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Energy Economics Group

DISSERTATION

Planning and Operation Strategies of Microgrids in Decarbonized Multi-Energy Systems

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"What we know is a drop, what we don't know is an ocean."

— Isaac Newton

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Abstract

Renewable energy measures are needed to enable the clean energy transition and decarbonize the energy sector. Microgrids provide the techno-economic potential to contribute to the decarbonization when designed and implemented optimally. The aim of this thesis is to assess, investigate, and address the optimal planning and operation strategies of microgrids in decarbonized multi-energy systems. Three different kinds of mixed-integer linear programming based optimization models are developed and applied to different case studies in Austria with objective functions of minimizing the total energy costs and total carbon dioxide emissions. The main focus of this thesis are thermal energy systems, hydrogen energy systems and mobility, and electricity based renewable energy communities that involve different distributed energy resources. Different optimization scenarios are designed and analyzed with respect to reference cases of individual energy system models that portray the current status quo. The results emphasize the importance of microgrids in achieving economic as well as ecological savings as compared to the reference cases. The role of seasonal storage for thermal sector is investigated and significant savings in objective functions are achieved as compared to non-seasonal behavior. The importance of renewable energy based hydrogen generation, storage and use in the mobility sector has been analyzed in detail and compared with the conventional fuel based mobility.

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The mechanism of energy sharing with multiple tariff schemes among different participants of the community is designed and analyzed to show the benefit of cumulative savings as compared to non-sharing mechanism. Additionally, the regulation and policy framework for each individual model are identified and further suggestions are provided for the future regulation and policymaking, especially with respect to reducing technology costs, introducing carbon prices for bridging the hydrogen-diesel cost gap and incentive based tariff schemes to enable energy sharing in renewable energy communities.

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Kurzfassung

Im Bereich der erneuerbaren Energien sind Maßnahmen notwendig, um den Übergang zu sauberer Energie zu ermöglichen und den Energiesektor zu dekarbonisieren. Microgrids bieten das technisch-ökonomische Potenzial zur Dekarbonisierung beizutragen, wenn sie optimal geplant und umgesetzt werden. Das Ziel dieser Arbeit ist es, die optimalen Planungs- und Betriebsstrategien von Microgrids in dezentralen, sektorgekoppelten Energiesystemen zu bewerten, zu untersuchen und zu behandeln. Drei verschiedene Arten von Optimierungsmodellen auf Basis gemischt-ganzzahliger linearer Programmierung werden entwickelt und auf verschiedene Fallstudien in Österreich angewandt, wobei die Zielfunktionen die Minimierung der Gesamtenergiekosten und der gesamten Kohlendioxidemissionen sind. Der Hauptfokus dieser Arbeit liegt auf thermischen Energiesystemen, Wasserstoff und Mobilität, sowie auf erneuerbaren Energiegemeinschaften, die verschiedene verteilte Energieressourcen beinhalten. Es werden verschiedene Optimierungsszenarien entworfen und in Bezug auf Referenzfälle, die den aktuellen Status Quo abbilden, einzelner Energiesystemmodelle analysiert. Die Ergebnisse unterstreichen die Bedeutung von Microgrids für das Erzielen wirtschaftlicher und ökologischer Einsparungen im Vergleich zu den Referenzfällen. Außerdem wird die Rolle der saisonalen Speicherung für den Wärmesektor untersucht, wobei signifikante Einsparungen bei den Zielfunktionen im

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Vergleich zum nicht saisonalen Verhalten erzielt werden. Die Bedeutung der Wasserstofferzeugung, -speicherung und -nutzung auf Basis erneuerbarer Energien im Mobilitätssektor wird detailliert analysiert und mit der konventionellen, kraftstoffbasierten Mobilität verglichen. Weiters wird ein Konzept zur gemeinsamen Nutzung von erneuerbarer Energie mittels unterschiedlicher Tarifmodelle unter verschiedenen Teilnehmern einer Energiegemeinschaft entworfen und analysiert, um den Nutzen der kumulativen Einsparungen innerhalb einer Energiegemeinschaft im Vergleich zum Status Quo zu zeigen. Darüber hinaus werden die regulatorischen und politischen Rahmenbedingungen für jedes einzelne Modell identifiziert und weitere Vorschläge für die künftige Regulierung und Politikgestaltung gemacht, insbesondere im Hinblick auf die Senkung der Technologiekosten, die Einführung von Kohlenstoffpreisen zur Überbrückung der Kostenlücke zwischen Wasserstoff und Diesel und anreizbasierte Tarifsysteme, um die gemeinsame Nutzung von Energie in erneuerbaren Energiegemeinschaften zu verstärken bzw. weiter auszubauen.

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Nomenclature

Abbreviations

CAPEX	capital expenditure
CPU	central processing unit
DER	distributed energy resources
DER-CAM	distributed energy resources - customer adoption model
DR	demand rates
ESS	energy storage system
EV	electric vehicle
FCEB	fuel cell electric bus
FCET	fuel cell electric truck
FCEV	fuel cell electric vehicle
FDS	Fuel Demand Share
HH	household tariff
HWB	hot water boiler tariff
LA	local authority tariff
LP	linear programming
LOH	level of hydrogen
MILP	mixed-integer linear programming
MINLP	mixed-integer nonlinear programming
MPP	monthly peak preservation
O&M	operation and maintenance
OC	optimization case
OF	objective function
OPEX	operational expenditure
Opt-3D	three daytypes based optimization model
Opt-8760	8760-hours based optimization model
PCC	point of common coupling
PEM	proton exchange membrane
PV	photovoltaic system
PWA	piecewise affine
P2P	Peer-to-Peer
RC	reference case
REC	renewable energy community
SOC	state of charge
TRNSYS	transient systems simulation
WTW	well-to-wheel

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Mathematical Symbols

Chapter 3:

a	slope of linear segment
b	intercept of linear segment
n	number of species
C	total annual energy costs
DER_{invest}	annualized investment cost per distributed energy resource
Π	annuity rate of the technology
$VarC$	variable capital cost of the technology
Cap	capacity of the technology to be invested
$FixC$	fixed capital cost of the technology
H	heat variable for different technologies
A	technology-specifc coefficient
$A^{S_{\text{th}}}$	decision variable for the solar thermal area
I	solar irradiance parameter
η	efficiency parameter
Θ	loss factor
T	temperature
φ	charging rate of the heat storage
F	fuel for heat
x	technology-specific capacity variable
δ	binary variable
λ	non-negative, continuous variable
ϵ	deviation error (residual)
$\vec{\alpha}$	fit parameter vector

Chapter 4:

C	total annual energy costs
Π	annuity rate of the technology
$VarC$	variable capital cost of the technology
Cap	capacity of the technology to be invested
$FixC$	fixed capital cost of the technology
γ	cost constraint parameter
H	variable associated with hydrogen fuel
E	variable associated with electricity
N	arbitrary large number
η	efficiency parameter
Θ	loss factor
φ	charging or discharging rate of storage
ρ	parameter for the level of hydrogen

Chapter 5:

η	efficiency parameter
γ	cost constraint parameter

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ζ	energy rate associated with the electricity
C	total annual energy costs
Π	annuity rate of the technology
$VarC$	variable capital cost of the technology
Cap	capacity of the technology to be invested
$FixC$	fixed capital cost of the technology
E	variable associated with the electricity
ESS	variable associated with the energy storage system electricity
N	arbitrary large number
Θ	loss factor
φ	charging or discharging rate of storage
ρ	parameter for the state of the charge
PV	normalized photovoltaic performance
δ	binary variable or parameter

Superscripts

Chapter 3:

S_{th}	solar thermal
stored	state of charge of the storage
in	input for storage
out	output from storage
loss	loss of stored energy
α	technology-specific exponent
amb	ambient

Chapter 4:

stored	state of charge of the storage
in	input for storage
out	output from storage
loss	loss of stored energy
El	electrolyzer
XOR	binary variable
fleet	hydrogen fuel cell vehicles

Chapter 5:

ESSin	electricity input to the energy storage system
ESSout	electricity output of the energy storage system
ESSons	onsite usage of the electricity related to the energy storage system
ESSRecExp	exported energy storage system electricity to the renewable energy community
stored	state of charge of the storage
in	input for storage
out	output from storage
loss	loss of stored energy

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XOR	binary variable
ref	reference
perf	performance
trans	transfer
UtExp	electricity related to the utility export
UtMax	electricity related to the maximum utility purchase
UtPur	electricity related to the utility purchase
UtFix	fixed utility fee
RecExp	electricity related to the renewable energy community export
RecPur	electricity related to the renewable energy community purchase
ps	purchase or sale
gc	grid connection

Subscripts

Chapter 3:

k	number of components in fit parameter vector
h	hours
d	daytypes
m	months
t	time
tech	technologies
up	upfront
char	charge rate of the storage
dis	discharge rate of the storage
O&M	operation and maintenance
i	index for binary and decision variables
HS	heat storage
s	storage operation
st	storage standby operation

Chapter 4:

h	hours
d	daytypes
m	months
t	time
tech	technologies
up	upfront
char	charge rate of the storage
dis	discharge rate of the storage
invest	annualized investment
textlim	limit on the costs
El	electrolyzer
press	pressurizer

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Chapter 5:

h	hours
d	daytypes
m	months
t	time
n, n'	nodes: n and n' are aliases
tech	technologies
up	upfront
char	charge rate of the storage
dis	discharge rate of the storage
invest	annualized investment
lim	limit on the costs
O&M	operation and maintenance

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Chapter 1

Introduction

1.1 Motivation

The growing attention to decrease the carbon dioxide emissions and at the same time to increase the penetration of renewable energy sources to meet the energy demand require to devise new strategies for the optimal use of distributed energy technologies. The decarbonization of the energy sector requires renewable energy measures to enable a clean energy transition [1]. While there are different actions and strategies undergoing, renewable energy based microgrids are on the rise to contribute to affordable and clean energy [2].

The renewable energy based microgrids provide extensive opportunities in terms of different perspectives. The environmental perspective of such microgrids has been provided by Tabar et al. [3] by proposing the sustainable planning of hybrid microgrids towards minimizing the environmental pollution. The economic perspective of the renewable energy based microrids has been addressed by Basu et al. [4] by providing a comprehensive survey of the microgrids. The social perspective of the renewable energy based microgrids has been highlighted by Schwaegerl and Tao [5] together with technical benefits of the microgrid operation.

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The energy system is quite complex if classified with respect to end-user demands such as electrical, thermal, mobility, etc. and the supplying technologies such as distributed energy resources. It is really important to model these individual systems and also their cross-sectoral interactions with respect to optimal planning and operation in microgrids.

In thermal energy systems, because of the mismatch between the thermal load (Space Heating and Water Heating) and supply of solar energy in summer, the affordable and carbon footprint-free solar energy has strong potential to meet the thermal energy consumption if the thermal energy storage can be designed optimally to store the heat from solar in summer and use it in winter [6]. This is achieved by using the concept of seasonal storage. The seasonal storage has more advantages in practical applications as compared to short-term storage, but it is challenging since it requires a larger storage volume [6]. The amount of available incident solar radiations on the roof of a typical home exceeds its yearly energy consumption, therefore, there is a large potential in using solar thermal technologies to convert solar radiation into usable heat [7]. The seasonal storage systems have the capability to mitigate the seasonal offset and variation of renewable energy sources.

Also, the increasing attention of decarbonizing the mobility sector in Europe and around the globe requires solutions that are technologically as well as economically viable and at the same time sustainable for the environment. The mobility sector is a major part of the ecosystem and abundantly dependent upon the fossil fuels at the moment. This dependency upon the fossil fuels is likely to increase and ultimately can increase the carbon dioxide emissions. The mobility sector is sought to be responsible for approximately 20% of the projected increase in the global energy demand and the greenhouse gas emissions by 2040 [8]. The mobility sector constitutes approximately a third of the total energy use and a quarter of the total greenhouse gas emissions in

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Europe [9].

The decarbonization of the mobility sector is both urgent and an important challenge in fulfilling the European Union's commitment towards the carbon neutrality by 2050 and for the global effort to the implementation of the Paris Agreement [10]. Thus, hydrogen is considered to be one of the solutions to achieve this challenge of decarbonization in the mobility sector [11]. The complete decarbonization of the mobility sector may not be possible solely by battery Electric Vehicles (EVs). It is because of the low specific energy, low energy density, low range and high charging times of the battery EVs as compared to the hydrogen fuel cell vehicles when the hydrogen is purely generated from renewable energy sources [12]. Therefore, the renewable hydrogen might be the missing link in the decarbonized energy transition of the mobility sector.

The concept of energy sharing among different actors of microgrids to reduce carbon emissions and economic costs of infrastructure and services as compared to a business as usual case is one of the major advantages of the renewable energy based microgrids. This concept of energy sharing is deployed through the setup of an Energy Community (EC) [13]. The energy sharing in communities makes individual consumers to be prosumers and share the surplus energy with other members of the microgrid.

This thesis provides a methodological framework based on optimization models that can decarbonize the multi-energy system based microgrids. Three different kinds of optimization models are developed during this thesis work and are applied to different case studies in Austria that involve thermal energy systems, hydrogen energy systems and mobility sector, and electricity based renewable energy community. These models provide solution to three research questions outlined in section 1.2. Based on the results of these models applied to the specific case studies, the optimal planning and operation

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dispatch of microgrids are analyzed and discussed.

1.2 Research Questions

This section describes the research questions that are the focus of this thesis. A short description of each of the research question is provided together with motivation and context of answering them.

As stated in previous section, the main goal of this thesis is to develop the optimization framework that can decarbonize the multi-energy system microgrids. This thesis is based on three peer-reviewed journal articles which touch the topic of the optimal planning and operation of microgrids with respect to three different systems applied to three different case studies. Hence, three different research questions are associated with these journal articles and are summarized in the Figure 1.1.

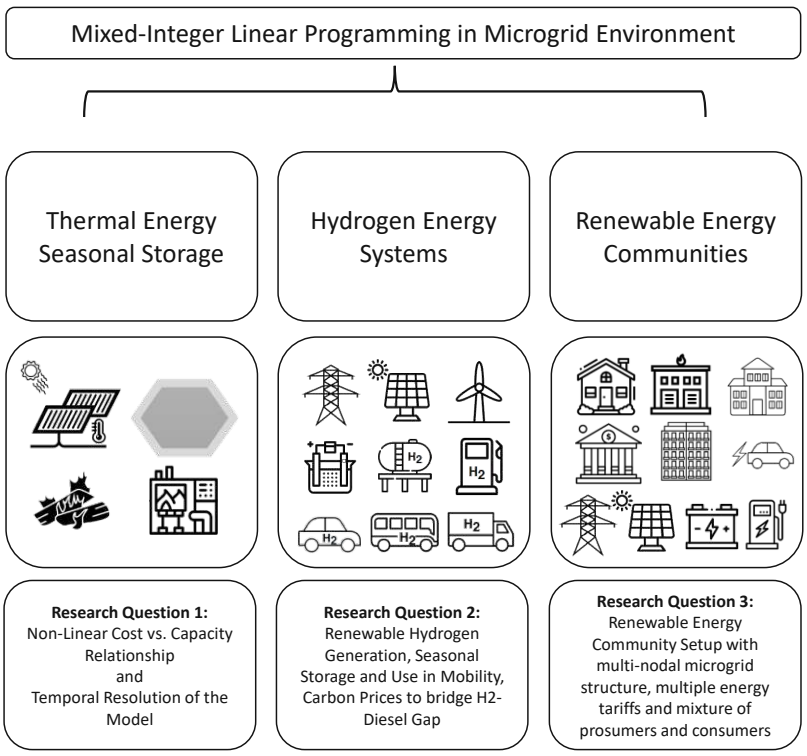

FIGURE 1.1: Summary of research questions focused in this thesis.

