all over the world, especially in developing countries. [34]

Finally, S. Salehin, A.K.M. S. Islam, et. all. Investigated the use of a hybrid system including a biomass generator in Bangladesh. The observed off-grid system in a small island in the south-east of Bangladesh. The Islands economy is mainly based on the rearing and use from cattle.

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[31] (Electrification T. A., 2015, pp. 12 - 13)

[32] (Electrification T. A., 2015, p. 7)

[33] (Electrification T. A., 2015, p. 13)

[34] (Organization, 2016, S. 11)

This led to a high amount of waste. Therefore, the use of this biomass provides besides the biomass power generation potential additional value in the disposal of the waste. The hybrid structure contains solar PV, a diesel generator, the biomass generator, and a storage device. After optimizing the model, they obtained significant results. In order to meet the total amount of demand, the biomass generator provides up to 82% of the electricity load. Followed by solar with 17% and diesel generation with 1% share. As seen in this result the systems energy supply is almost completely supplied by renewable power generation. [35]

The current status of the research work is quite diverse. Different system configurations are investigated and bundled with certain advantages and drawbacks. The hybrid system structure is heavily depending on the local conditions and, accordingly to the analysis of these conditions, it is essential to develop a suitable solution. Also, there is a trade-off between the conventional electric generators and renewable generation. The conventional ones normally have the advantages of lower investment costs and mature technology design in comparison with the higher investment cost of renewables and the smaller maturity of these technologies. Indeed, the renewables provide electricity at much lower variable costs and without or at least much lower emission levels. Admittedly, the uncertainty regarding renewable technologies as wind and solar and the resulting alternation energy output is not finally solved. A combination of conventional and renewable configurations provides a reasonable solution, but there is still room for improvements. A more ecological approach could be the implementation of storage devices. But here the lack of maturity of the storage technologies and the strongly economically limited capacity could not substitute back-up diesel units in every circumstance. Therefore, alternative approaches might compensate for the drawbacks of diesel generator or storage devices. The less uncertain renewable technologies as hydroelectric and biomass generation have the potential to provide sufficient and continuous baseload capacity to overcome the drawbacks, but this is also limited under certain conditions. The properties of the location as the availability of waters or biomass sources, that are dictating the used amount of them.

In the end, the configuration of the system, the choice, and combination of the used technologies must be adapted to the present conditions of the location. Hence the system architecture should be developed under the use of optimization techniques that provide the most efficient design and cost structure. One logical approach is the utilization of optimizing computer models, that are capable of processing the environmental conditions and cost parameters.

In the upcoming part, different computer models and tools are introduced and explained regarding their procedure, effects and results.

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[35] (Salehin, et al., 2014, pp. 1,2,6)

2.2 Computer models

Optimization is general is applied to improve tools, organization structures or total systems in order to reduce the duration or the costs to raise the precision of contained processes. Whereas a certain real system is transformed into a modelling, which should picture the desired problem as exactly but simple as possible. [36]

To provide feasible universal access the usage of computer models with respect to optimization techniques is a rational and efficient approach. The problem structure of rural electrification includes several sub-problems that must be solved independently. Therefore, the existing number of techniques are high and diverse.

Regarding grid planning optimization, there are three main problem structures. The power generation selection and sizing, the siting, and scheduling. The generation selection and sizing process seek for a design that provides an adequate level of generation and storage in order to supply the peak demand under cost efficiency and reliability in a certain system condition. The siting should solve the problem corresponding generation allocation and the structure of the network under cost and losses efficiency and reliability. The scheduling problem is related to the operational planning of generator and storage units in order to cover the systems load at minimal costs, environmental impact, and maximum quality.[37]

The problem-solving mechanisms are diverse and strongly related to the treated optimization problem. General speaking the approaches could be divided into a selection of structures. Regarding this thesis, the main important algorithms are the iterative mathematical optimizations and heuristic solving methods.

The next subsection provides a table and a description of the available tools related to power generation and network sizing are mentioned and regarding the framework of rural electrification.

Computer models	
Rural electrification tool	• LAPER • Network Planner • OnSSET • InTiGIS • GEOSIM
Generation sizing tools	• Hybrid2 • iHOGA • HOMER • DER-CAM

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[36] (Grimme & Bossek, 2018, pp. 1 - 2)

[37] (Gamarra & Guerrero, 2014, pp. 415 - 416)

Network design tools	VIPOR RNM NPAM Aneto
Other tools	RetScreen Master4all PVsyst

Table 1: Computer models

2.2.1 Rural electrification tools

LAPER

The Rural Electrification Planning Software (LAPER) was invented by Electricité de France (EDF) and the Agency for Environment and Energy Management of France. [38] It provides a solution of rural electrification for a large-scale scope. Under the use of geographical and socio-economic data, different village types are created. The purpose is to provide a basic structure to use standardized electrical equipment for several demand types. The add-in of different investment and operation cost structures within the system results in a high number of standardized combinations, that could be used in the different village types. In order to compare the different outcomes of the configuration of the systems regarding the network composition, different solutions occur. LAPER provides not only a costs-based solution for the large-scale planning also, a suitable and sustainable equipment structure. [39] In comparison to REM, LAPER could process more generation technologies, but the catalogue components are less diverse. [40]

Network Planner

The Network Planner is an open-source model developed by Columbia University. The purposes are to determine the best solutions of an existing grid extension related to minimal costs. To determine the solution a Minimum Spanning Tree is used. [41] The model considers also the three different network modes but with much less resolution regarding the customers level. The lack of precision of the demand structuring provides less detailed networks information. Therefore, the usability as a network design tool is limited; the costs and operational data is the main outcome, less the technical design. [42]

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[38] (Cotterman, 2017, p. 26)
[39] (Fronius & Gratton, 2001)
[40] (Cutillas, 2016, p. 3)
[41] (Laboratory, 2018, p. 8)
[42] (Li V. , 2016, p. 19)

OnSSET

The Open Source Spatial Electrification Tool (OnSSET) was developed by the KTH Royal Institute of Technology. In order to provide a cost-efficient electrification solution, with the three network modes. OnSSET considers spatial properties related to the network, energy potentials, distribution of population and others. The main purpose is to enhance the existing grid with geospatial data to provide the most economical strategy. [43]

InTiGIS

The IntiGIS tool was developed at the CIEMAT but reviewed and enhanced by the Energy Centre KNUST in Ghana. The tool considers general data of the observed area as population and power line distribution and density and raster of solar radiation and wind speed. [44] The tool provides minimum LCOE regarding electrification. [45]

GEOSIM

The GEOSIM tool was developed by the Innovation Energie Développement in France in order to form an adequate decision-support model to enhance the rural electrification approach in several countries. This tool has four modules that include a spatial analysis and planning phase, a load estimation, optimization of supply and the sizing of standalone systems. The spatial analysis considers different social and economic development parameters to optimize them in the planning stage concerning the occurring demand estimations and the optimal generation and network design. [46]

2.2.2 Generation sizing tools

Several tools deal with the design and the sizing of the power generation in general. The solution of the related problems should be enforced to provide a sufficient power generation to meet the demand properties even in peak hours in the observed location. The generation sizing is mainly optimized under the condition of maximal cost efficiency, high system reliability and the lowest environmental impact possible. The generation sizing approach is targeting for a strategic solution to the problem to fulfill long-term system requirements. [47]

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[43] (Analysis & Technology, 2019)

[44] (Gaisie-Essilfie, 2019)

[45] (Laboratory, 2018, pp. 7 - 8)

[46] ((IED), 2010, p. 10)

[47] (Gamarra & Guerrero, 2014, p. 415)

The generation sizing tools could be separated into different subproblems. On the one hand the Hybrid system generation design tools, on the other the Hybrid system simulation tools.

The Hybrid System simulation tools analysis the performance and proceeding of an existing generation design in order to achieve some information regarding the users of the system. [48]

Hybrid2

One representative is Hybrid2 software. Hybrid2 was developed to analyze the behavior of diverse hybrid power systems. The simulation tool could process several power generation technologies like wind, solar PV and diesel. In addition, different types of load, storages and conversion devices in an AC or DC configuration. Hybrid2 provides an economic system analysis based on a long-term operation in high detail. The model uses a solving method based on a probabilistic computer model, that uses input data of a time series structure related to the above-mentioned technologies environmental conditions. The economic analysis is provided in high resolution and could be feed with a variety of more precise input data as taxes or additional load data. [49]

The Hybrid system generation design tools, in contrast, provide a generation design solution for an existing demand structure.

iHOGA

The improved Hybrid Optimization by Genetic Algorithms (iHOGA) was developed by the University of Zaragoza and deals with the power generation of renewable energies of hybrid stand-alone system structures. iHOGA provides generation designs based on several generation technologies like solar PV, wind, hydroelectric and conventional fuel generators. Also, a variety of inverter, storages and charger devices could be assimilated with related cost and environmental climate data. The energy load could be modeled in AC or DC and simulated and optimized in a stand-alone configuration. In addition, the connection to the grid of the whole system could be considered in AC. iHOGA uses a multi-objective optimization structure to provide the demanded design output. The genetic algorithm offers an optimal solution of the generation sizing within short computation times. [50] [51]

HOMER

The worldwide most used generation design tool is the Hybrid Optimization Model for Electric Renewables (HOMER). This tool was developed by the National Renewable Energy

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[48] (Cutillas, 2016, p. 4)
[49] (Center, 2019)
[50] (Zaragoza, 2019)
[51] (Kumar, 2019, p. 4)

Laboratory (NREL) in the USA. HOMER can perform a simulation, optimization and sensitivity analysis of different generation technologies configurations. Considered technologies are similar to the iHOGA approach. In addition, HOMER could process biomass generator and provides beside an economic a technical analysis. Also, different system design as stand-alone and grid-connected variants are processed. The input data contain several cost information regarding installations, replacement and operation, and maintenance. The sensitivity analysis allows a comprehensive determination of multiple influencing factors of the cost structure, the related generation technologies, the environmental conditions, and the load patterns. The main advantages of HOMER are short computation times and easy handling. Additionally, the wide variety of simulation options expand the analysis possibilities. The drawbacks are the non-utilization of dynamic aspects regarding the voltage fluctuation and the lack of import opportunities of average time series data, which would make the tools solution even more precise. [52]

DER-CAM

The Distributed Energy Resource-Customer Adoption Model (DER-CAM) is a tool based on a mixed integer problem in General Algebraic Modelling System (GAMS) software and solved with CPLEX. This tool was developed by the Berkley Lab. The DER-CAM tool provides a design of distributed generation subjected to minimal annual costs and the load requirements. The objective function is optimized under the conditions to meet the total amount of demand in every hour. Therefore, the hourly generation dispatch is provided as a result of the optimization process. [53]

2.2.3 Network design tools

The network design tools determine optimal network structures in relation to the observed locations or regions. In order to provide an accurate framework for further procedures, the network design tools are based on different approaches and methods.

VIPOR

The Village Power Optimization Model for Renewables (VIPOR) determines an optimal system design for isolated power systems. This tool considers several consumer connections points from a starting point. Iteratively new connections are added, or others are removed in order to get an almost optimal solution. [54] The VIPOR tool provides an optimal solution based on costs and revenues. [55]

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[52] (Kumar, 2019, p. 3)
[53] (Bailey, Creighton, Firestone, Marnay, & Stadler, 2003)
[54] (Cutillas, 2016, p. 3)
[55] (Rout & Parida, Volume 4, Issue 12, December 2013, p. 129)

RNM

The Reference Network Model (RNM) is used to plan the extensions of large-scale distribution networks from scratch, the Greenfield, or within an existing network (brownfield). RNM considers topographical data representing the composition of the surrounding terrain properties. A standardized equipment catalog including the different voltages level technologies and the related substation, transformers and other necessary components and the demand related geographical data points are considered in the solving procedure. RNM provides technical and economical parameters of the used systems components as well as their localization within the observed configuration. The final results also include precise costs data and equipment distribution for the different load points. [56]

NPAM

The Network Performance Assessment Model (NPAM) was developed to control the financial earnings of a distributed system operator by the Swedish Energy Agency. The main approach of the tool is the correlation assumption of the distribution network with certain customer value. [57] The tool uses several input data as system and customer data, reliability indices and a reference representation of the network to determine a debt rate, that will be the basis for regulatory remuneration and revenue supervision. [58]

Aneto

The Aneto tool was used to determine the incurred cost of a utility that supplied electricity services within the distribution network in the context of the liberalization procedure. The main assumptions are based on building up the network from scratch and a consideration of the electrical demand and the related geographical and further technical customers data. [59]

2.2.4 Other tools

RetScreen

The Renewable Energy Technologies Screen (RETScreen) was developed by the Ministry of Natural Resources of Canada. In order to evaluate the environmental and economical costs. The RETScreen tools use several input parameters as the systems properties, economic parameters and climate data from a database, that covers worldwide weather condition information. The tool is capable of performing economic and technical analysis regarding electric power generation structures from solar PV and wind in combination with a storage device.

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[56] (Domingo, 2019)

[57] (L. Bertling & Wallnerström, 2008, p. 1)

[58] (L. Bertling & Wallnerström, 2008, p. 3)

[59] (Conejo, Bartolome, Exposito, & Montanes, 2007, pp. 1 - 3)

The major advantages are the simple handling with EXCEL sheets and the strong performance of the financial analysis. Admittedly there are certain disadvantages: The tool is quite limited in considering different generation technologies and the applied input data possibilities are limited. [60]

Master4all

The Master4all model is used to analyze energy roadmap to universal access. The model determines the solution within a partial equilibrium linear program model. The optimal supply is calculated in a time horizon of one year under the condition to find the minimal sum of the total private energy costs and the social costs of CO2 emissions. [61]

PVsyst

The PVsyst is a tool that performs sizing, simulation and data analysis regarding stand-alone, pumping, grid-connected and DC-grid systems. This model uses system modules and metrological and locational data. The capabilities are related to economic and technical analysis within a PV system and give output data about the behaviour of the used components, in the form of the PV arrays restrained properties and inverter efficiencies. Drawbacks of this model exist in the occupation of errors within the simulation. The major advantages are the used of real running parameters with high precision and the identification of systems design weaknesses. [60]

2.3 Introduction of the Reference Electrification Model

The Reference Electrification Model calculates a minimum-cost electrification solution for a given demand in a certain environment with diverse scales regarding the number of contained individuals and sizes of the considered areas. In this context, the essential and subjected constraints regarding the technical power system and the user-related constraints are implemented and respected. The solving method could be executed under a variety of constraints and delivers an electrification plan within the chosen framework which is usually a combination of grid-extension designs, mini-grids, and stand-alone systems. [62]

These three electrification modes provide different expansion solutions. The grid expansion constitutes an extension of the available grid structure. The supplied electricity is injected by large-scale generation and feeds the load point through transmission and distribution network services. The mini-grid solution is a local, small to medium scale power system without a connection to the main grid. The points of demand are supplied due to a local distribution network

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[60] (Kumar, 2019, p. 4)

[61] (Gonzalez-Garcia, Perez-Arriga, & Moreno-Romero, 2014, pp. 1 - 2)

[62] (Laboratory, 2018, p. 11)

that is a conglomerate of several consumer types of the nearby surrounding areas. Normally, these networks are supplied by local renewable generator technologies or diesel generators. The stand-alone system supplies only one single consumer. The generation composition is highly depending on the consumer types such as domestic, business or institutional. [63]

To compute the network costs and the network structure of the three network designs, REM uses a network design software, which is the Reference Network Model (RNM). The network designing process must be executed various times by the RNM to obtain the necessary numbers and structures of the optimal network design of the REM. Depending on the existing grid or a new grid implementation, the greenfield or brownfield approach of the RNM is used. The information based on the determination of the network structure considering a catalogue that includes network components. The RNM model also contemplates the topological properties of the observed environment. The features of the terrains contain different slopes and altitudes. To model, the terrain parts that are not usable for network expansion or are only inefficiently deducible, forbidden and penalized zones are defined, which lead to no or less consideration, because of the cost-minimizing method. Additionally, there are certain limits within the demand areas, which are implemented similarly. [64]

REM could be used in two different modes. The first mode is a large-scale planning strategy for whole countries or large regions. The second manifestation is a local mode that is used to receive an off-grid design for a village or a group of buildings. The regional REM provides a solution of optimal generation and network design beneath the use of all three grid modes mentioned above. The local REM in comparison delivers an optimal design for microgrids or isolated systems. [63]

The static nature of the REM regards only a single future year as the observed horizon and solves the occurring optimization problem for the estimated and corresponding demand of the same year. Therefore, the demand pattern of an initial year and the related growth rate up to the relevant year must be provided. The time horizon between the initial and a final year is defined to set a reference for the decision-making point and the occurrence of the systems expansion execution while meeting a related constraint. [65]

The solving method of the REM is based on heuristic methods. The minimized total costs are divided into the actual incurred costs which include the cost components for investment, operation, maintenance, and management plus a penalty for social costs that are related to loss of

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[63] (Cotterman, 2017, p. 24)
[64] (Laboratory, 2018, p. 12)
[65] (Ellman, 2015, p. 10)

welfare. The decrease of welfare is caused by the non-efficient level of quality of service and limitations of the potential added value of the new connected electricity. [64]

2.3.1 Purpose

The purpose is to calculate an optimal or quasi-optimal technical network and generation design of the electrical modes and their related costs, which lead to an estimation of the total project's costs. These estimations enable the user to analyse and assists the decision-making and planning process for electrification of rural areas. In order to reach the objectives and to intensify the expressive capability, the efficiency and the effectiveness of the universal energy access expansion of inadequate connected or isolated locations. The further development of the assisting REM tool is an important goal of the Energy Access Research Group of the MIT and the IIT. [65]

2.3.2 Input data

The REM model uses different types of input data to compute the desired results.

The first one contains information about the locality. Mainly the technical components of the existing network with the segmentation of the lines, their voltage level and additional elements regarding electric networks as substations. Furthermore, the different manifestations of consumption. The different types of building and customers and their load profiles and patterns. Finally, the shape of the surrounding environments, geographical and topographical data. This data is contained in solar output properties, the formation of the terrain, elevations levels forbidden areas (which lines cannot cross). The second one includes data within a catalogue, that contains the technical components for the generation and network of the modes of the different systems with their related cost parameters. The network components mainly consist of different types of lines and structures of the different voltage levels. The components of the other systems modes include several generator types and different power electronics and storages devices. Additionally, input data is always subjected to an individual circumstance and their related structures. [66]

Regarding the model´s modes, the regional or the local one, the input data slightly differ. The regional REM includes the following.

The regional REM as seen before is used to determine the strategy of electrifying a large area or even whole countries. Therefore, the existing grid and potential grid enhancement within the three grid options, in an optimizing way, are the main pillars, which are founded on the input data. The REM´s input data types are the equipment catalogue, the local information, and the

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[66] (Laboratory, 2018, pp. 13 - 14)

user options. These types are representing the above-mentioned input data types. Only to add are the user options, which are parameters, that define several specifications and influence the model's operation. The local REM inputs are more based on small-scale and are less aggregated, but also are considered by the REM in order to exercise its tasks. [67]

The local REM as shown in the Master´s thesis from T. Cotterman uses input data on the level on regions and the customer nodes as the following:

The most important inputs on the local REM level are according to the consumption, the weather, the financial conditions, and the component catalogues. [68]

Consumers

The consumer input data bundles the geographical positions of the consumption's types with their related demand patterns within a specified resolution. Further, details correspond to the daily load duration schemes and other demand precising information.

Weather

The input data regarding weather is directly linked to a change in the consumption behaviour, for instance, temperatures intervals. Herewith the alternating of temperature levels leads to the switch-on or switch-off of heating or cooling devices. In addition, the hourly radiation level of a region is considered to determine the solar potential generation output. Furthermore, as a purpose of this thesis, daily wind profile should be included to identify wind power generation outputs.

Financial

The relation of the design of the system with cost data and reception of an economic efficient result requires several financial inputs. For instance, the discount rate of the invested volume, the average diesel costs, and the penalties, representing the cost of non-served energy.

Catalogues

Two components catalogues are used in LREM. Both containing the precise data of the technical components and their subjected cost data. The generation catalogue includes the techniques regarding solar, diesel and potentially other generation and different power electronics as charge controllers, inverters, converters, and storages devices. The network catalogue, however, contains network components as lines, conductors, transformers and protection devices of different voltages levels.

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[67] (Cotterman, 2017, p. 28)
[68] (Cotterman, 2017, p. 43)

The differences between REM and LREM input data are mainly in their observed scale and the level of aggregation. On a large scale, the aggregation and conglomeration of data are higher to not occupy too many computational capacities; on small scale, the required resolution of the data is more accurate to provide more details and precise outcomes.

2.3.3 Structure of REM

The imposition of data is the first important step in the utilization of the REM. The purpose of the imposition is the gathering of the necessary input data of the observed area. With the usage of several tools regarding data types as the composition of the surrounding nature, different customer types and representative demand data is collected to abstract patterns of consumption. [69]

Within this, the organization of data is referring to different geographical levels as pointed out in the master´s thesis from D. Ellmann. He mentioned the prior data level of the studied area, that constitutes the complete expanse the REM deals with. The main data is corresponding to the study area. The division of these areas into sub-division allow modelling limitations and enclosures of secondary constraints, which could be representing administrative conditions and regulations. Regarding the efficient allocation of the resources of computation, the sub-districts are divided further. The definitions of regions as subordinated units provide the feasibility of solving the sub-district within the subdivision. Additionally, the geographical regions are resolute as customer nodes, that are representing the load points. [70]

Depending on the scope of the analysed areas the input data must be provided on the different geographical levels.

The architecture of (regional) REM could be separated into five main processes, that are introduced upcoming. The local REM, that is an extraction from the RREM, works slightly different and is explained afterward.

Data processing

The first part is the data preparation or processing. This part contains the generation of the necessary input data. As the determination and localization of the demand points as consumers or buildings. Additionally, the properties of the terrain and demand patterns must be prepared in order to get used by the REM. [71]

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[69] (Laboratory, 2018, p. 12)

[70] (Ellman, 2015, p. 13)

[71] (Laboratory, 2018, p. 13)

Micro-grid generation design

To execute the REM and obtain the most effective generation design possible, the generation and storage capacity of each potential customer or customer group must be optimized determined under their variety of demand profiles. In order to gain computational resources and accelerate the computation within the optimizing procedure, these capacities are ascertained in advance as pre-selected dispatch strategy design. These strategies contain several combinations of different representative consumer types generation designs subjected to their individual demand patterns and are captured in the look-up table. These quasi-optimal and approximated solutions could be interpolated for future estimations on generation costs within the clustering process of potential local micro-grid consumers types. [72] [73]

Clustering

The clustering process is subjected to the purpose to determine the best combination of consumers to form candidate mini-grids and grid extension designs. The main idea is to bundle several similar customers into a cluster if the expected connection costs of the cluster are lower than the costs of a separate connection. Therefore, besides the temporals savings, the connection is even more effective related to costs estimations. The precision of the estimated costs is the key factor for clustering decisions. [72]

Final design

The final design is based on the evaluation of the clustering structure. The clustering is provided within the RNM determination, which provides the cost-optimal network result. Afterward, REM computes the most efficient matching combinations of the different network modes. While this processing grid clusters are added or removed from the design of the system until the best solution is reached. [72]

Post-processing and reports

The final step is the post-processing and reporting. Whereas additional information besides the optimal design is provided within reports and data sheets. [72]

Further information and a more precise description of the different step could be found for instance within: (Laboratory, 2018), (Li V. , 2016) or (Ellman, 2015).

