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Bachelorarbeit

Title

Subtitle

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Berlin, Wednesday 16th January, 2019

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Berlin, Wednesday 16th January, 2019

Maximilian Eissler

Abstract

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1 Introduction

In this document the topic, motivation and approach of my bachelor's thesis shall be outlined. The aim is to give the reader an idea of what I try to accomplish with the choice of topic and methods, as well as a look at the first iteration of the mathematical model I am aiming to build.

more here, definition microgrid, more topic introduction, definitions of words, pv, distributed generation

1.1 Motivation

As the technological requirements for a decentralized energy system increasingly mature, the importance of understanding smaller units within the electricity system grows. There is a possibility of increasing reliance on small, partially autonomous grid units (microgrids) in the future. This calls for a better understanding of how such systems might operate. Especially the possible efficiency gains over a centralised system and the circumstances on which these efficiency gains might depend should be of interest to science and will be the focus of thesis.

more here, GERMANY, capacity building, distribute technological know-how

1.2 Research Question

what is a linear model, theory, MILP, different optimisation methods

In my thesis I want to create a model of a small electricity grid with a single point of access to the main grid. The microgrid will contain 25 households of different types that will aim to reduce their total electricity costs. To attain this goal there will be two possible courses of action available:

1. First, the option to invest in electricity generation and storage facilities, in this case only solar pv and battery storage.

2. Secondly, the possibility of unrestricted trade within the microgrid, meaning there will be no variable transaction costs, as they would usually occur in the form of fees and levies on electricity being transferred.

The aim of this approach is to determine the cost-saving potential in comparison to pure electricity consumption from the main grid in subject to the characteristics of the main parameter types to this model, which are:

1. The environmental conditions, primarily pertaining to the availability of renewable resources - in this case, solar irradiation - as well as temperature and changing seasonal energy demand.

2. The 'behaviour' of the participants in this microgrid, primarily their willingness to shift or avoid loads depending on the current price of electricity within the microgrid or the main grid.

3. The price of power from the main grid as a function of the time of day and season, as well as the price of power generated by the households themselves.

1.3 Methods

To model the outlined situation I want to use the computational modelling language 'Julia' and construct a linear optimisation model which can be solved with it. The goal is to minimise the cost of electricity for the households in the microgrid. It is notable at this point, that the non-consumption of electricity as well as the delay of consumption will be seen as a cost to the actor forgoing her demand. There will be an investment opportunity at the beginning of the examined timeframe of 20 years. The number of timeslices considered in the optimisation will be depending on performance of the model and can therefore not be determined yet.
As a case study for this thesis I want to apply the model to the example of a community in Northrhine-Westfalia. With environmental variables set, I will then construct a number of scenarios with variations in electricity price and actor behaviour parameters.
Another goal of this project is to make this a functional piece of research by reducing performance requirements as far as possible and creating an intuitive user interface that enables the user to 'play' with different scenarios. I prefer this approach over a few detailed and rigid scenarios because the future external factors are presently highly uncertain, which drives me to the conviction that an understanding of the dynamics involved in the examined system is of greater value than an exact solution to an unlikely scenario.

1.4 Expected Results

The result should be a tool that enables an intuitive understanding of the characteristics and the potentials of microgrids, even to non-economists. I intend an exemplary application of the model to the case of a Northrhine-Westfalian community. From this application I expect an insight into the efficiency gains achievable by microgrids in the German context. Also the required external factors for these efficiency gains to materialise should become evident. Under the right conditions I expect a double digit percentage drop in electricity costs compared to a purely consumption-based system. I hope to arrive at practical conclusions regarding present use cases for microgrids and required future regulation.

rundown of all main chapters

2 Literature Review

In this section I shall attempt to give an overview over the current status quo regarding the optimizaton of microgrids and more especially the tools available to do so. I will pursue this by answering a number of broad question, which I think are crucial regarding my subject. The procedure will be structured by utilizing a consistent and reproducible methodology described in detail below. In addition to scientific literature other sources will also be taken into account at my discrection if they are neccessary or helpful in answering a question.

2.1 Key Questions

This literature review will attempt to answer the following key questions in the context of my subject:

1. What are the most eminent scientific standards for modelling a microgrid allocation and dispatch?
2. What is usually within the scope of such a model (what types of generation assets, only electricity or also thermal energy and so on)?
3. What are the common methods used to determine some of the key variables required in such a model such as interest rates, CAPEX and OPEX of assets and so on?
4. What are the most commonly used (commercial) tools for optimizing a microgrid? Are there any free or open source solutions?

2.2 Methodology

To arrive at a dataset of scientific literature that is reproducible I use the methodology described in : add reference to papers here

1. Define a search string
2. Choose scientific databases to which to apply that search string
3. Due to the possibly large amount of papers brought up by this kind of search I am only considering the 100 most relevant papers from each database.
4. Define keywords, which have to occur in the abstracts of the publications. All publications that

lack a keyword are discarded.

5. Define Inclusion as well as Exclusion criteria. A publication must satisfy all inclusion criteria as well as none of the exclusion criteria to be included in the literature review.

Due to the nature of some of the questions I am trying to answer in my literature review it is additionally necessary to include further non-scientific sources at my discretion. The search strings, used databases, as well as the dataset of literature at each step will be included in the appendix.

include info and datasets in the appendix

2.3 Descriptive Analysis

After filtering the original dataset of 275 unique publications in the way described in the last chapter, I arrive at a set of 61 publications. The publication year, as can be observed in Figure 1 is for most publications quite recently: 27 out of 61 papers were published 2017 and after. This could indicate a rising interest in the subject, but is probably at least partly due to the way the different search engines employed compute relevancy.