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The first journal article [14] is related to the thermal energy systems in microgrids, the second journal article [15] is related to the hydrogen energy systems in microgrids and the third journal article [16] is related to the electricity based renewable energy community system in microgrids. The journal articles [14] and [15] have been published as first author and the journal article [16] has been published as co-author. In all three journal articles, the author of this thesis has remained the corresponding author. These three independent journal articles are applied to case studies in Austria and answer three different research questions outlined below.

Research question 1: *How can we effectively model optimal planning and operation dispatch of a thermal seasonal storage taking into account its non-linear cost vs. capacity relationship using the linear programming models? Also, how do the different temporal resolutions affect the system and the run-time of the optimization models?*

This research question addresses the topic of thermal seasonal energy storage systems in microgrids and describe two important challenges when modeling such systems in optimization. On the one hand, there is a non-linear relationship between the cost and capacity of thermal energy storage. Since seasonal storage is comparably bigger than the non-seasonal storage systems, so modeling this non-linear relationship is a challenge using linear programming models to reduce the complexity. On the other hand, temporal resolution of an optimization model plays an important role in assessing the results including the objective function savings in terms of costs and carbon dioxide emissions, investment decisions, operation dispatch and run-time of models.

This research question is answered in [14] by developing two different optimization models, one with low temporal resolution and the other with high temporal resolution, taking into account the piecewise affine methodology to convert non-linear relation of cost vs. capacity behavior of seasonal thermal

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energy storage system into mixed-integer linear programming based model.

Research question 2: *What is the impact of renewable based hydrogen energy systems in decarbozining the mobility sector using microgrids and how it is compared with the state-of-the-art diesel fuels? Also, how can we drive the paradigm shift from conventional to renewable hydrogen based mobility using carbon prices and policy framework?*

This research question addresses the topic of hydrogen generation, its seasonal storage and use in mobility sector using renewable energy based microgrids. The main challenges encountered by the mobility sector are its increasing carbon footprint and mobility demand across the globe and specially in Europe. The conventional fuels such as diesel results in ecological degradation. The shortcomings of electric vehicles such as low specific energy, low energy density, low range and high charging times of the battery are motivating factors to devise innovation solutions which can meet the mobility demand and the at same time decarbonize the mobility sector.

This research questions is answered in [15] where it is emphasized that the renewable hydrogen might be the missing link in the decarbonized energy transition of the mobility sector. The hydrogen electrolyzer, the hydrogen storage, and the hydrogen mobility are modeled together with solar PV and wind power to assess the optimal planning and operation of such microgrid systems using mixed-integer linear programming and applied at a real test facility in Austria. The results are assessed with respect to the optimal sizing and dispatch of the technologies, the economical viability, the environmental impact, a comparison between the optimal hydrogen fuel costs and the current market costs of the diesel fuel to identify the hydrogen-diesel cost gap and the calculation of the carbon prices to close the hydrogen-diesel cost gap.

Research question 3: *How can renewable energy based microgrids contribute towards the clean energy transition set by Clean Energy Package (CEP) of European*

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Commission using Renewable Energy Community (REC) concept? Also, how would a REC based mechanism behave in terms of renewable energy sharing, multiple energy tariffs and mixture of prosumers and consumers in the multi-nodal microgrid structure?

This research question addresses the topic of renewable energy communities that can enable the clean energy transition of the energy sector especially the electrical sector. The framework for the renewable energy transfer among different participants of a community is very new for Austria. There exists some regulatory framework to enable the setup of energy transfer among prosumers and consumers but have not been applied yet in practice in Austria. Therefore, it is of great importance that optimal planning and operation of such REC based systems should be assessed which involve the multi-nodal structure of the participants and multiple energy tariffs for purchase/sale of energy.

This research question is answered in [16] where a renewable energy community consisting of 9 different community participants is modeled using mixed-integer linear programming and applied to a real case study in Austria. Three different reference and optimization cases are analyzed and considered with the corresponding mixed-integer linear programming model using different electricity tariff scenarios and market signals including feed-in tariffs. The results include the optimal sizing and the full-year operational dispatch of the technologies. Furthermore, the results also include the comparisons with the reference cases in terms of the energy costs and CO_2 savings, the total annual energy costs per node and the distributed renewable energy transfer to each node for the different tariff scenarios.

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1.3 Structure of the Thesis

Following the research questions described above, the rest of the thesis is structured in the following way.

Chapter 2 provides state-of-the-art literature review related to the topics of the research questions in a very selected manner and includes the most relevant and recent sources. It touches the topic of smart and microgrids from high level and dives into the investment planning and operation of microgrids using optimization techniques. Thermal energy storage systems, hydrogen energy systems and renewable energy communities are described and potential challenges are highlighted with respect to modeling such systems in microgrids. Finally, the novelty of this thesis work and contribution beyond the state-of-the-art are provided.

Chapter 3 investigates the first research question, provides the mathematical framework to solve challenges occurred in modeling seasonal thermal energy storage systems in microgrids and answers the question by assessing the results obtained from a case study evaluated in Austria.

Chapter 4 tackles the second research question, extends the current microgrid testbed facility in Austria for modeling the hydrogen energy system technologies including electrolyzer, seasonal storage, mobility and renewable energy sources and evaluates the technical and economical viability of such systems to decarbonize the mobility. It also provides the policy framework to drive the use of hydrogen fuel in comparison to the conventional diesel fuel.

Chapter 5 tackles the third research question, provides the mathematical framework to model the renewable energy community structure using microgrid technologies and assesses the renewable energy transfer among the

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different participants of the energy community using different tariff structures.

Chapter 6 discusses and synthesizes the findings referring to the research questions of this thesis, highlights the strengths and limitations of the proposed methodologies and provides necessary suggestions for the amendments in future regulations and policy framework.

Finally, Chapter 7 concludes the thesis and provides future outlook for the topics tackled in the research questions.

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Chapter 2

State-of-the-Art and Contribution Beyond

2.1 Smart and Microgrids

The world is facing several issues, of which, most pressing are the increasing energy demand, declining of primary energy resources, conventional and old grid infrastructure and increasing greenhouse gas emissions that are prime cause of global warming. These significant issues call for the need of new innovative solutions that can meet the growing energy demand while getting most of the limited energy resources and also be feasible with respect to practical investments, low carbon footprints and technological evolution. The filed of smart and microgrids has this potential to solve these issues by keeping an eye on the feasibility of resources via optimization techniques.

A Smart grid is a network system that uses digital technologies for improvement of efficiency, reliability, resiliency and security of the energy system and addresses the utilization and integration of the Distributed Energy Resources (DERs) [17]. However, there is a difference between a smart grid and a microgrid. A small scale system that is located in the vicinity of consumers/prosumers is called a Microgrid system [18].

Microgrid plays a very important role in smart grid system concept. Microgrid is a part of the larger grid that includes most of the components of the

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larger utility grid on smaller scale. Microgrids can operate with larger utility grid or independently from the larger utility grid.

A microgrid can be defined as a local and small distribution system that includes certain distributed energy resources such as photovoltaic systems, microturbines, diesel generators, energy storage systems, fuel cells, controllable and uncontrollable loads in connection to grid i.e. grid connected mode or operating independently from the grid i.e. island mode when experiencing disturbances or in case of remote location, thus enhancing the supply quality, resiliency and security of the energy system [19]. Most importantly, microgrids have the ability to provide lower investment costs, decrease carbon dioxide emissions, enhance energy quality and decrease the energy losses in the grid [18].

There are two main challenges regarding microgrids which are given below:

1. Which distributed energy resource technologies (e.g. solar PV, solar thermal, battery energy storage system, thermal energy storage system, heat pumps, biomass based central boiler, etc.) should be installed to what extent (i.e. capacities) and where in the grid in order to guarantee economic and environmental viability?

2. How should these distributed energy resource technologies be operated depending on dynamic boundary conditions (e.g. weather, changing loads or changing energy prices with respect to time) in order to actually achieve the practical economic and environmental goals?

The first challenge can be associated with the investment planning problem in microgrids and the second challenge cab be associated with the operational dispatch problem in microgrids. This thesis aims to contribute to the solution of the above mentioned challenges in microgrids by using mixed-integer linear programming based optimization methodologies for several

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different distributed energy resources in a multi-energy system environment.

2.2 Distributed Energy Resources (DERs) and Multi-Energy Systems

Distributed energy resource technologies are the basic part of a microgrid that are located near or at the Point of Common Coupling (PCC). The distributed energy resource technologies of microgrids are getting higher attention in recent literature due to their vast and diverse advantages such as supporting the microgrids in terms of stability, resiliency, reliability, security, efficiency and reduction of energy losses [20]. A systematic approach in terms of microgrids is a better way to realize the increasing potential of distributed energy resources [21].

A microgrid based system does not necessarily depend upon just one sector of energy. It can include more than one energy sector as primary energy source such as electricity can be converted into heat, cooling, and fuels and stored in multiple energy formats. This potential of energy conversion calls for solutions to the microgrid problems in terms of multi-energy systems. A very detailed and comprehensive overview of multi-energy systems is provided in [22] which indicates that multi-energy systems are very important to demonstrate the opportunity to enhance the economic, technical and ecological performance of integrated energy systems as opposed to the conventional energy systems where energy sectors are treated separately.

The complexity of multi-energy system based microgrids can be seen in Figure 2.1 which shows different distributed energy sources, the sector coupling between multi-energy systems and the end-user demands in terms of energy flow optimization.

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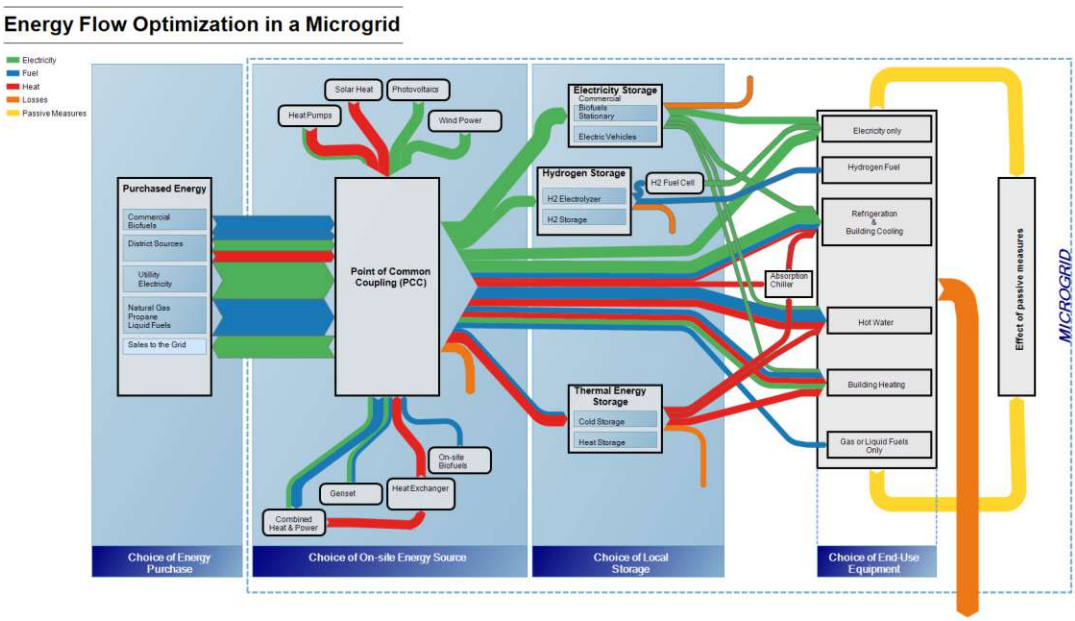

FIGURE 2.1: Sankey diagram of multi-energy system based microgrid showing energy flow from inputs to outputs [23].

The most common distributed energy resource technologies include solar PV and battery in electrical energy systems, solar thermal, natural gas based boilers and thermal storage in thermal energy systems, and electric chillers and cold storage in cooling energy systems. With sector coupling, the applications of different distributed energy resource technologies are increased such as the electricity that is generated via solar PV can be utilized to provide to end-user demand of electrical by using batteries or directly providing it, or it can be utilized to provide to end-user demand of heating by using combine heat and power technology, or it can be also utilized to generate hydrogen fuel to provide to end-user demand of mobility network.

The complexity of such networks depend upon the methodology of modeling using best practices and practical constraints and boundaries of these multi-energy systems. Therefore, optimization techniques are used to achieve these goals which are explained in further details in next sections.

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2.3 Investment Planning and Operational Dispatch in Microgrids

The field of investment planning and operational dispatch in microgrids includes the optimization based techniques that solve the mathematical model of such systems designed according to several factors such as input data resolution, type of optimization technique used, extent of DER portfolio, sector coupling, etc. The model is also classified with respect to considering the practical aspects of the system such as technical boundaries, ecological boundaries and economical boundaries.

While there are many studies in the state-of-the-art that focus on one or more aspects of modeling such systems individually, but they lack in other aspects, creating possibilities to explore these gaps and bridge them. This thesis aims to explore these gaps and develops optimization methodologies that go beyond the state-of-the art to bridge those gaps.

The optimization techniques for the investment planning of microgrid include models such as mixed-integer linear programming (MILP) [24] and mixed-integer non-linear programming (MINLP) [25]. These models can be of deterministic nature where the variables are considered with certainty and can also be of stochastic nature where the variables are considered with probability distribution [26]. This thesis focuses on the mixed-integer linear programming based optimization techniques with deterministic nature.

MILP is a special class of Linear Programming (LP) that restricts all or some of the decision variables to integer values while keeping the problem linear. The basic structure of a MILP problem is illustrated in Figure 2.2 where the $f(P, x)$ is a linear function of parameter P and decision variable x.

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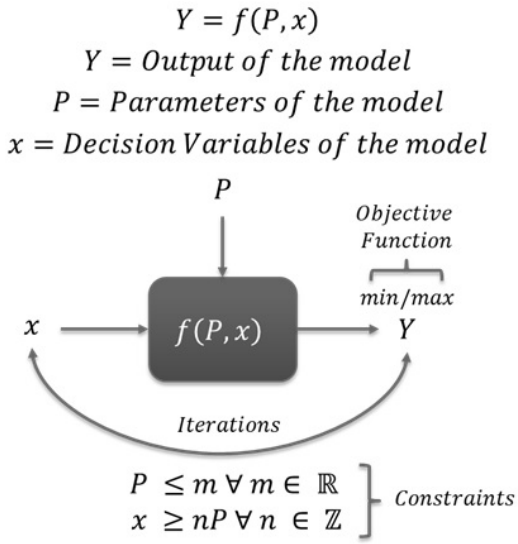

FIGURE 2.2: Basic structure of a MILP problem.

MILP based optimization is better suited to determine the optimal design of a system model taking into account various input parameters, decision variables, system constraints and objective functions. Sensitivity analysis can also be done in optimization if more than one optimal solution has to be observed by changing input parameters, system constraints and mathematical framework of objective functions. MILP optimization considers defining the system boundaries i.e. constraints placed on various parameters and decision variables to get output of the objective functions. System models based on MILP optimization are relatively complex to model and consume higher computational power as compared to simulation based models.