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[72] (Laboratory, 2018, p. 13)

[73] (Li V. , 2016, p. 22)

As slightly mentioned in the overview the local REM models differ from the regional one. The purpose of this model is the provision of the off-grid systems design for a limited network size or demand sphere in a most efficient and cost-effective way. Even the similarities of the regional and local REM mode, the latter could be used independently. In contrast to the regional REM, LREM does not use the large-scale assumptions, that are necessary to manage the trade-off between computational time and systems design precision. Also, it does not include the demand clustering and not necessarily uses pre-determined look-up table; it provides the optimal network and generation design to receive the generation-demand-balance with the installed generation and storage capacities and computes precise technical and financial data as output. [74] Furthermore, to give a more detailed perspective the most significant differences of the REM and LREM are described in the next paragraph.:

LREM is not considering the pre-determined network and generation options, which includes the assumption to build the generation and network from scratch. That is equivalent to ignoring the existing grid. The assumption of the required connection of every consumer to the off-grid structure ensures a not significant impact of the status of electrification of the costumer. Also, the supply cost only influences the generation design of the isolated microgrid and not the whole systems generation solution. Lastly, the potential economies of scale impacts are not relevant on the microgrid scale, in contrast to the high importance of the locational conditions of nature. [75]

2.3.4 Output data

The obtained outputs are related to REM architecture. Each one of the steps mentioned above is producing intermediate results. The data impositions process provides the necessary output for the following pre-design of the micro-grid generation strategy. The generation design provides the design for each customer type within its network space and forms the basic data for the further optimization procedure. The clustering of the demand side is an aggregation of the total load points into several groups. As the output from the general optimization process a final design occurs with precise data regarding the key issues of the network and generations design. Additionally, the post-processing step provides accessory information and reports for further development of the results. [76]

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[74] (Cotterman, 2017, p. 39)
[75] (Cotterman, 2017, pp. 43 - 44)
[76] (Laboratory, 2018, pp. 49 - 51)

2.3.5 Status quo regarding the generation

The current architecture of the REM model regarding generation technologies is shown in Figure 2.:

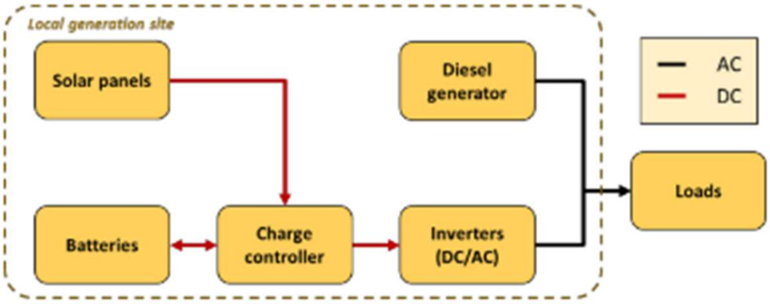

Figure 2: Current REM microgrid architecture [77]

Figure 2 shows that the current model contains two different generation technologies. The diesel generator that supplies alternating current and a solar PV module that provides direct current. The solar panel is coupled with a storage's device via a charge controller in order to operate the charge and discharge procedure within the direct current lines. A DC/ AC inverter is transforming the direct current into alternating current to feed the systems load.

The actual model of the generation design considers 6 different components. the architecture includes a single diesel or solar units, a combination of diesel and solar units, each diesel and solar with a storage's device and finally the design in Figure 2 with both generators and a battery. [78]

The addition of further generation technologies such as wind, hydro or biomass could improve the REM generation design and provide more adaption possibilities to different rural areas conditions.

Further conditions, purposes and determination methods such as the scaling axis of the generators and the evaluation processes regarding the REM generation systems structure are defined and explained later in order to bundle them within the additions related to the purposes of this master´s thesis and to provide a clearer view of this process.

The approaches and determination techniques for rural electrification tools are very diverse. Each tool has some advantages and disadvantages, but there is no tool that clearly outperforms the remaining ones in every aspect. Therefore, the improvement and enhancement of the existing tools will provide more precise results and systems designs in order to archive the defined targets. Indeed, the REM model is a powerful tool, but also, this will increase the

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[77] (Laboratory, 2018, p. 19)
[78] (Laboratory, 2018, p. 36)

operational usability, severity of results and the capability to an include representative and realistic conditions. Therefore, the addition of wind power generation into the generation block of REM is the main goal of this thesis.

3. Problem setting

The worldwide wind formations contain a high amount of stored energy, which could potentially be used for the generation of electricity. Besides, the zero emissions during electricity production, the current technical equipment is mature and in comparison, with other generation types low or neglectable in operation costs. Furthermore, the components are having low-maintenance needs and are installable in small or large production scale. It is obvious that wind power has the potential to provide significant benefits to the hybrid-system approach for rural electrification. In order to achieve an implementation of wind generators within REM different data must be accessible. One of the most important data is the wind speed profile distribution, which provides basic information to determine the wind turbine power output. In this regard, the main influencing factors on wind speed must be analysed and other important determinants must be developed. Especially, in the context of local small-scale generation, this is of particular importance.

The third chapter contains a discussion about some problematic aspects of wind power generation in the framework of rural electrification. The consideration of the major implications and corresponding parameters are developed and analysed to localize the problematic issues. However, first beginning with a brief overview of the potential benefits and advantages of the utilization of wind power. Followed by an introduction of the dependencies of wind power generation and the related occurring influencing factors and the processing possibilities. Often the necessary data is not available in the observed regions. This is even more often in rural areas or countries with lower development levels. Therefore, the usage of different statistical, interpolation or extrapolation methods is rational to gather and analyse the scarce data available. Accordingly, an explanation of actual techniques to represent the properties of the wind and finally, the general definition of the importance of wind power generators and a mathematical representation of wind energy conversion.

3.1 Wind speed properties

The main driving force or the existence of the occurrence of wind is based on solar radiation or solar energy that the sun is emitting. This amount of radiation is transformed into energy and is warming the earth’s surface. In this regard, the use of wind energy could be interpreted as a non-direct or indirect use of solar energy. Due to the high diversity of the earth’s relief and geography, the solar absorption patterns of different regions are quite varying. These lead to diverse values of the pressure, the density and the temperature of the atmosphere in different areas. These spreads between the properties, lead to compensation or balancing the movement of the air mass. Even additionally strengthened by the influence of differences within night and day conditions. [79]

Next, to the air movement due to the rebalancing of the differences of winds properties, the Coriolis-force constrains the rotation of the earth's hemispheres air mass in contrary directions. Supported by another impact on wind movement, an effect that occurs in medium height. A spiral movement, that takes place when the distance of an air particle to the rotation axis of the earth decreases. The speed of the particles increases due to the law of impulse conversation with a smaller distance to the axis. [79]

The current state of the art of wind power generation technologies transfers wind energy into electric energy in a maximum height around 200 m. The wind conditions near the surface are beside the global influencing factors determined by the roughness and friction of the terrain and certain objects on the surface. Therefore, the actual values of wind speed, heavily depend on the local conditions. For instance, the texture of a valley or a mountain channels the wind and accelerate it, which would boost the level of the withdrawn energy. A forest, however, would slow down the wind speed due to the higher friction value and reduce the potential energy withdrawal. Therefore, the existence of wind and the value of its properties depend on different conditions concerning global or local scale. [80]

Today the utilization of wind energy mainly is focused on producing electricity. Different approaches as only using mechanical energy are rare. The transformation into electricity provides the opportunity for universal usage and application of wind power generators. The architecture and structures could be tuned finely to adapt to the prevailed characteristics. The habitual use could be roughly divided into two main types. The first mainly describes the combination of multiple big generators with a high installed capacity to form a composite power plant in order to provide electricity. In the framework of this thesis, this appearance type is not further relevant. [81]

The interesting usage of wind power in the context of rural electrification is the use of smaller generators within off-grid systems. The utilization of wind energy provides several advantages, but also some disadvantages.

The purpose of electrifying the areas without access only using wind power is until today not feasible. To deal with the difficulties of the provision of permanent electricity supply to supply the total demand at any timeframe, a storage device or an alternative, normally conventional generator, is necessary to guarantee the security of supply in case of not sufficient wind

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[79] (Hau, Windkraftanlagen, 2016, p. 558)
[80] (Hau, Windkraftanlagen, 2016, p. 559)
[81] (Hau, Windkraftanlagen, 2016, p. 699)

conditions. According to these the actual storage technologies are limited in their capacity and therefore, limit the size of potential load amount that could be fed regularly. This might be solved in the future when more powerful and economic storage techniques are developed, till then the wind generator usage takes place within hybrid systems. These represent a structure that combines different generation types to deal with the unique load type properties of the rural off-grid systems. [82]

Due to the fact that almost all hybrid system contains a back-up diesel unit to guarantee the security of supply in lack of renewable electricity, the implementation of wind-power generators adds additional value to the hybrid system. On the one hand, the systems architecture could enable substitution of the diesel aggregate. This means that the wind power generator could supply the load in high wind conditions alone or at least in combination with an additional storages device to flatten the demand peaks. In low wind conditions, the diesel generator is producing. On the other hand, the use of both generators in parallel could be an alternative approach. In this case, the diesel generation gets reduced to a certain level depending on the actual wind conditions. This leads to savings regarding the high fuel costs of the diesel generator. Also, the emission output could be reduced drastically. Therefore, the main advantages must be seen related to the savings of costs due to fuel usage and less environmental impact. Furthermore, depending on the actual generation design further advantages thru technical control might lead to more efficient operation and additional costs savings and enhancement of quality of supply.[83]

3.2 Main influencing parameters and determinants

As mentioned before the properties of the wind depend on a variety of different influencing factors. Besides the influence of large-scale wind patterns especially the local conditions of observed areas are relevant for the concrete distribution and values of the wind. In order to determine the local conditions to estimate the potential wind energy production, the calculation considers both parts. In particular, the local determination is key to obtain a realistic result. In this regard upcoming some relevant parameters that should be considered.

A first parameter is the roughness of the terrain. This parameter represents different types of objects that could be buildings, vegetation as trees or plain surfaces. The roughness mainly points out the relation between the height of the object and the surface that is touched by the wind concerning an average horizontal surface in case of homogeneity of the objects. According to this the roughness of a city with multiple buildings is high and the roughness of a flat and

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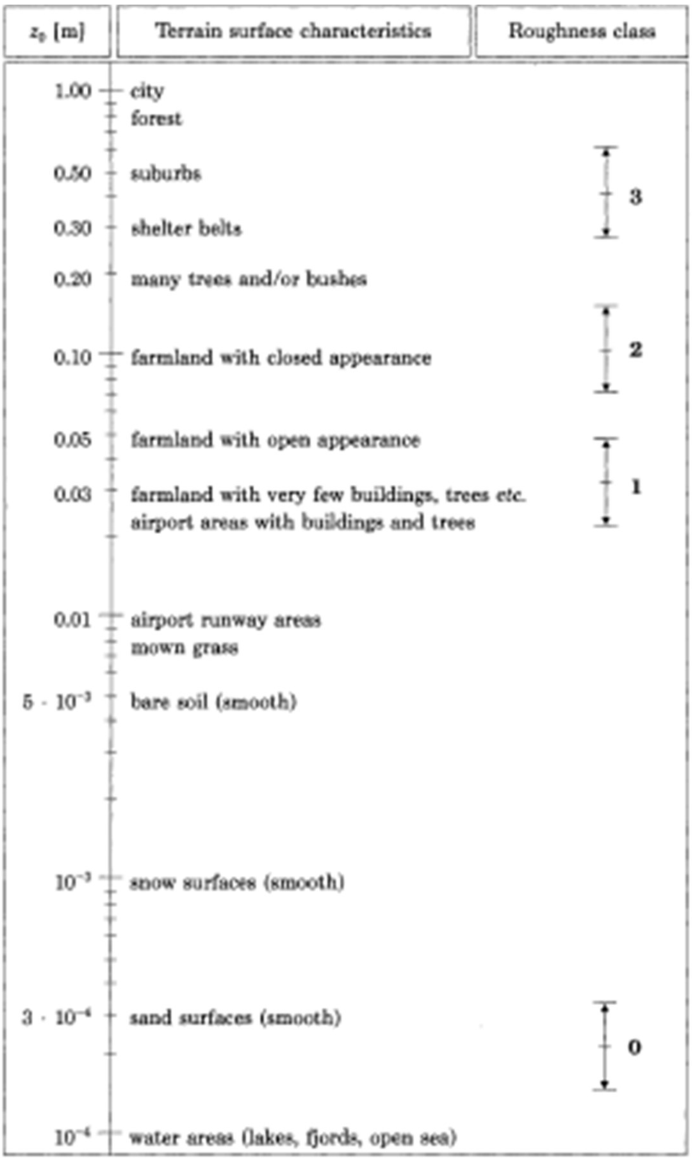
[82] (Hau, Windkraftanlagen, 2016, pp. 700 - 701)

[83] (Hau, Windkraftanlagen, 2016, pp. 719 - 720)

plain landscape and the sea or a lake is low. This empirical relationship could be improved due to additional assumptions in the case of specialties that could be seen in the European Wind Atlas. [84]

Some examples of these factors' values could be seen in the figure 3 below.



z_0 [m]	Terrain surface characteristics	Roughness class
1.00	city forest	
0.50	suburbs	3
0.30	shelter belts	
0.20	many trees and/or bushes	
0.10	farmland with closed appearance	2
0.05	farmland with open appearance	
0.03	farmland with very few buildings, trees etc. airport areas with buildings and trees	1
0.01	airport runway areas mown grass	
$5 \cdot 10^{-3}$	bare soil (smooth)	
10^{-3}	snow surfaces (smooth)	
$3 \cdot 10^{-4}$	sand surfaces (smooth)	0
10^{-4}	water areas (lakes, fjords, open sea)	

Figure 3: Overview of roughness factors [85]

The second parameter is related to the decrease in wind speed behind an object. This objects parameter provides a kind of protection or wind shadow in contrast to the roughness, that measures the deceleration of the wind. This parameter depends on the distance and height of

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[84] (Department, Troen, & Petersen, 1990, p. 41)

[85] (Troen & Petersen, 1989, p. 58)

the object and the measuring point and, on the length and porosity of the object. [86] The following figure 4 shows the reduction of wind speed in percent due to the object.

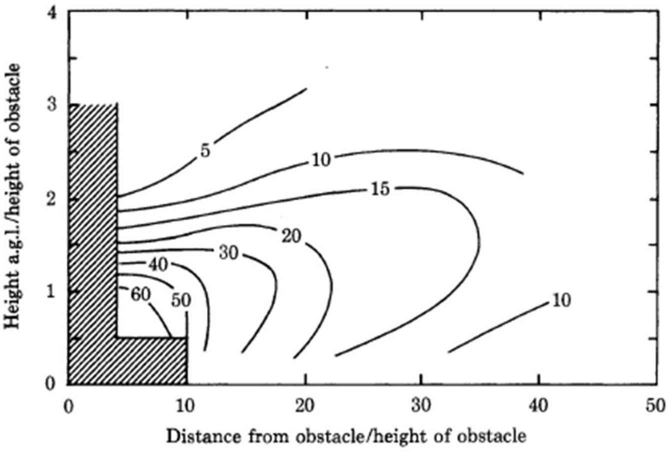

Figure 4: Wind decrease factors [87]

The third parameter is the topography of the terrain. The variation of the height as hills, for instance, could have a high impact on the wind speed depending on the positioning of the measuring point. On the top of a hill, the wind speed could be accelerated up to 80 %, in front or behind the hill a deceleration effect could be around 20 – 40 % in comparison to a wind speed distribution without the hill within other things held constant. [88] The figure 5 below points out the increase in wind speed provided due to a higher positioning in the terrain of the measuring point. The acceleration is drawn in its wind speed profile distribution.

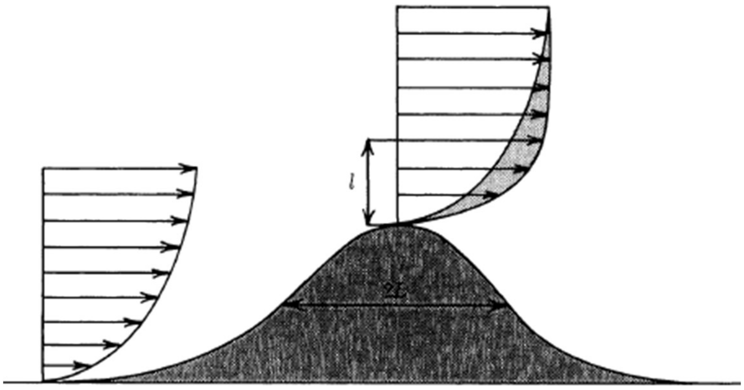

Figure 5: Wind acceleration factors [89]

Beside these introduced parameters there are multiple others that could be mentioned. Such as the fluctuations, turbulences, and bows of the wind, that lead to a discontinuous behaviour.

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[86] (Department, Troen, & Petersen, 1990, p. 45)

[87] (Troen & Petersen, 1989, p. 59)

[88] (Department, Troen, & Petersen, 1990, p. 48)

[89] (Troen & Petersen, 1989, p. 64)

Additionally, the seasonality within different timeframes, the uncertainty in general related to weather and climate and many other factors should be considered.

In the end, this points out that the dispute with the general conditions is highly relevant to determine the value of the wind generation locations and estimate the potential energy that could be withdrawn. To keep the determination effort as low as possible there is always the trade-off between the realistic representation of the conditions and the calculation effort or computation time needed. Therefore, it is usual to use some interpolation and representation methods that could be used to simplify and speed up this process. Some of them will be introduced in the following part.

3.3 Representation methods:

Stochastic and probabilistic methods

In order to evaluate a particular location for the usage of wind power generation, some information and parameters must be investigated and gathered. In the short-term parameters as the fluctuations are important to determine the necessary mechanical load resistance of the wind turbine. In the long-term the actual wind profile and average wind speed during an observed timeframe are important. According to this, the determination of average annual wind speed and temporal frequency distribution of wind speed is the key. The wind speed is measured at a pre-set height within different time intervals over one or more years. Afterward, the data points are grouped into different wind speed zones. Under the usage of these data, it’s possible to determine the relative frequency of distribution and the corresponding summed functions. The relative distribution shows the percentual number of occurrence forms of each wind speed during the observed time frame, the sum-function the cumulative percentage the wind speed is lower than a certain level. [90]

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[90] (Hau, Windkraftanlagen, 2016, p. 571)

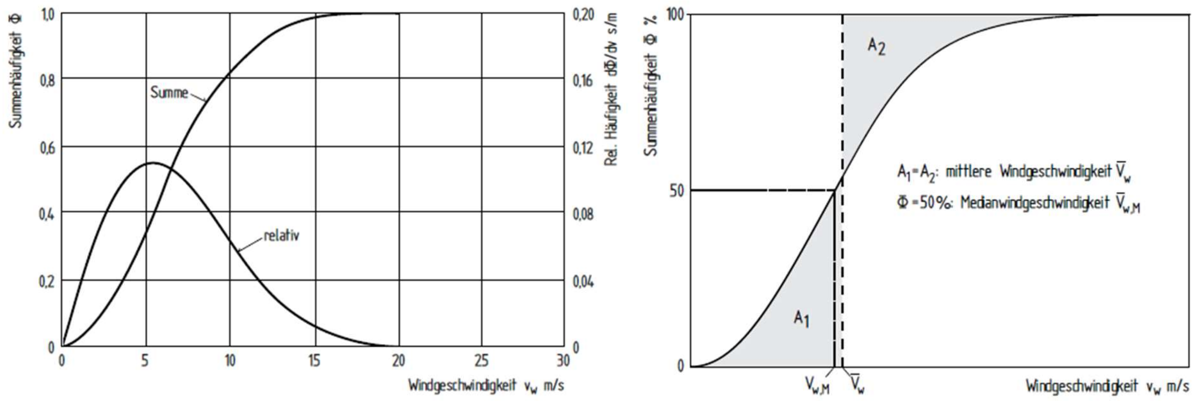

Figure 6: Wind speed distribution function [91]

Through the sum-function, the average annual wind speed could be computed. It is defined as the value of wind speed that provides two equal spaces within the sum-functions cumulative progress as seen in the graphs above. The data gathering and the use of this method frequency distribution functions is, in reality, difficult to execute. In order to obtain a representative statistic information, the data gathering should be done at least for a timeframe around 10 years to cover even the impact of several years cycling weather phenomena and behaviour. In practice, this data is not available for most locations, especially in undeveloped countries. Therefore, the use of an approximative mathematical method is rational. [92]

The method of choice is the Weibull method that provides a statistical model to determine the wind speed distribution. The sum-function is defined as: [92]

$$\Phi = 1 - \; e^{-(\frac{v}{A})^k}$$

$$with:$$

$$A = scaling\ factor,$$

$$k = shape\ parameter,$$

$$e = natural\ logarithm\ base,$$

$$\Phi = distribution\ function,$$

$$v = wind\ speed$$

The shape parameter is determined by the characteristics of the wind and the height of the measuring point. A high value represents a continuous and constant behaviour, a small value the opposite. In order to obtain preferable detailed results, the shape parameter should be as

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[91] (Hau, Windkraftanlagen, 2016, pp. 572 - 573)
[92] (Hau, Windkraftanlagen, 2016, p. 573)

precise as possible. In case of only existence of average wind speed, the parameter is set to k = 2. [92] The scaling factor A describes the average value of all wind levels over time in the context of wind distribution. [93]

The frequency distribution function is provided due to the derivative as seen in the graph below. In practice is was shown that the Weibull method is adequate to simulate the distribution of wind speed profiles and for the further determination of performance parameters of the wind generators.