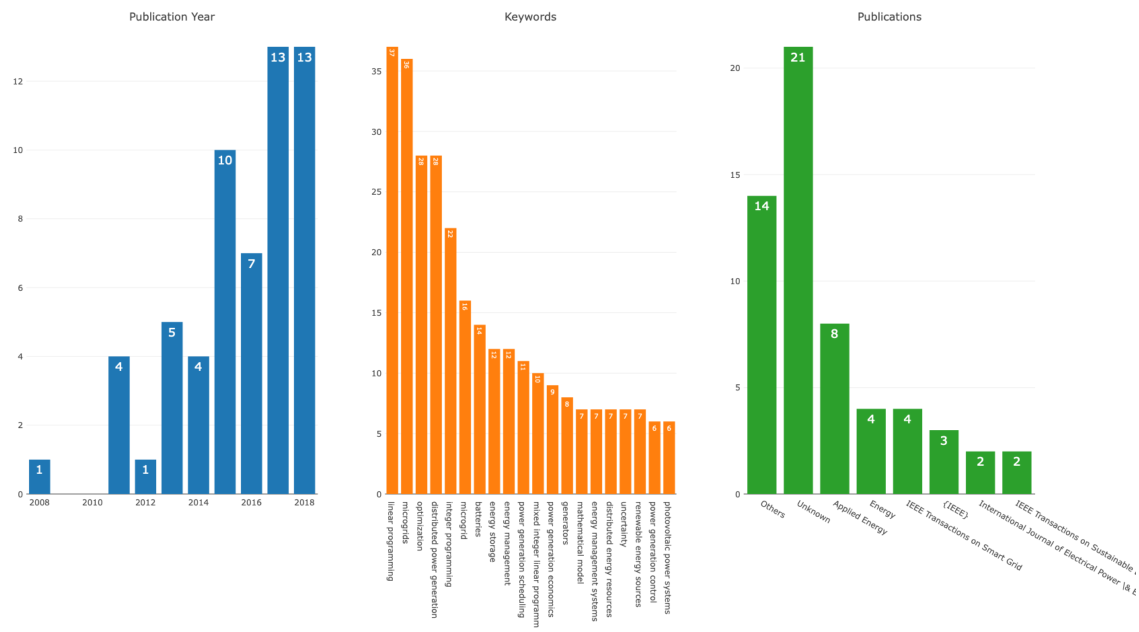

Figure 1: Results of an automated Descriptive Analysis

Source: Own illustration.

Looking at the keywords used to describe the publication shows that, unsurprisingly, the most often occuring keywords are the ones used in conducting the search: 'linear programming', 'micrograds' and 'optimization'. 'distributed energy generation' and 'distributed energy resources'are mentioned 37 times, 'batteries' and 'energy storage' a total of 28 times, and 'renewable energy sources' and 'generators' a total of 16 times. This illustrates the focus on decentralized energy sources and storage, more specifically renewables and small scale combined heat and power generation that prevails throughout the literature.

The publication chart is not very enlightening. This is due to the fact 28 out of 61 publications are conference papers which either appear under others because there is only one instance of that particular conference or unknown. From a more general point of view though almost all papers are published either by Elsevier or IEEE, with very few exceptions.

2.4 Literature Overview

The first question in need of an answer in optimizing a microgrids design and dispatch is the question of the modelling approach itself. Although the dataset of literature derived from the methodology described in 2.2 is biased towards Linear Programming, which was one of the search and filter criteria, it contains multiple employed methodologies. For example, [17] employ both a Mixed Integer Linear Programming (MILP) model and a Genetic Algorithm (GA) and come to the conclusion that while both deliver accurate and robust results the MILP model is faster. [25] mostly concur. While in this case, the results of the GA were better in two scenarios, it was outperformed by the MILP model in the remaining three. A key problem of MILP however seems to be its deterministic nature, which anticipates perfect knowledge of all the parameters involved. Especially for optimisation problems regarding a short timeframe, such as day-ahead scheduling this is a significant problem, since actual parameters may be different. Several methods addressing this problem can be found in literature.

One such method are rolling time horizons. This approach optimizes the dispatch of a microgrid for a fixed time horizon based on steadily updated forecasts of the uncertain paremeters. The optimization is repeated periodically to reflect the updated forecasts [27] [36] and increase dispatch accuracy in the nearer future. Rolling Horizon Optimization is however unfit to optimize investment, since it is not possible to adapt investment decisions ex post to changed conditions.

While the rolling time horizon method helps to limit uncertainty by reacting to changes of input parameters, Robust Optimization and Stochatsic Optimization try to proactively account for a variety of possible scenarios. Robust Optimization achieves this by optimizing for a number of scenarios deemed equally likely, as in [6] using ensemble weather forecasts or in [13] and [48] using upper and lower boundaries for uncertain parameters. Stochastic Optimization on the other hand uses detailed probability distributions to weigh the probability of each scenario occuring as explained in [23]. To arrive at these distributions secondary tools are usually needed. Shams et al use a simple Gaussian randomization to make their demand data reflect uncertainty, as well as more specific distributions for irridiation and wind speeds. A number of other methodologies appear in literature such as employing a Monte Carlo simulation [51] or deriving multiple scenarios and corresponding realization probabilities from historical data [26].