There can also be more than one objective function which is known as multi-objective optimization. The example of such kind of model can include the minimization of energy costs of an energy system and at the same time minimizing the carbon dioxide emissions of the same system having some linear relation to the energy costs.

The state-of-the-art literature review of MILP based models used in investment planning and operation of microgrids is provided in next sections in

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line with the topics touched by this thesis. The possible gaps of the current methodologies have been identified and potential solutions have been provided by developing innovative methods, assessing practical case studies and contributing beyond the state-of-the art.

2.4 Thermal Energy Storage and Concept of Seasonality

There is always a mismatch between the total solar availability and the thermal demand during the summer and winter months of the year. Figure 2.3 shows the mismatch between the solar insolation and heat demand requirement.

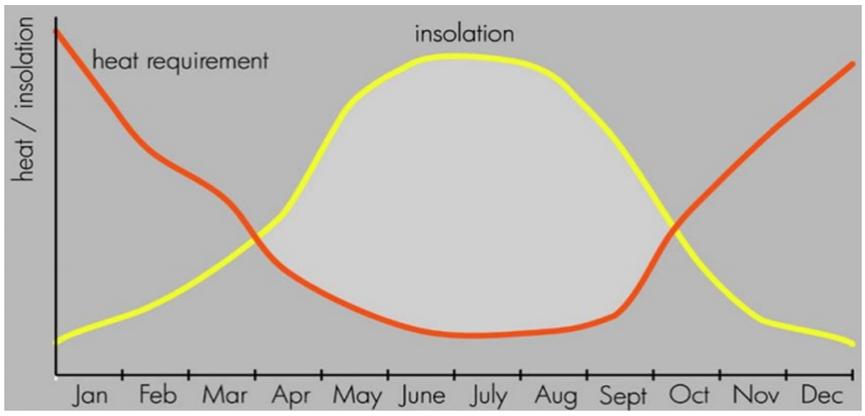

FIGURE 2.3: Mismatch between solar availability and thermal energy demand [27].

It can be seen from the Figure 2.3 that the heat requirement is significantly lower in the summer months and at the same time solar insolation is very high, creating a need for storing this potential of free solar energy. This behavior drives the concept of seasonality in thermal energy systems where the most intriguing idea is to store the surplus of solar insolation in the thermal storage during summer months and utilize this surplus during the months when the heat requirement is higher and lesser amount of solar insolation

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is available. Although the idea of seasonal thermal energy sounds practical, there are two main important challenges when modeling this behaviour in microgrid optimization. These challenges are described in the following sections.

2.4.1 Challenges in Modelling Thermal Energy Seasonal Storage

There are mainly two challenges for the optimal design and operation of a solar thermal system with a large thermal seasonal storage. The first challenge is that the proper modeling techniques require higher resolution of time series data. This challenge of temporal resolution is far more critical when dealing with integration of renewable energy sources [28]. The second challenge lies in the non-linear relationship between the capacity and the cost of technologies involved in thermal energy systems [29]. These challenges are explained in the sub-sections 2.4.2 and 2.4.3 respectively.

2.4.2 Time-Horizon and Representative Periods

The adequate and appropriate modeling of seasonal storage system requires a time series that spreads over a full year time horizon at least. However, using full year time horizon increases the computational time. In order to solve the issue of computational time, time series aggregation techniques are used to reduce the original full year data into typical design profiles depending upon the aggregation criteria for weekdays, months or seasons. These aggregated design profiles must adequately preserve the significant characteristics of the full year data. Fazlollahi et al. [30] use k-means clustering technique to reduce the yearly time series data into typical periods. Nahmmacher et al. [31] use hierarchical clustering as time series aggregation methodology for solar and wind data. Lozano et al. [32] reduce the time series via averaging

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into 24-hours based profiles defined by weekdays. Averaging into 24-hours based profiles defined by months has been studied by Mehleri et al. in [33]. Averaging into 24-hours based profiles defined by seasons has been studied by Samsatli et al. in [34]. Fahy et al. [35] present the Monthly Peak Preservation (MPP) method to reduce the yearly time series data into three typical periods based on weekdays, weekend days and peak days. Although the time series aggregation reduces the computational time significantly, it can also change the results as compared to a full year time series optimization [36].

2.4.3 Piecewise Affine Functions to Solve Non-Linearity

The real life costs of thermal energy system technologies such as solar thermal and heat storage are dependent on size and larger capacities have lower technology costs. The modeling of this non-linear relationship inside optimization problems imposes certain limits since most of the optimization problems in state-of-the-art literature are formulated as linear programming or mixed-integer linear programming problems to keep computational costs and complexity in a reasonable range. Mashayekh et al. [37] use MILP approach to find optimal distributed energy resources in multi-energy system microgrids. Siddiqui et al. [38] use MILP modeling for the heat and power applications. Stadler et al. [39] optimize the distributed energy resources and building retrofits using MILP approach. Steen et al. [40] model the thermal energy storage using MILP framework. Optimal design of energy conversion units and envelopes for residential building retrofits has been studied in [41] using MILP model. Lindberg et al. [42] propose a methodology for the optimal system design of zero energy buildings using MILP approach. The short-term and long-term thermal energy storage models have been studied

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using MILP framework in [43]. In order to solve the issue of non-linear relationship between the capacity and the cost of technologies, piecewise affine (PWA) cost functions can be used instead of non-linear cost functions, but these functions introduce additional decision variables, thus increasing the complexity of models.

2.4.4 Modelling of Thermal Energy Seasonal Storage

Various studies have been carried out in the field of seasonal thermal storage based on simulations in recent years. Böhm and Lindorfer [44] present techno-economic assessment of seasonal heat storage in district heating with different thermo-chemical materials. The socio-economic assessment of seasonal heat storage in district heating systems with waste heat integration has been provide in [45]. A simulation-based methodology for a pit seasonal thermal storage with heat pump has been investigated in [46]. The potential of seasonal solar thermal energy storage using thermo-chemcial sorption for domestic application has been studied in [47]. Ciapmi et al. [48] perform thermo-economic sensitivity analysis by dynamic simulations of solar district heating system with seasonal borehole thermal energy storage. The solar seasonal storage system coupled with ground-source heat pump has been investigated using a simulation for thermal equilibrium in [49]. Xu et al. [50] demonstrate the potential and evaluate the performance of solar heating system integrated with seasonal energy storage for greenhouse applications. Li et al. [51] present a performance analysis of an integrated energy storage system for seasonal storage and solar thermal energy applications. These simulation-based studies focus on very specific topics related to techno-economic assessment and performance investigation of seasonal storage systems but lack the modeling framework with respect to optimal system design. These studies also provide gaps in realizing the solutions to

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the challenges faced while modeling the thermal energy systems such as time series aggregation and non-linear cost versus capacity behavior of thermal technologies. Therefore, it is required to focus on addressing these gaps on a system design level so that an optimal planning of thermal energy systems can be realized.

Few studies have been conducted in recent years which are based on optimization in the field of seasonal thermal storage. Launay et al. [52] propose a simplified multi-criteria optimization considering levelized cost of energy as an objective function for a residential building having inter-seasonal solar heat storage. This study does not consider the modeling of costs in terms of piecewise affine functions. Köfinger et al. [53] use a simplified MILP framework considering the minimization of total energy costs for the optimized integration and operation of seasonal heat storage for district heating networks. The optimization problem does not consider the modeling of costs in terms of piecewise affine functions and the modeling details of the seasonal heat storage are also limited in this study. Gabrieli et al. [54] propose two MILP based optimization methods to model a seasonal storage for a multi-energy system by using time series aggregation of a full year data into a set of representative design days given by k-means clustering. This study uses the piecewise affine approximate cost function only for the heat storage technology, but does not consider the piecewiese affine cost function for the solar thermal technology. Kotzur et al. [55] aggregate the time series into a set of representative design periods given by k-means before using them into three different design optimization models. These optimization models do not consider the solar thermal into the technology portfolio and also the non-linear relationship between cost and capacity for the heat storage technology is not modeled as piecewise affine functions. Although k-means is a popular technique to aggregate time series into typical representative periods,

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preserving the peak demand is critical and requires further implications to maintain the peak of the original demand profile.

The model simplification in using a single linear cost function for solar thermal and heat storage technologies can lead to a significant difference as compared to using a piecewise affine cost function when modeling seasonal thermal energy systems. It is because the seasonal behavior requires larger capacities, and the investment costs for these larger capacities need to be lower when using the correct non-linear cost versus capacity behavior. The modeling of these non-linear cost functions into piecewise affine cost functions has not been addressed in the state of the art studies combinely for solar thermal and seasonal heat storage technologies. Also, the comparison between the investment decisions of the optimization models using the fixed linear (Non-PWA) cost functions and PWA cost functions has not been provided in the state of the art studies. Moreover, longer time horizon based optimization problems have not been discussed extensively at a design phase of storage based thermal energy systems and maintaining the peaks of thermal demand while aggregating the time series is critical to the optimal design of these systems.

2.5 Hydrogen Energy Systems and Hydrogen Mobility

About 96% of the current hydrogen production is based on the fossil fuels *i.e.* 48% from natural gas, 30% from oil, 18% from coal and only 4% is based on the electrolysis of water [56]. The life-cycle greenhouse gas emissions of the hydrogen production via fossil fuels are considerably high *i.e.* 10 tonne-CO_2/tonne-H_2 from natural gas, 12 tonne-CO_2/tonne-H_2 from oil and 19 tonne-CO_2/tonne-H_2 from coal [57]. Even though the electrolysis is a small

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part of the current hydrogen production chain globally, it is the only process towards 100% carbon neutral production of the hydrogen fuel when it is produced completely via renewable energy sources. The solar PV and wind power technologies would constitute most of the installed power capacity in the global energy supply by 2050 [58]. Hence, grid-connected or islanded renewable energy based microgrids with the solar PV and wind power technologies have a high potential to decarbonize the hydrogen generation process and ultimately decarbonize the mobility sector.

Comprehensive reviews on water electrolysis have been provided in Ref. [59] and Ref. [60] for highlighting the advantages and disadvantages of hydrogen electrolyzer technologies including the alkaline electrolyzer and the Proton Exchange Membrane (PEM) electrolyzer. Although the PEM electrolyzer has higher performance and rapid system response but it has highest costs as compared to other hydrogen electrolyzer technologies, it needs noble metal catalyst for operation and it has capacity stacks below megawatt (MW) range. On the other hand, the alkaline electrolyzer is cost efficient, mature technology which has been undergoing recent developments as well [61], does not require any noble metal catalyst and has capacity stacks in MW range.

2.5.1 Hydrogen Storage

Recently, Lin et al. [62] have provided a comprehensive overview of the prominent scientific literature related to the integration of hydrogen energy in smart grids including grid-connected as well as islanded microgrids, hydrogen fuel cell electric vehicles, hydrogen economy in smart grids and different models for energy systems that include hydrogen. Nicita et al. [63] have conducted a techno-economic-financial analysis to evaluate the profitability of green hydrogen production system by solar PV based renewable energy source. Basic research in the hydrogen production, its use and its

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comparison with the conventional fossil fuels have been carried out by Bartels et al. [64], Barthelemy et al. [65] and Ajanovic et al. [66]. But, these studies lack the optimization modeling framework with respect to the optimal system design for production, storage and user application levels for microgrids. The optimization models are necessary to evaluate the most appropriate design of the technologies including renewable energy sources for achieving the economical and environmental objectives of the hydrogen energy systems.

Recently, A Mixed-Integer Linear Programming (MILP) based microgrid solution has been proposed in Ref. [67] that considers a solar PV based hydrogen energy system for airport electrification. The previous study highlights the importance of the hydrogen over the conventional fuel based electrification of remote aircraft auxiliary power units via fuel cells. Hassanzadehfard et al. [68] use particle swarm optimization methodology to realize a hybrid microgrid system where hydrogen is produced via renewable energy sources as well as natural gas reforming process. A grid-connected solar PV and hydrogen power optimization approach has been proposed in Ref. [69] for a typical household application that considers hydrogen electrolyzer, hydrogen storage and hydrogen fuel cells. The scale of the previous study is relatively small but it is important to show the use of the hydrogen technology in hybrid energy systems for the grid-connected microgrids. Arlt et al. [70] investigate the cost effectiveness of a hydrogen energy system in microgrids through MILP approach using time-series aggregated data sets. The time-series aggregation, considered in that study, provides the representative periods over which optimization is performed but does not include the modeling of the seasonal storage behavior of the hydrogen storage and catching the variability of the renewable energy sources correctly. Zhang et al. [71]

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study the storage sizing and rule-based operation of the grid-connected energy system including solar PV, hydrogen generation, hydrogen storage and battery storage technologies through genetic algorithm optimization. The optimization objectives, considered in that study, are based on the cost functions but do not include the carbon emission optimization and the modeling of the mobility load. An optimal design of a low carbon multi-energy system including the hydrogen seasonal storage using MILP has been carried out in [72] to satisfy the thermal load demand via hydrogen fuel. The previous study uses the optimization to minimize the energy costs and the CO_2 emissions but does not include the modeling of the mobility load. Therefore, it is limited in assessing the economic viability of the hydrogen fuel in comparison with the conventional fossil fuels in the mobility sector.

Few studies have been conducted in recent years in Austria which are based on optimization in the field of microgrid design. Zwickl-Bernhard and Auer [73] have recently examined a cost minimizing energy technology portfolio using an open source energy model with MILP for an energy community in Vienna, Austria. An optimization study considering two different MILP methodologies has been conducted in Ref. [14] for the optimal planning of renewable energy based microgrid in Austria to minimize the total annual energy costs and the total annual carbon dioxide emissions. Although the studies reported in Ref. [73] and Ref. [14] support the optimal energy system planning in microgrid structure in Austria but are limited in not considering the hydrogen technology and modeling of the mobility load. Caglayan et al. [74] have recently proposed a robust design of a future 100% renewable european energy supply system with a hydrogen infrastructure and have concluded that Austria might serve as a channel for hydrogen transport in the region. Ajanovic [75] has conducted an economic analysis for different value chains of hydrogen production and its usage in mobility sector for Austria.

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The main focus of the study in Ref. [75] is the production of hydrogen from renewable energy sources in Austria and considers simple investment calculation methods to evaluate the current hydrogen energy costs and projects the future energy service costs with a learning rate. Although the previously mentioned study is relevant to this research work but it is relatively old, lacks optimization methodology to assess the techno-economic viability and is limited in realizing the real deployment of renewable energy based hydrogen production, seasonal storage and service use in mobility sector of Austria.

2.5.2 Carbon Prices and Policy Framework

Since hydrogen can be generated via electrolysis using renewable energy sources and stored, it has potential to be considered as zero carbon fuel. If not completely generated via renewable energy sources, it has still potential to be considered as low carbon fuel. Although the conventional fuels such as diesel and gasoline are widely used in mobility sector at the moment, these fuels are contributing significantly to the overall carbon footprint of the environment.

Hanley et al. [76] provide extensive review perspectives for the role of hydrogen in low carbon energy futures and provide assessment for policy makers about various options that can be considered in moving towards decarbonized energy transition. Mansilla et al. [77] provide an overview of the key economic issues and perspectives of hydrogen applications and discuss its cost goals. It is believed that clean hydrogen still costs too much to be widely used [78].