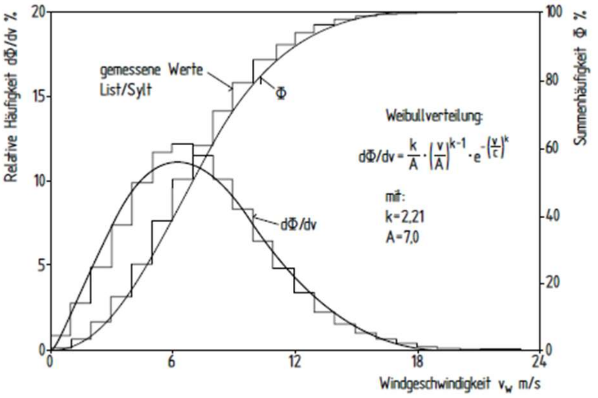

Figure 7: Weibull distribution function [94]

As the scaling factor and the shape parameters could be set the only additional input is the wind speed. As wind speed is usually measured in one particular height and at single locations, their change in vertical and horizontal directs must be considered in order to keep the simulated wind profiles as representative and precise as possible. Depending on the used technologies and the location of the generator the actual height of the turbine is different. Also, as discussed earlier the altitude has an additional impact on the wind profile. Therefore, the interpolation and extrapolation of parameters could be necessary.

Interpolation methods:

Subsequently, some interpolation methods are reviewed to increase the understanding of the importance of the inclusion of these influencing parameters. Especially to point out their relevance on the large-scale representation of wind speed.

The data collection of wind usually is punctual, not uniform and not standardized distributed. Due to this fact, the nationwide availability of adequate wind speed data often is not given. The lack of measuring infrastructure is even higher in less developed countries. In order to enable an evaluation of potential wind power generation locations, additional instruments must be

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[93] (Bergsträßer & M. Steimer, 2013, p. 7)
[94] (Hau, Windkraftanlagen, 2016, p. 573)

considered to achieve this purpose. One method type to obtain this could be a spatial interpolation.

Spatial interpolation is defined as a gathering of methods to determine or estimate observed values within a not analysed location. The reference for this determination is a measured or captured data point at a certain reference location. To provide a good representation for these unknown locations values the interpolation uses spatial continues surfaces as the terrain that changes within the distance from the measuring points. The method assumes that the surrounding next to the known point is similar to them. Two data points with the higher distance between each other have fewer similarities. In general, the spatial interpolation could be divided into deterministic and stochastic methods, whereas the deterministic one uses a weighting relation between the data points and the stochastic one considers additional correlative relationships. Depending on the distribution of data points the used interpolation method and the quality of the results are diverse. According to this the data point could be regular, randomly or clustered distributed. [95]

Following a brief overview of some deterministic and stochastic interpolation methods that are used in the context of wind speed interpolation. Further details, information and additional methods could be taken from the references.

In general, the most interpolation methods are based within a weighted average of the observed data. As mentioned in the work of J. Li and A. D. Heap, a representative formula is provided: [96]

$$\hat{z}\,(x_0) = \sum_{i=1}^{n} \lambda_i \, z\,(x_i)$$

$$with$$

$$\hat{z} = estimated\ value,$$

$$x_0 = observed\ point,$$

$$z = observed\ value$$

$$x_i = \ observed\ point,$$

$$\lambda_i = weighting\ of\ observed\ point,$$

$$n = number\ of\ point$$

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[95] (Riha, pp. 35 - 37)

[96] (Li & Heap, 2008, p. 4)

Furthermore, they reviewed in a total of 42 different spatial interpolation methods. [96] Additional information could be gathered from N. Siu-Ngan Lam´s work also. [97] Therefore, an interested reader could get some useful additional information from this work.

In the context of wind speed interpolation, the polynomial interpolation, inverse distance weighting, spline interpolation within the deterministic methods are used in several studies. According to this a brief description of these three methods.

Deterministic methods:

Method	**Notes**
Polynomial interpolation [98] [100]	• The methods search for a polynomial function that touches all observed points • It uses regression procedure of a method of smallest squares • Divided in global and local polynomial interpolation • Small variations in the observed areas • Most suitable for trend surface analysis • Estimation and removal of spatial trends • The base for further interpolation methods
Inverse distance weighting [99] [100]	• The local and exact method • Considers the environment around the unknown point • Weighting inversely proportional to the distance and describes the relative importance of every point; closest values have the strongest impact • One of the most suitable and flexible deterministic method • Disadvantages of oscillation with high order polynemes • Assume that interdependencies are reducing with the distance
Spline Interpolation [101] [100]	• Uses piecewise polynomial functions to form a steady and harmonic curve • Uses radial basic functions for the piecewise fit • Don't has the disadvantages of the oscillation of the inverse distance weighting

Table 2: Deterministic interpolation methods

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[97] (Lam, 1983, p. 130)
[98] (Riha, pp. 39 - 40)
[99] (Riha, pp. 40 - 43)
[100] (Ackere, et al., 2015, p. 8691)
[101] (Riha, pp. 43 - 46)

Stochastic methods:

In contrast to the deterministic methods, the stochastic methods are a combination of mathematical and statistic approaches. The search or estimation process of the sought values is based on probabilities. These probabilities are derived from variograms, which represent a spatial relation of a certain point with its neighbour points within a random field or a stochastic process. This method could be further used and developed in geostatistical applications as spatial wind speed interpolation. Therefore, Kriging was developed. Also, the Kriging is based on regressions techniques with the purpose to minimize the variance of the value estimation. The difference to the deterministic regression approach is that the stochastic one is not only based on the selected deterministic weighting of the sought points locations. The spatial stochastic relationship from the variogram is determining the weighting and therefore contains properties that are covered due to the available data. [102]

Normally the kriging methods are following three main steps. In the beginning, the variogram is developed. The known points are divided into groups of point pairs that represent the same distance between each other, following an expected value for all equal pairs regarding distance is determined. For each distribution, this will be repeated, and a probability function is derived. Then the half among of the expected value is set concerning the distance groups and a distribution curve subdivided from this relation. A theoretical distribution curve will be adapted to the experimental distribution with the use of a smallest square method. With this adapted function the optimally weighted distances could be determined, and the unknown values estimated. [103]

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[102] (Riha, pp. 46 - 47)

[103] (Niederberger, 2000, p. 38)

Method	**Notes**
Simple kriging [104]	- Most simple kriging occurrence form - Rarely used, because average value often not determinable - Presupposes a known average value determined from the existing data within the observed environment
Ordinary kriging [105]	- Most used kriging method - Presupposes also an average value, but must not be determined, means it could be unknow
Universal kriging [106]	- Considers also a spatial trend in contrast to the two above-mentioned kriging methods - More generalized approach - A constant average value of the observed area is not necessary
Lognormal kriging [107]	- Estimation of random variables that are log-distributed - Values must be logarithmically transformed
Co-kriging [108]	- Expansion of the kriging method within more dimensions - More than one variable investigated - Requires more data and information about the correlation between the different variables

Table 3: Stochastic interpolation methods

Additional information could be extracted from J. Li and A. D. Heap work. [109]

W. Luo, M. C. Taylor, and S. R. Parker investigated the performance of four deterministic and three stochastic or geostatistical interpolation methods in England and Wales. In order to estimate the assess of the distribution of crop diseases that spreads due to the air over the country depending on the wind speed. The result of the estimations was compared with independent wind data to evaluate the results of the selected interpolation methods. Due to the punctual measurement of wind data the interpolation of the wind speed of the surrounding areas seemed to be an adequate method the estimate these values. The assumptions of the spatial interpolation methods to consider common attributes of nearby points and fewer similarities with higher distances could provide a representative wind behaviour. The study investigated the performance of the trend surface analysis, the inverse distance weighting, local polynomial,

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[104] (Riha, pp. 48 - 50)
[105] (Riha, pp. 50 - 51)
[106] (Riha, pp. 52 - 53)
[107] (Riha, pp. 53 - 54)
[108] (Riha, p. 55)
[109] (Li & Heap, 2008)

thin plate spline, ordinary kriging, universal kriging, and ordinary cokriging. The Input data executed within the geographical information system ArcGIS. [110]

The results of the study have shown that the cokriging provided the best estimations. The estimated data had a higher resolution in contrast to the other interpolation methods. Additionally, the cokriging was considering the altitude of the landscapes as covariable that enables a more precise estimation and smaller prediction errors. Finally, the authors pointed out that further ongoing methods should be investigated to gain additional improvements and the results always strongly depend on the quality and the meaningfulness of the available data and must be interpreted in this regard. [111]

S. M. Ali, A. S. Mahdi and A. H. Shaban investigated the most suitable interpolation method to estimate wind speed in Iraq. They also used some deterministic methods as inverse distance weighting, polynomial, and spline interpolation and some stochastic interpolation methods as different kriging methods. Their investigation was executed in the ArcGIS software. Their results pointed out that the inverse distance weighting was most precise followed by the ordinary kriging method. Their evaluation of the results was linked to the mean error and root mean error square error determination to measure the suitability of the obtained data.[112]

Finally, it should be noticed that the above-mentioned selection of interpolation is only a brief overview of this topic. The main idea of the different methods of spatial interpolation is quite similar and merely the respective execution conditions and requirements, as well as necessities of the subtypes, are different depending on the quality of the available data, the prevailing properties of the areas and the observed variables within them. Regarding the study, the precision of the used method is corresponding to the among of considered input factors. Therefore, as more data could be processed as more representative the results are, subjected to the existing trade-off between accuracy and computation effort.

Extrapolation methods:

In contrast to the spatial interpolation, that estimates the unknown under the assumption of similarities to the surrounding environment. The additional approximation is needed that considers different approaches. Upcoming a brief introduction of the vertical extrapolation concerning the changing characteristic of wind regarding the height. As assessed earlier, the wind speed is increasing with height. The first layer of the air, the Prandtl-layer, that covers the first 100 m of air pillar, is depending on different impact parameters. Even though parameters as

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[110] (Luo, Taylor, & Parker, 2007, pp. 947 - 950)
[111] (Luo, Taylor, & Parker, 2007, p. 958)
[112] (Ali, Mahdi, & Shaban, 2012, pp. 48 - 51)

humidity and temperature also, have an impact on the wind, it was shown that the long-term average values mainly depend on the roughness. [113]

As F. Bañuelos-Ruedas, C. Angeles-Camacho and S. Rios-Marcuello introduced in their study on the extrapolation on wind speed data at different heights, there are different approaches in order to execute this. One of the most often used approaches is the Monin-Obukhov method that uses a logarithmic term to exercise the extrapolation as seen in the formula below: [114]

$$v\,(z) = \frac{v_f}{K} * \left[\ln\frac{z}{z_0} - \xi\left(\frac{z}{L}\right)\right]$$

$$with\ v\,(z) = wind\ speed\ at\ height\ z,$$

$$v_f = velocity\ at\ friction,$$

$$K = Karman\ constant,$$

$$z_0 = roughness\ of\ the\ surface,$$

$$L = Monin - Obukhov\ lenght,$$

$$\xi = function\ regarding\ solar\ radiation$$

Especially for short-term observation, this formulation is suitable as shown in several studies referring to the above-mentioned study on extrapolation. In order to exercise more general usage, the need for a more simplified approach is given. Even though with some losses regarding the precision and meaningfulness of the results. According to this, there is the Hellmann exponential law or power law that enables the wind speed determination within two different height levels. The formula as follows: [115]

$$\bar{v}_H = \bar{v}_{ref} * \left(\frac{H}{H_{ref}}\right)^{\alpha}$$

$$with$$

$$\alpha = \ Hellmann\ exponent$$

$$\bar{v}_H = \ average\ wind\ speed\ in\ height\ H,$$

$$\bar{v}_{ref} = average\ wind\ speed\ in\ reference\ height\ H_{ref},$$

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[113] (Hau, Windkraftanlagen, 2016, p. 575)
[114] (Banuelos-Ruedas, Angeles-Camacho, & Rios-Marcuello, 2009, p. 2385)
[115] (Hau, Windkraftanlagen, 2016, p. 577)

$$H_{ref} = reference\ height,$$

$$H = height,$$

The Hellmann exponent is a function that considers the constitution of the environment and could be taken from tables that contain different values for different landscapes. However, these values could variable during the day. [116]

An additional approach that represents the relation between a specific and a reference high is given due to the logarithmic wind law: [117]

$$\bar{v}_H = \bar{v}_{ref} * (\frac{\ln(\frac{H}{z_0})}{\ln(\frac{H_{ref}}{z_0})})$$

$$with$$

$$\bar{v}_H = average\ wind\ speed\ in\ height\ H,$$

$$\bar{v}_{ref} = average\ wind\ speed\ in\ reference\ height\ H_{ref},$$

$$H_{ref} = reference\ height,$$

$$H = height,$$

$$z_0 = roughtness,$$

$$\ln = natural\ logrithm$$

The formula determines the average wind speed in a certain height concerning a reference average wind speed in a reference height, assuming that there is a logarithmic relation within this height deviation. This formula is only valid for properties of the Prandtl-layer and a homogenous roughness of the surface. The actual values for the roughness could be taken from figure 3 above. For varying conditions, the formula could be improved by considering additional parameters, but in practice, these must be estimated or forecasted. What accordingly would be questionable, if these data are adequate enough representing the real conditions. [117]

Additionally, to the values given for the roughness length or the Hellmann exponent, these values could be estimated with a different method. Also, these values change with time of the day and direction of the wind. Both will not be further developed in the scope of this thesis but might be interesting additions in future work. However more precise estimation methods are always determined by additional uncertainty that could make the results and the assumption,

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[116] (Banuelos-Ruedas, Angeles-Camacho, & Rios-Marcuello, 2009, p. 2385)

[117] (Hau, Windkraftanlagen, 2016, p. 575)

these are based on, questionable. Even though concerning the small wind power generators that are occurring the rural electrification context and the small height of these turbines, the approaches might be suitable enough to estimate the wind speed changes with the height deviation.

Referring once again to the study from F. Bañuelos-Ruedas, C. Angeles-Camacho and S. Rios-Marcuello that investigated these different approaches with pre-determined factors within three different case studies. The cases contained data from an urban, a rural and a reference base situation. The obtained result pointed out that the calculation of the wind energy potential under the usage of predetermined Hellmann exponents and roughness values must be interpreted carefully. The variety of impact factors could be strong and provide misleading results. According, to this, this approach seems to be most suitable for a first evaluation of the observed locations but not selective and precise enough for an overall appraisal. However, there are no methods that produce similar results within the same effort level, which makes these approaches most economical. [118]

Finally, similar to the interpolation methods the extrapolation of the wind speed with the height provides strong tools to fill the data gap where no other data is available. But these estimations also often are not reliable in every extent. The interpretation and the derived evaluation must be done carefully. These measurements could be used as a first indicator but should be always covered by additional data bases.

3.4 Wind energy conversion

Upcoming a brief introduction on the relation of the energy withdrawn from an airstream. The introduction of the technical components of the wind generator will be performed in the scope of the wind generators catalogue.

The wind converters could be separated into two main approaches. On the one hand, the system that uses the drag on a surface to move. This approach was used in the past to grind flour from wheat and other grain. Today the commercial technologies use wind converters that benefit from the aerodynamic uplift. [119] Additionally, the wind power generators could be subdivided regarding the alignment of the rotation axis. In this regard, this work is focusing on the horizontal axis. Other approaches didn´t reach market maturity so far. All commercial areas of application are dominated by the horizontal axis driven converters, which additionally, provide a variety of advantages in correspondence due operation and efficiency. [120]

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[118] (Banuelos-Ruedas, Angeles-Camacho, & Rios-Marcuello, 2009, p. 2390)

[119] (Hau, Windkraftanlagen, 2016, p. 67)

[120] (Hau, Windkraftanlagen, 2016, p. 71)

The basic principle of wind power generators is the transformation of kinetic energy in the wind into mechanical energy of the rotatory components and the conversion into elective energy due generators. The German physicist Albert Betz was the first person that discovered some relations regarding the energy content in an airstream and the maximum withdrawable power within a round cross-section. Even though he used some simplistic assumption the provided results are precise enough to estimate the real procedure.[121]

Following a short derivation of this theory.

Starting with the formula for the kinetic energy E within the air mass it could be written:

$$E = \frac{1}{2} m \, v^2$$

Considering a round cross-section A, which is passed by an airstream with the speed v or the derivative of the way concerning the time and a density of the air ρ, we obtain the mass flow ṁ. [122]

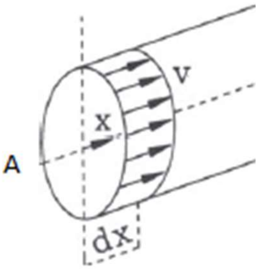

Figure 8: Wind tube [123]

$$\dot{\mathrm{m}} = \rho * \frac{d_x}{d_t} * \mathrm{A} = \rho * \mathrm{v} * \mathrm{A}$$

The power is defined as the energy due to a time interval. Therefore, it applies:

$$P = \dot{\mathrm{E}} = \frac{dE}{dt} = \frac{1}{2} \dot{\mathrm{m}} \, v^2 = \frac{1}{2} * (\rho * \mathrm{v} * \mathrm{A}) * \mathrm{v}^2 = \frac{1}{2} * \rho * \, v^3 * \mathrm{A}$$

This formula represents the power that is contained in an airstream due to a round cross-section.

In order to use this the energy content of the airstream, it must be determined how much energy could be withdrawn. Under the assumption of a constant airstream (mass stream), it

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[121] (Hau, Windkraftanlagen, 2016, p. 85)
[122] (Gasch & Twele, 2005, p. 35)
[123] (Gasch & Twele, 2005, p. 37)

could be derived that the wind speed must be reduced, to remove energy. The reduction of the wind speed is related to an increase of the round cross-sections surface, because of the constant mass stream.

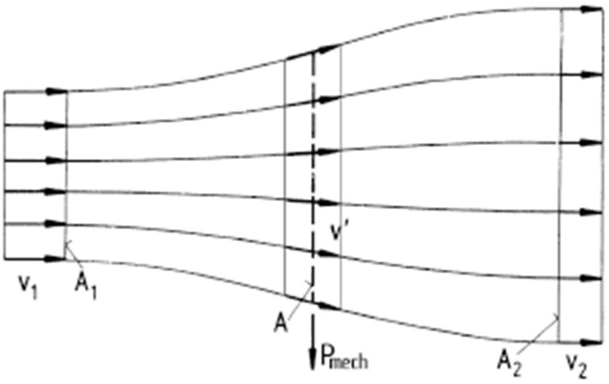

Figure 9: Wind tube expansion [124]

The mechanic converter withdrawn power could be determined as the difference of the power content in front of the converter and the power content behind the converter. The withdrawal of power could be interpreted as a deceleration of the air stream. A. Betz found out that the maximum power withdrawable by a converter is given by a special relation between v_1 and v_2. The relationship is given due $v_2 = 1/3 * v_1$ and it follows the Betz-factor, which is the maximum theoretical efficiency factor for wind power. [125] It results:

$$P_{max} = \frac{1}{2} * \rho * v^3 * A * c_P \; ; with\ c_P = \frac{16}{27} \approx 0{,}59$$

In this regard, the power of the wind generator is limited by this efficiency.

The practical energy produced due to wind generators is determined by several other factors. Therefore, efficiencies of the electric components and generators, also, have an impact on the actual power. Regarding this brief introduction in the transmission procedure of withdrawing wind energy, this is not further relevant at this point. Any additional parameters will be introduced later or could be derived from the current literature.

Finally, this chapter described the origin of the wind streams of the earth. Whereas the relationship between the different physical forces is complex, today there are some developments that explain the conditions in a sufficient resolution. Furthermore, some estimation methods were introduced to prepare necessary wind data or estimated information gaps in order to obtain a homogenous wind profile for further determinations. Lastly, the specification of the

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[124] (Hau, Windkraftanlagen, 2016, p. 86)
[125] (Gasch & Twele, 2005, p. 37)

physical relations that form the basis for the actual power generation and uses the wind profile data as input.

In the upcoming chapter 4, the proposed methods will be described and applied for the REM and a real case example. The necessary technical components, conditions and the processing of the generators and model are introduced in order to bundle the information and the execution at the same place.

4. Proposed method – REM components

In chapter 3 we developed and analysed the main influencing parameters and determinants of the wind speed. In order to use wind energy to provide electricity to certain consumers, generation technologies are needed. The gathering of wind generators and they're related technical and economic data must be provided in an adequate form to execute the implementation. In this regarding certain assumptions are relevant to enable a causal adaptation of the model and functional usage. Furthermore, the corresponding part of the REM must be introduced to provide the necessary knowledge to be able to follow the changes, which are based on the new technology consideration. The processing and procedure of the current and the adapted model must be introduced and developed. Respective difficulties regarding the architecture and optimizing algorithms have been reviewed and further enhanced.

In this regard, the upcoming fourth chapter is forming the key component of the thesis. This chapter contains a detailed description of the due to the wind implementation, modified parts of the Reference Electrification Model in order to point out the functioning and the methods of these parts. Additionally, the adaptation of the respective components is introducing a brief description to provide a view on the enhancement of the model. The procedure will follow the logical approach of first explaining the current version of the process supplemented by the enhancement. Furthermore, the structure of the chapter contains a separation between the optimizing and non-optimizing processes of the model. The latter includes the definition of the generation catalogue and certain adding’s of the generators for wind power. Subsequently, the development of the new model’s architecture regarding micro-grids and the elaboration of a certain approach favoured over several alternative structures. Multiple grid architectures will be discussed in this regard. As the last part of the non-optimizing procedure, the dispatching method is considered and introduced. The optimizing part contains the description of the master-slave properties and their enhancement in correspondence to the necessary method adaptation. Upcoming the essential processes of REM to provide wind implementation, which will be introduced. Besides these specific parts, the REM contains a variety of other procedures or methods, which will be not further elaborated within this thesis. In case of desiring additional information some of the mentioned references could be reviewed.

4.1 Generation catalogue

4.1.1 Generation catalogue of the current REM:

The first component of the non-optimizing part is the generation catalogue. The current version of the REM uses a generation catalogue that includes power generation from diesel and solar panels. Whereas the diesel generator operates in AC within 3-phases, the solar panels in DC.