The scope of the microgrid models found in literature varies greatly. A constant however is the definition of a microgrid as bounded, operating in a small geographical zone and with a clear electrical boundaries [38][21][14]; managing local loads [46] [50]; possibly containing various generation units and storage [36][19] and possibly being able to exchange power with the main grid [25][8], from whose perspective it is seen as a single entity [15].

While most of the selected literature consider cases where a grid connection exists and can be used at all times, there is a number of publications that consider either completely islanded microgrids [47][27] [33][32] or microgrids that can sustain themselves in islanded mode for extended periods for exapmle in case of natural disasters [38].

The clearest distinctions between microgrid models, after the object and applied methodology is properly defined, is based on the aspect or aspects that the model is supposed to optimize. The literature can be split in two groups, either optimizing only dispatch or both investment (e.g. the planning phase) and dispatch. The former group is definitely the larger, with only 12 out of 61 publications considering investment. Notably only one of these [23] uses any of the methods to model uncertainty discussed above.

There is also significant diversity in literature when it comes to the technologies considered in modelling. Modelling dispatchable (eg. non-renewable) as well as non-dispatchable (eg. renewable) generation is rather common, but the specifics differ: While most models consider PV or Wind as well as a CHP generator, the included generation technologies are as diverse as geothermal generators [17] and gas turbines [39] [25]. In addition to modelling electricity, some publications also consider heat generation and transmission [16][43]. This is valuable, because the economic performance of a non-renewable generation unit (usually CHP) present in most models depends heavily on if and how the heat is used, as [5] point out.

The types of storage used in literature also vary. Although battery storage [2][39][44] or an abstract storage device [28][45] are the most common choices, there are a number of papers modeling heat storage [46][48][16][43], and some with more exotic technology choices such as flywheels [31] or an electrolyzer [10].

In addition to these generation and storage technologies some publications also model the network topology [20][4][35] and some even consider electrical phenomena such as active and reactive power losses [19][21] and voltage deviation [19].

Demand side management, which some models implement is usually represented by dividing loads into different categories. [4] distinguish between 'critical loads' ,meaning loads that absolutely have to be satisfied, 'shiftable loads', meaning loads that have to be satisfied, although there is a time window, rather than an exact point in which they can be serviced, and 'adjustable' loads, which can be dropped if needed. Although the terms may vary, and many publications do not introduce the 'shiftable loads' category alltogether, these conceptual distinctions are made by a number of other authors [36][48][49]. The model results depend almost as much on the given input parameters used in case studies as on the modelling approach itself. There is however only a limited number of publications with detailed documentation of the parameters used. The used parameters can be broadly categorized as either economic parameters, such as capital and operation and maintenance cost for the technologies used, generation related parameters such as irradiation and wind speeds, and load data, representing consumer behaviour.

In publications documenting cost parameters there is a clear trend towards a split of technology cost into investment and maintenance cost. However, whereas [16] define maintenance cost as a fixed cost per unit of time, [43] define it as a function of kilowatthours produced, a measurement which [16] call 'fuel costs'. [2] choose a definition closer aligned with the former, they however define yearly maintenance cost simply as a flat percentage of the units' investment cost.[15] seem to neglect maintenance costs alltogether focusing only on investment costs. While some models document econimic paramters such as discount rates [2], many don't and it is unclear if future flows of value are properly discounted in these models. Furthermore many of the publications declare cost parameters as assumptions rather than trying to derive them from sources, although a few such as [16] and [43] do so.

The selected literature offers multiple ways of obtaining input parameters of metereological data. [11] use historical metereological data while [27] build a prediction model for forecasting irridiation and wind speeds. Similarly there are authors who use historical data for load parameters such as [11] and ones who generate synthetic data based on appliance use and probabilistic models [46][45][48] or neural networks using empirical data [27].

When it comes to modelling tools DER-CAM [16][51][20] and HOMER [1][51][16] are the most often referenced. DER-CAM or Distributed Energy Resources Customer Adoption Model is an optimizatioon tool developed at Berkeley Labs and uses Mixed Integer Linear Programming to optimize portfolio, placement, sizing and dispatch of Microgrid Energy Systems [7]. HOMER Grid is a commercial optimization tool for behind the meter systems. Its main advantage is it's large database of components and tariff rates in the United States and Canada [12]. The most often mentioned solver is the CPLEX commercial solver [34][25][40][19]... . Most of the models are written in GAMS [36][40][6]..., although many are written in MATLAB [19][4]... .

Open source tools seem scarcely available. A search of 'microgrid optimization' on github.com, the major open source software platform, brings up only 3 items with more than one star, none of them has more than ten (popular libraries might have thousands)[9]. The most up-to-date one has not been updated for a year and none features a graphical user interface.

3 Model

3.1 Time

The range of scenarios and complexity the model can handle is, among other things, dependant on its implementation of discrete time. More and smaller timesteps and a representative sample of diverse expectable conditions regarding the parameters leads to higher model accuracy. Of course the amount of timesteps is limited by processing power and therefore by model complexity. To enable both diverse and therefore potentially discontinuous parameter sets and a reasonable length for each set, the length of 1 hour is chosen for the basic timestep $t; t \in [1, T]; T \in \mathbb{N};$. T denotes the number of hours in each discontinuous sets of supply and demand parameters. Furthermore the ability of including multiple discontinuous sets of supply and demand parameters of the same length in one scenario is gained by introducing a second iterator $s; s \in [1, S]; S \in \mathbb{N};$. S denotes the number of discontinuous sets of supply and demand parameters.