Therefore, an assessment for the hydrogen fuel is needed in terms of trade-off between the current market price of conventional fuels and the hydrogen fuel generated via cleaner production means i.e. electrolysis using renewable

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energy sources in microgrids. The idea is that if the cost of hydrogen production is higher than the conventional fuels in the market, a policy framework can be established to impose carbon dioxide prices on the conventional fuels to actually drive the market towards the extensive use of hydrogen and protect the environment. Although there is already an EU Emission Trading System (EU ETS) that is world's first carbon market for setting policy to reduce the greenhouse gas emission cost effectively [79], the new policy framework is needed which should impose the carbon price or carbon tax on mobility network of ground transportation that use conventional fuel.

This thesis provides a major assessment for the clean hydrogen fuel costs in comparison to the conventional diesel fuel costs, identifies the hydrogen-diesel cost gap and proposes a carbon price or carbon tax as a policy framework that can drive the extensive use of hydrogen fuel with nearly zero carbon dioxide emissions in mobility sector using microgrids.

2.6 Renewable Energy Communities and Energy Transfer

Energy communities hold a significant role in the clean energy transition presented by the Clean Energy Package (CEP) [80]. There are two types of energy communities presented in CEP based on two different directives. The Directive 2018/2001 [81] presents the Renewable Energy Community (REC). The Directive 2019/944 [82] presents the Citizen Energy Community (CEC). This research work is focused on a real case study of a microgrid based REC in Austria. For many EU countries, the concept of energy sharing in communities is still new from a legislative point of view [83]. In order to promote decentralized energy supply and strengthen regional supply concepts, RECs receive increased attention in Austria currently. Energy communities

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are legally defined and anchored in the Erneuerbaren Ausbaugesetzes (EAG) [84]. According to EAG §74 paragraph 1, a REC can produce energy from renewable sources and consume, store or sell the produced energy. Therefore, for each community member it is possible to exchange energy from renewable sources (such as PV, wind power, combined heat and power systems, fuel cells and energy storage systems) within the defined community. The membership is open to private individuals, small and medium-sized enterprises (SMEs), public authorities (including municipalities), climate and energy model regions, e5-communities (a community which fulfills certain rules to be more efficient) and tourism regions. To create a financial incentive for the participants, a reduced distribution grid tariff is introduced for the electricity exchanged within the REC, as well as other financial advantages such as the cancellation of all electricity taxes and green electricity fees.

Energy sharing has been discussed extensively in the literature recently, with a special focus on Peer-to-Peer (P2P) local markets where energy surplus is traded. Park and Yong [85] have provided a comprehensive review on the P2P electricity trading with a focus on providing potential development and future challenges for governments and private corporations that are interested in energy sharing. A comprehensive review of existing P2P energy trading projects has been provided by Zhang et al. in Ref. [86] with a focus on their use in local energy microgrids. Recently, P2P energy sharing has also been researched using decentralized models via bilateral contracts, auction models and blockchain based models. The Brooklyn Microgrid [87] considers a blockchain based microgrid energy market to satisfy the request of the energy management. Leong et al. [88] propose an auction based P2P energy trading mechanism via a Bayesian game bidding strategy. Morstyn et al. [89] propose P2P energy trading via bilateral contracts for a new scalable

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market design. Long et al. [90] have investigated energy sharing for different Distributed Energy Resource (DER) producers in a community microgrid with PV and battery systems. Reihani et al. [91] propose a framework to consider energy sharing that allows energy buyers to reduce their energy costs by exchanging energy with neighbouring peers and local utility. Cui et al. [92] present an efficient energy sharing mechanism for various prosumers in an energy community. A recent study by Lin et al. [93] considers the optimal energy sharing of solar PV, wind power and battery among different residential houses on just 24-hours of time resolution. The studies mentioned above consider the renewable and battery energy sharing among the microgrid participants based only on the operation phenomenon, neglecting the optimal investment of the DER technologies. It is completely different to optimally design a microgrid with DER investments and optimal energy sharing than just operate the already established microgrids. It is because of the fact that the fixed sizing of the DER technologies of the already established microgrids can pose certain limitations on the energy sharing among participants. Moreover, the variability of renewable energy technologies such as solar PV and wind power can affect the energy sharing among microgrid participants in different times of the year. Hence, an optimal renewable energy sharing mechanism can not be guaranteed. Therefore, it is important to develop certain models which consider both the optimal planning of microgrids and the optimal energy sharing from DER technologies in an energy community setup with at least a yearly time horizon.

2.6.1 Optimization Models for Renewable Energy Communities

Microgrids connect various renewable energy resources and create a dynamic and complex integrated energy system [94]. The optimal planning of such

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microgrids within the REC infrastructure requires advanced modeling techniques that can bring such systems into reality. It is mainly due to the large number of decision variables related to the number of community participants and the distributed technologies involved. Huang et al. [95] propose a Mixed-Integer Linear Programming (MILP) based peer-to-peer energy trading mechanism in a microgrid with a distributed PV and battery energy storage system. The objective function considered is the minimization of total energy costs of all individual participants of the microgrid. The capacities of the technologies were assumed to be fixed in the case study. Although the previously mentioned study contributes towards renewable energy based microgrids, it can not be applied to the optimal planning of such microgrids in RECs. Fleischhacker et al. [96] use an open source model to perform portfolio optimization to establish an energy community in a city district. Although the complex multi-energy system proposed in Ref. [96] considers the minimization of the costs and carbon emissions on a district level, it is limited in providing an optimal planning of RECs with different utility tariffs, demand rates and market signals including feed-in-tariffs for a microgrid. Also, different clustering techniques have been used to disaggregate the time-series input data which makes the optimization models vulnerable in terms of time series connectivity of technologies. To overcome this disadvantage, full-scale yearly optimization techniques based on 8760-hours have been used recently for the planning of renewable energy microgrids such as the optimal planning of a thermal energy system with a seasonal storage in Ref. [14], a performance comparison of two different MILP based models including 8760-hours for 13 different microgrid case studies in Ref. [97] and the use of a 8760-hours modeling approach for the optimal planning of microgrid technologies including hydrogen electrolyzer, hydrogen seasonal storage and hydrogen mobility for a case study in Austria in Ref. [15]. Zwickl-Bernhard and

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Auer [98] have recently examined a cost minimizing energy technology portfolio using an open source energy model with MILP for an energy community in Vienna, Austria. Although the study reported in Ref. [98] supports sustainable urban energy planning in community structure, it is limited in not using the full-scale optimization and also not considering the yearly operational energy scheduling of the technology portfolio.

The mechanism of renewable energy sharing within the community participants can be profitable if the self-consumption of renewable electricity generated is increased. The aggregation of the load of different prosumers can also increase the profitability. Fina et al. [99] have analyzed the sharing of rooftop PV generation in multi-apartment buildings. The maximization of the value of PV in apartment buildings with different arrangements have been studied in Ref. [100]. Fleischhacker et al. [101] have proposed a game theoretic model with a welfare maximization for the shared use of a solar PV and energy storage system in a multi-apartment building. These previously mentioned studies only consider the application of renewable energy transfer in apartment buildings. It is necessary to diversify the application of the optimization models and include different kind of end users to have a genuine concept of a community setup. It is also important to have a mixture of prosumers and consumers inside an energy community to realize different energy sharing mechanisms.

2.6.2 Multiple Tariff Structures

A recent study by Perger et al. [102] considers a linear optimization model with different prosumers (apartments and businesses etc.) in an energy community concept for energy sharing under willingness-to-pay criteria. The energy tariffs considered by Perger et al. [102] for the purchase and sale of the energy to the grid and within the community are fixed retail electricity prices.

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Another recent study by Jiang et al. [103] considers a two-stage optimization model for renewable energy sharing among prosumers and consumers of an energy community setup. The optimization model considered by Jiang et al. [103] is based on a single day *i.e.* 24-hour time horizon and considers time-of-use tariffs only. Both Perger et al. [102] and Jiang et al. [103] assume same energy prices for all participants (prosumers and consumers) and do not consider demand charges and variable market signals including feed-in tariffs. Therefore, the applications of such optimization models are limited and different electricity tariff scenarios and market signals including feed-in tariffs should be considered to realize the real-life renewable energy based community microgrid setups.

2.7 Novelty and Contribution beyond the State-of-the-Art

This thesis has multifold contributions and novelties as compared to the state-of-the-art described in previous sections. The contributions are made in the research field of optimal planning and operation of multi-energy system based microgrids from multiple perspectives such as economical, ecological and social. In this thesis, we can distinguish three set of contributions to the literature, each related to the topics of thermal seasonal energy storage, hydrogen energy systems and renewable energy communities respectively. These contributions are described in details below.

Chapter 3 addresses the gaps mentioned in the state-of-the-art literature review of thermal seasonal energy storage as follows:

- It develops two different MILP optimization models *i.e.* Opt-3D and Opt-8760 for a thermal energy system in a microgrid having central heating, solar thermal and heat storage as technologies.

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- It also includes the essential modeling of non-linear cost functions in terms of piecewise affine (PWA) cost functions for solar thermal and heat storage technologies while keeping the optimization problem as MILP.

- The Opt-3D model considers the typical profiles based optimization of the system, but preserving the load peaks by the maximum peak preservation method in the daytypes compared to the other works which use k-means clustering. The Opt-8760 model considers the full year time horizon *i.e.* 8760-hours based optimization for the same kind of thermal energy system. The main objective of the MILP framework is to minimize the total energy costs and the total CO_2 emissions.

- This work presents the application of the developed methods to the planning of a case study, quantifying the costs and CO_2 emissions of a reference fuel-based heating system, and showing the cost and CO_2 emission implications of transitioning to a joint solar and fuel-based heating system involving seasonal thermal storage while studying the feasibility *i.e.* solar potential of the necessary heating network for a microgrid.

Chapter 4 overcomes the gaps mentioned in the state-of-the-art of hydrogen energy systems and their application in mobility sector as follows:

- It designs a MILP modeling framework for the optimal planning of microgrid technologies. These technologies include solar PV, wind power, hydrogen electrolyzer and hydrogen storage to satisfy the mobility demand for the decarbonization of the mobility sector.

- The framework is applied to a case study for designing the renewable energy based hydrogen production and hydrogen seasonal storage for a small-scale hydrogen fueling station at a real microgrid testbed in

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Wieselburg, Austria. In this study, the MILP framework has a multi-objective setting which considers the CO_2 minimization scenarios with the cost limitations. The optimization framework uses one year time series data because the adequate modeling of the optimization techniques requires a full year time horizon at least for incorporating the renewable energy sources and seasonality of the hydrogen storage in microgrids.

- This research work approaches the modeling of the mobility demand by considering a variety of hydrogen fuel cell vehicles including passenger cars, busses and trucks. The optimization is performed relative to two different reference cases *i.e.* the diesel basecase and the utility basecase.

- After setting up the reference cases, the investment optimization is performed by minimizing the CO_2 emissions and keeping a limit on the energy costs that vary in different scenarios. The results include (1) the optimal sizing and dispatch of the technologies, (2) the economical viability, (3) the environmental impact, (4) a comparison between the optimal hydrogen fuel costs and the current market costs of the diesel fuel to identify the H_2-Diesel cost gap and (5) the calculation of the carbon prices to close the H_2-Diesel cost gap. The uniqueness of this research work stems from contributions toward the decarbonized energy transition in the mobility sector by addressing the five highly important points mentioned above in a single study.

Chapter 5 overcomes the gaps mentioned in the state-of-the-art of renewable energy communities and goes beyond it. The main contributions of this research work relative to the already existing studies are provided below:

- A key difference to the existing literature is the development of an advanced MILP framework for the optimal planning and the optimal

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operation dispatch with the option of transferring renewable energy between the energy community participants (nodes), combined with newly introduced node-specific time-of-use electricity rates and market signals using a full-scale optimization horizon.

- A real case study is analyzed for both the optimal investment and operation dispatch planning of a renewable energy community testbed in a microgrid setup with a leading energy service provider in Austria. Although other technologies can be considered, this REC considers multiple PV and Energy Storage System (ESS) as decentralized and centralized technologies in the community.

- The REC testbed considers nine diversified community participants (three households, three apartments, a government institution, a fire fighting station and a bank) connected to the utility grid. The developed MILP model considers each participant as a separate node of the microgrid system with a full-scale time horizon *i.e.* 8760-hours. Six different reference and optimization cases are analyzed and considered with the corresponding MILP model using different electricity tariff scenarios and market signals including feed-in tariffs. After setting up the reference cases, the optimization is performed relative to each reference case, where the renewable energy transfer is enabled among the community participants and further investment options are enabled.

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Chapter 3

Optimal Planning of Thermal Energy Systems in a Microgrid with Seasonal Storage and Piecewise Affine Cost Functions

3.1 Introduction

This chapter aims to assess, investigate and solve the Research Question 1. The thermal seasonal energy storage system is effectively modeled using mixed-integer linear programming based two different models. Each of the model uses different temporal resolution and consider the Piecewiese Affine (PWA) methodology to convert the non-linear cost vs. capacity relationship of thermal energy storage into linear relationship. The importance of using each model is emphasized and the results are presented for a case study in Austria considering solar thermal, thermal energy storage, biomass based central heating technologies to supply to the thermal heating demand.

The rest of this chapter is structured as follows. Section 3.2 describes the formulation of the optimization problem for Opt-3D, Opt-8760 and PWA cost functions. Section 3.3 provides detailed information considering the case

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study, including pre-processing and analytics of data. Section 3.4 presents the detailed results. Finally, the resume is provided in Section 3.5.

3.2 Formulation of Optimization Problem

This work presents the comparison between two different optimization models using Mixed-Integer Linear Programming (MILP) for thermal energy system, based on DER-CAM [37] and further developed within this research. The MILP minimizes the total annual energy costs or total annual carbon dioxide emissions as separate objective functions and balances the demand by services offered through optimized technology portfolio. The MILP framework, which is used in this study, considers the solar thermal and heat storage as technologies options provided that heat from fuels *i.e.* central heating grid is always available to meet the marginal heating demand when solar thermal and heat storage technologies are not available. Since the optimization is based on MILP, piecewise affine functions are used to model the costs associated with the solar thermal and heat storage technologies to approximate the non-linear behavior.

3.2.1 Opt-3D: Optimization Model with Uncoupled Representative Days

The first model uses time series aggregation to reduce the yearly data into 24-hours based three representative daytypes for each month by using monthly peak preservation method [35]. The daytypes include weekday, peak and weekend representative profiles. The choice of these three different daytypes in each month is considered because the thermal load has variation in the consumption pattern within weekdays and weekend days of each month. Therefore average profile of this different consumption within four weeks of

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each month requires two representative daytypes to capture the variation of weekdays and weekend days. As averaging the consumption within weekdays and weekends lowers the original maximum demand, therefore peak days are required in each month which can preserve the maximum of demand in each hour of the month so that the optimization decisions are made by keeping into account the original maximum demand within each month. The peak profiles are generated by taking the maximum of demand in every hour of all days in the month. The weekday and weekend profiles are then generated by subtracting the peak demand value in the hour of weekdays and weekend where that maximum occurred. The subtraction of the peak demand values depends upon the occurrence of that maximum in original weekday or weekend day. Finally, all the demand values of weekdays and weekends are summed up over hours and then divided by the number of the respective original weekdays and weekends less one (considering one peak day per month) in that particular month. It is because of the separation of the peak demand values from these weekdays and weekend days that average values must be adjusted downwards to maintain the monthly total consumption in reasonable range. The time horizon is disintegrated into hours $h \in \{1, 2, \ldots, 24\}$, daytypes $d \in \{1, 2, 3\}$ and months $m \in \{1, 2, \ldots, 12\}$. The optimization takes every decision variable into account for each time-step h within each daytype d of every month m. The monthly and annual quantities are scaled up by using the number of the days $n_{m,d}$ (such that $\sum_{m=1}^{12} \sum_{d=1}^{3} n_{m,d} = 365$) for each daytype in every month.