Additionally, batteries and operational devices are considered, like inverters, converters and charge controller. [126]

The generation catalogue bundles several information about the production units. The basic information regarding diesel and solar contains data regarding the capacity, different load levels, minimum power, start and stop times and other technical parameters; more details visible in the table below. [127]

Moreover, some data regarding costs as the current prices for fuel, costs for operation and maintenance, costs due to losses and occurring cost values thru scaling and sizing of different generator sites and configurations. Supplementary some measures to define the cost calculation procedure either with optimization techniques or interpolation methods in order to store these predetermined values in the look-up table. Other parameters limit the operation of the generators and therefore, have a direct influence on the optimum, these parameters could be interpreted as constraints. Lastly, values related to a specific dispatch strategy could be included; they define the properties of operation and form certain characteristics of the generation dispatch. [128]

Referring to the current version, the REM considers two different sizes of solar-battery-bundle. One adapted to the large-scale generation, the other one for small isolated systems. The generation catalogue is generally, flexibly customizable to the actual conditions on a certain location or country. [129]

In order to provide a general overview of the generation catalogue, parameters that the current model considers are shown; upcoming a parameter table based on the work of E. Douglas. [130]

Component	**Contained data**
Solar panel	• Size/ capacity • Investment costs • Lifetime • Installation costs • Annual O&M • Annual O&M man-hours • Annual capacity losses
Batteries	• Investment costs • Initial charge stage

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[126] (Laboratory, 2018, p. 19)
[127] Generation catalogue current REM
[128] (Laboratory, 2018, p. 19)
[129] (Laboratory, 2018, pp. 19 - 20)
[130] (Ellman, 2015, pp. 27 - 28)

	• End of lifetime capacity • Installation costs • Annual O&M • Annual O&M man-hours • Kinetic Battery parameters • Lifetime energy output
Diesel generators	• Size/ capacity • Fuel consumption/ partially consumption • Minimum Power • Start-up fuel • Lifetime • Investment costs • Installation costs • Annual O&M • Annual O&M man-hours
Inverter/ Rectifier	• A series of converter sizes paired with costs • Minimum size • Lifetime • Inverter efficiency • Rectifier efficiency • The ratio of rectifier capacity to inverter capacity • Installation cost as a fraction of converter cost • Annual O&M as a fraction of converter cost • Annual O&M man-hours
Charge controller	• A series of charge controller sizes paired with costs • Minimum size • Lifetime • Efficiency • Installation cost as a fraction of charge controller cost • Annual O&M as a fraction of charge controller cost • Annual O&M man-hours
Others	• O&M labour cost • Additional costs per system

Table 4: Parameters REM generation catalogue

As it is shown in the table above the generation catalogue could be developed in different detail levels depending on the case studies conditions.

4.1.2 Generation catalogue adaptation to implement wind power generation:

In order to implement wind power as a new generation source, some adequate wind generators must be added. The sizes of small-scale wind generators are normally located in the range of 1 kW up to around 300 kW depending on the region, the consumer distribution, the size of the loads and other influencing factors. But a consideration of larger generators might be rational if the conditions change. This usually could be justified by the appearing of efficiency advantages based on economies of scale. Whereby cost benefits or operational advantages might occur.

The wind generators will be considered as a complete and operationally ready for use system. In general, a wind turbine contains different stages of construction and the process could be separated into different subunits, but regarding the small-scale turbine, this is less relevant related to the context of costs and planning resources. Even though when extensions regarding larger turbines take place, this could be an issue worth considering.

Hence, the turbines investment costs are reflecting the provision of a ready to operate the turbine with all necessary constructing, planning, connecting and operational procedures or devices in place.

As the wind generators use the rotation of the mechanical gear or similar technology to transform wind energy in electricity, the actual economically feasible and most used approach contains generators providing alternating current (AC) in a 3-phase architecture. Though there is the possibility of the usage of DC wind turbines, these are mainly utilized today for direct battery charging and not for supply load of several consumers through a network. [131] Because of that the generation catalogue exclusively considers AC turbines.

Moreover, the generator’s architecture could be synchronous or asynchronous, which would provide the necessity of the installation of different devices to control the frequency of the generator, that must be equal to the network’s frequency at any time. This circumstance is solved due to a frequency converter so that this isn´t necessarily an issue in operation. [132]

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[131] (Hau, Windkraftanlagen, 2016, p. 424)

[132] (Hau, Windkraftanlagen, 2016, pp. 423 - 428)

Regarding other constructive properties, today exist a variety of different types. As mentioned in chapter 3 the turbines differentiate related to the positioning of the turbine's axis and additionally in the number of blades. Since the horizontal axis structure is economically the most efficient and technically most mature, other structures will be left unconsidered. [133]

Concerning the number of blades, the generation catalogue only considers the 3-blade turbines, because these provide the highest theoretically possible power coefficient in comparison with other numbers. Still, it should be mentioned, that the 2-blade approach could provide some benefits regarding the operation and maintenances costs and the volume of the total investments. [134]

Furthermore, differentiations corresponding to the operation control at different wind conditions, e.g. the different positions, and the gearbox construction have a high impact on the cost distribution and the executed operational procedure. In the context of small-scale wind power generation, these properties are either not technically implemented in their variant's variety or principally neglectable. Therefore, these characteristics are not further contemplated in the generation catalogue. In order to enhance the resolution and the precision of the obtained results of the modelling, this might be considered in futures work especially when including larger-scale generation.

In a nutshell, the considered wind generators are characterized due an AC 3-phase 3-blade horizontal architecture, any evaluation regarding the operation control, frequency control, variations of the number blades, positioning of the axis and the gearbox types are not further developed. This is justified, because of the cost-based evaluation of the generators under local wind conditions and the trade-off of usage of other generation technologies concerning their corresponding cost structures in the observed grid. A more extensive observance would be exceedingly complex and surpass the scale of this theses and would also, require a profound extension and progressive development of the model.

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[133] (Hau, Windkraftanlagen, 2016, p. 71)
[134] (Hau, Windkraftanlagen, 2016, pp. 111 - 113)

Subsequently the introduction table 5 of the new generation catalogues parameters.

Parameters:	**Description:**
Generation size:	The generators size defines the theoretical maximum power output of the generator. [135]
Rated power:	The rated power is the maximum power that a generator could provide while operating without getting damages due to material fatigue. [136]
Cut-In speed:	The Cut-In wind speed is the level of wind at which the turbine starts to produce power. That includes the compensation if power losses and own consumption, i.e. the wind speed that provides a net power output of the turbine. [137]
Cut-Out wind speed:	The Cut-Out wind speed is the maximum wind speed at which the turbine operates. Beyond this level, the turbine shuts down its production. (Querverweise 504)
Rated wind speed:	The wind speed at which the wind turbines generator reaches the maximum permanent or rated power output. (Querverweise 504)

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[135] (purchasing.com, 2019)

[136] (Dictionary, 2019)

[137] (Hau, Wind Turbines - Fundamentals, Technologies, Application, Economics, 2006, p. 504)

Maximum Cp:	The maximum efficiency factor with which the wind generator could transform wind energy in electricity. [138]
Diameter:	The diameter is relative to the circular area formed by the turbine's blades.
Swept Area:	The swept area is the surface formed by the blades of the turbine while rotating. The area could be approximated with the formula for the circle area content: ($A = \pi * r^2$).
Lifetime:	The lifetime is the time duration the wind generator is expected to operate.
Investment costs:	Amount of costs that are necessary to obtain the ready to operation status directly related to the construction of the wind turbine.
Operation and Maintenance costs:	The necessary costs to keep the turbine in operation and for reparation in case of damages.
Specific costs:	Amount of investment costs divided by the capacity of the turbine.

Table 5: Parameters generation catalogue wind power generation

The following table 6 contains the selected wind turbines for the generation catalogue.

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[138] (Association, 1997 - 2003)

Technical parameters:

	Gen. 1	**Gen. 2**	**Gen. 3**	**Gen. 4**	**Gen. 5**
Rated Power [kW]	0	1,9	4	18	3000
Cut-in speed [m/s]	1,5	1,5	1,5	1,5	1,5
Cut-out speed [m/s]	60	60	60	30	25
Max. Cp [-]	0,35	0,41	0,45	0,48	0,48
Swept area [m²]	0	11,34	14,5	75,4	7854
Lifetime [y]	25	25	25	25	25

Table 6: Technical parameters wind generation catalogue

In order to enable the determination of different generation sizes within the continues wind generation axis, a minimum and maximum generator must be provided. Theses generator set the axis limits and form the basis for the interpolation in-between different generator capacities.

The technical data regarding the Generators 2 to 4 are based in the productions of the company Enair, which produces small wind turbines. This producer was selected due to the variety of the accessible data and the adequate capacities provided in their products to provide a generation catalogue with different sizes. [139]

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[139] (Enair, 2019)

Cost parameters:

	Gen. 1	Gen. 2	Gen. 3	Gen. 4	Gen. 5
Investment costs [€] [140]	0	13060	14535	40000	2203000
Installation costs as fraction of wind turbine cost [%] [141]	50	50	50	50	50
Annual O&M as fraction of wind turbine costs [%] [142]	5	5	5	5	5
Annual O&M manhours [h] [143]	53	53	53	53	53

Table 7: Economic parameters wind generation catalogue

The cost parameters either corresponds to the data found on the webpage of the producer or are appropriate assumptions based on the literature or on certain expertise.

The selection of the above-mentioned generators and the generation catalogue, in general, is based on several assumptions to provide an adequate base for the following optimization process:

Homogenic production:

The precision regarding the technical parameters is one of the most critical issues regarding the generation catalogue. The decision on a certain specific producer has neglectable relevance from the technical perspective and is ultimately only influencing the overall investment

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[140] (Enair, 2019)

[141] (Hau, Windkraftanlagen, 2016, p. 892)

[142] (Hau, Windkraftanlagen, 2016, p. 920)

[143] Maintenance contract expertise

costs. But a homogeneity regarding the considered wind generators technique is important to provide comparability in-between them corresponding to the optimal size for certain local conditions and accordingly influencing the optimal economic dispatch. Additionally, this assumption is enabling the effect of economies of scale and a respective decreasing of the friction on capacity, which must be possible in order to model realistic cost behaviour. In any other case, the discrepancies within different technical components would contain a variety of other influencing variable regarding the technical parameters and inhibit comparability based on costs. Technical equality removes these additional issues. Therefore, the generation catalogue includes different blocks of different generator sizes from the same producer.

Parameter adaptation:

In order to deal with some local conditions of the observed regions, it could be necessary to adapt some parameters following REM logic. This is because some values could be contrary to the model's logic and lead to interdependencies, which cause issues within the determination process. Before adapting these values, it will be secured that this intervention does not produce major changes or impacts on other determinants.

Parameter interpolation:

In order to prevent some discontinuities in the optimization process, there is the possibility of interpolation in-between the discrete generator sizes. This circumstance will be further explained and developed in the optimization part of the REM. But this approach is mainly used to prevent the selection of local optima for certain local conditions in the search algorithm. Whereas it otherwise could be possible to obtain a change from a wind turbine solution to a non-wind turbine solution and back for the same region and constancy of all other conditions, only based on changes in the amount of population. This outcome would lead to inconsistencies since this potentially could indicate; e.g. that a village, which is fed by wind generation, reconstruct their wind generators when doubling in size and substitute production by a diesel engine. But install other new wind generators, when growing once again. Within a causal logic, a re-construction would make less sense, whereas, the parallel operation of the existing turbine and an additional generation unit is most straight forward.

4.2 Architecture:

4.2.1 The architecture of the current REM:

As mentioned above the current REM version only considers electricity generation from a diesel engine or a solar - battery bank and the corresponding operation control devices. As the solar panel produce electricity in DC, it´s connected with a charge controller and the battery within a DC circuit. The diesel generator provides power in AC in 3-phases within an AC circuit. The customer's load is considered in the same current, whereas the diesel directly supplies the loads through the AC network. Both circuits are coupled thru a two-way DC/ AC inverter in order to provide the consumer with power either from the solar panel or the batteries as seen in the figure10 below: [144]

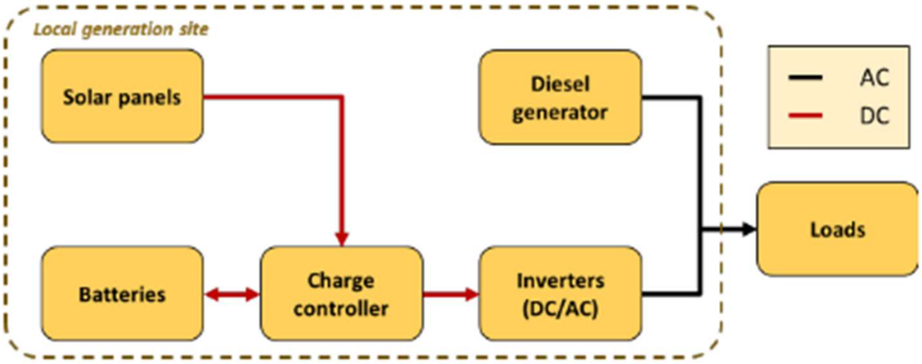

Figure 10: Current REM microgrid architecture [145]

In general, the architecture of the micro-grid should be adapted to the local conditions of the loads. Due to the fact that the optimizing algorithm selects an adequate design for the properties of the local system, some components might be included or not. The AC circuit, at load level, provides the advantages that a grid extension to the existing grid could be obtained easily, which would provide some saving regarding costs in comparison to a DC circuit at load level. On the other hand, the DC circuit approach would be less cost-intensive regarding the whole structure and more suitable to the current devices used within loads of rural areas. In the end, the combined approach provides flexible adaptation to local properties and the search algorithm will provide the actual grid design with the corresponding circuits in AC, DC or both coupled. [146] [147]

4.2.2 Architecture adaptation for wind power implementation:

The implementation of wind generation re-opens the consideration of the micro-grid architecture and the positioning of the turbine’s connection within the micro-grid. As discussed earlier the wind power generation could provide electricity either in DC or AC. Forthgoing a brief discussion on different approaches and the final selection on one a certain architecture.

Assuming that AC wind generators are considered in the generation catalogue exclusively, the DC technology is excepted from the utilization and the related connecting location variants.

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[144] (Laboratory, 2018, p. 18)
[145] (Laboratory, 2018, p. 19)
[146] (Li V. , 2016, p. 36)
[147] (Ellman, 2015, p. 47)

But potentially all connection points that are considered for AC turbines could be used for a DC generator as well, only eventually coupled with an inverter.

An investigation conducted by the Alliance for Rural Electrification pointed out three different potentially micro-grid structures to connect different generation technologies. They are presented and evaluated below in a slightly changed occurrence form. [148]

The first architecture is based on a main AC grid approach. All generating units are either directly connected with AC/ AC converters or with a DC/ AC inverter if the generation uses DC. [148]

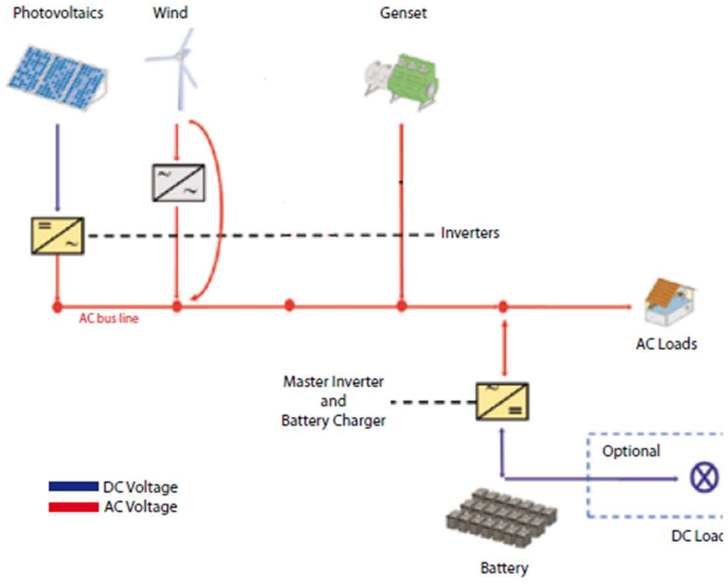

Figure 11: Microgrid architecture 1 [148]

The structure enables a direct AC connection with the AC loads, but an additional inverter must be installed if DC loads should be fed. The advantage of this approach is that over-production of all units could be saved in the storage devices. A potential drawback could occur within the frequency balancing and operation control. It must be secured that the generation frequency corresponds to the load frequency at any given moment in order to provide system stability. Additionally, the use of several inverters could lead to further losses due to different efficiency factors while transforming the current types. In accordance with this the produced energy by the solar panel, which is provided in DC, gets inverted to feed the AC grid. In order to store this energy in the battery, the amount must be converted again, which would lead to inefficiencies in contrast to direct DC-gird storage. [148]

The second potential architecture is shown in the following figure 12:

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[148] (Electrification A. f., 2011, p. 28)

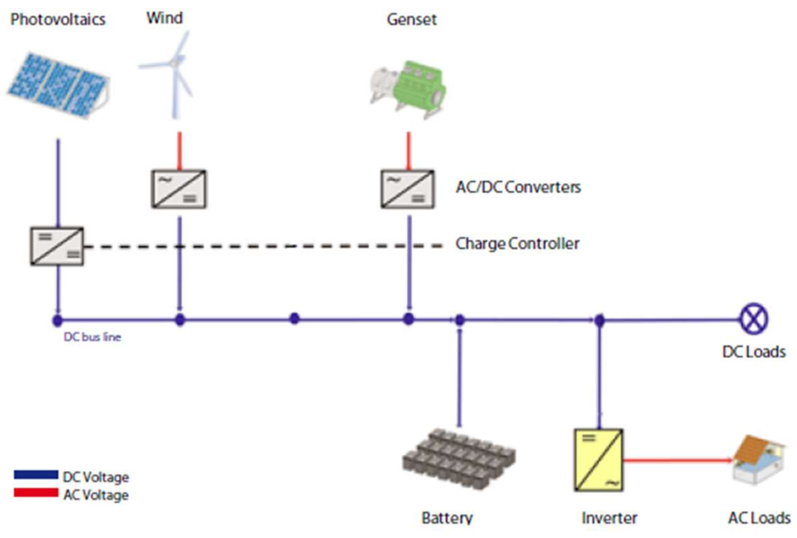

Figure 12: Microgrid architecture 2 [149]

In this architecture, all generating units are connected to a DC bus either directly or due with an AC/ DC converter. Additionally, the battery and DC loads are directly connected to the DC bus, that enables a more efficient battery charging in comparison to the former architecture. AC loads must be coupled with a DC/ AC inverter to be supplied under subjected conditions. Because of the direct transformation in DC current, the frequency balancing is not an issue in the main grid. The needed adaptation takes place in the inverter directly connected to the AC loads; this might result in less operational control effort. [150]

The third approach is based on the generation connection on a DC and an AC bus.

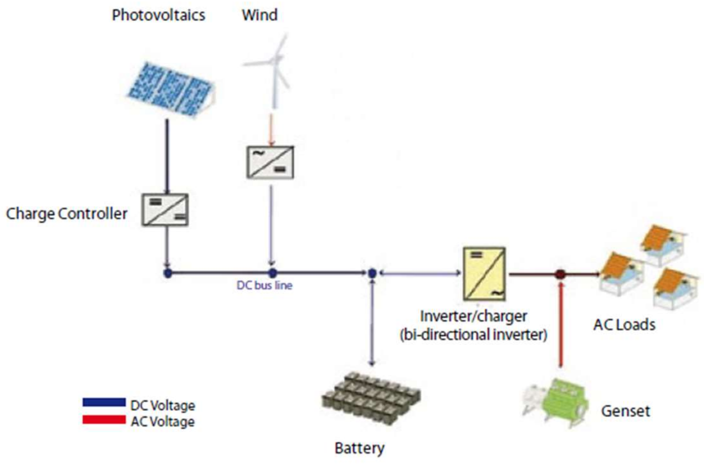

Figure 13: Microgrid architecture 3 [150]

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[149] (Electrification A. f., 2011, p. 29)
[150] (Electrification A. f., 2011, p. 29)

Within this architecture the diesel generator is connected to an AC bus equally as the AC loads; all other generation sources are connected to the DC bus either directly or with to a converter. This approach combines the advantages of the two former architectures. On the one hand, the frequency stability is secured with the diesel engine and respective adaptation from other generators with the bi-directional inverter, that connects the DC and the AC bus. On the other hand, the battery could be directly charging within the DC grid, which provides more efficient charging. Regarding efficiency, this approach might lay in-between the other two. [150]

Finally, none of these architectures will be used for the implementation of wind power generation in the REM model. Admittedly, the first structure is quite close to the new REM architecture. In order to contain the higher efficiency in the transforming of wind generation, these will be connected within the AC part of the micro-grid, also the solar panel is directly connected within the DC grid, which leads to efficiency gains during storage. The difficulties regarding the frequency equality could be solved with a frequency converter. Additionally, this approach is more similar to the current architecture used by REM and therefore, follows the whose general idea, which seems most straight forward.

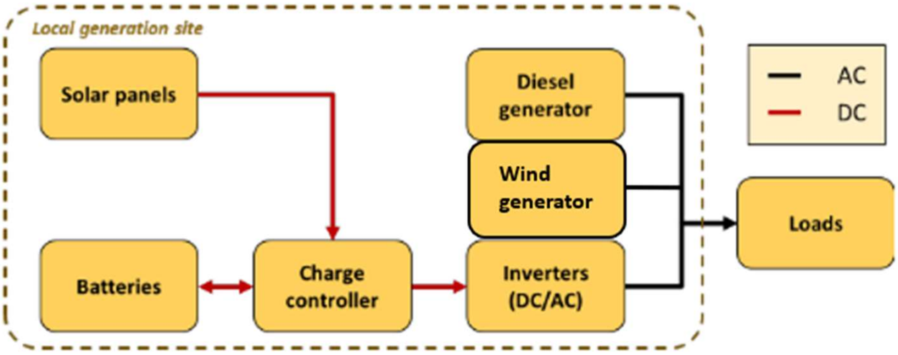

Figure 14: New REM microgrid architecture

Furthermore, REM optimization process has the objective to provide large-scale wind generation solutions. Accordingly, this is more feasible in an AC grid regarding frequency control and efficient power supply.

4.3 Dispatch current and adaptation:

REM obtains the corresponding hourly generation dispatch as a by-product while providing the generation and network design. The determination considers the total economic and social costs to obtain the optimal solution. The actual dispatch strategy depends on the conditions of the related generation design, network design, and demand patterns. [151] Additionally, some dispatch strategies could be defined in advance to solve trade-offs regarding the usage of a certain generator or not. For the scope of this thesis, REM uses a "load following" strategy.[152] That means solar energy is used to supply the demand firstly. If there is a surplus of solar production and the batteries are not fully charged, the charging process is executed. If the solar output is not sufficient the stored energy of the battery is used to supply the demand. In case, solar and the battery production is not high enough to cover the current load the diesel engine is providing the residual demand. The solar production is prioritized because it operates at zero operation costs; the diesel generator has operation costs due to the costs for fuel.[153]

The adaptation due to wind implementation follows a similar approach. The availability of wind provides the opportunity for an additional generation technique. The wind power generation is producing like solar at zero operation costs. Therefore, solar and wind could be considered as quasi-equivalent. The only difference is that the wind generators could potentially run 24 hours, the solar normally only during the day hours, with high solar radiation.