3.2 Households

To properly conduct trading and for the future possibility of adding voltage and topological constraints to the model, the households are modelled as independent entities, each with its own demand, generation and storage. Therefore a third iterator $u; u \in [1, U]; U \in \mathbb{N};$ is introduced. U denotes the number of households modelled. An abstract household H is defined as a tuple of storage and generation devices as well as demand curves. For discrete storage and generation devices two separate sets of positive integers define how much of each option available in the scenario was installed. Additionally each household has a price $shiftP$ and $curtP$ at which they are willing to shift or curtail a unit of their load respectively.

$$H := (GEN, ST, dGEN, dST, DEM, shiftP, curtP) \tag{1}$$

A concrete household H_u implements these values:

$$GEN \in \mathbb{R}^K; GEN_k \geq 0 \forall k; k \in [0, K] \tag{2}$$

$$ST \in \mathbb{R}^L; ST_l \geq 0 \forall l; l \in [0, L] \tag{3}$$

$$dGEN \in \mathbb{N}^M \tag{4}$$

$$dST \in \mathbb{N}^N \tag{5}$$

with

$k, l\ in\mathbb{N}$

and

$K, L, M, N \in \mathbb{N}$

and

$shiftP, curtP \geq 0$

K and L denote the amount of generation and storage devices in household H_u.This, in practice, is equal to the amount of linear scaling investment options for each category, since a zero capacity device is still modelled as a device. M and N denote the amount of discrete investment options in their respective category. GEN_k and ST_l are the capacities installed of the k-th and l-th linear investment option respectively. GEN_m and dST_n are the amount installed of the m-th and n-th discrete investment option available. DEM is further defined in the subsection demand.
A list of instances of the structure H and its length U are both model parameters.

3.3 Internal Variables

The objective of the model is to find optimal investment, dispatch and trade. Therefore, the following sets of internal parameters are introduced:
$\forall u, s, t$:

$$toTR_{u,s,t}, fromTR_{u,s,t} \geq 0 \tag{6}$$

The trade supply variables $toTR_{u,s,t}$ and $fromTR_{u,s,t}$ reflect the amount of traded power, to the trading pool and from the trading pool, respectively. They are defined for each household at each timestep.

$\forall u, k, m, s, t$:

$$genS_{u,k,s,t}, dgenS_{u,m,s,t} \geq 0 \tag{7}$$

The generation supply variables $genS_{u,k,s,t}$ and $dgenS_{u,m,s,t}$ describe the amount of energy produced by each linear or discrete generation option respectively. They are defined for each generation option in each household and at each timestep. It is useful to keep in mind though, that not every household needs to implement all the generation options. In case of zero instances of the discrete generation option $dGEN_2$ installed in household H_5, for example, $dgenS_{5,2,s,t} = 0$ for all s and t.

$\forall u, l, n, s, t$:

$$fromST_{u,l,s,t}, toST_{u,l,s,t}, fromDST_{u,n,s,t}, toDST_{u,n,s,t} \geq 0 \tag{8}$$

The storage supply variables $fromST_{u,l,s,t}$ and $toST_{u,l,s,t}$ indicate the amount of power fed into or withdrawn from a linear storage investment option. They are defined for each linear investment option and each household at each timestep. The variables $fromDST_{u,n,s,t}$ and $toDST_{u,n,s,t}$ have the equivalent function for all discrete storage investment options.

$\forall u, s, t$:

$$toSC_{u,s,t}, fromSC_{u,s,t} ncS_{u,s,t}, \geq 0 \tag{9}$$

The shifted consumption supply variable $toSC_{u,s,t}$ represents the amount of power consumtion shifted by each household at each timestep. $fromSC_{u,s,t}$ indicates the amount of power consumption that has previously been shifted and is now consumed. The non-consumption supply variable $ncS_{u,s,t}$ designates the amount of power consumption curtailed for each household at each timestep.

$\forall u, s, t$:

$$fromGR_{u,s,t}, toGR_{u,s,t} \geq 0 \tag{10}$$

Finally, the grid supply variables $fromGR_{u,s,t}$ and $toGR_{u,s,t}$ denote the amount of power supplied by and to the respectively by each household at each timestep. Only power flowing out of and into the microgrid included in this definition, power traded internally, while using the (micro)grid, is reflected in the trade variables. (see formula (6))

$\forall u, k$:

$$H_u \hookrightarrow GEN_k \geq 0 \tag{11}$$

$\forall u, l$:

$$H_u \hookrightarrow ST_l \geq 0 \tag{12}$$

$\forall u, m$

$$H_u \hookrightarrow dGEN_m \in \mathbb{N} \tag{13}$$

$\forall u, n$

$$H_u \hookrightarrow dST_n \in \mathbb{N} \tag{14}$$

$H_u \hookrightarrow GEN_k$, $H_u \hookrightarrow ST_l \geq 0$, $H_u \hookrightarrow dGEN_m$, $H_u \hookrightarrow dST_n$ are variables describing the realized capacities of each linear and discrete investment option in each household. They are explained in more detail in section 3.2.