The simplified objective function related to the total annual energy costs C can be represented by eq. (3.1).

$$C = \sum_{\text{tech}} DER_{\text{invest}} + \sum_{m,d,h} C_{\text{utility}} + \sum_{m,d,h} C_{\text{O\&M}} \tag{3.1}$$

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where DER_{invest} is the annualized investment cost per technology *tech*, C_{utility} is related to volumetric fuel costs and other fixed costs related to utility and $C_{\text{O\&M}}$ is related to the operation and maintenance costs. DER_{invest} can be further described as shown in eq. (3.2) and eq. (3.3).

$$DER_{\text{invest}} = \sum_{\text{tech}} (C_{\text{up}}\, \Pi_{\text{tech}}) \tag{3.2}$$

$$C_{\text{up}} = VarC_{\text{tech}}\, Cap_{\text{tech}} + FixC_{\text{tech}} \tag{3.3}$$

where C_{up} is the upfront capital cost of the technology, Π_{tech} is the annuity rate of the technology, $VarC_{\text{tech}}$ is the variable capital cost of the technology, Cap_{tech} is the technology capacity to be invested, $FixC_{\text{tech}}$ are the fixed capital costs of the technology. The variable capital costs vary with the amount of capacity that is invested, while the fixed capital costs are independent on the size of the technology and cover engineering costs.

The simplified objective function related to the total annual carbon dioxide emissions can be represented by eq. (3.4). It is the summation of the carbon dioxide emissions from burning different fuel types used in providing the heat.

$$CO_2 = \sum_{\text{fueltype}} \sum_{m,d,h} CO_{2\text{fuels}} \tag{3.4}$$

The heat received from solar is given by eq. (3.5).

$$H^{S_{\text{th}}}_{m,d,h} = A^{S_{\text{th}}}\, I_{m,h}\, \eta^{S_{\text{th}}}_{m,h} \tag{3.5}$$

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where $A^{S_{\text{th}}}$ is the decision variable for the solar thermal area, $I_{m,h}$ is the parameter for the solar irradiance modeled based on [104] and $\eta^{S_{\text{th}}}_{m,h}$ is the parameter for the solar thermal efficiency modeled according to [105]. For Opt-3D model, the solar irradiance and solar thermal efficiency are modeled by weather data that are averaged on monthly basis over hours and the resulting heat from the solar decision variable assumes the same output for all the three daytypes in each month.

The heat storage model is defined by eq. (3.6-3.9).

$$H^{\text{stored}}_{m,d,h} = H^{\text{stored}}_{m,d,h-1} + H^{\text{in}}_{m,d,h} - H^{\text{out}}_{m,d,h} - H^{\text{loss}}_{m,d,h} \tag{3.6}$$

$$H^{\text{in}}_{m,d,h} = H^{\text{for}}_{m,d,h}\, \eta_{\text{char}} \tag{3.7}$$

$$H^{\text{out}}_{m,d,h} = H^{\text{from}}_{m,d,h}\, 1/(\eta_{\text{dis}}) \tag{3.8}$$

$$H^{\text{loss}}_{m,d,h} = H^{\text{stored}}_{m,d,h-1}\, \Theta_{\text{s}} + Cap_{\text{HS}}\, \Theta_{\text{st}}\, \frac{(T_{\text{min}} - T^{\text{amb}}_{m,h})}{(T_{\text{max}} - T_{\text{min}})} \tag{3.9}$$

where $H^{\text{stored}}_{m,d,h}$ represents the state of the charge of the heat storage, $H^{\text{in}}_{m,d,h}$ is the input for heat storage, $H^{\text{for}}_{m,d,h}$ is the heat required for storing in heat storage, η_{char} is the charging efficiency, $H^{\text{out}}_{m,d,h}$ is the output from heat storage, $H^{\text{from}}_{m,d,h}$ is the heat required from the heat storage, η_{dis} is the discharging efficiency, $H^{\text{loss}}_{m,d,h}$ is the heat lost in heat storage during working and standby conditions, Θ_{s} is the loss factor during storage operation, Θ_{st} is the loss factor during storage standby condition, Cap_{HS} is the capacity of the heat storage, T_{min} is the minimum temperature of the storage, T_{max} is the maximum

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temperature of the storage and $T^{\text{amb}}_{m,h}$ is the ambient temperature. The heat storage model constraints are given by eq. (3.10-3.13).

$$H^{\text{stored}}_{m,d,1} = H^{\text{stored}}_{m,d,24} + H^{\text{in}}_{m,d,1} - H^{\text{out}}_{m,d,1} - H^{\text{loss}}_{m,d,1} \tag{3.10}$$

$$H^{\text{stored}}_{m,d,h} \leq Cap_{\text{HS}} \tag{3.11}$$

$$H^{\text{in}}_{m,d,h} \leq Cap_{\text{HS}}\, \varphi^{\text{max}}_{\text{char}} \tag{3.12}$$

$$H^{\text{out}}_{m,d,h} \leq Cap_{\text{HS}}\, \varphi^{\text{max}}_{\text{dis}} \tag{3.13}$$

where eq. (3.10). represents the periodicity constraint in dynamic condition and shows that the first hour of the state of the charge of heat storage is linked with the last hour of the respective daytype d in the month m of the state of the charge of heat storage. $\varphi^{\text{max}}_{\text{char}}$ is the maximum charging rate of the heat storage and $\varphi^{\text{max}}_{\text{dis}}$ is the maximum discharging rate of the heat storage. The higher level energy balance can be represented in a simplified manner by eq. (3.14).

$$H^{\text{load}}_{m,d,h} + H^{\text{for}}_{m,d,h} = H^{S_{\text{th}}}_{m,d,h} + H^{\text{from}}_{m,d,h} + H^{\text{fuels}}_{m,d,h} \tag{3.14}$$

where $H^{\text{load}}_{m,d,h}$ is the thermal load of the system to be satisfied and $H^{\text{fuels}}_{m,d,h}$ is associated with the fuel for heat $F^{\text{heat}}_{m,d,h}$ by an efficiency parameter represented by η_{fuel} as given in eq. (3.15).

$$H^{\text{fuels}}_{m,d,h} = \eta_{\text{fuel}}\, F^{\text{heat}}_{m,d,h} \tag{3.15}$$

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3.2.2 Opt-8760: Optimization Model with 8760-Hours Time Horizon

Since the Opt-3D model considers the time series aggregation and the resulting representative daytype profiles, it does not keep any connectivity between the optimization days, and thus, can not model the seasonal storage behavior directly. The Opt-8760 model uses a full scale yearly time horizon *i.e.* 8760-hours and increases the time resolution of the MILP model used in Opt-3D by replacing $m \in \{1, 2, \ldots, 12\}$, $d \in \{1, 2, 3\}$ and $h \in \{1, 2, \ldots, 24\}$ with $t \in \{1, 2, \ldots, 8760\}$ for all the demand as well as the weather input data. This full scale optimization considers connectivity between all the optimization time-steps and can therefore model seasonal storage behavior directly.

3.2.3 Piecewise Affine Cost Functions for Solar Thermal and Heat Storage

The cost functions of the technologies that are used in thermal systems *i.e.* solar thermal and heat storage are not always justified as linear functions [29]. The costs of large hot water heat storage systems are dominated by the material for the tank since the storage capacity is proportional to the volume of the tank. A simple dimensional analysis demonstrates that for the most common type of heat storages (hot water tanks), an approximate power-law given by eq. (3.16) can be used when comparing typical costs for storage tanks [29]. Similarly, the costs of large solar thermal systems are observing non-linearities with its capacity and can be represented as given in eq. (3.16) [106]:

$$C_{\text{up}}(x) = A\, x^{\alpha} \tag{3.16}$$

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where $C_{\text{up}}(x)$ is the non-linear cost function, x is the capacity of the solar thermal or heat storage and A and α are the technology-specific parameters (e.g. $A = 0.661$ [Million-EUR/MW] and $\alpha = 0.835$ for solar thermal [106] and $A = 141$ [EUR/kWh] and $\alpha = 0.667$ for heat storage [29]).

A Piecewise Affine (PWA) linear approximation approach is used in this study to model the non-linear cost function $C_{\text{up}}(x)$ for both solar thermal and heat storage technologies as compared to other works which only consider heat storage technology for PWA approximations. This is in particular desirable because mixed integer non-linear programming (MINLP) problems can be translated into the MILP problems for which efficient algorithms and optimization software packages are widely available. In general, PWA functions consist of several discrete linear segments (pieces) that are used to describe a univariate function $f(x)$. The location where one of these linear segments ends and a new one begins are designated as breakpoints x_i. A PWA linear function $\tilde{f}(x)$ can be described as the following set of linear equations:

$$\tilde{f}(x) = \begin{cases} a_1(x - x_1) + b_1 & x_1 < x \leq x_2 \\ a_2(x - x_2) + b_2 & x_2 < x \leq x_3 \\ \vdots & \vdots \\ a_{n-1}(x - x_{n-1}) + b_{n-1} & x_{n-1} < x \leq x_n \end{cases} \tag{3.17}$$

where a_i are the slopes, b_i are the intercepts of the different linear segments, n is the number of breakpoints x_i and $(n-1)$ represents the total number of linear segments. A schematic illustration of a PWA approximation function $\tilde{f}(x)$ with three linear pieces of an arbitrary non-linear function $f(x)$ is demonstrated in Figure 3.1. A fundamental issue in modeling non-linear functions for MILP problems is how to represent the PWA approximation

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function $\tilde{f}(x)$ as a set of linear equations using discrete and continuous decision variables [107]. This issue is addressed in this study by using the Convex Combination Model [108] to represent PWA approximation functions $\tilde{f}(x)$.

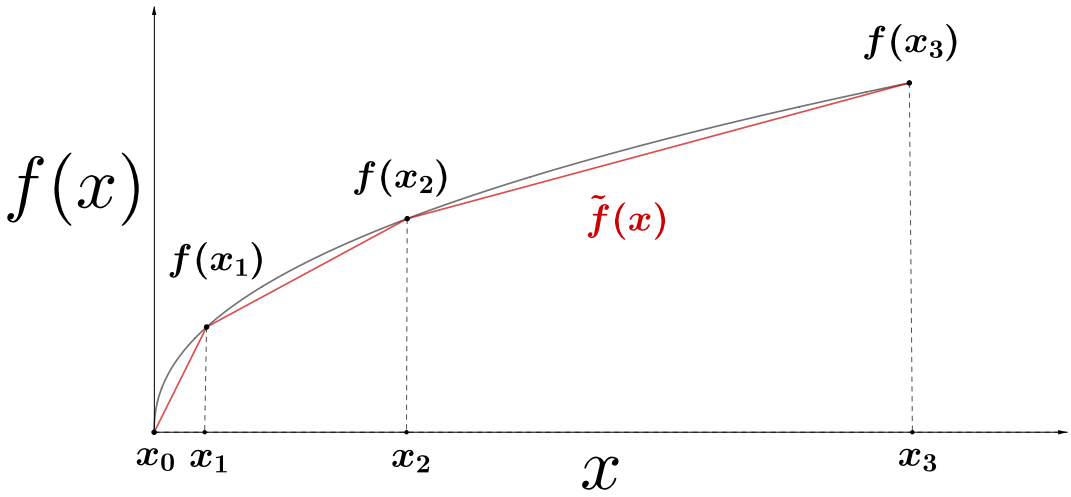

FIGURE 3.1: A schematic illustration of the PWA approximation function $\tilde{f}(x)$ with three linear pieces.

Convex Combination Model

The convex combination model represents the PWA approximation functions $\tilde{C}_{\text{up}}(x)$ as a linear combination of the breakpoints x_i as given in eq. (3.18-3.19).

$$\tilde{C}_{\text{up}}(x) = \sum_{i=1}^{n} \lambda_i \, C_{\text{up}}(x_i) \tag{3.18}$$

$$x = \sum_{i=1}^{n} \lambda_i \, x_i \tag{3.19}$$

where all coefficients λ_i are non-negative, continuous variables between 0 and 1 and summed up to 1 as given in eq. (3.20-3.21).

$$\lambda_i \in [0, 1], \qquad i = 1, \ldots, n \tag{3.20}$$

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$$\sum_{i=1}^{n} \lambda_i = 1 \tag{3.21}$$

The constraints related to λ_i are given in eq. (3.22).

$$\lambda_i \leq \begin{cases} \delta_{i+1} & \text{for } i = 0 \\ \delta_i + \delta_{i+1} & \text{for } i = 1, \ldots, n-1 \\ \delta_i & \text{for } i = n \end{cases} \tag{3.22}$$

where δ_i are binary variables and are modeled as given in eq. (3.23-3.24).

$$\delta_i \in \{0, 1\}, \qquad i = 1, \ldots, n \tag{3.23}$$

$$\sum_{i=1}^{n} \delta_i = 1 \tag{3.24}$$

The binary variables δ_i and the listed constraints given by eq. (3.22) enforce the condition that at the most two weighting factors λ_i are non-zero, in which case they must be adjacent.

Therefore, if the binary variable δ_{i+1}= 1 for instance, then the point $(x, \tilde{C}_{\text{up}}(x))$ = $(\lambda_i\, x_i,\, \lambda_i\, C_{\text{up}}(x_i)) + (\lambda_{i+1}\, x_{i+1},\, \lambda_{i+1}\, C_{\text{up}}(x_{i+1}))$ is given by the linear (convex) combination of the two points $(x_i,\, C_{\text{up}}(x_i))$ and $(x_{i+1},\, C_{\text{up}}(x_{i+1}))$ since $\lambda_i + \lambda_{i+1}$ = 1 and $0 \leq \lambda_i \leq (\delta_i + \delta_{i+1})$ = 1, $\lambda_{i+1} \geq 0$.

Fitting Non-Linear Cost Functions

The optimal positions of the breakpoints x_i are not always known. Moreover, a simple linear connection using just the convex combination model between the original cost function values $C_{\text{up}}(x_i)$ leads to a PWA approximation $\tilde{C}_{\text{up}}(x)$, where the functional values are systematically smaller than that of $C_{\text{up}}(x)$ *i.e.* $\tilde{C}_{\text{up}}(x) \leq C_{\text{up}}(x) : \forall x$ except at the breakpoint locations

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x_i where $C_{\text{up}}(x_i) = \tilde{C}_{\text{up}}(x_i)$. Therefore, performing a linear fit process before using the convex combination model minimizes the deviation errors (residuals) $\epsilon_i = \mid C_{\text{up}}(x_i) - \tilde{C}_{\text{up}}(x_i) \mid$. In this study, a preliminary analysis is performed using logarithmically spaced separation which suggests that at least five linear segments are needed to cover five orders of magnitude for heat storage and solar thermal with a deviation error of less than 10%. Thus, the linear fit process is performed by considering $n = 6$ breakpoints (five linear segments) and minimizing the sum-of-squares of the residuals ϵ_i as given in eq. (3.25).

$$\min_{\vec{\alpha}} \sum_{i=1}^{n} \left(C_{\text{up}}(x_i) - \tilde{C}_{\text{up}}(x_i; \vec{\alpha})\right)^2 = \min_{\vec{\alpha}} \sum_{i=1}^{n} \epsilon_i^2 \tag{3.25}$$

where the components $(\alpha_1, \ldots, \alpha_k)$ of the vector $\vec{\alpha} \in \mathbb{R}^k$ are the fit parameters of the linear segments. The regression analysis method is performed several times for five continuous linear pieces until the minimum deviation error is found.