The impact of this is analysed within the case study in chapter 5. For additional information regarding dispatch strategies the cited references could be used.

In the following section, the optimization part is introduced and explained. As this is the most complex and most relevant part of the thesis, the description is provided in more dept regarding details and precision. The general concepts and methods are not straight forward and need some additional effort to present a decent explanation.

4.4 Current REM optimization:

To be able to follow the extensions of the wind power implementation an overview and understanding of the current REM approach is essential. Therefore, following a detailed explanation of the relevant procedures and parts of the REM.

4.4.1 Costs:

The optimization procedures of REM aim for the minimization of the total cost for the generation design either for the local micro-grids candidate design or for the overall generation and total network system design. In this regard, the minimization of the considered costs is the purpose of the economic measure. As introduced in the brief REM introduction in chapter 2 the economic evaluation is divided into two different components. On the one hand, the monetary

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[151] (Laboratory, 2018, pp. 10 - 12)
[152] (Laboratory, 2018, p. 19)
[153] (Laboratory, 2018, p. 40)

costs that are directly related to electricity production as the operation and maintenance costs, management costs, energy costs and other additional expenditures for prospective core activities. Moreover, costs of the unit's provision are regarded, i.e. the investment costs for establishing the ready to operate status of the generators. Furthermore, REM enables the consideration of intertemporal cost effects with discount rates. Since the optimization procedure determines the optimal solution for one certain year in the future, the discounting of costs values from different timescales are necessary. To achieve this, the costs are transferred to annuities into the observed timeframe. Whereby the values of a different lifetime of the assets, owning structures and risk profiles could be included in the optimization process subjected due to the usage of the annuities and discount rates. [154]

Supplementary, REM contemplates costs that are not based on investing and operation measures. In order to consider the reliability of supply within the generation and network design, certain penalties are considered as costs to prevent low-reliability design solutions. Therefore, the cost of non-served energy is determined and included in the cost-minimizing process. Whereby, a balancing and weighting between increasing direct monetary costs due to increasing reliability levels and non-monetary social cost or penalties due to non-served energy based on lack of reliability takes place. [155]

To point out in more detail a further explanation of the pre-determined process of the optima calculation for the look-up table or the mini-grid candidate designs. The REM runs subjected to the local conditions of each individual consumer group or load points the optimization procedure, the so-called generation sizing algorithm.

4.4.2 Hooke – Jeeves - Algorithm:

The generation sizing algorithm is based on a similar idea as the Hooke – Jeeves – Algorithm. Primarily a brief explanation on this algorithm's operation, to receive a deeper understanding of the following approach.

The Hooke – Jeeves – Algorithm is an iterative search method to determine a minimum point of a function. Whereas from an initial starting point the surrounding points are analysed to find a point closest to the optimum. This search steps could be divided into an exploratory and a progressive step, which will be iterated until a certain abort condition is reached. As seen in

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[154] (Laboratory, 2018, pp. 37 - 38)

[155] (Laboratory, 2018, p. 38)

the document from the University of Ulm on non-restricted optimization the Hooke – Jeeves – method could be formulated as the following: [156] [157]

The searched optimum point could be represented due:

$$x^* \in \mathbb{R}^n$$

The initial starting point is $x^{(k)}$ and an approximation of x^*:

$$x^{(k)} \in \mathbb{R}^n$$

Additionally, there are the vector h as the step size and e as a canonical base vector:

$$h_1, \dots, h_j \in \mathbb{R}_+^j,\ e_1, \dots, e_n \in \mathbb{R}^n$$

Exploratory step: [1]

Starting at the initial starting point it will be checked if applies to: [156]

$$f\left(x^{(k)} + hjej\right) < f\left(x^{(k)}\right), j = 1, \dots, n$$

If this is the case: $x^{(k)}$ is set to $x^{(k)} + hjej$.

If not, it will be tested, if it applies to:

$$f\left(x^{(k)} - hjej\right) < f\left(x^{(k)}\right)$$

If this is the case: $x^{(k)}$ is set to $x^{(k)} - hjej$.

This procedure is executed for all the canonical directions until we obtain a vector $y^{(k)}$:

$$f\left(y^{(k)}\right) < f\left(x^{(k)}\right)$$

Now there are two different possibilities: [156]

Either vector $y^{(k)}$ and $x^{(k)}$ are equal ($y^{(k)} = x^{(k)}$) or they are not equal ($y^{(k)} \neq x^{(k)}$).

In case they are the equal the step size will be reduced by half for instance, and the above-mentioned procedure [1] will be repeated within the exploratory step in order to find the directions of the minimum function value.

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[156] (Ulm, 2019)

[157] (Hooke & Jeeves, 1960, pp. 1 - 4)

Progressive step:

If they are not equal, we obtained the direction of the decreasing function values. Now the progressive search for the minimum will be further developed in the decreasing values direction, i.e. $y^{(k)}$ will be directed into $y^{(k)} - x^{(k)}$.

For the progressive step, an additional vector is defined as: [156]

$$w^{(k)} = 2y^{(k)} - x^{(k)} = x^{(k)} + 2 * (y^{(k)} - x^{(k)})$$

Starting from $w^{(k)}$ an additional exploratory step is executed in all directions. This lead either to a vector $z^{(k)}$ with

$$f\left(z^{(k)} \right) < f\left(x^{(k)}\right)$$

Then it applies $x^{(k+1)} = z^{(k)}$, otherwise it, is $x^{(k+1)} = y^{(k)}$.

The abort condition is the following: [156]

$$\left\| x^{(k+1)} - x^{(k)} \right\|_{\infty \leq \epsilon}, \epsilon \leq 0$$

It is recommended to select the step size, s that the values

$$\left| f\left(x^{(k)} \pm hjej\right) - f\left(x^{(k)}\right)\right|, j \in \{1, \dots, n\}$$

comparable sizes, to obtain a certain precision.

The procedure has visualized the figure 15. The initial starting point is the coordinate origin. Starting from this point the algorithm explores the points in all directions of the base vectors. If the above-mentioned conditions are fulfilled the approximation of the search optimal point is adapted to the point explored, which corresponds to the necessary conditions. (1. Vector). This procedure is iterated, until the minimum point of the function is found. The vectors 1., 2., 3. and 4. Are representing the progressing steps to new explored better approximations of the searched points. As it could be seen within the red vectors in the graph, which are also related to the step sizes. The step distances reduce during the procedure when in the former step size, no better approximation is found.

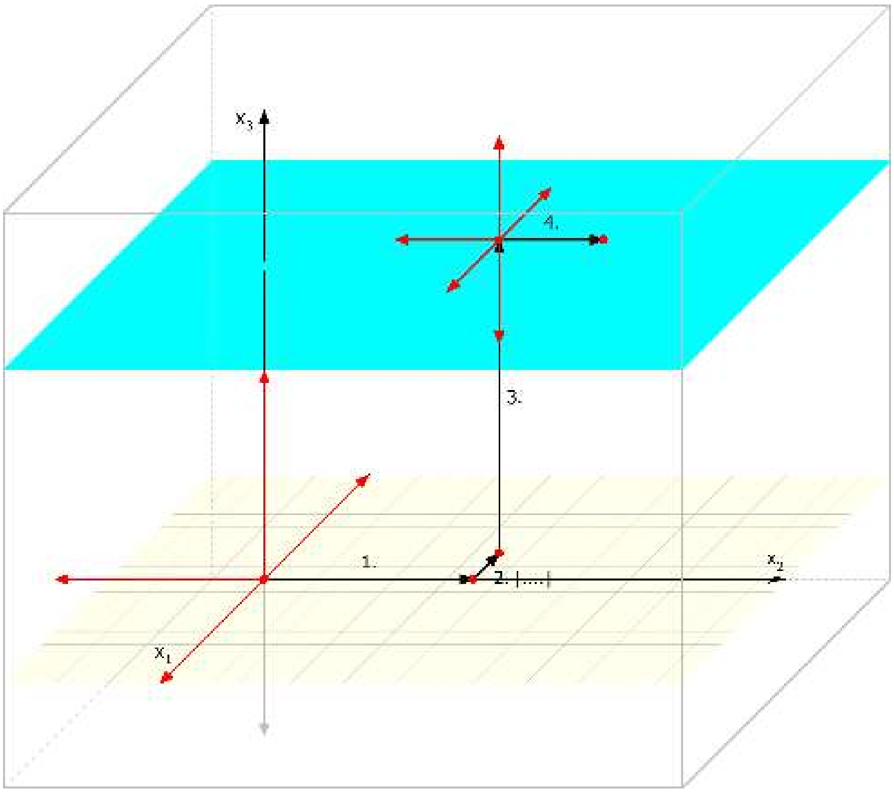

Figure 15: Overview of the Hooke-Jeeves algorithm

Once again referring to the generation sizing algorithm of the REM the optimization idea is similar to the Hooke – Jeeves – method. The differences of the approaches will be further developed in the upcoming section, but first, we provide an introduction into the Master-Slave problem configuration.

4.4.3 Master-Slave – Problem current REM:

The approach of using a master-slave problem structure is since the diesel generators capacity is not evenly distributed in its search space. This could be justified due to the fact that the diesel engines ordinate provides some challenges when operated in parallel. One the one hand the REM only considers one generation site in each mini grid, which prevent a parallel usage. [158] On the other hand, some technical operational issues would occur when it is done this way. These difficulties are based on interdependences in-between the generators regarding the synchronization and the load distribution of the generators, which could lead to some issues regarding their control. [159] Due to this, the gaps between the diesel capacity sizes could be significantly different and not evenly scalable and the determination regarding

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[158] (Laboratory, 2018, p. 80)
[159] (Electric, 2019)

the cost-efficient balancing between diesel and the solar - battery is not obvious. This is because the relation between the different generating technologies is based within non-linear continuous and discrete dependencies. [160] Whereas there might occur minimal solutions for a certain consumer structure, that are local minima. To prevent the appearing of locally optimal solutions the generation sizing problem is decoupled into two separated problems. The master level is defining the diesel capacity problem, which is an input variable for the slave problem or the solar -battery sizing problem. Therefore, the solar - battery sizing optimization starts from a fixed initial diesel size and determines a corresponding optimal solar-battery capacity.[161]

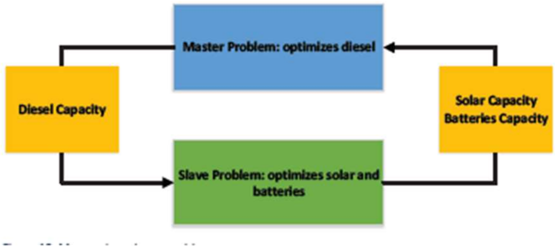

Figure 16: Current master-slave-decomposition [162]

4.4.4 Search method current REM

The search space of the optimization method is a three-dimensional space, where the three axes are representing the diesel, the solar and the battery storage capacity. As said before the diesel axis is not equally distributed within its search space axis, whereas the distances between the potential points in the axis are not equally. The solar and battery capacity are equal scalable because they could be operated in parallel so that they behave in similar within their axes. [161]

The sizing algorithm used in the REM is moving within this search space in order to determine the optimal cost points. At first, the boundaries of each generator’s axis are set within a maximum and a minimum value. In the following table 8, the boundary values are seen. [160]

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[160] (Li V. , 2016, p. 31)
[161] (Laboratory, 2018, p. 39)
[162] (Laboratory, 2018, p. 40)

Generator type	Minimum boundary	Maximum boundary
Diesel	0	1,25 times peak demand
Solar	0	5 times power need on an average day
Battery	0	5 days average demand

Table 8: Definitions of the initial values search algorithm

The definition of the initial value of the diesel axis depends on the respective consideration of the generators capacities properties. In case of a discrete consideration, the initial diesel generator is the smallest one that can cover the peak demand. This initial diesel value is provided into the slave problem and opens the first solar – battery plane within the direct search method takes places. After obtaining a corresponding optimum the search process is stopped. The algorithm returns into the diesel axis and fixing the next smallest available generator. Then the related solar – battery plane opens and performs the optimum search once again. This process is repeated until all diesel generation capacity are analysed and the overall lowest cost solutions found. [160]

Slightly different is the consideration of the diesel generator capacity axis as continues. In this mode, all possible capacity could be interpolated from two bounding known capacities. This consideration is used to prevent some inconsistencies that take place within the optimization procedure. For instance, it could occur a certain generation design for a specific number of consumers that considers a 10-kW diesel generator. For a candidate-grid with ten times the consumers, a bigger diesel generator is needed. The next available one could be 100-kW that might get installed. For a consumer group with around nine times the initial one, the 10-kW is to small the 100-kW generator so large. In this context, there could occur an optimal solution that considers the small generator coupled with a solar - battery instead of the bigger diesel one. This solution could be a locally optimal solution but not necessarily the lowest cost solution. Regarding reliability, this solution is not optimal overall. In order to prevent this, the diesel is considered consciously due to linear interpolation. In the current REM, this is the actual approach. [163]

The initial point is the minimum or a zero-kW generator. The algorithm is trisecting the axis between the minimum and the maximum points with certain step size and determining the corresponding closest to the optimal point within the solar – battery plane. Then the corresponding total cost optimal diesel point is selected and fixed; the section of the axis of the point

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[163] (Laboratory, 2018, p. 39)

most far from the closest to optimal one and the next other point gets deleted. This point is the new iteration starting point in the reduced axis. This procedure is repeated until the step size reaches an abort condition. This means an optimized solution is found. [161]

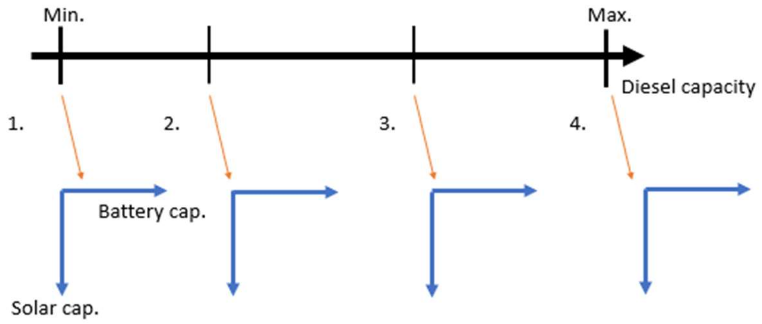

Figure 17: Overview 1 direct search method

In contrast to the Hooke – Jeeves – method, which performs a continuous to search in every direction regarding all its dimensions of the search space, the REM algorithm analysis the surrounding generation candidate-designs only within the solar – battery plane related to a certain diesel value. The determination of the diesel value is a decoupled procedure; both problems are bundled due to their handover values but solved in different manners. It could be said the slave level performs a kind of reduced Hooke - Jeeves – method regarding the dimensions of the search space, but in contrast of discovering every surrounding base vector direction, it selects neighbouring points in the plane even in diagonal directions. The iterative distance reduction during the search is a similar idea. This also, is visible thereby the solar – battery could be considered as quasi-continues due to the almost incremental scalability. A continues diesel axis could be obtained due to interpolation in-between two different generator capacity, but contradicts, because of the non-parallel operation. However, it is used to prevent local minima in contrast to the potential change within different consumer group sizes and theirs regarding generator sizes, which could lead to inconsistencies. Especially this plays an important role in the context of wind power implementation and will be reapplied later.

Figure 18 shows the systematic of the algorithm and the switch within the different solar – battery planes in relation to the fixed diesel values.

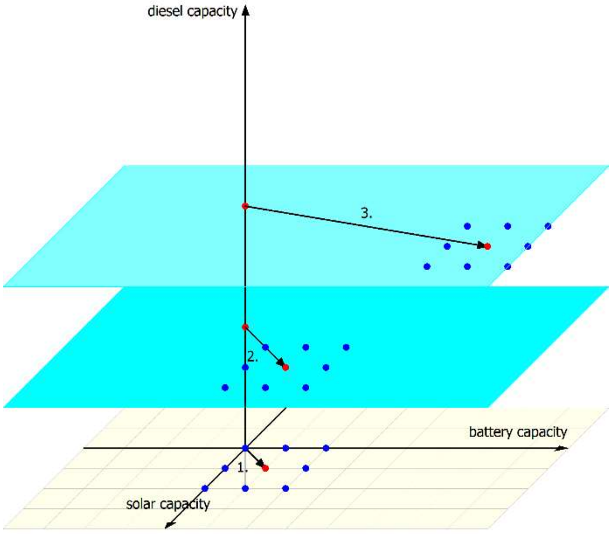

Figure 18: Overview 2 direct search method

In the following graphs the direct search method in the solar – battery plane and the feedback to the diesel axis is visualized and explained:

Starting from the initial point the algorithm is determining the total cost of the surrounding neighbouring points. When a minimum cost point is found this point is selected as the new starting point for the next iteration.

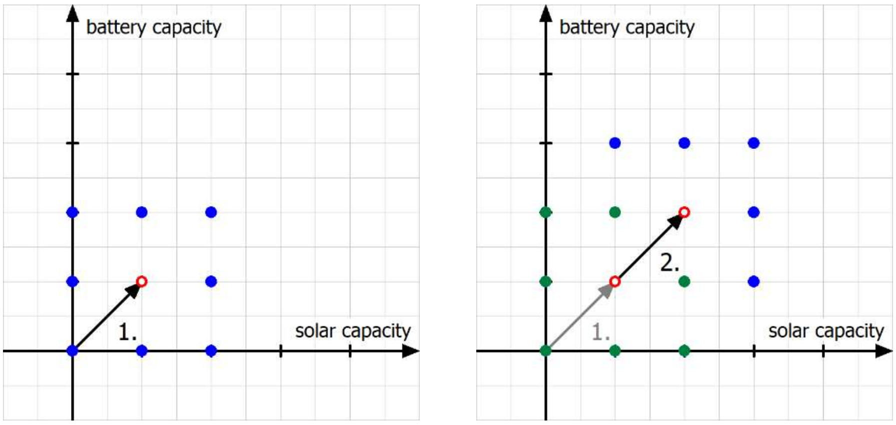

Figure 19: Overview 1 slave-level search algorithm

In the following step starting from the new centre point the surrounding neighbours are analysis once again. The new minimum is selected and considered as an additional new starting point.

This procedure is repeated until no neighbouring point with lower total costs could be found. If this is the case the step size is reduced to reach neighbours in less distance. These are determined and the same process takes place.

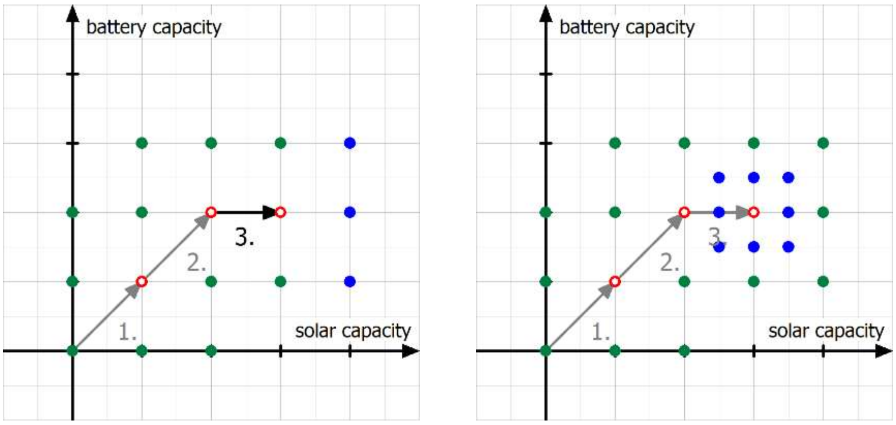

Figure 20: Overview 2 slave-level search algorithm

The optimum in the solar – battery plane is found until a certain abort condition is reached, that means when the step size is reduced to a certain minimum distance.

Furthermore, the size or capacity of any other devices from the generation catalogue are determined afterward when the generation design is calculated and known. [164]

4.4.5 Look-up table and final design:

The look-up table stores the different optimal generation designs related to a certain number of consumers. To reduces the computational effort, micro-grid that differs from the stored ones are linearly interpolated with the two nearest designs regarding their consumer number. After executing this procedure for the whole system and the adaption due to the clustering the final design regarding the distribution of micro-grid modes is obtained. Further information on these procedures could be taken from the cited references but are beyond the scope of this thesis. [164]

4.5 Adaptation of the REM optimization regarding wind power implementation:

The implementation of wind generation required a consideration of the feasible adaptation method to obtain causal results within the optimizing procedure. One of the main issues was the establishing of the sizing mode of the wind generator, either in parallel and equally scalable or not as the diesel generator. This decision would have a major influence on the scaling possibilities of the wind generators within the search space and accordingly, on the optimization procedure. Additional it must be determined how the wind turbines are operated concerning the diesel engine.

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[164] (Laboratory, 2018, p. 40)

Regarding the latter, it must be pointed out that theoretically the operation of diesel and wind generators together could be executed in a parallel operation or in a substitutive way. The parallel operation is funded on a permanently running and main supplying diesel engine. In timeframes, with sufficient wind conditions, the wind turbine produces electricity and is lowering the production of diesel and reducing fuel consumption and emission output. [165] The advantage of this approach is that the grid-frequency is mainly influenced by the diesel engine and accordingly stabile. The change in the composition and the ration between diesel and wind capacity could potentially change the frequency stability. The increase of the wind power capacity, accordingly, rises the frequency impacts and requires the need for operation control within the wind turbine in order to balance the frequency of both generators' types with the grid frequency. This higher control effort leads to more complex techniques, devices, and higher costs. [166]

The other option would be the alternative operation or a substantive operation of the diesel and the wind generator. Regarding the frequency, the same problem occurs as above in an even higher intensity, because the wind turbine must, if operating, provide frequency stability solely. Moreover, the installed wind turbine must be able to supply the full load during operation in order to provide a complete substitutive level. This requires a bigger turbine regarding the capacity in contrast to a parallel operation, where the actual size of the wind capacity does not depend on the diesel capacity. Therefore, the alternative approach requires higher investments and operation control efforts in comparison to the parallel operation. [167]

Furthermore, there is the divisibility of a parallel use or not, regarding the scalability of the specific generation technology. The wind turbine could be implemented either as one big turbine or as few smaller ones in the micro-grid. Both executions require different measures to solve the variations. Including only one high capacity turbine provides the advantages that the operation control is less intense because the frequency control must only be performed within this one turbine. Additionally, the higher capacity provides some economies of scale that lead to cost superiority. The usage of more than one turbine, in contrast, change some conditions. As benefits, it could be mentioned that the installation of multiple turbines enables a more precise capacity adjustments to the local network's conditions, that corresponds to more precise investment's volumes. The drawbacks are based on higher operation controls requirements, because every turbine must be controlled regarding their frequency and the multiple

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[165] (Hau, Windkraftanlagen, 2016, p. 716)
[166] (Hau, Windkraftanlagen, 2016, p. 718)
[167] (Hau, Windkraftanlagen, 2016, p. 719)

generators also, must be controlled within the load distribution. This led to a more complex grid architecture due to the bigger occurrence of control devices and power electronics. [168]

The current architecture of REM and the executed systematics are limiting the implementation possibilities. Corresponding to this, the selected structure for the implementation regarding the operation mode is that the wind turbine only reduces the supply of the diesel engine. A substitutive operation is not used beforehand; the wind and diesel generators are operated in parallel. Even though a complete reduction of diesel production while operation due to wind generation is possible within this approach, but not considered as a base condition within the optimization process. This is based on the one generation site assumption of the model and due the higher control effort if considered differently.