3.4 Generation

For a model, explicitly built to optimize decentralized generation in microgrids, a robust and flexible mathematical representation of generation options is required. Therefore an abstract linear generation device GEN and an abstract discrete generation device $dGEN$, which can represent a range of technology options, are defined:

$$GEN := (C_{Cap}, C_{OpFix}, C_{OpVar}, T_{Life}, EFF_{el}, PR, maxFl) \tag{15}$$

$$dGEN := (CAP, C_{Cap}, C_{OpFix}, C_{OpVar}, T_{Life}, EFF_{el}, PR, maxFl) \tag{16}$$

$CAP \geq 0$, which is only required for discrete investments, defines the generation capacity of the discrete investment option. $C_{Cap} \geq 0$ defines the total investment cost for discrete generation devices. For linear generation devices the investment cost is expressed in terms of one unit of capacity. $C_{OpFix} \geq 0$ expresses the fixed maintenance cost per unit of time. In the case of linear generation they expressed in proportion to capacity, while for discrete generation they express the maintenance cost of one discrete device. $C_{OpVar} \geq 0$ expresses the variable maintenance cost per unit of input consumed. $T_{Life} \in \mathbb{N}$ defines the life expectancy of a generation device, e.g the time before it is replaced. $EFF_{el} \in [0,1]$ defines the ratio of supplied energy, for example sunlight or gas, to produced electricity. $PR \in [0,1]$ is another definable penalty to electricity production, which can, for example, express the degradation of solar cells. $maxFl \in \mathbb{R}^{S \times T}, maxFL \geq 0 \forall s,t$ denotes the maximal possible flow of input energy, e.g. sunlight in case of solar pv or gas in case of a fuel cell. This enables the represantation of intermittent availability for wind and solar. It could nevertheless be used to model any condition that would restrict a conventional generation device from running at capacity at certain times, for example air quality regulation.

All instances of the GEN structure are collected in one list. The same is true for all instances of the $dGEN$ structure. These lists and their sizes K and M are parameters. The model uses the iterators k and m to represent individual instances of these structures. (see section 3.2)

In addition, to model generation appropriately, several sets of constraints need to be defined:

$\forall u, k, s, t$:

$$\begin{aligned} genS_{u,k,s,t} \leq min(\frac{GEN_k \hookrightarrow EFF_{el} * GEN_k \hookrightarrow maxFl_{s,t}}{H_u \hookrightarrow GEN_k}, 1) \\ *H_u \hookrightarrow GEN_k * GEN_k \hookrightarrow PR \end{aligned} \tag{17}$$

$\forall u, m, s, t$:

$$dgenS_{u,m,s,t} \leq min(\frac{GEN_m \hookrightarrow EFF_{el} * GEN_m \hookrightarrow maxFl_{s,t}}{H_u \hookrightarrow dGEN_m * dGEN_m \hookrightarrow CAP}, 1) \\ *H_u \hookrightarrow dGEN_m * dGEN_m \hookrightarrow CAP * dGEN_k \hookrightarrow PR \tag{18}$$

The capacity constraints restrict the use of any linear generation device GEN_k or any discrete generation device $dGEN_m$ to its capacity rating and the maximum flow of input energy supplied to it. The constraints differ due to the capacity of linear generaton devices being stored in the household structure directly, while for discrete generation devices the household structure only contains an integer representing the amount implemented. This value is then multiplied with the capacity of one unit of the concerned discrete generation device to compute the total installed capacity. In both cases the result is multiplied with the performance ratio PR of the concerned device, which acts as a penalty to capacity(see above). The minimized term calculates the ratio of maximum output achievable with the available maximum input to the capacity of the device. If the input suffices for running at capacity the term returns a maximum of 1, not restricting supply further, otherwise it restricts capacity to the maximum possible under current resource input.

3.5 Storage

The introduction of the concept of energy storage is necessary if the use of a large proportion of intermittent power production while maintaining intermittent power demand is to be seriously explored. Therefore an abstract linear storage device ST and an abstract discrete storage device dST, which can represent a range of technology options, are defined:

$$ST := (C_{Cap}, T_{Life}, EFF_{+-}, LOC_{1h}, maxP_{+}, maxP_{-}) \tag{19}$$

$$dST := (CAP, C_{Cap}, T_{Life}, EFF_{+-}, LOC_{1h}, maxP_{+}, maxP_{-}) \tag{20}$$

$CAP \geq 0$, which is only required for discrete investments, defines the usable capacity of the discrete investment option. $C_{Cap} \geq 0$ defines the total investment cost for discrete storage devices. For linear storage investment options the investment cost is expressed in terms of one unit of capacity. $T_{Life} \in \mathbb{N}$ defines the life expectancy of a storage device, e.g the time before it is replaced. To be able to better estimate this value it is assumed, that storage is, on average, cycled once per day. $EFF_{+-} \in [0, 1]$ defines the roundtrip efficiency, e.g. what proportion of one unit of power is left after charging and discharching inefficiencies. It is used to compute the charge and discharge efficiencies. The charge efficiency EFF_{+} is defined as $EFF_{+} = \sqrt{EFF_{+-}}$ and the discharge efficiency EFF_{-} as $EFF_{-} = 1/EFF_{+}$.[16]

$maxP_+ \geq 0$ and $maxP_- \in [0,1]0$ denote the maximum charge rate and discharge rate respectively, relative to the devices capacity. All instances of the ST structure are collected in one list. The same applies for all instances of dST. The two lists and their sizes L and N are model parameters. The model uses the iterators l and n to represent individual instances of these structures. (see section 3.2) To model storage appropriately several sets of constraints need to be specified:
$\forall u, l, s, t$:

$$toST_{u,l,s,t} \leq ST_l \hookrightarrow maxP_+ * H_u \hookrightarrow ST_l \tag{21}$$

$$fromST_{u,l,s,t} \leq ST_l \hookrightarrow maxP_- * H_u \hookrightarrow ST_l \tag{22}$$