After performing the linear fit process, the PWA approximation functions $\tilde{C}_{\text{up}}(x)$ are modeled through the convex combination model as described in section 3.2.3. The resulting PWA parameters for solar thermal and heat storage technologies are given in Table 3.1. Depending upon the capacity chosen by the optimization model, the respective linear segment of the piecewise affine function is activated and the costs are calculated using the variable cost and fixed costs of that active linear segment. The cost vs. capacity curves using linear cost functions, non-linear cost functions and PWA cost functions for solar thermal and heat storage technologies are illustrated in Figure 3.2 and Figure 3.3 respectively. It can be seen from Figure 3.2 and Figure 3.3 that the upfront capital costs of solar thermal as well as heat storage technologies

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are significantly lower for the large capacities considering the resulting linearly fitted piecewise affine function as compared to just single linear cost function.

Parameter	Solar Thermal	Heat Storage
Min. Cap.	0 [kW]	0 [kWh]
Breakpoint 12	350 [kW]	350 [kWh]
Breakpoint 23	4,238 [kW]	3,500 [kWh]
Breakpoint 34	11,443 [kW]	35,000 [kWh]
Breakpoint 45	21,741 [kW]	350,000 [kWh]
Max. Cap.	35,000 [kW]	3,500,000 [kWh]
Cost Value at Min. Cap.	0 [€]	520 [€]
Cost Value at Breakpoint 12	345,884.14 [€]	6,820 [€]
Cost Value at Breakpoint 23	2,249,511.90 [€]	33,119.88 [€]
Cost Value at Breakpoint 34	5,092,805.40 [€]	155,206.46 [€]
Cost Value at Breakpoint 45	8,675,353.80 [€]	722,005.19 [€]
Cost Value at Max. Cap.	12,893,566 [€]	3,350,130.58 [€]
Fixed Costs of Linear Segment 1	0 [€]	520 [€]
Fixed Costs of Linear Segment 2	174,511.57 [€]	3,897.79 [€]
Fixed Costs of Linear Segment 3	577,170.54 [€]	19,554.70 [€]
Fixed Costs of Linear Segment 4	1,112,048.18 [€]	92,228.82 [€]
Fixed Costs of Linear Segment 5	1,758,462.20 [€]	429,991.26 [€]
Variable Cost of Linear Segment 1	988.24 [€/kW]	18 [€/kWh]
Variable Cost of Linear Segment 2	489.64 [€/kW]	8.35 [€/kWh]
Variable Cost of Linear Segment 3	397.62 [€/kW]	3.88 [€/kWh]
Variable Cost of Linear Segment 4	347.88 [€/kW]	1.80 [€/kWh]
Variable Cost of Linear Segment 5	318.15 [€/kW]	0.83 [€/kWh]

TABLE 3.1: Investment parameters for solar thermal and heat storage technologies with piecewise affine (PWA) cost functions. The non-linear cost functions are considered according to [29, 106].

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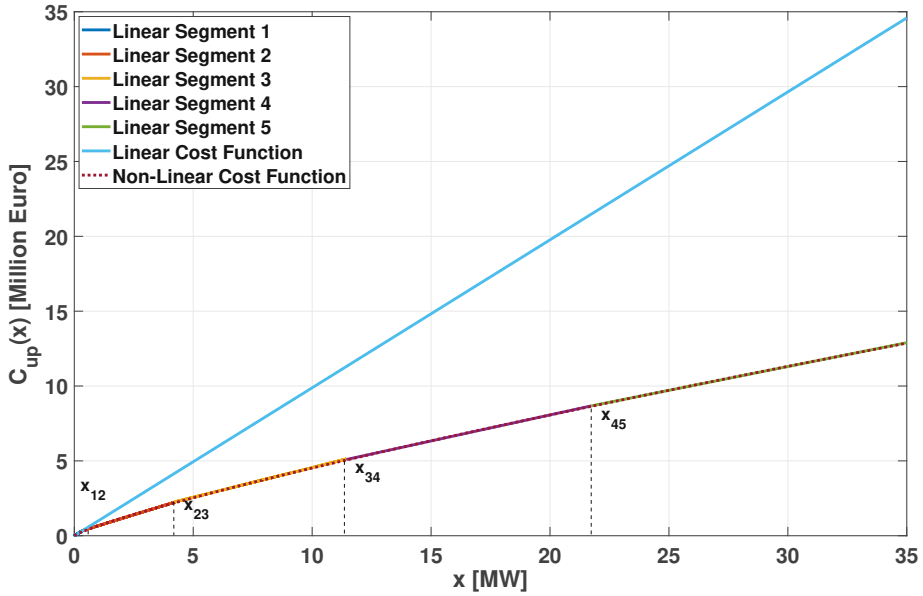

FIGURE 3.2: Cost vs. Capacity curve of solar thermal technology using linear, non-linear and PWA cost functions.

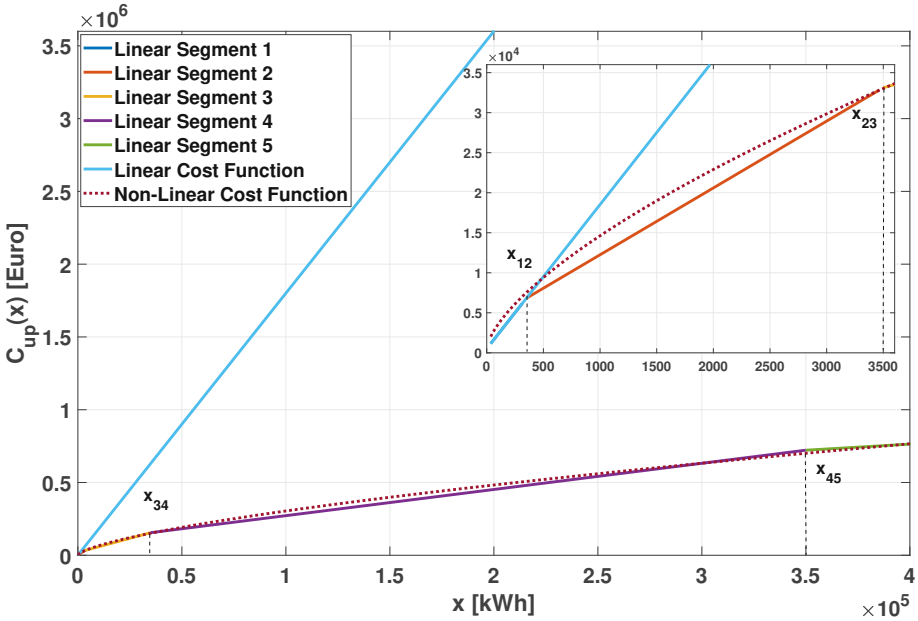

FIGURE 3.3: Cost vs. Capacity curve of heat storage technology using linear, non-linear and PWA cost functions.

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3.3 Case Study

This section covers the general overview of the approach to the definition of the case study, data analytics and pre-processing. The case study is related to a set of community residential buildings in Austria. Only space heating load is considered for this study and it is generated using TRNSYS [109] simulations on hourly basis for a whole year. Central heating through biomass fuel, solar thermal and heat storage technologies are considered to satisfy the thermal load. The heat storage considered for this study is a hot water tank storage. The schematic diagram of the researched thermal system is illustrated in Figure 3.4.

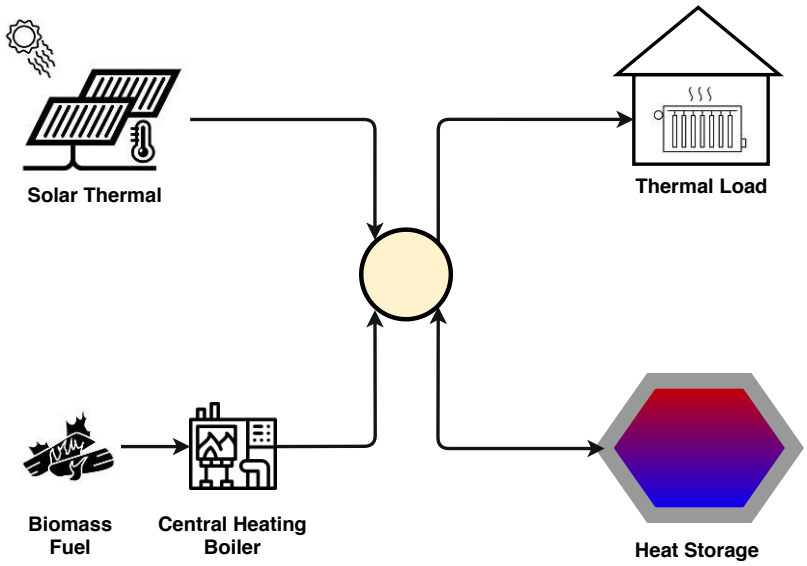

FIGURE 3.4: Schematic diagram of investigated thermal system.

3.3.1 Time Series Data Analysis and Processing

The hourly load profile of the thermal load for the whole year is demonstrated in Figure 3.5. The thermal load profile shown in Figure 3.5 is also used directly in the Opt-8760 model. The annual load is around 2004 MWh/a with a peak load of 2 MW_p. The seasonal behavior is clearly evident from Figure 3.5 and shows no load in the summer months.

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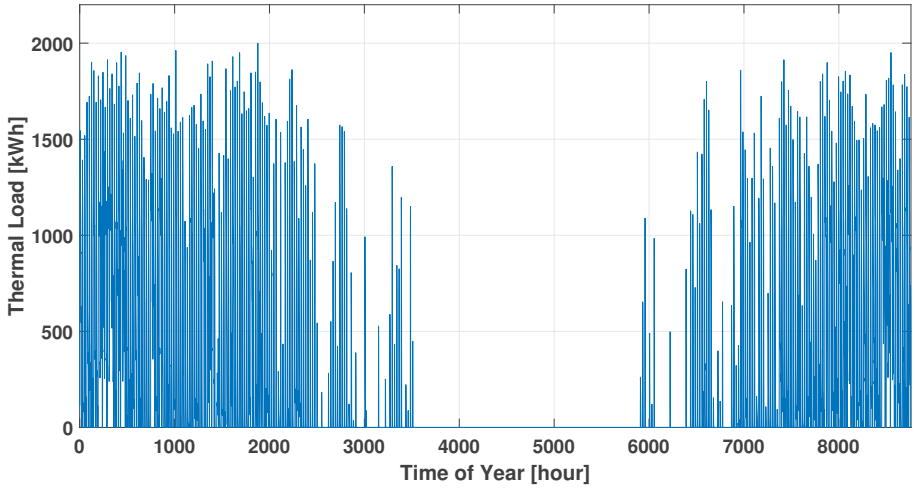

FIGURE 3.5: Thermal load profile on hourly basis for all the year [109].

The yearly profile is then reduced by time series aggregation as mentioned in section 3.2.1. This results in 24-hours based three representative daytypes *i.e.* week, peak and weekend for all the 12 months. The resulting representative profiles are shown in Figures 3.6-3.8 and are used for the Opt-3D model. It can be seen from Figure 3.7 that the peaks for every month are preserved and the week and weekend profiles are averaged after subtracting the peaks form the respective occurring daytypes. The number of the days for the week, peak and weekend daytypes are selected according to Table 3.2. The total annual thermal load based on these number of days associated with respective profiles results in 2003 MWh/a, a 0.05% difference relative to the original yearly thermal demand, with the same peak load of 2 MW_p. This shows that the time series aggregation method captures the monthly variations adequately in terms of week days, weekend days and peak days so that the percentage difference between the original yearly thermal demand and the up-scaled yearly thermal demand from the reduced representative profiles in each month is almost negligible.

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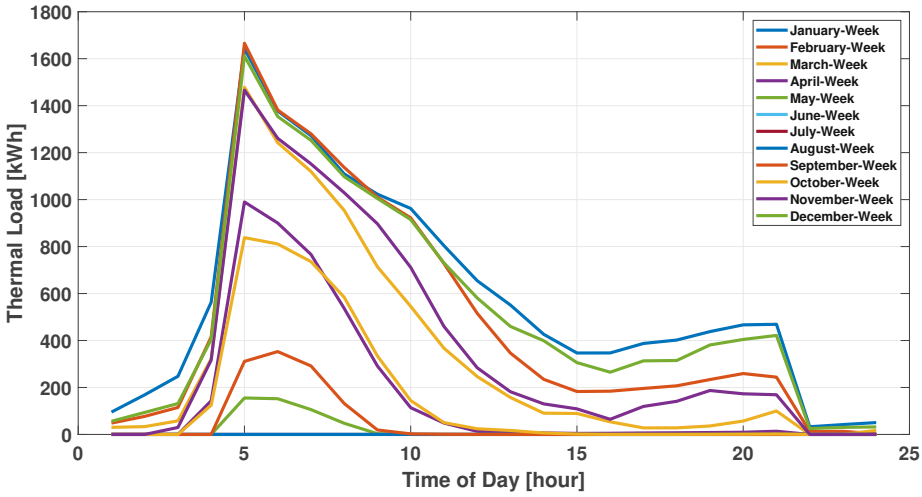

FIGURE 3.6: Week days time series aggregated representative profiles of the thermal load for all the year.

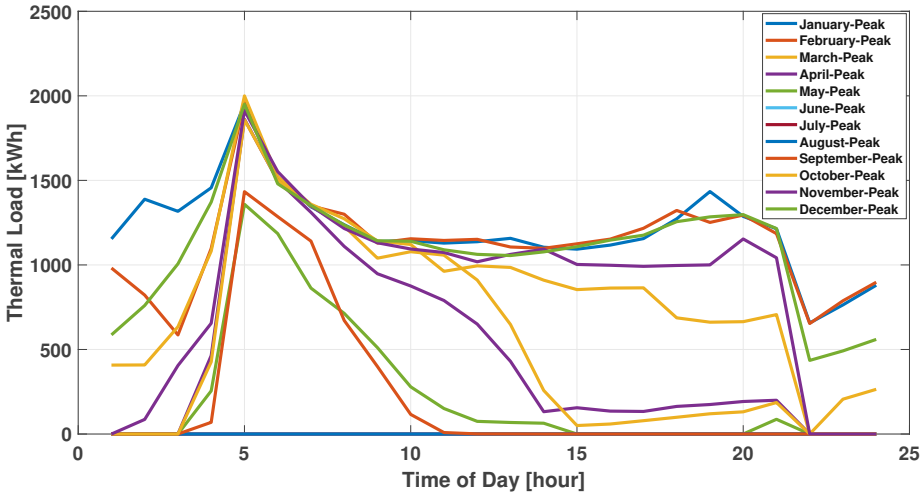

FIGURE 3.7: Peak days time series aggregated representative profiles of the thermal load for all the year.