In the context of the scalability, wind turbines are not considered as interconnectable in parallel as the solar – battery - banks. Because the behaviour of the wind turbines is comparable to diesel generators regarding the internal operation control of multiple units as mentioned above. The occurring interdependences are difficult to consider and could lead to local minima, which should be prevented.

Even though the search space is using a continuous axis, based on interpolation, to solve the problem of occurring inconsistency related the micro-grid designs with the actually implemented generators. Accordingly, for the first implementation, the wind turbines are handled similarly to the diesel generator. The causes of the similarities are founded on different reasons, but the difficulties could be dealt with in similar manners. That means that the wind turbine is considered as a single generator, not scalable in parallel, but operating parallel with the diesel generator.

4.5.1 Master-Slave adaptation:

The consideration of wind turbine in this particular way leads to an adaptation of the master-slave- problem. Due to the fact that diesel and wind turbines behave similarly, the wind generation is considered within the master problem level. A slave consideration is not causal due to the lack of parallel sizing capabilities. The slave level problem is almost not changing in its general method, the differences are only that the handover values from the master level have two dimensions (wind, diesel) instead of the former one-dimensional (diesel) structure.

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[168] (Hau, Windkraftanlagen, 2016, p. 720)

Figure 213: New master-slave decomposition

The master level is solved in a different manner because the objective is to find an optimal diesel – wind combination to provide to the salve problem. The master problem has one additional dimension.

4.5.2 Search method

As said before the method of the slave optimization don’t change. The description above is still valid and the direct search method the same. Therefore, it will be not further described in this part.

The master – optimization admittedly follow a slightly different approach. The search space of the diesel – wind generators is forming a two-dimensional plane with a continuous axis. Similar to the former approach in the first step the boundaries of both axes are set at the minimum zero capacity generators and the maximum generators with 1,25 times the peak demand capacity units. Then the initial point is selected, within this search method, the coordinate origin with the zero-diesel and zero-wind generators is forming the starting point.

The first iteration step takes place within one of the generation’s technology axis interval between the minimal (initial) and the maximum (cap) points. Which of both technologies are selected first is neglectable, because both sequences would lead to the same results. Corresponding to a beforehand defined step size the interval of the chosen technology is divided into three sub-intervals or 4 points. The other generation technology´s initial value is kept constant. Then the procedure divides the not chosen generator axis into the 3 sub-intervals and kept the opposite generation technology constant. Within both axes, there are 4 points or 4 generation capacities available. The combinations of both are formed, which leads to sixteen generation capacities combinations as seen in the figure 22 below. Following these values are handed over into the slave-problem and the corresponding optimal solar-battery solutions are determined and returned into the master-problem. Then the one point of the sixteen points with the lowest total costs is selected as the new starting point or centre point.

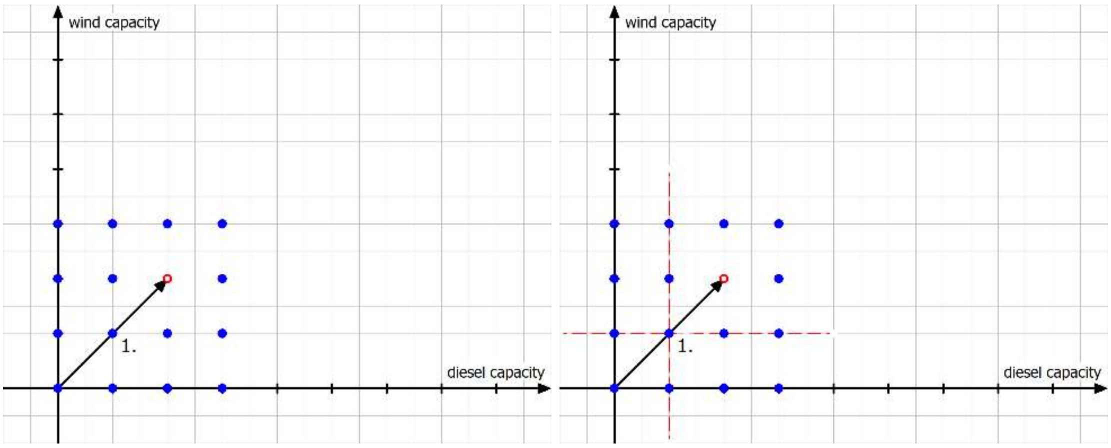

Figure 22: Overview 1 new master-level search method

This trisecting method of both axes provides a new lowest cost point within the caped intervals and the related combinations in the wind-diesel plane. That means for every blue point in the figures the corresponding solar – battery – optimum is determined and the lowest total cost with the specific diesel – wind – the combination is obtained. Starting from the new centre point that is displayed within its axes, the point of the respective axes that have the highest distance from the new starting point´s axes projection is chosen. The interval between this point and the next point on the axis are cut-off and the search space is reduced, by this fraction of the interval (red dashed line figure 22, 23). The first iteration of the search method has been executed. Initiated from the new starting point within the reduced search space, the next iteration is started. This is repeated until a certain abort condition is reached, i.e. when a specific distance minimum is attained, or the optimal point is found. The advantages of this approach are that the reduction of the search space is executed by a factor of 5/9 in ever iteration. The trisecting method of the former REM search in comparison reduced the search space by 1/3 within every iteration.

Additionally, the usage of this trisecting approach provides the benefit of covering the complete search space due to the procedure. No potential combinations are skipped and not considered. Furthermore, this approach is following in a logical way the current implementation of the one-dimensional master – problem.

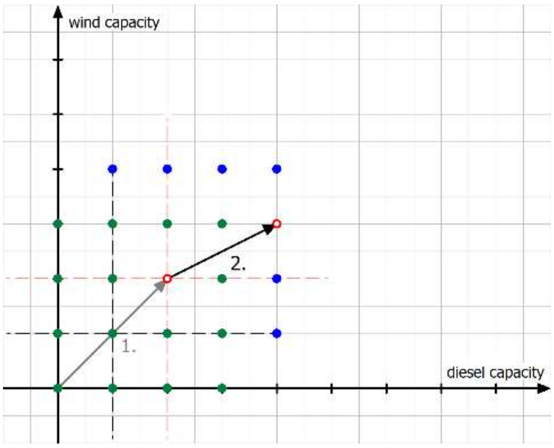

Figure 23: Overview 2 new master-level search method

4.6 Future work

For future works, different implementation approaches and the dissolution of some REM assumption might be interesting and beneficial. The use of multiple units in one micro-grid regarding diesel generators and wind turbines could potentially provide more operational system stability. Multiple units of each type could absorb the failure of one and prevent the total system from failure. Additionally, the efficiency of operation could be increased significantly. The usage of more than one diesel generator would provide the opportunity to stop performance throttling if the demand or generation values are changing. Particularly, in the combination with wind turbines, where the actual energy output underlays a lot of uncertainty and could change within minutes. Therefore, a switch on or switch off the possibility of an additional diesel engine could be done. However, this must be evaluated in comparison of the higher fuel consumption in the heating up phase in comparison to the reduced performance level, but potentially provide more cost efficiency. The usage of an architecture that allows multiple wind turbine provides the advantages of generation extension due to additional turbines if the demand is increasing. Finally, a bundling of multiple turbines, a storage device, and a diesel engine could be connected in a specific way that also a substitutive diesel – wind - operation is feasible, which would lead to additional efficiencies. Even though for now these approaches seem to be less accurate for a small rural grid, this might be relevant in the future, when corresponding realization costs reduce. [169]

Furthermore, the wind power generators output is depending on their individual power coefficient. In this work, the maximum power coefficient of the respective generator is considered to determine electricity production. In reality the coefficient is different depending on the current wind speed and the corresponding load on the turbine. Therefore, this value should be implemented as a variable. In cases the related Cp function is known, the values could be easily

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[169] (Hau, Windkraftanlagen, 2016, p. 719)

determined. If not, the values could be interpolated, when at least some points of the function are known. The consideration of the Cp – wind speed relation will provide much more precision in the actual generation design and the corresponding dispatch.

Moreover, depending on the used wind generation technology, operation control has an impact on the grid and correlated parameters. In order to provide more precise designs, some additional variable should be concerned. Also, the operation control within the hybrid system and between the different generator types requires higher consideration as currently done. Though this must always be evaluated within the trade-offs in-between accuracy and computational effort.

The enlargement of the generation catalogue and a wider selection of considered wind turbine might provide additional adaptation possibilities and cost benefits. Also, different turbine structures as a vertical axis and turbine with different blade numbers might be beneficial in some cases.

Besides the detail depth of the wind turbines per se, the analysis of wind profile and their representation could be developed further. Depending on the available wind data and the current height of the candidate wind turbines, the values could be adapted within extrapolation or depending on the location from the data´s centre point interpolated. This clarification and adjustment to local conditions enable higher resolution and meaningfulness regarding the reality of the results.

Furthermore, different search approaches for the solving of the master – the problem could be possible. For instance, it might be an option to implement the same search method within the master-level as used in the slave-level, the Hooke-Jeeves-modification. If there occur potential benefits regarding computational effort, accuracy or precision This enhancement possibilities provide interesting features for future research work.

As seen in this chapter the implementation of wind generation has been executed and their respective conditions and assumption have been introduced and defined. In order to evaluate these potential improvements, a case example must be analysed within the change's conditions. Only through the execution of the case study the functioning, the potential enhancements, and certain costs benefits of the model´s adaptions could be approved.

5. Case study

To investigate the performance of the model adaptation and to measure the potential improvements it is necessary to execute a case example and interpret the occurring results. In the context of a selected case study, with rural area conditions and the necessary respective input data, the changes due to the new generation technology implementation will be analysed and evaluated.

As the main part of this thesis is the changes in the generation design, the enhancements will be tested within this part of the REM. The composition of the generation technologies obtained in the look-ups table as a resulting from the pre-determination procedure will be analysed. To evaluate the changes in design due to wind implementation, they will be evaluated within the generation dispatches. Additionally, to provide an overall reaction and in order to locate potential respective discontinuities, the final design is analysed. This analysis is executed briefly because it is beyond the scope of the thesis, but to provide a complete approach should be contained.

5.1 Case description

The observed case study is located in Rwanda in Africa. The case contains 47.243 consumers within different grid types in total and is settled in the surroundings of Kayonza in the east of Rwanda. Demand structures only consider residential consumers.

Figure 24: Map Rwanda [170]

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[170] (premiumtimesng, 2019)

The origin of the data regarding the wind potential is the webpage (www.renewables.ninja) that provides annual hourly wind profiles for the multiple locations worldwide. For the execution of the case study, we considered different wind speed profiles from Rwanda from the year 2014. Before selecting an adequate region and wind location, we raised profiles from the 8 wind main directions of the country at 10 m height. [171]

Besides the fact that we found an appropriate consumer distribution to observe and execute the case study in the east of Rwanda, the wind speed within this data series seems most promising in the same region. As seen in the table 9 below the wind profile from the east part of Rwanda provides the highest values in most of the analysed parameters.

	South-west	**South-east**	**South**	**West**	**East**	**North**	**North-east**	**North-west**
Average wind speed	1,87	1,95	2,25	1,96	2,34	1,27	1,42	2,12
Sum of wind speed	16.371,27	17.092,07	19.693,57	17.138,23	20.461,05	11.137,57	12.441,69	18.573,06
Maximum wind speed	5,98	5,94	6,50	5,95	6,86	4,30	4,84	7,81
Sum of wind speed: If wind speed > Cut-In Speed (1,5 m/s)	12.495,63	13.477,60	17.236,58	13.555,66	18.445,11	5.031,34	6.433,87	15.514,15

Table 9: Comparison of wind profiles

Below the both most promising wind speed profiles are illustrated and their distribution during the observed year in hourly resolution.

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[171] (Pfenninger & Staffell, 2019)

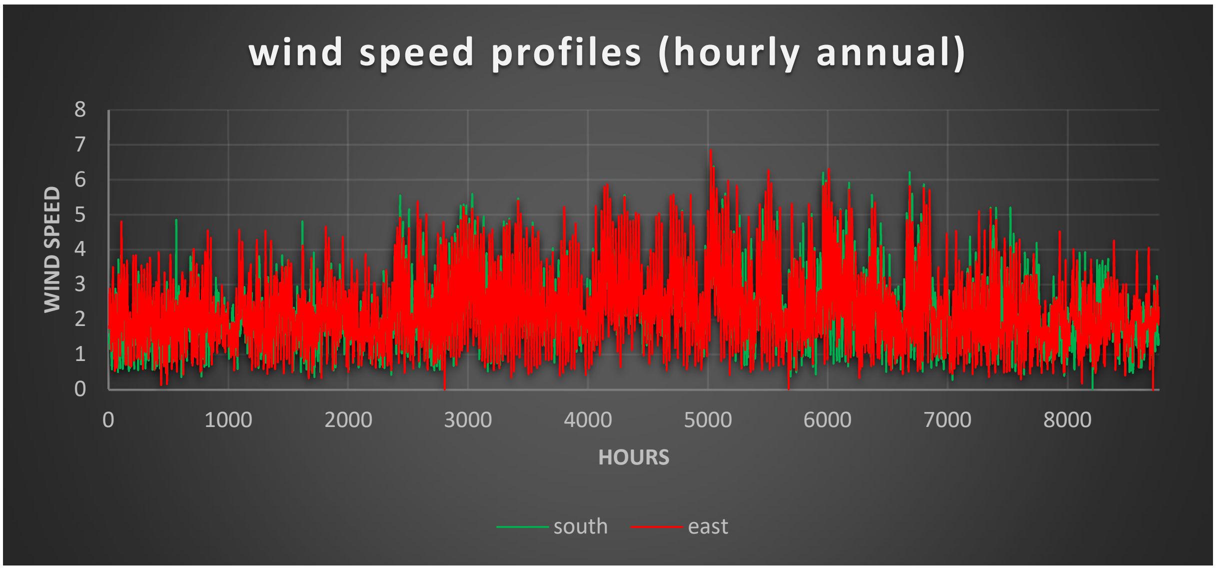

Figure 25: Annual hourly wind speed profiles

Even though it should be concerned that this wind data did not provide an overall statement regarding most adequate wind speed locations, because it covers only a small timeframe.

Demand profile:

Before analysing the dispatch of the generation, we provide, a brief overview of a daily load profile, which could be assumed as representative. The demand is divided into critical and non-critical load. The critical loads are considered with a higher penalty as one of the non-critical in case they are not supplied. Critical loads normally are considering load types that have a certain high or essential value for the consumers. The demand peak is in-between hour 17 and hour 23. The rest of the combined load, when aggregated, is almost constant. The peak in the night hours might be justified by the fact that the consumers arrive their homes from the workplace and consume energy within preparing meals and using electric devices at home. While during the day hours they normally, leave the house to work and in the later night hours they sleep, correspondingly the demand is lower at these hours.

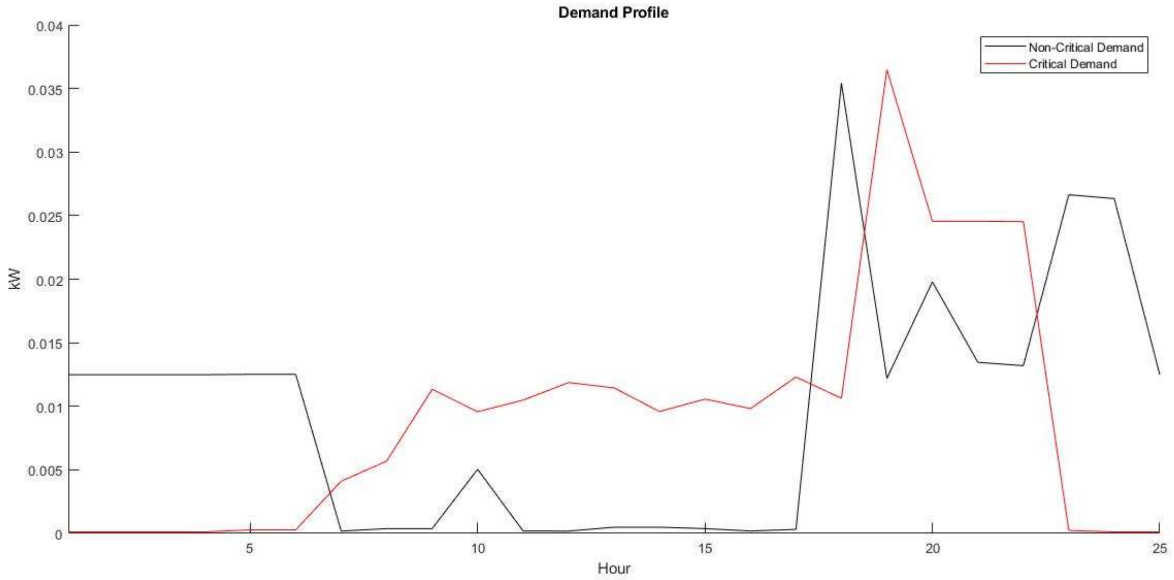

Figure 26: Demand profile

The observed case study contains six different scenarios in order to analyse the react of the model enhancement when some conditions changes. Regarding these changes in the wind speed profiles, the demand patterns and the costs of fuel for the diesel will be analysed. Accordingly, these changes will be introduced due to scaling factors.

The graph below shows the location of the consumers and the power grid of the case study. The black lines are representing the existing grid in the observed region and the green one the demand point or the consumers. The representative demand pattern above corresponds to the demand points in the structural overview map below.

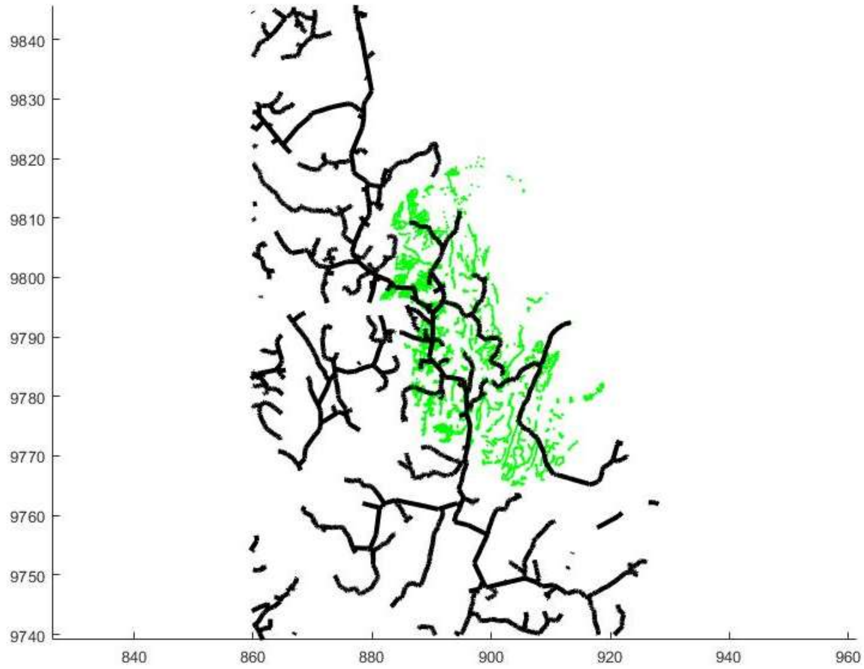

Figure 27: Grid and consumer structure (existing grid (black), consumers (green))

Scenario 1 - Base case: Wind profile x1, Demand x1, Diesel fuel cost 1.2 $/l

The look-up table for the case study contains 6 different pre-determined consumer group sizes within 1 up to 5000 consumers as seen in the table below. These sizes form the basis for the interpolation of different consumer group sizes. Correspondingly, the peak and average annual demand amount are contained also. Additionally, the consumer groups size will be mostly limited by the size of 5000 consumers due to the fact that a mini grid is normally within this range.

The base case considers the above-mentioned wind profile, the demand level of the look-up table and a diesel fuel cost of 1,2 $/l.

Number of Customers	**1**	**5**	**50**	**500**	**1000**	**5000**
Peak Demand (kW)	0,016	0,081	0,811	8,112	16,225	81,123
Average Demand (kW)	0,006	0,031	0,311	3,107	6,214	31,072

Table 10: Lookup table – demand parameters

Scenario 2: Wind profile x4, Demand x1, Diesel fuel cost 1.2 $/l

In the first sensitivity scenario, the demand level and the diesel fuel cost are considered as constant and did not change in comparison to the base case. Regarding the wind speed profile, the values are multiplied by 4 to measure the impact of a significant increase in wind speed.

Scenario 3: Wind profile x4, Demand x3, Diesel fuel cost 1.2 $/l

The second sensitivity considers beside the higher wind speed profile values also a higher demand multiplied by 3 times the base case demand level. Therefore, this scenario evaluates the impact of changes in demand.

Scenario 4: Wind profile x1, Demand x1, Diesel fuel cost 0.6 $/l

The sensitivity 3 uses the base case wind and demand data, but additionally, considers a high decrease in fuel costs by 50 %.

Scenario 5: Wind profile x4, Demand x1, Diesel fuel cost 0.6 $/l

This sensitivity evaluates the higher wind profile of factor 4 under the assumption of lower fuel costs for the diesel and the base case demand.

Scenario 6: Wind profile x4, Demand x3, Diesel fuel cost 0.6 $/l

The last sensitivity measures the high demand, high wind conditions subjected to low diesel fuel costs.

In the table 11 below a brief summary of the determinants of the difference occurrence forms of the case study within the pre-determined consumer group of 1000 consumers.