The flow constraints for linear storage constrain the maximum in- and outflow for each linear storage device to its maximum in- and outflow rate relative to capacity.
$\forall u, n, s, t$:

$$toDST_{u,n,s,t} \leq dST_n \hookrightarrow maxP_+ * H_u \hookrightarrow dST_n * dST_n \hookrightarrow CAP \tag{23}$$

$$fromDST_{u,n,s,t} \leq dST_n \hookrightarrow maxP_- * H_u \hookrightarrow dST_n * dST_n \hookrightarrow CAP \tag{24}$$

The flow constraints for discrete storage work similar to the linear ones, with the slight distinction of how capacity is computed. Rather than stored directly in the H_u structure, it is stored as an attribute of the discrete storage device structure dST_n and is multiplied by the integer amount of units implemented stored in H_u. (see 3.2)
$\forall u, l, s$:

$$\sum_{t=1}^{T}(ST_l \hookrightarrow EFF_+ * toST_{u,l,s,t'} - ST_l \hookrightarrow EFF_- * fromST_{u,l,s,t'}) = 0 \tag{25}$$

$\forall u, n, s$:

$$\sum_{t=1}^{T}(dST_n \hookrightarrow EFF_+ * toDST_{u,n,s,t'} - dST_n \hookrightarrow EFF_- * fromDST_{u,n,s,t'}) = 0 \tag{26}$$

The model assumes the storage to be full at the start of each simulated discontinous period s and requires it to be full at the end of each period. This means inflows minus outflows weighted by the respective efficiencies need to sum up to zero for the entirety of each period s.
$\forall u, l, s, t$:

$$\begin{aligned} toST_{u,l,s,t} * ST_l \hookrightarrow EFF_+ \leq \\ \sum_{t'=1}^{t-1}(-ST_l \hookrightarrow EFF_+ * toST_{u,l,s,t'} + ST_l \hookrightarrow EFF_- * fromST_{u,l,s,t'}) \end{aligned} \tag{27}$$

$\forall u, n, s, t$:

$$toDST_{u,n,s,t} * dST_n \hookrightarrow EFF_+ \leq \sum_{t'=1}^{t-1} (dST_n \hookrightarrow EFF_+ * toDST_{u,n,s,t'} - dST_n \hookrightarrow EFF_- * fromDST_{u,n,s,t'}) \tag{28}$$

The storage capacity constriants prohibit storage usage beyond the storage devices capacity. The remaining storage capacity at time (s, t) is in theory calculated as the capacity minus current storage level, which is the sum of all inflows and outflows weighted by in- and outflow efficiency. Since the storage at each timestep $(s, 0)$ is required to be full, the capacity is subtracted once, which eliminates it and leaves only the sum. The constraint is implemented equivalently for discrete storage.
$\forall u, l, s, t$:

$$fromST_{u,l,s,t} * ST_l \hookrightarrow EFF_- \leq H_u \hookrightarrow ST_l + \sum_{t'=1}^{t-1} (ST_l \hookrightarrow EFF_+ * toST_{u,l,s,t'} - ST_l \hookrightarrow EFF_- * fromST_{u,l,s,t'}) \tag{29}$$

$\forall u, n, s, t$:

$$fromDST_{u,n,s,t} * dST_n \hookrightarrow EFF_- \leq H_u \hookrightarrow dST_n * dST_n \hookrightarrow CAP + \sum_{t'=1}^{t-1} (dST_n \hookrightarrow EFF_+ * toDST_{u,n,s,t'} - dST_n \hookrightarrow EFF_- * fromDST_{u,n,s,t'}) \tag{30}$$

Finally, the storage level constraints prohibit the storage level to fall below zero. This means there can be no more power withdrawn, weighted by outflow efficiency, than is currently stored in the device. Because we assume the storage to be full at the start of each period s, the current charge amounts to one full charge (storage capacity) plus the sum of all transactions during the current period up to the current timestep t. The only distinction for discrete storage devices is the way capacity is calculated. (see 3.2)

3.6 Trade

Trade is implemented as an exchange platform, which sums up deposits and withdrawals of power at each timestep and always needs to be balanced. This approach has the advantage of reducing the number of constraints and therefore complexity greatly, although it is not very well suited to handle grid topology constraints which might be added in the future.

The trade constraint is defined as:

$\forall s, t$:

$$\sum_{u=1}^{U}(toTR_{u,s,t} - fromTR_{u,s,t}) = 0 \tag{31}$$

3.7 Demand

Abstract demand data DEM is defined as a set of the size S of demand profile sets of the size T:

$$DEM := \{DEM_s | s \in [1, S]; s \in \mathbb{N}; \forall DEM_s, DEM_s := \{DEM_{s,t} | t \in [0, T]; t \in \mathbb{N}\} \tag{32}$$

As frequently applied in literature, $DEM_{s,t}$ is not a demand value, but rather a tuple of three demand values, critical demand, shiftable demand and curtailable demand [36][48][49][4] :

$$DEM_{s,t} := (critDEM_{s,t}, shiftDEM_{s,t}, curtDEM_{s,t}) \tag{33}$$

$\forall u, s, t$:
$H_u \hookrightarrow critDEM_{s,t}, H_u \hookrightarrow shiftDEM_{s,t}, H_u \hookrightarrow curtDEMs, t \geq 0$