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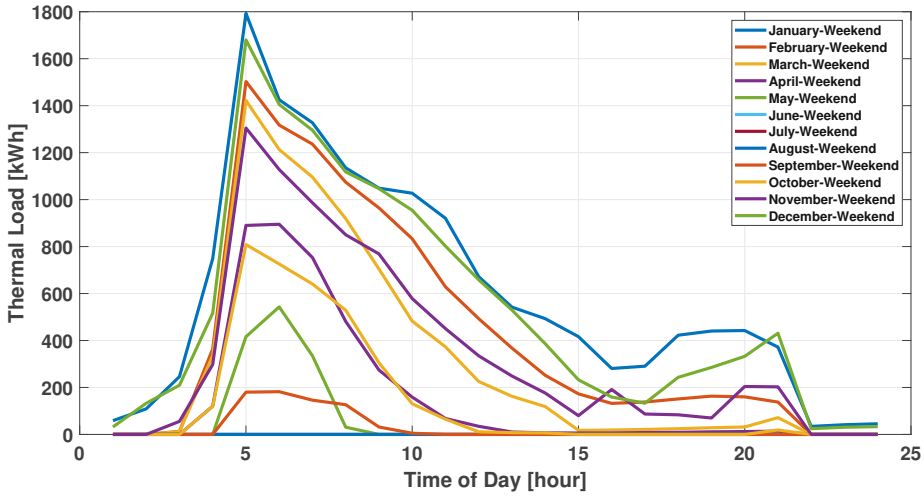

FIGURE 3.8: Weekend days time series aggregated representative profiles of the thermal load for all the year.

Month	Week Days	Peak Days	Weekend Days
January	21	1	9
February	19	1	8
March	22	1	8
April	20	1	9
May	22	1	8
June	21	1	8
July	21	1	9
August	22	1	8
September	20	1	9
October	21	1	9
November	21	1	8
December	21	1	9

TABLE 3.2: Number of the days for representative profiles in each month.

The weather data include the global irradiance, diffuse irradiance and ambient temperature. These data are gathered through Metenorm [110] for the location of the considered case study. The weather data are available for one full year on hourly time-steps and used for the Opt-8760 model. The hourly based weather data are shown in Figure 3.9. These weather data are also reduced using time series aggregation methods to get average values per month for Opt-3D model and are shown in Figures 3.10-3.12.

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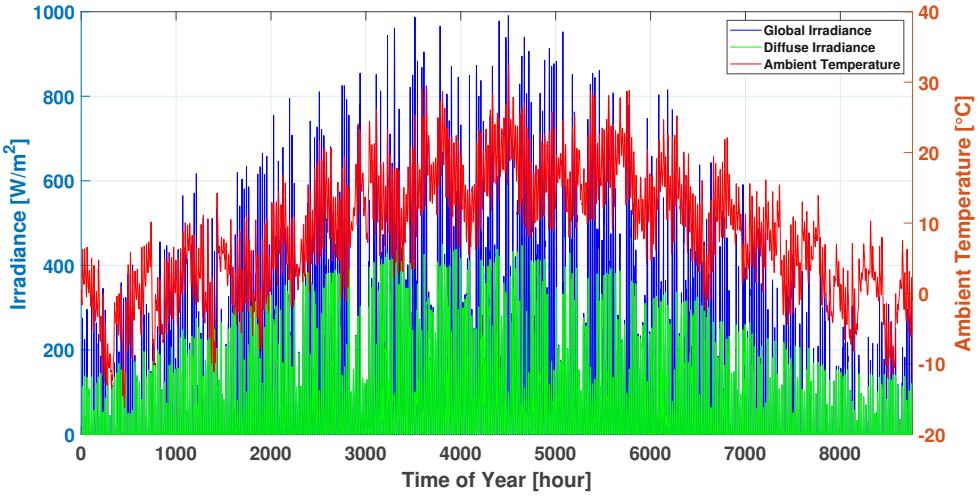

FIGURE 3.9: Weather Data: Global Irradiance, Diffuse Irradiance and Ambient Temperature on hourly basis for all the year [110].

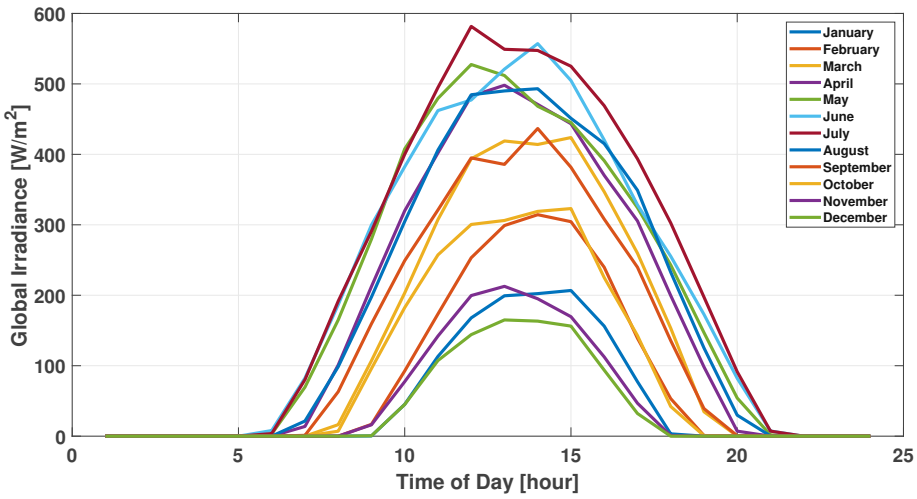

FIGURE 3.10: Global irradiance time series aggregated representative profiles of the thermal load for all the year.

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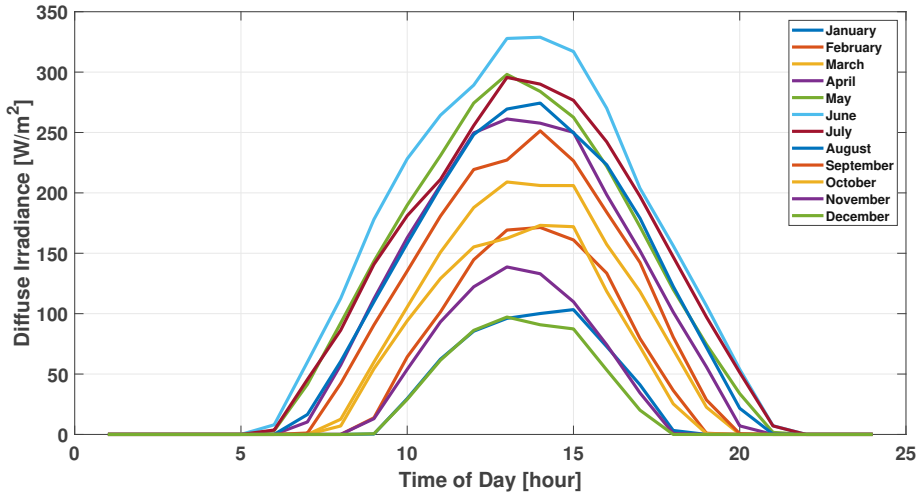

FIGURE 3.11: Diffuse irradiance time series aggregated representative profiles of the thermal load for all the year.

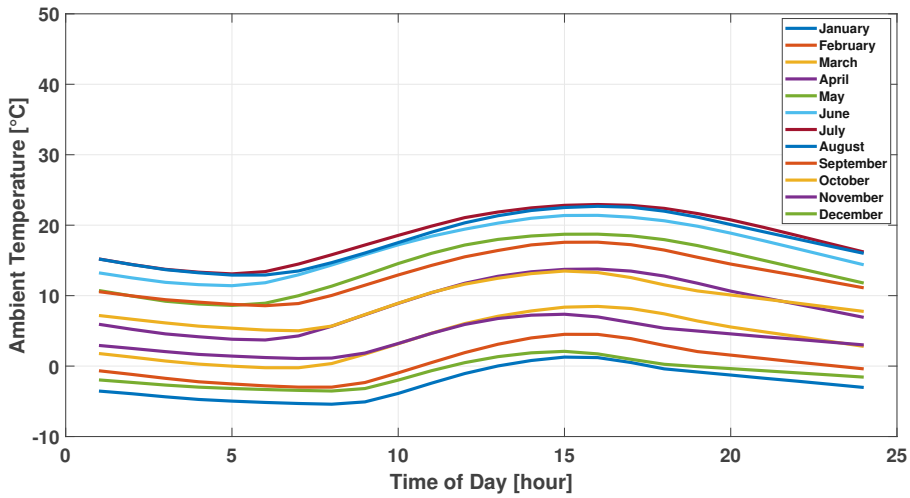

FIGURE 3.12: Ambient temperature time series aggregated representative profiles of the thermal load for all the year.

3.3.2 Techno-Economical Parameters

The economic parameters for both Opt-3D and Opt-8760 optimization models are the same. These include the investment parameters such as fixed capital costs, variable capital costs, fixed maintenance costs, lifetime and annuity rate. The fixed and variable capital costs for solar thermal and thermal storage are different when considering the fixed linear *i.e.* Non-PWA cost functions and PWA cost functions. The economic parameters for central heating,

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solar thermal and heat storage considering Non-PWA fixed cost functions are reported in Table 3.3 based on [111, 112]. The economic parameters for solar thermal and heat storage considering the PWA cost functions are given in Table 3.1.

Technology	Fixed Cost	Variable Costs	Fixed Maintenance Costs	Lifetime	Annuity Rate
	[€]	[€/kW] or [€/kWh]	[€/kW] or [€/kWh] per month	[Years]	[%]
Central Heating	13,821	270	1.72	25	5.74
Solar Thermal	0	988	0	20	6.72
Heat Storage	520	18	0	25	5.74

TABLE 3.3: Investment parameters for central heating, solar thermal and heat storage technologies with fixed linear (Non-PWA) cost function [111, 112].

The solar thermal collectors have horizontal orientation with a tilt angle of 20°. The technical parameters for the heat storage contain the charging and discharging efficiencies, maximum charge and discharge rates, minimum and maximum temperatures and losses. These parameters are same for the Opt-3D and the Opt-8760 models except the parameters of losses. The losses for the Opt-8760 model are assumed in accordance with [43]. Whereas, the losses for the Opt-3D model are assumed to be 8% higher than the Opt-8760 model given that the Opt-3D is a non-seasonal model and the losses for short-term non-seasonal heat storage are higher than the long-term seasonal storage [113]. These parameters are given in Table 3.4 and are based on [40, 43, 113].

Parameter	Value
η_{char} [%]	90
η_{dis} [%]	90
$\varphi_{\text{char}}^{\text{max}}$ [%]	75
$\varphi_{\text{dis}}^{\text{max}}$ [%]	75
T_{min} [°C]	15
T_{max} [°C]	65
$\Theta_{\text{s}}/\Theta_{\text{st}}$ [%]	Opt-3D: 0.08
	Opt-8760: 0.01

TABLE 3.4: Technical parameters for heat storage [40, 43, 113].

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The technical parameters for the central heating contain the fueltype, volumetric fuel costs, fuel to heat efficiency and marginal CO_2 emissions. These parameters are based on [111] and are given in Table 3.5. The biomass based central heating technology does not consider the minimum output constraint in terms of production mode and the optimizer chooses the optimal capacity based on the maximum $H^{\text{fuels}}_{m,d,h}$ output as defined by the eq. (3.15).

Parameter	Value
Fueltype	Biomass
Fuel Costs [€/kWh]	0.05
η_{fuel} [%]	78
CO_2 Fuel Emissions [kg CO_2 / kWh]	0.02

TABLE 3.5: Technical parameters for central heating [111].

3.3.3 Optimization & Testing Framework

For testing the case study, the Opt-3D and the Opt-8760 optimization models are tested for different scenarios reported in Table 3.6.

Scenario	Optimization Model	Minimization
Scenario-0 (a): Basecase	Opt-3D	Cost
Scenario-0 (b): Basecase	Opt-8760	Cost
Scenario-1 (a): 0% relaxation w.r.t basecase	Opt-3D	Cost
Scenario-1 (b): 0% relaxation w.r.t basecase	Opt-3D	CO_2
Scenario-2 (a): 0% relaxation w.r.t basecase	Opt-8760	Cost
Scenario-2 (b): 0% relaxation w.r.t basecase	Opt-8760	CO_2
Scenario-3: 50% relaxation w.r.t basecase	Opt-3D	CO_2
Scenario-4: 50% relaxation w.r.t basecase	Opt-8760	CO_2

TABLE 3.6: Different scenarios for the optimization and testing framework.

Scenario-0 is the basecase where the central heating technology is only considered for supplying to the load and no heat storage and solar thermal technologies are allowed. The optimal total energy costs and total CO_2 emissions are calculated for both models by using cost minimization. These costs and CO_2 emissions are then taken as reference for the rest of scenarios and objective function savings. Costs and CO_2 emissions are calculated relative to these references in the respective cost and CO_2 optimization runs for

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Scenario-1 to Scenario-4. Scenario-1 includes the cost and CO_2 minimization using the Opt-3D model with 0% relaxation to their respective reference costs and CO_2 emissions. A 0% relaxation means that the objective function from the optimization case cannot be higher than the one from the reference case. Scenario-2 includes the cost and CO_2 minimization using the Opt-8760 model with 0% relaxation to their respective reference costs and CO_2 emissions. Scenario-3 and Scenario-4 include the CO_2 minimization using the Opt-3D and the Opt-8760 models respectively with 50% relaxation in the reference costs, meaning that the objective functions can be 50% higher than the one in the reference cases, allowing for more progressive results. Scenario-1 to Scenario-4 are tested by considering fixed linear (Non-PWA) cost functions as well as PWA cost functions for both models. The results are compared based on the investment decisions by the optimizer, objective function savings, absolute run time, objective function difference and the run time savings between both the Opt-3D and the Opt-8760 models for all scenarios. The optimality gap of the optimization solver was set to 0.2% for all the scenarios. The MILP optimization for both models was performed on a server with a 6 core Intel Xeon E5-1650 v3 CPU @ 3.5 GHz and 192 GB of RAM.

3.4 Results

This section provides the comparison between the results of all scenarios given in Table 3.6. The resulting investment decisions chosen by the optimizer for all the scenarios are reported in Table 3.7. The objective function difference and the run time savings between both the Opt-3D and the Opt-8760 models relative to the Opt-8760 are reported in Table 3.8 and illustrated in Figure 3.13.

The results of scenario-0 (a) and scenario-0 (b) indicate that the total energy

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	Scenarios	Model	Min.	OF Costs [k€]	OF CO2 [tons]	Central Heating [kWh]	Solar Thermal [kW]	Heat Storage [kWh]	OF Savings [%]	Run Time [s]
	Scenario-0 (a)	Opt-3D	Cost	194.02	59.05	2,000	-	-	-	0.81
	Scenario-0 (b)	Opt-8760	Cost	194.06	59.07	2,000	-	-	-	8.03
Non-PWA	Scenario-1 (a)	Opt-3D	Cost	183.44	59.05	1,612	8	2,791	5.45	2.06
	Scenario-1 (b)	Opt-3D	CO_2	194.02	58.92	1,643	31	10,717	0.22	2.59
	Scenario-2 (a)	Opt-8760	Cost	180.01	59.07	1,411	20	5,701	7.24	81.3
	Scenario-2 (b)	Opt-8760	CO_2	194.06	58.5	1,406	63	17,839	0.98	91.64
	Scenario-3	Opt-3D	CO_2	291.02	58.2	1,675	262	90,045	1.44	2.11
	Scenario-4	Opt-8760	CO_2	291.08	54.73	1,380	358	101,101	76.6	49.52
PWA	Scenario-1 (a)	Opt-3D	Cost	179.36	59.05	1,389	44	15,186	7.56	3.14
	Scenario-1 (b)	Opt-3D	CO_2	194.02	58.55	1,479	143	49,138	0.85	3.38
	Scenario-2 (a)	Opt-8760	Cost	173.37	59.07	1,148	70	19,655	10.66	177.47
	Scenario-2 (b)	Opt-8760	CO_2	194.06	54.45	814	569	160,471	7.83	361.59
	Scenario-3	Opt-3D	CO_2	291.02	57.97	2,046	497	170,875	1.83	2.11
	Scenario-4	Opt-8760	CO_2	291.08	13.82	191	4,512	1,500,870	76.6	224.91

TABLE 3.7: Results of the investment decisions of all scenarios for both the Opt-3D and the Opt-8760 models using fixed linear (Non-PWA) cost functions as well as piecewise affine (PWA) cost functions.

costs and the total CO_2 emissions are almost same for both the Opt-3D and the Opt-8760 models with an objective function difference of 0.02%. These two scenarios set the reference case for the next scenarios. This also indicates that the time aggregation method used is effective when reducing the data into three representative daytypes.