Comparison table	**1**	**2**	**3**	**4**	**5**	**6**
1000 consumers						
Peak Demand (kW)	16,225	16,225	48,674	16,225	16,225	48,674
Average Demand (kW)	6,214	6,214	18,643	6,214	6,214	18,643
Fuel costs ($/l)	1,20	1,20	1,20	0,60	0,60	0,60
Wind speed factor	1,00	4,00	4,00	1,00	4,00	4,00
Demand factor	1,00	3,00	3,00	1,00	3,00	3,00
Diesel factor	1,00	1,00	1,00	0,50	0,50	0,50

Table 11: Overview Scenarios

5.2 Case results

Following the results of the executed case study and their related sensitivities. In order to provide the evaluation based on the changes in the generation design the related developments regarding composition and costs are analysed.

5.2.1 Costs developments

Total cost proportions:

Regarding the generation designs the costs related to the different scenarios and the base case change. Within their proportions, they differ corresponding to the consumer group sizes. At first, it could be seen that the total costs increase significantly when the demand increases (scenarios 3 and 6). This is justified due to the higher generation capacity needed and the higher investment costs for the additional assets.

The scenarios 1 and 4 contain the values of the base case wind speed profile; 2 and 5 include the wind profile multiplied by factor 4. It could be seen that the proportions of total costs reduce when higher wind energy is available. This is based on the reduction of diesel generation related to savings of fuel costs and the higher generation of wind turbines, which produce at zero operation costs. Respective cost reductions due to economies of scale are not visible, because of the relative presentation of the costs. However, this effect will be exposed to the other following figures.

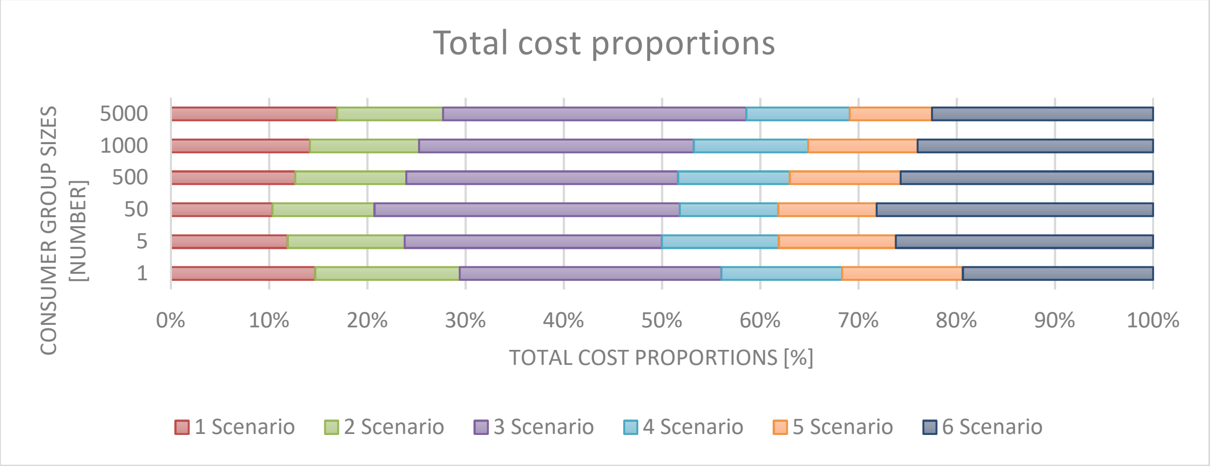

Figure 28: Total cost proportions

Total costs per user:

The costs per user are different within the diverse sub-cases and within the size of the consumer group. In the graph below it is visible that the costs underlay economies of scale within the increasing size of the consumer group. In all six scenarios, the total costs per costumers are exclusively the highest in the 1 consumer grid and the lowest in the 5000-consumer grid. Additionally, the impact of the demand increase with the corresponding higher capacity necessity could be seen in scenarios 3 and 6. The impact of the higher wind generation leads to a related reduction in costs per user. The less fuel consumption cost effect could be visualized when comparing the base case (1) and scenario 2. However, the overall effect is not visible in all the costs data due to interdependencies in-between. Therefore, the effects are provided within a pairwise comparison.

	Scenario	**500**	**1000**
Total Cost per user ($/year)	1	15,85	14,48
Total Cost per user ($/year)	2	15,73	13,8

Table 12: Pairwise comparison 1

In the table 12 could be seen that the costs per user reduce, within the consumer groups with 500 and 1000 consumers. Since no other conditions change within these two scenarios, it could be justified due to the higher wind energy.

The reduction of diesel fuel costs in certain scenarios also has an impact on the costs.

	Scenario	**500**	**5000**
Total Cost per user ($/year)	2	15,73	11,17
Total Cost per user ($/year)	5	15,73	8,68

Table 13: Pairwise comparison 2

The changes from scenario 2 to 5 of the costs per user for the consumer groups with 500 and 5000 reduce or are equal. This is due to the decreasing costs of fuel. The other conditions are constant, and the values are resolved from the wind increase impact because both scenarios consider the same wind load.

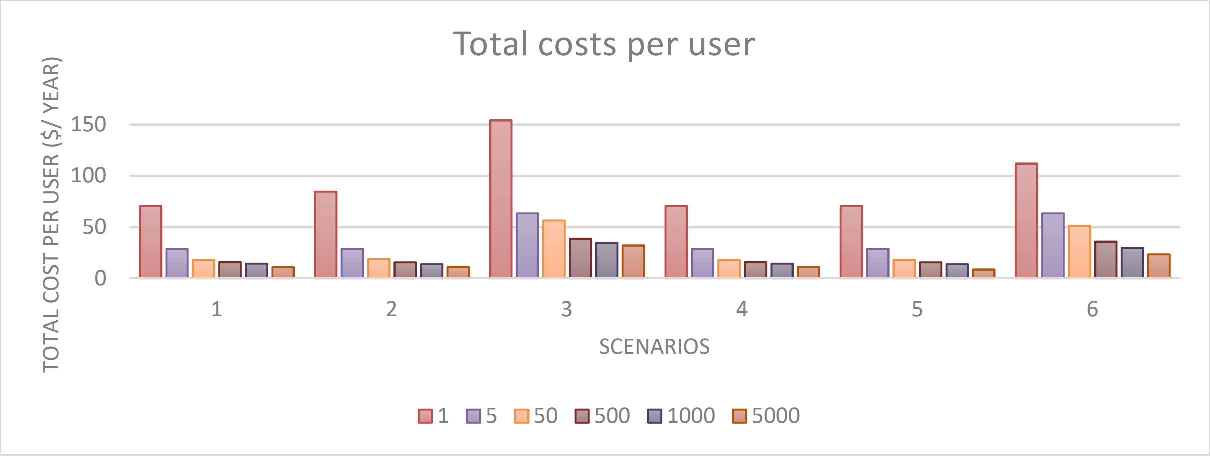

Figure 29: Total costs per user

Total cost per demand served:

In the costs per demand, two different causes for the economies of scale are visible. At first, the reduction of the supply cost due to the increasing size of the consumer group, which takes place in all scenarios within the increase in the number of consumers. The second effect is the decrease in costs for demand served due to the higher installed capacity in cases, which contains the demand increase (scenario 3 and 6).

	Scenario	**1**	**5**	**50**	**500**	**1000**	**5000**
Total Cost per Demand Served ($/kWh)	1	1,61	0,53	0,35	0,33	0,33	0,33
Total Cost per Demand Served ($/kWh)	2	1,61	0,53	0,35	0,29	0,26	0,21
Total Cost per Demand Served ($/kWh)	5	1,34	0,53	0,34	0,29	0,26	0,16

Table 14: Pairwise comparison 3

Similar to before the wind increase and fuel decrease effects are visible when comparing pairwise by numbers. In-between scenario 1 and 2 the wind effect provides a decrease in costs or they stay constant. The fuel reduction effect, in contrast, is visible in the change between scenario 2 and 5. Whereas the values stay constant or reduce as well.

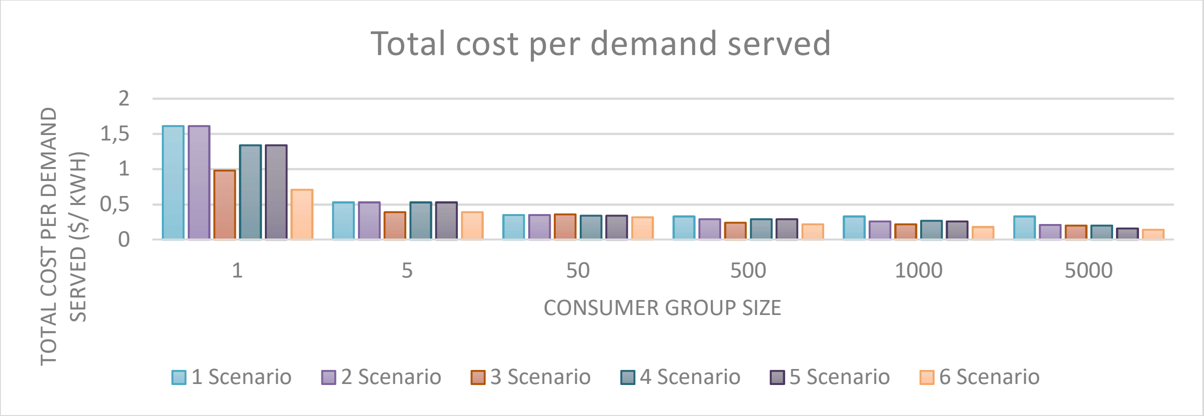

Figure 30: Total cost per demand served

<u>The fraction of demand served:</u>

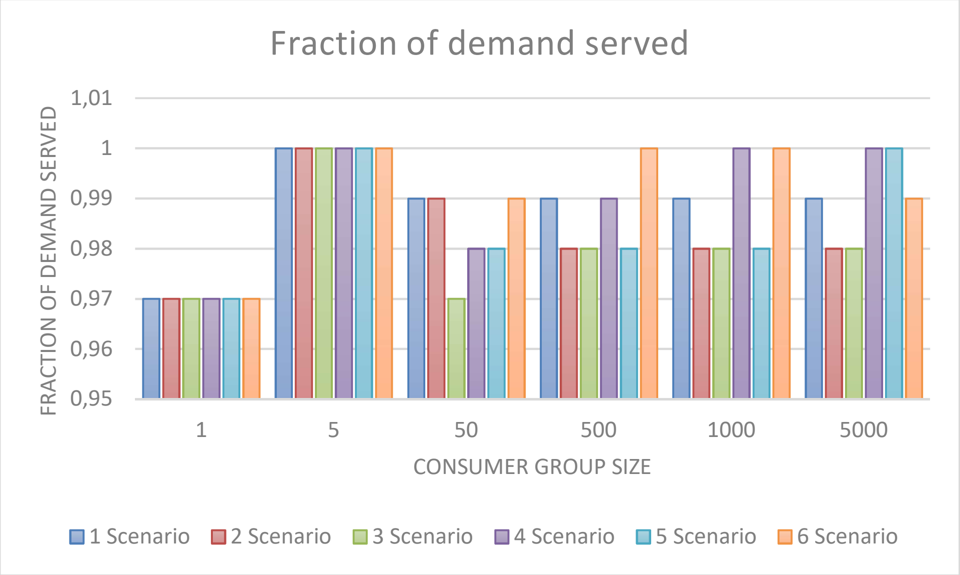

Figure 31: Fraction of demand served

The meaningfulness of the fraction of demand served is limited. In general, the values lay between 0,97 and 1 for all scenarios and all consumer groups. The cost for energy non-served is 1 $/ kWh for critical and 0,8 $/ kWh for non-critical loads. These costs are high enough to force the design to meet the demand at any time. The values within 0,97 to 1 could be considered as meeting the demand permanently. The slight differences are based on the simulations and the heuristic algorithms of REM that could produce minimal deviations in this regard.

Upcoming an overview of the compositions of the generation designs of the different scenarios and within the different consumer groups.

5.2.2 Generation design compositions

Scenario 1 - base case:

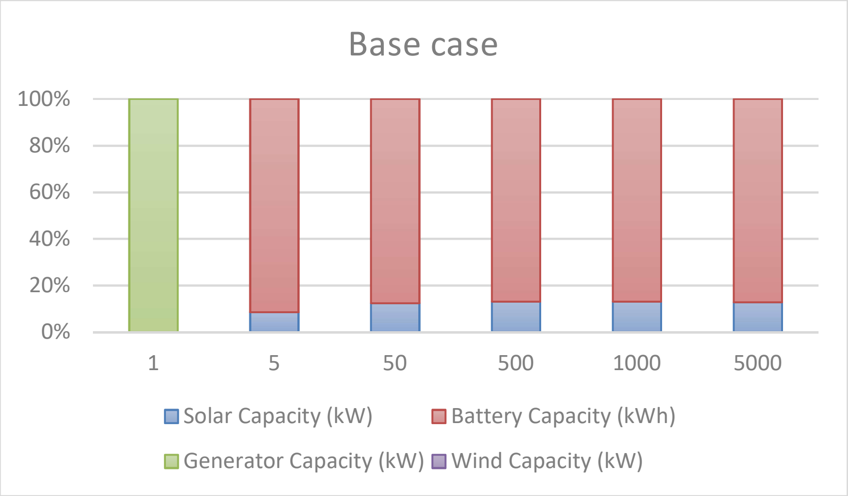

Figure 32: Scenario 1 composition

The compositions in the base case point out a combination of solar and battery capacity in the consumer group 5 to 5000 consumers. The isolated 1 consumer system is powered by a diesel generator. Within this structure, the wind profiles did not provide enough wind energy to consider wind turbines producing in this composition. Within the 1 consumer grid, a certain specialty occurs. The minimal capacity of the battery is too big related to cost to be operated in this grid. Due to the fact that solar and battery are considered as quasi-continuous, the algorithm produces this result. The diesel is a continuous variable and therefore obtain as an infinitesimal generation unit. This feature occurs in every case example and is based on the current structuring of the generation catalogue of the REM. It might be rational to add a battery size feasible for a 1 consumers grid to prevent this model limitation.

Scenario 2: (Wind profile x4)

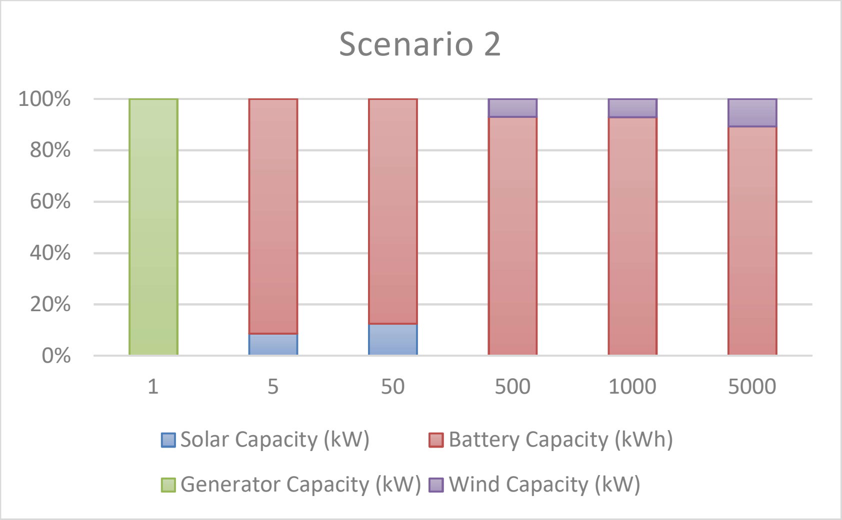

Figure 33: Scenario 2 composition

It is visible that the wind turbines are an adequate generation technology for the bigger consumer groups. The other generation designs stay constant and did not change in contrast to the base case. Therefore, wind turbines seem to be able to substitute solar capacity under the changed wind conditions, when the number of consumers increases.

Scenario 3: (Wind x4, Demand x3)

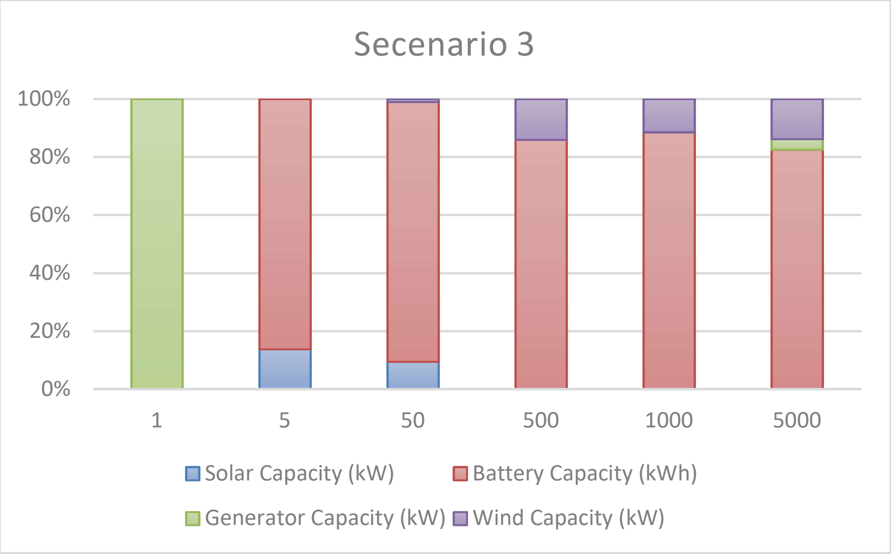

Figure 34: Scenario 3 composition

When demand increases by factor 3 the necessary generation capacity must be raised. In the composition of this case, this leads to higher wind generation in the50 to 5000-consumer group and in the latter also to some additional diesel generation. The wind turbine installations with the corresponding wind potential seem not to be able to supply the total demand solely.

Scenario 4: (Wind x1, Demand x1, Fuel x0,5)

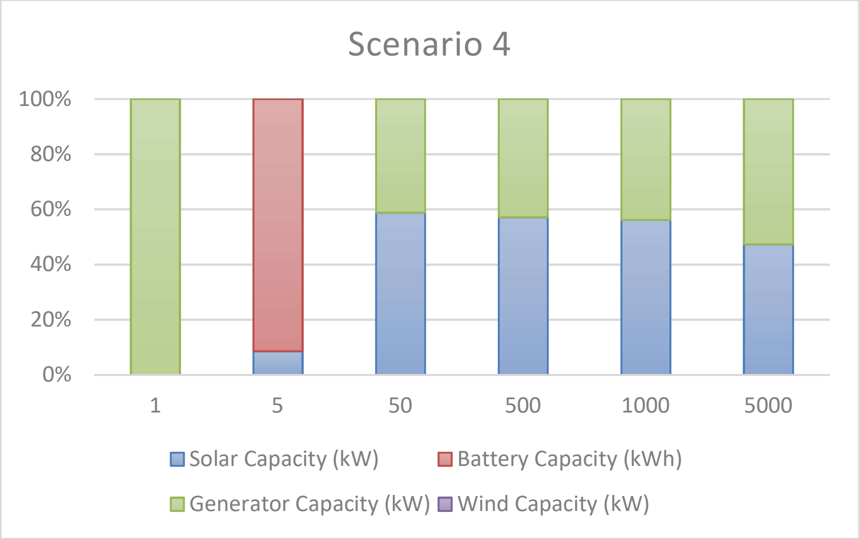

Figure 35: Scenario 4 composition

The decrease in fuel costs leads to significant changes in the scenario's composition. Considering the base case regarding wind and demand, the 50 to 5000 consumer groups are power by solar and diesel combinations. Only the 5 consumer grids are still supplied by solar – battery capacities. The cost saving due to fuel cost reduction enables a more economical generation of diesel engines, which overcome battery capacity in costs.

Scenario 5: (Wind x3, Demand x1, Fuel x0,5)

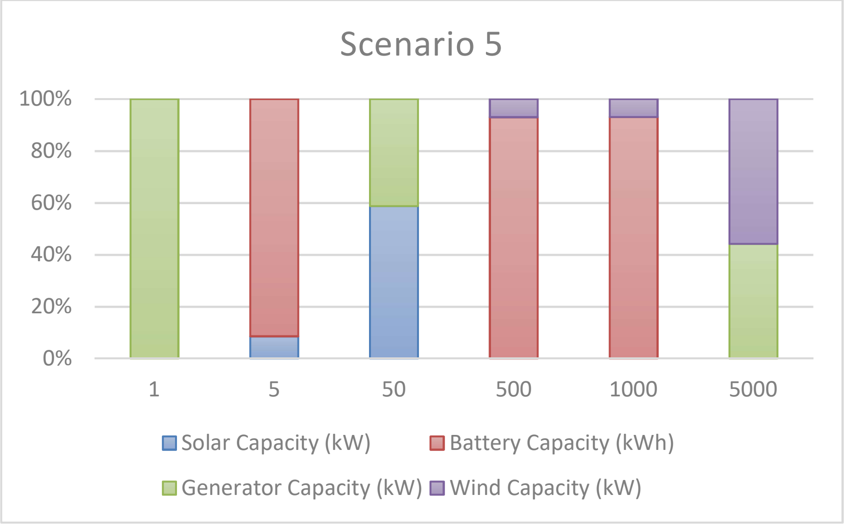

Figure 36: Scenario 5 composition

An additional raise of the wind potential produces once again compositions changes. The 1 and 5 grids have the same generation designs in comparison to scenario 2. The 50 consumers group is supplied by a solar-diesel combination, the 500 and 1000 grids by wind turbines and battery capacity and the 5000-consumer grid by a wind turbine – diesel generation design.

Therefore, the used amount of wind turbines due to a higher wind potential and reduced fuel costs enable a higher proportion of these technologies in the composition.

Scenario 6: (Wind x4, Demand x3, Fuel x0,5)

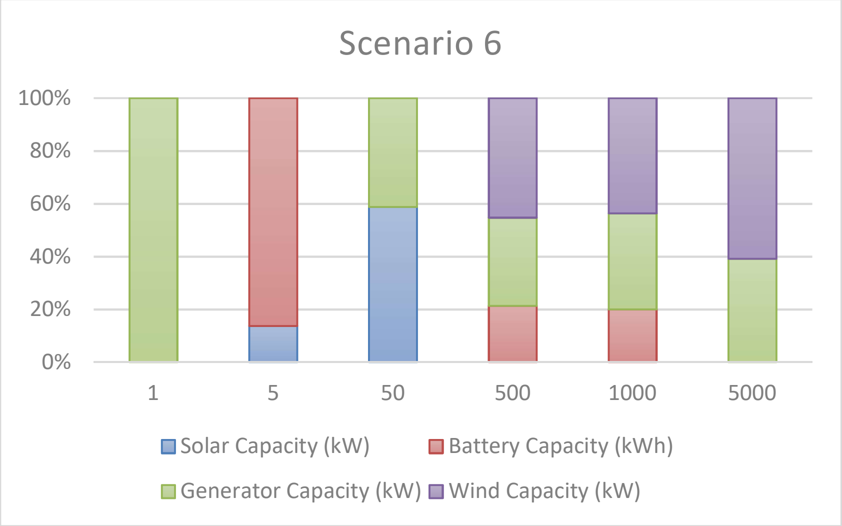

Figure 37: Scenario 6 composition

The fuel cost reduction combined with a higher demand enables even more diverse generation designs. The structures of 1, 5, 50 and 5000 remain with the same generation types as before, but the proportions changes. The 500 and 1000 are supplied by diesel – battery – wind turbine capacities. This could be justified by lower fuel costs, that provide a cheaper diesel generation. Therefore, diesel represses some battery capacity in comparison to the former compositions.