Critical demand will be met by the model as it is seen as a constraint. Shiftable demand can be shifted by one hour at a fixed rate defined for each household. Curtailable demand can be dropped at a fixed rate defined for each household. The restrictions on shiftable and curtailable demand is expressed by the following sets of contraints:
$\forall u, s, t$:

$$scS_{u,s,t} \leq H_u \hookrightarrow shiftDEM_{s,t} \tag{34}$$

$$ncS_{u,s,t} \leq H_u \hookrightarrow curtDEM_{s,t} \tag{35}$$

3.8 Grid

The modelled microgrid is connected to the grid via a common point of coupling. The grid is defined as:

$$GRID := (maxS, maxD, gridC, feedC) \tag{36}$$

with

$maxS, maxD, gridC, feedC \in \mathbb{R}^{S \times T}$

and $\forall s, t$:

$maxS_{s,t}, max_{s,t}, gridC_{s,t}, feedC_{s,t} \geq 0$

$maxS$ describes the maximum amount of power supplied by the grid at each timestep (s, t), while $gridC_{s,t}$ expresses the price at which this power can be bought. $maxD$ describes the maximum amount power that can be fed into the the grid at timestep (s, t), while $feedC_{s,t}$ expresses the price at which the grid buys this power.

To model the expected behaviour of the grid several sets of constraints need to be introduced:

$\forall s, t$:

$$\sum_{u=1}^{U} (fromGR_{u,s,t} - toGR_{u,s,t}) \leq maxSs, t \tag{37}$$

The first grid contraint, restricts the sum of each housholds "trade balance" with the grid to the maximum power the grid can supply at each timestep.

$\forall s, t$

$$\sum_{u=1}^{U} (toGR_{u,s,t} - fromGR_{u,s,t}) \leq maxDs, t \tag{38}$$

The second grid constraint does the reverse, in that it restricts the sum of each housholds "trade balance" with the grid to the maximum power the microgrid can feed into the grid at each timestep.

3.9 Power Balance

The power balance constraints describe the need for a balance between supply and demand at each node at each timestep:

$\forall u, s, t$:

$$\begin{aligned} H_u \hookrightarrow critDEM_{s,t} + H_u \hookrightarrow shiftDEM_{s,t} + H_u \hookrightarrow curtDEM_{s,t} \\ = \\ fromGR_{u,s,t} - toGR_{u,s,t} + \sum_{k=1}^{K} genS_{u,k,s,t} + \sum_{m=1}^{M} dgenS_{u,m,s,t} \\ + fromTR_{u,s,t} - toTR_{u,s,t} + scS_{u,s,t} - scS_{i,s,t-1} + ncS_{u,s,t} \\ + \sum_{l=1}^{L} fromST_{u,l,s,t} - toST_{u,l,s,t} + \sum_{n=1}^{N} fromDST_{u,n,s,t} - toDST_{u,n,s,t} \end{aligned} \tag{39}$$

The power balance constraint requires electricity supply and demand to balanced for each household at each timestep. On the demand side the three types of demand of the concerned houshold and the current timestep are summed up. The supply side is made up of several terms:
$fromGR_{u,s,t} - toGR_{u,s,t}$ expresses the momentary trade balance with the grid, while $fromTR_{u,s,t} - toTR_{u,s,t}$ denotes the momentary trade balance with the microgrid's trading pool. $scS_{u,s,t} - scS_{i,s,t-1}$ is the balance of consumption shifted from the current timestep into the future and past shifted demand realized now. $ncS_{u,s,t}$ reflects loads dropped in the current timestep. Finally the power generated by all linear and dicrete generation devices is summed up, as well as the balance of storage use for all linear and discrete storage devices.

3.10 Cost Minimisation Formula

The cost minimisation formula calculates the cost of all investment and dispatch decisions made:

$$\min C_{total} = C_{Investment} + C_{Operation} + C_{Dispatch} \tag{40}$$

The total cost can be broken down into investment, operation and dispatch costs.

$$\begin{aligned}
C_{Investment} = \sum_{u=1}^{U}[\sum_{k=1}^{K}(GEN_k \hookrightarrow C_{Cap} * H_u \hookrightarrow GEN_k) \\
+ \sum_{l=1}^{L}(ST_l \hookrightarrow C_{Cap} * H_u \hookrightarrow ST_l) \\
+ \sum_{m=1}^{M}(dGEN_m \hookrightarrow C_{Cap} * H_u \hookrightarrow dGEN_m) \\
+ \sum_{n=1}^{N}(dST_n \hookrightarrow C_{Cap} * H_u \hookrightarrow dST_n)]
\end{aligned} \tag{41}$$

The investment costs consist of all investment into generation and storage devices throughout the microgrid. In the context of the model this means for linear investment options the installed capacity times the costs of capital per unit of capacity and for discrete investment options the costs of capital for a single instance of a device multiplied with the number of instances installed.

$$\begin{aligned}
C_{Operation} = \sum_{u=1}^{U}[\sum_{k=1}^{K}(GEN_k \hookrightarrow C_{OpFix} * H_u \hookrightarrow GEN_k * S * T) \\
+ \sum_{m=1}^{M}(dGEN_m \hookrightarrow C_{opFix} * H_u \hookrightarrow GEN_m * S * T)]
\end{aligned} \tag{42}$$

The operation costs are the sum of all fixed operation costs of all generation devices deployed. They are calculated for each investment option in each household by multiplying its fixed operation costs with the installed capacity (or pieces in the case of discrete investment options) and the total number of timesteps. The sum over all of these investment options are the total maintenance costs for generation in the microgrid. Since there is no fixed maintenance cost defined for storage this value is equal to all the maintenance costs incurred.

$$\begin{aligned}C_{Dispatch} = \sum_{s=1}^{S}\sum_{t=1}^{T}\sum_{u=1}^{U}[gridC_{s,t} * fromGR_{u,s,t} - feedC_{s,t} * toGR_{u,s,t} \\ +H_u \hookrightarrow curtP * ncS_{u,s,t} + H_u \hookrightarrow shiftP * scS_{u,s,t} \\ + \sum_{k=1}^{K}(GEN_k \hookrightarrow C_{OpVar} * genS_{u,k,s,t}) \\ + \sum_{m=1}^{M}(dGEN_m \hookrightarrow C_{OpVar} * dgenS_{u,m,s,t})]\end{aligned} \tag{43}$$

The dispatch cost consist of the fuel costs (or variable operation costs C_{OpVar}) incurred by the use of all deployed generation devices as well as the value of all shifted and curtailed loads. In addition all transactions with the main grid are valued at the power and feed-in rates for their respective timestep and summed up.

4 Implementation

5 Case Study

5.1 Meterological Data

Hourly irradiation data (in KWm^{-2}) for «PLACE» is sourced from [29].

5.2 Investment Options

Table 1: Parameters describing the conversion technologies

Parameter	Name	Unit	Value	Reference
Photovoltaic System				
Installation Cost	information	€KW^{-1}	1300	Estimate based on [42], [37], [22]
Maintenance Cost	information	€$KW^{-1}yr^{-1}$	50	Estimate
Lifetime	information	yr	25	[42]
Electric Efficiency	information	$\%$	17	[42]
Performance Ratio	information	$\%$	85	[42]
CHP Micro Fuel Cell				
Installation Cost	information	€KW^{-1}	3500	Estimate based on [16]
Maintenance Cost	information	€$KW^{-1}yr^{-1}$	175	Estimate based on [16]
Fuel Cost	information	€KWh^{-1}	0,0608	[24]
Lifetime	information	yr	15	[16]
Electric Efficiency	information	$\%$	60	[3]
Thermal Efficiency	information	$\%$	21	[3]
Minimum Gas Flow	information	$\%$	30	[16]

Table 2: Parameters describing the storage technologies

Parameter	Name	Unit	Value	Reference
Li-Ion Battery 1				*Tesla Powerwall*
Installation Cost	information	€	10000	Estimate based on [30]
Usable Capacity	information	KWh	13.5	[30]
Lifetime	information	yr	10	Estimate based on [30]
Roundtrip Efficiency	information	$\%$	90	[30]
Self-Discharge	information	$\%hr^{-1}$	5	[16]
Max. charging power	information	kW	4.6	[30]
Max. discharging power	information	kW	4.6	[30]
Initial State of Charge	information	$\%$	100	Assumption
Terminal State of Charge	information	$\%$	100	Assumption
Li-Ion Battery 2				*Victron Energy Lithium HE Batterie*
Installation Cost	information	€	5000	Estimate based on [41]
Usable Capacity	information	KWh	4	based on [18] considering maximum depth of discharg
Lifetime	information	yr	10	Estimate based on [18]
Roundtrip Efficiency	information	$\%$	92	[16]
Self-Discharge	information	$\%hr^{-1}$	5	[16]
Max. charging power	information	KW	4.8	[18]
Max. discharging power	information	KW	7.2	[18]
Initial State of Charge	information	$\%$	100	Assumption
Terminal State of Charge	information	$\%$	100	Assumption

5.3 Further Assumptions

Table 3: Further Assumed Parameters

Parameter	Name	Unit	Value	Reference
Discount Rate	information	$\% yr^{-1}$	1.5	Estimate
—	information	information		
—	information	information		

6 Results and Discussion

7 Appendix

7.1 Literature Review

The used search String was: [microgrid AND (optimization OR opimisation) AND linear programming]
The used databases are ScienceDirect, IEEE Xplore and Google Scholar.
The original dataset consistet of 300 publication of which 275 remained after duplicates where merged.
The search string for the Abstract Keyword Search was [(microgrid OR micro-grid OR off-grid) AND (optimization OR optimisation OR optimise OR optimal OR optimally) AND (linear programming OR linear program OR mixed integer)
After the abstract keyword search was conducted 106 publications remained.
The inclusion criteria were:

1. An optimization model is employed.
2. There is some discussion about the design of the model.
3. The objective of the model is the optimization of design or dispatch of a single microgrid.
4. There is some sort of case study conducted.

The exclusion criteria were:

1. The publication is not in English language.
2. The full text is not obtainable for this author with reasonable effort.
3. The publication is a Work-In-Progress / Conference Paper version of a publication published in a journal and also included in this dataset.
4. The mathematical model designed is non-linear.
5. The mathematical model designed only considers a specific aspect of dispatch or design, not the entirety.
6. The mathematical model is mostly focused on heat generation/distribution rather than electricity.

After the filtering by inclusion and exclusion criteria 58 publications remained.

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