5.2.3 Dispatch and demand profiles

Dispatches:

In order to evaluate the generation design within the generation dispatch upcoming some of the hourly dispatches for the 5 and 1000 consumer groups for 4 of the scenarios. The different dispatches are selected from the same day regarding the input data to allow a causal comparison.

5 consumer group dispatch:

The graphs colours correspond to the legend seen below:

Figure 38: Legend

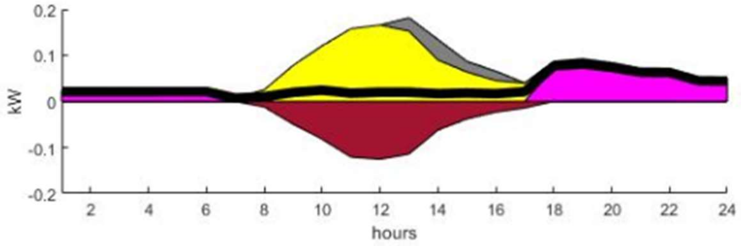

Figure 39: Scenario 1 – 5 consumers

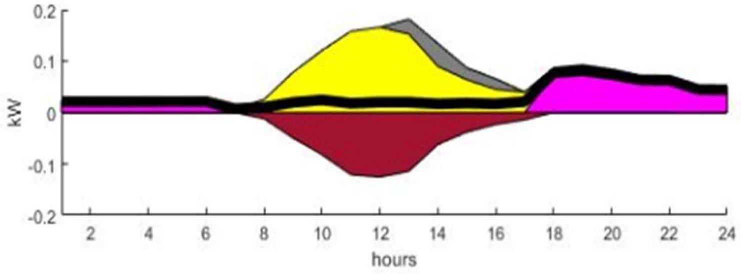

Figure 40: Scenario 2 – 5 consumers

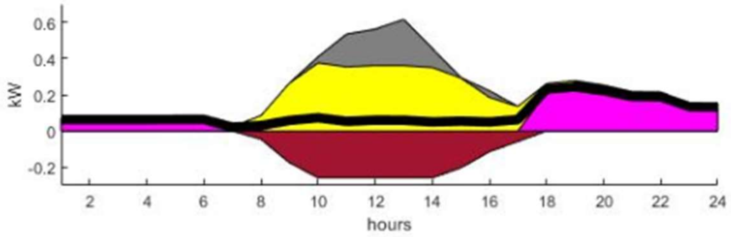

Figure 41: Scenario 3 – 5 consumers

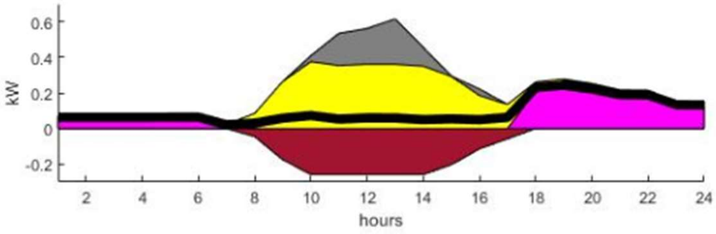

Figure 42: Scenario 6 – 5 consumers

It is visible that all graphs are equal related to their generation design. The demand is supplied by a solar – battery capacity. This is causal in comparison to the design composition in the related graphs. In the 5-consumer group, the solar – battery combination is dominating every other generation design within economical terms. Even in the case with higher demand, the compositions are the same, only the supplied amount differs. The hourly distribution of the dispatch is generally based on solar production during the day when the radiation is strongest. At this timeframe, the current demand is supplied. Additionally, the battery is charged, if they are not fully loaded. Any respective overproduction could not be used and occurs as solar energy spills. Besides the solar production hours, the battery supplies the load due discharging their capacity. Within all the observed scenarios the solar – battery capacity is sufficient to cover the full daily demand and energy non-served did not occur. But this does not necessarily imply that it could not be obtained on any other day. But as seen above the system reliability corresponds almost to a 100 % level.

<u>1000 consumers:</u>

The 1000-consumer designs dispatches are more various. The base case does not contain enough wind potential to use wind power generation in the dispatch. The generation design is based on a solar – battery combination. When increasing the wind potential as in the second graph the wind capacity is able to supply the demand most economic. A wind – battery combination enables full provision. An equal design in the third scenario with the scaled-up demand. The wind production covers the full demand. The last dispatch considers also some diesel generation, which is justified due to the reduction in fuel costs and the higher demand. The diesel substitutes some wind capacity.

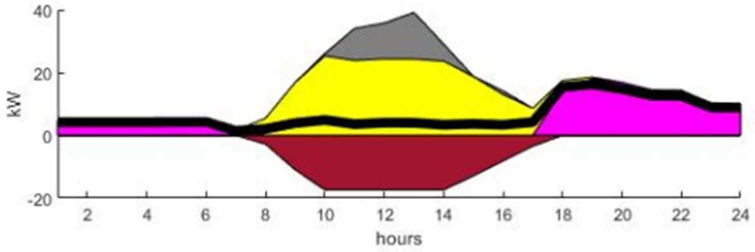

Figure 43: Scenario 1 – 1000 consumers

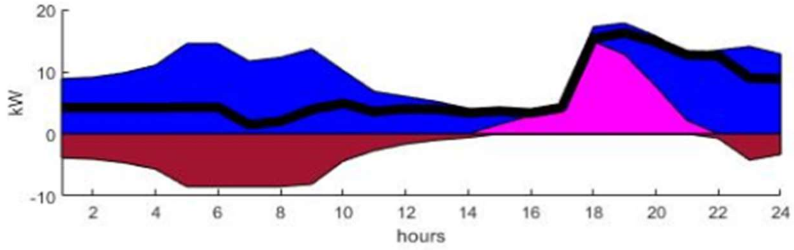

Figure 44: Scenario 2 – 1000 consumers

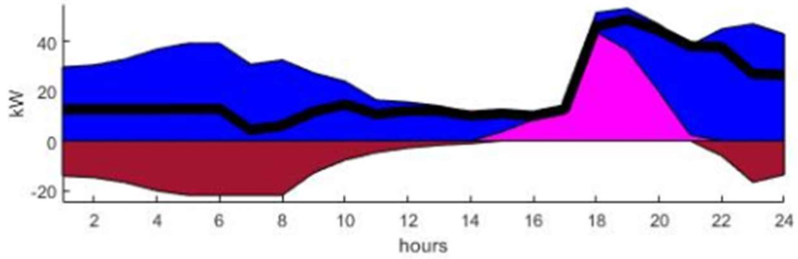

Figure 45: Scenario 3 – 1000 consumers

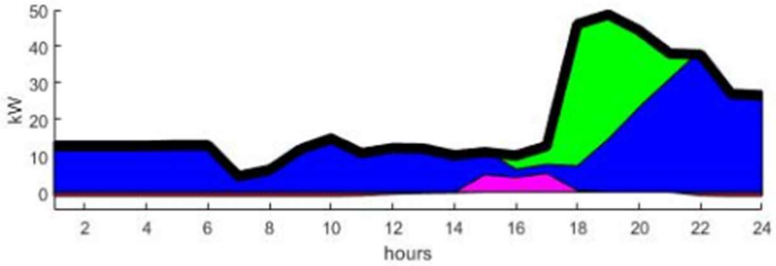

Figure 46: Scenario 6 – 1000 consumers

All the dispatches follow the occurring compositions in the generation designs and seem causal. The distribution of the production in the dispatches is very diverse. Within the base case, the solar produces during the day hours when the radiation is most powerful. At the same time, the battery is charged. In the night hours the battery discharges and supplies the demand.

In scenarios 2 and 3, where different higher wind capacities are implemented in the dispatch, the storage time is different. Generally, the wind turbines have higher production in the night hours and correspondingly the batteries are charged at these times. The high wind production could be justified by the fact that the reduction of radiation and the related heat of the sun, is less or not in the night hours. This lack of heat potentially forms a bigger gradient within the air temperature. This might lead to an increase in wind speed as a balancing movement in-between two areas and accordingly to higher wind speeds. The peak demand is supplied by a mixture of the actual wind energy production and some energy provided due to battery discharge. There also is a spill of wind energy that could not be used. In the last scenario, which contains the lower fuel cost and the higher demand the dispatch includes additional diesel capacity. This capacity is producing in the peak hours in order to keep the most economic operating dispatch. [172]

5.2.4 Final electrification solution

In order to demonstrate that the final electrification solution of the REM optimization reacts causally to the new generation design, we could briefly analyse some major trends within this solution. A deeper analysis is not adequate, because the sub-processes beneath the generation design as the clustering have a high impact on the final design and also is beyond the scope of this thesis. But the general behaviour could be derived and interpreted. This provides the possibility so point out that the implementation leads to appropriate grid structuring without visible contradictions.

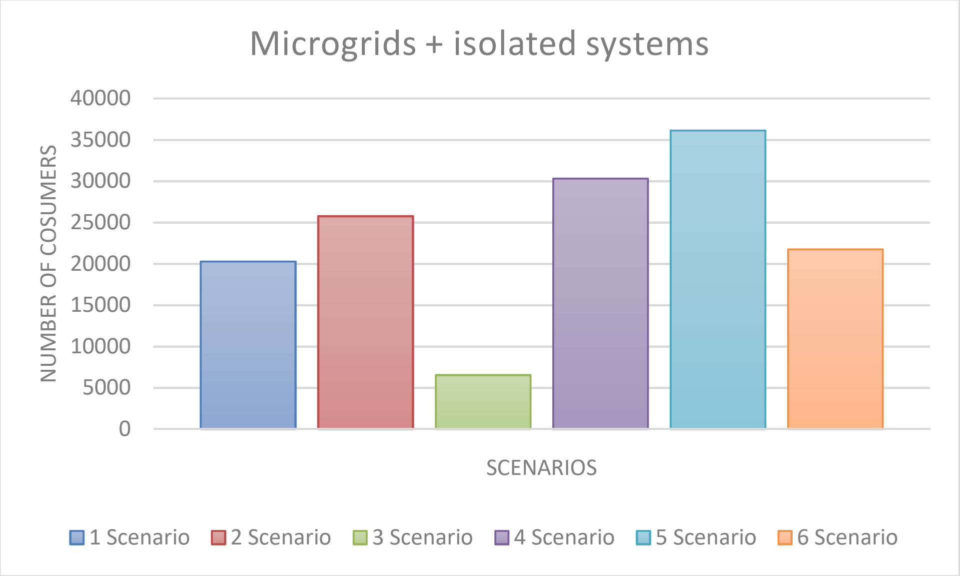

Figure 47: Aggregated microgrids and isolated systems

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[172] (Hau, Windkraftanlagen, 2016, p. 578)

Regarding the microgrid and isolated systems, which are aggregated in the figure [..] related to the number of contained consumers. It could be seen that the number of microgrids and isolated systems increases when the wind potential increases. This is causal because the wind generator potentially providing the possibility of a more feasible and economic solution in order to meet the demand within this grid structures. This effect could be seen within scenarios 1 and 2 or 4 and 5. This behaviour could be returned to the wind impact but is not adjusted by the effects of other procedures as the clustering. The same applies to the reduction of diesel fuel costs, which might enable a shift to higher use of grid independent structures.

In the scenarios of higher demand, the grid extension might be a more economical solution. This could be observed indirectly due to the strong decrease in the number of microgrids either on scenarios 3 or 6 in comparison the 2 and 5, which have the same conditions besides the demand increase.

The grid extensions numbers are finally following these observations. They show the effects in a contrary manner, but with the same statement. The number of grid extensions is smaller, when wind or diesel generation becomes more economical, and is higher when the demand is raising.

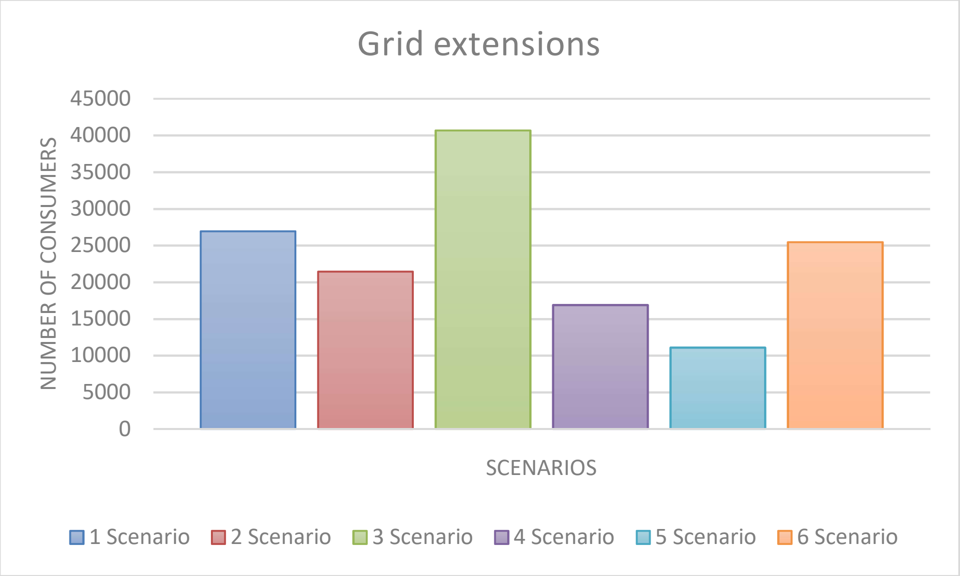

Figure 48: Grid extensions

As a result of the optimization process, the graph below provides the output structures of the REM regarding the different grids. The green lines represent the isolates system grids, the blue lines the mini grids, the red lines the grid extension and the black lines the existing main grid structures. Regarding the selected case study, the structuring below is the final electrification design produced due to the REM optimization procedures.

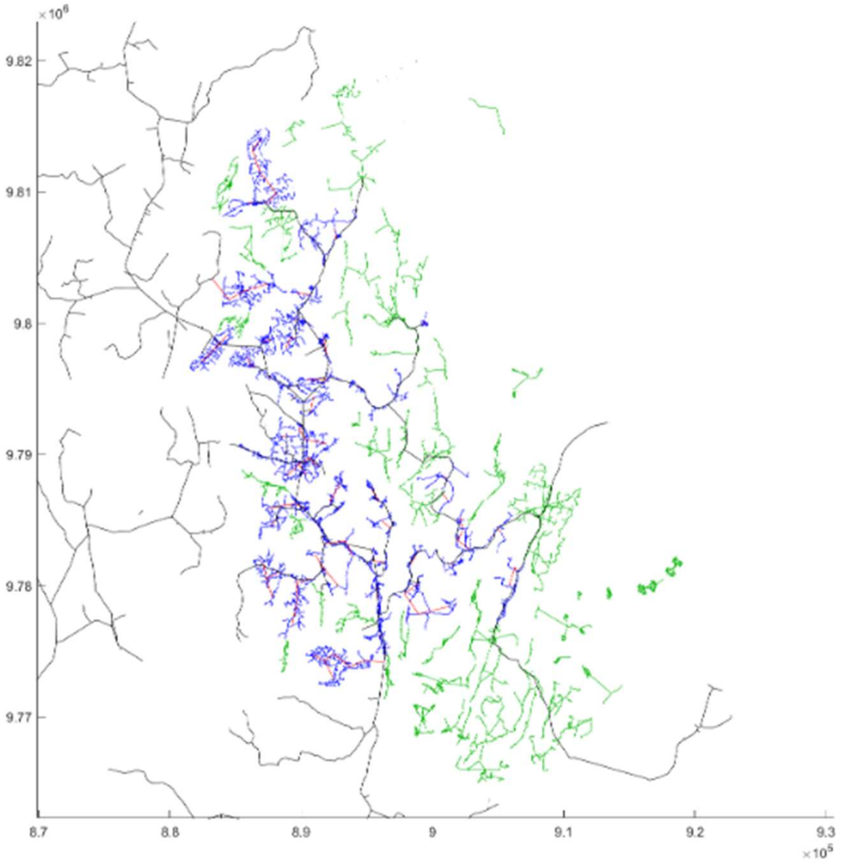

Figure 49: Network structure (LV isolated systems (green), LV microgrid (blue), MV grid extension (red), MV existing grid (black))

The final design shows the enhancement of the grid structures concerning the input data regarding the demand points. It could be seen that the new structures are exactly located at the consumer point and connecting them within the different grid types.

As seen in the graphs above the final design of the REM within the new generation technology, wind power, react causally to the implementation. This points out that the general implementation is working consistent in the model.

The analysis of the case study provides results from the optimizing algorithm of the generation design of the REM. The implementation of the wind power generation added some additional values regarding costs to the systems designs under certain conditions. The major impact of system benefits corresponds to a sufficient wind potential in order to provide the lower cost operation of wind turbines. As seen in this chapter the implementation of the generation design seems to work without obvious discontinuities. The final grid design reacts causal to the adaptation of the generation designs. For future works, the further extension of the generation catalogue and the other enhancements might be an option.

6. Conclusion

This master´s thesis deals with current questions and challenges regarding the electrification of rural areas. These tasks are performed within the context of computer modelling, which are powerful tools to determine cost optimal design for the generation and network structuring. Accordingly, the Reference Electrification Model (REM) is the model of choice that is used in the scope of this thesis. The main purpose is provided due to the implementation of wind power generation into the architecture of the current REM. The focus was set on enhancing the generation design due the implementation, development, and analysis of the respective determinants, conditions and limitations, which are essential for this task's execution.

The reviewing and information gathering of the main influencing parameters and introducing of usable representation methods to determine wind speed profile estimations under certain conditions was done to understand the properties of the wind as generation input data. Furthermore, the processing of the REM and the technical components of the wind turbines were worked out, analysed and edited to match both within a new generation design. This process steps were divided into different subunits:

- The development of a generation catalogue that contains the new generation technologies.
- The adaptation of the generation design procedure of the REM subjected to the wind power generation.
- Verification of the functioning of the implementation approach through a case study and evaluation of the results.

The new generation catalogue contains turbines with different capacities and other technical and economical parameters to provide an adequate fit to versatile consumer groups and enable a supply of the corresponding demands. The adaptation to the REM part that is related to the generation designs touched different processing. Where the structuring of the master-slave decomposition and the adapted search method of the master-level optimization must be mentioned. The case study lastly proofed the functionality of the adaptations and provided causal results.

The case study compared a low wind scenario with other scenarios that were related to high wind, high wind plus high demand and both beforementioned additionally, under low diesel fuel costs. It was shown that the generation design reacts to changes in the current conditioning with higher or lower participation of wind power generation. Under the assumption of a "load following" strategy that considers generation technologies with zero operation costs as solar or wind primarily. It was observed that the proportions of these technologies increase when the necessary input factors potential (radiation, wind speed) were adequate. These participations were measured with different cost types, generation compositions and daily dispatch involvement within the different scenarios and the consumer group sizes. From the development of the cost types, it was possible to derive that the costs were significantly decreasing when the available wind potential raises. This corresponds to the statement that wind implementation leads to lower overall costs regarding generation when the wind speeds are appropriate. Additionally, some economies of scale were observed within the large consumer groups, which provided further costs advantages in contrast to other designs. The compositions of the generation mainly corresponded to these observations of the cost developments. However, it was visible that the supply of certain demand sizes through wind generation was limited by its wind potential. Therefore, under some conditions, a pure renewable supply was not feasible. Especially, when conventional generation reduced in operation costs. The involvement of the daily dispatch showed similar results. Furthermore, the production times of electricity changed due to wind implementation. The highest wind productions, for instance, were in the night hours and early mornings. Whereas solar only produced in the day hours. As a consequence of the participation of wind power generation, the possibility of a more flexible productive timeframe occurs in order to produce the necessary electric loads, admittedly under the assumptions of the availability of storages devices.

These measurements allow concluding that the implementation of wind power generation seems to work sufficiently in the way it is done. This is justified by the provided cost benefits, the higher flexibility of production and a more economic and ecologic dispatch due to renewable generation technology. Additionally, the final design provided due to the REM indicates no obvious contradictions. Some parameters as the number of consumers in the grid extensions and mini grids behave as expected. However, this must be evaluated carefully, because a variety of other determinants and influencing factors have an impact on the final design. But certainly, the final design is not inconsistent with the enhancements, which at least did not proof the opposite. Regarding this, the REM improvements could be considered as adequate in relation to asked research questions.

Generally, these results of this thesis provide a first approach to implement wind power generation in the generation design procedure of the REM. The adaptations of REM optimizing processes provide causal results that could be analysed and evaluated within practical case examples. Therefore, this basic approach could be potentially a starting point for further work in this research field.

Even though the first approach is promising there is space for several expanding’s as mentioned at the end of chapter 4. The detail depth of the turbine modelling should be extended to come closer to real conditions. This could be done through a variable consideration the power factors of wind turbines, which has significant differences in its values depending on the operating level. Furthermore, the consideration of a wider generation catalogue could provide more precise adaptations to the demand conditions of the observed regions and might lead to more cost efficiency. This extension could contain different generators regarding their capacity, diverse types within the number of blades, the location of the rotating axis and the synchronization approach. Also, differences reading the type of current produced might be beneficial under certain conditions. Additionally, the consideration of operation control and the operational modes as the parallel extension with more than one turbine might provide advantages. Moreover, an embedding in more complex microgrid structures makes control of the wind generators more efficient.

Another part of future enhancement could be improvements of the consideration of wind profiles. As elaborated in this thesis the local conditions of regions have a major impact on the wind potential. Regarding this the consideration of additional parameters such as wind fluctuations, bows and stalls might be interesting. A more precise representation and forecasting of the local wind conditions should be a purpose for further research in order to closer approximate the reality.

Finally, further thoughts could be focused on the REM itself. As shown in the case study for the one consumer isolated system the quasi-continuous character of the battery – solar axes might be transformed into complete continuous properties to get even sharpened results and obtain more precise designs. The release of the one site assumption might lead to more flexible generation and cost improvements through more efficient operation control. Additionally, an implementation of other generation technologies, especially renewable ones, potentially provide more advantages and wider adaptation possibilities for rural electrifications generation designs. A continuing review of the current features, processes, and characteristics would provide additional values and improve an already powerful model even further.

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