When considering 0% relaxation in the reference case, the cost minimization in scenario-1 (a) and scenario-2 (a) invests in a small amount of solar thermal and heat storage technologies, but this reduces the capacity of central heating and provides almost the same objective function savings for both models and just 1.78% objective function difference using Non-PWA cost functions. With PWA cost functions, the objective function savings in scenario-1 (a) and scenario-2 (a) are higher than that of Non-PWA cost functions for both models but the objective function difference is also higher than that of Non-PWA.

When considering 0% relaxation in the reference case, the CO_2 minimization in scenario-1 (b) invests more in solar thermal and heat storage as compared to its cost minimization runs, but even this amount of solar thermal and heat storage is not effective since objective function savings are almost insignificant (less than 1%) using either Non-PWA or PWA cost functions. The size of heat storage is not big enough to be qualified for the seasonal storage as the volume of 849 m^3 related to the biggest capacity of 49138 kWh in scenario-1 (b) using PWA cost functions is less than the practical range of seasonal heat

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storage volume [27]. This is also true for the CO_2 minimization in scenario-2 (b) using Non-PWA cost functions which invests in heat storage capacity of 17839 kWh (equivalent to 308 m^3 of volume). Whereas, the CO_2 minimization in scenario-2 (b), which uses Opt-8760 model, invests in bigger capacities of solar thermal and heat storage and lower capacity of central heating using PWA cost functions as compared to its Non-PWA run which can be considered as seasonal storage with 7.83 % of CO_2 savings. The objective function difference between scenario-1 (b) and 2 (b) using PWA for CO_2 minimization run is 6.98% which is higher than that of the Non-PWA optimization run.

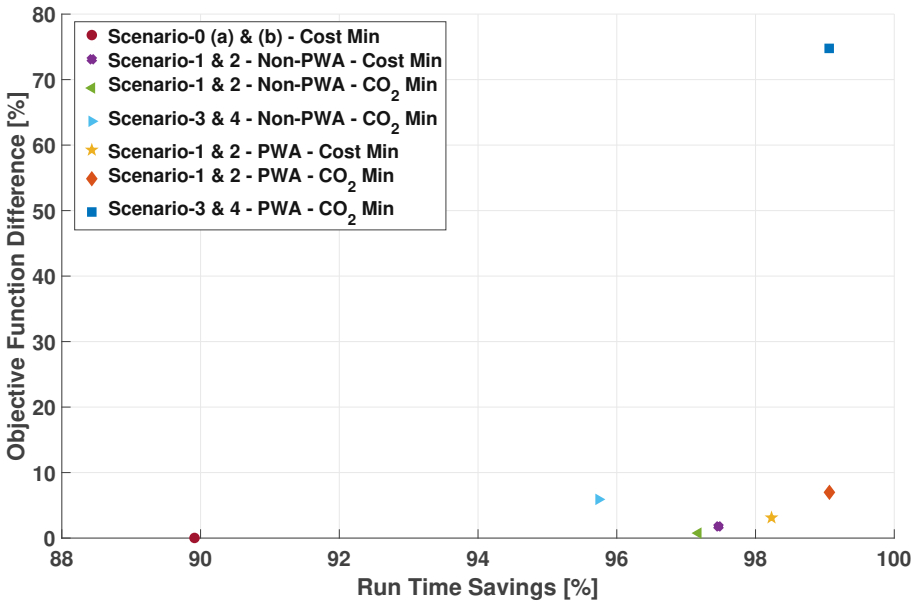

FIGURE 3.13: Comparison between the results of objective function difference and run time savings between Opt-3D and Opt-8760 models relative to Opt-8760 model for different scenarios.

When considering 50% relaxation in the reference costs and Non-PWA cost functions, the CO_2 minimization in scenario-3 using Opt-3D model and scenario-4 using Opt-8760 model have an objective function difference of 5.91%. The sizes of the solar thermal and heat storage are bigger than in the previous respective scenarios as the costs are relaxed thus moving towards the expensive bigger systems for seasonal storage. Even though the size of the heat storage

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is comparable between both two models, which is a surprising result due to the lack of connectivity between the daytypes in the Opt-3D model, the daytype model is not able to transfer the energy provided by solar thermal in summer months and shift it to winter months, thus increasing the objective function difference relative to the Opt-8760 model. This result indicates that when considering the Opt-3D model, it can provide the investment decisions in a good agreement with the Opt-8760 model with reduced run time, when specific constraints and assumptions are made.

	Scenarios	**Min.**	**OF Difference [%]**	**Run Time Savings [%]**
	Scenario-0 (a) & Scenario-0 (b)	Cost	0.02	89.91
Non-PWA	Scenario-1 (a) & Scenario-2 (a)	Cost	1.78	97.47
	Scenario-1 (b) & Scenario-2 (b)	CO_2	0.76	97.17
	Scenario-3 & Scenario-4	CO_2	5.91	95.74
PWA	Scenario-1 (a) & Scenario-2 (a)	Cost	3.1	98.23
	Scenario-1 (b) & Scenario-2 (b)	CO_2	6.98	99.07
	Scenario-3 & Scenario-4	CO_2	74.77	99.06

TABLE 3.8: Results of objective function difference and run time savings between Opt-3D and Opt-8760 models relative to Opt-8760 model for different scenarios. Scenario-0 (a), Scenario-1 (a), Scenario-1 (b) and Scenario-3 consider the Opt-3D model. Scenario-0 (b), Scenario-2 (a), Scenario-2 (b) and Scenario-4 consider the Opt-8760 model.

When considering 50% relaxation in the reference costs and PWA cost functions, the CO_2 minimization in scenario-3 using Opt-3D model does invest in bigger capacities for solar thermal and heat storage, but due to the lack of connectivity between the daytypes, these bigger capacities are not able to provide significant objective function savings as compared to that of scenario-4 using Opt-8760 model. The results of scenario-4 with PWA cost functions indicate a huge reduction in central heating capacity followed by the big investments in solar thermal and heat storage capacities. This is because of the use of the PWA functions, which considers lower costs for higher capacities of these technologies. The objective function savings are about 76.6% with a 1.5 GWh capacity of heat storage (25,918 m^3) and a 4,512 kW capacity of

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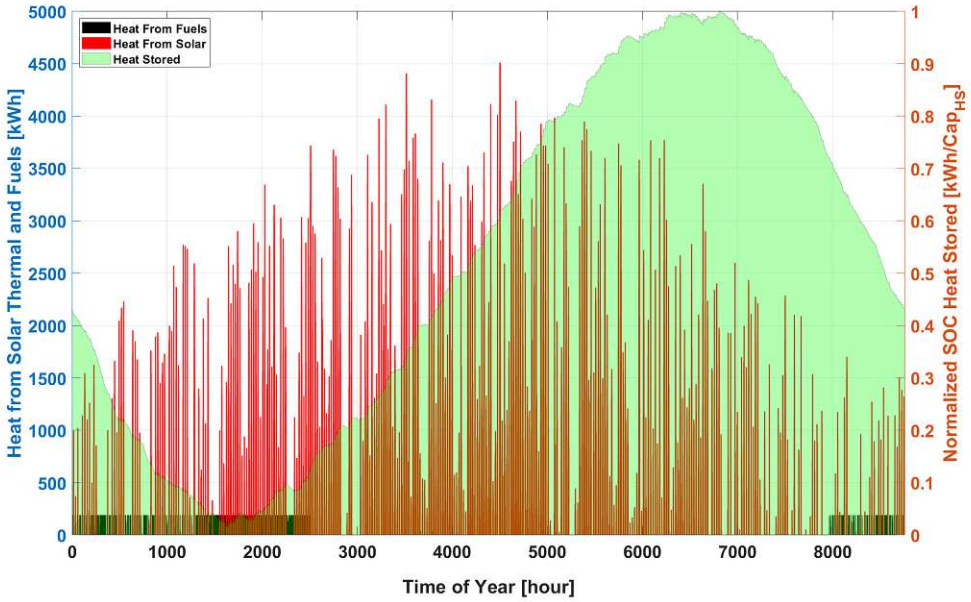

FIGURE 3.14: Optimal dispatch for Scenario-4: 50% relaxation w.r.t basecase considering the Opt-8760 model with CO_2 minimization using piecewise affine (PWA) cost functions.

solar thermal (5,679 m^2 of solar collector field area). The resulting optimal dispatch of scenario-4 using the PWA cost functions is demonstrated in Figure 3.14. The dispatch results of scenario-4 using the PWA cost functions show the seasonal effect of the heat storage by storing the energy in summer months and using the stored heat in winter months.

3.5 Resume

The optimal design of microgrids with thermal energy system requires optimization techniques that can provide investment and scheduling of the technology portfolio involved. In the modeling of such systems with seasonal storage capability, the two main challenges include the low temporal resolution of available data and the non-linear cost versus capacity relationship of solar thermal and heat storage technologies. This work overcomes these challenges by developing two different optimization models based on

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mixed-integer linear programming with objectives to minimize the total energy costs and carbon dioxide emissions. Piecewise affine functions are used to approximate the non-linear cost versus capacity behavior. The developed methods are applied to the optimal planning of a case study in Austria. The results of the models are compared based on the accuracy and real-time performance together with the impact of piecewise affine cost functions versus non-piecewise affine fixed cost functions. The results show that the investment decisions of both models are in good agreement with each other while the computational time for the 8760-hours based model is significantly greater than the model having three representative periods. The models with piecewise affine cost functions show larger capacities of technologies than non-piecewise affine fixed cost function based models.

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Chapter 4

Advanced Optimal Planning for Microgrid Technologies including Hydrogen and Mobility at a Real Microgrid Testbed

4.1 Introduction

This chapter aims to assess, investigate and solve the Research Question 2. The impact of the renewable energy based hydrogen energy systems is quantified for the decarbonization of the mobility sector. Also, the hydrogen is compared with the state-of-the-art diesel fuel systems. Finally, the carbon prices and policy framework to drive the paradigm shift from conventional fuel systems to renewable hydrogen mobility systems are discussed.

The rest of this chapter is structured as follows. Section 4.2 describes the formulation of the optimization problem. Section 4.3 provides the detailed information of the case study and its testing, including pre-processing and analytics of data. Section 4.4 discusses the detailed results followed by the resume in Section 4.5.

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4.2 Formulation of Optimization Problem

The methodology considers the optimization model using a MILP framework based on the Distributed Energy Resources - Customer Adoption Model (DER-CAM) [37] and further developed within this research to include the hydrogen production, seasonal storage and use in the mobility sector with a yearly time horizon. A major difference to the existing literature and DER-CAM is the addition of the hydrogen production via water electrolysis, hydrogen seasonal storage and use in the mobility using full-scale optimization horizon. It is because of this wider range of the time horizon and connectivity linkage between time steps that the seasonality can be taken into account in the optimization. Therefore, this MILP framework considers the full scale optimization *i.e.* 8760-hours by replacing the previously MILP framework (with time series in terms of 24-hours based three representative daytypes for each month) having months $m \in \{1, 2, \ldots, 12\}$, daytypes $d \in \{1, 2, 3\}$ and hours $h \in \{1, 2, \ldots, 24\}$ with $t \in \{1, 2, \ldots, 8760\}$.

The MILP optimization framework minimizes the total energy costs and the total CO_2 emissions. The simplified objective function related to the total annual energy costs C can be represented by eq. (4.1).

$$C = \sum_{\text{tech}} DER_{\text{invest}} + \sum_{t} C_{\text{utility}} + \sum_{t} C_{\text{O\&M}} \tag{4.1}$$

where DER_{invest} is the annualized investment cost per technology *tech*, C_{utility} is related to electrical purchase minus sales to the utility grid and other fixed costs related to utility *i.e.* time-of-use tariffs and daily and monthly demand charges of the electricity purchased and $C_{\text{O\&M}}$ is related to the operation and maintenance costs.

DER_{invest} can be further described as shown in eq. (4.2) and eq. (4.3).

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$$DER_{\text{invest}} = \sum_{\text{tech}} (C_{\text{up}}\, \Pi_{\text{tech}}) \tag{4.2}$$

$$C_{\text{up}} = VarC_{\text{tech}}\, Cap_{\text{tech}} + FixC_{\text{tech}} \tag{4.3}$$

where C_{up} are the upfront capital costs of the technology, Π_{tech} is the annuity rate of the technology, $VarC_{\text{tech}}$ are the variable capital costs of the technology, Cap_{tech} is the technology capacity to be invested, $FixC_{\text{tech}}$ are the fixed capital costs of the technology. The variable capital costs vary with the amount of capacity that is invested, while the fixed capital costs are independent on the size of the technology and can cover engineering costs.

The total annual energy costs C can also be limited in the optimization by the cost constraint of C_{lim} according to the eq. (4.4) and eq. (4.5).

$$C_{\text{lim}} = (1 + \gamma)\, C_{\text{reference}} \tag{4.4}$$

$$C \leq C_{\text{lim}} \tag{4.5}$$

where $C_{\text{reference}}$ are the input costs associated with the reference case and γ is the cost constraint parameter responsible for limiting the total annual energy costs. This is particularly very important to conduct sensitivity analysis where CO_2 optimizations are performed by keeping the limit on the total annual energy costs and effectively establish a multi-objective frontier.

The simplified objective function related to the total annual carbon dioxide emissions can be represented by eq. (4.6). It is the summation of the carbon dioxide emissions occurred in providing the electricity from the grid. The carbon dioxide emissions can also be considered form other technologies

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such as a combined heat and power system running on natural gas, but only electricity from grid is considered as a source of carbon dioxide emissions in this study.

$$CO_2 = \sum_t CO_{2\text{grid}} \tag{4.6}$$

The hydrogen produced by the electrolyzer can be represented by eq. (4.7) and the electrolyzer capacity constraint can be represented by eq. (4.8).

$$H_{2_t}^{\text{in}} = E_t^{\text{El}}\, \eta_{\text{El}}\, \eta_{\text{press}} \tag{4.7}$$

$$E_t^{\text{El}} \leq Cap_{\text{El}} \tag{4.8}$$

where $H_{2_t}^{\text{in}}$ is the hydrogen produced by the electrolyzer and the input to hydrogen storage system, E_t^{El} is the electricity required by the electrolyzer, η_{El} is the electrolyzer efficiency, η_{press} is the pressurizing efficiency for the hydrogen and Cap_{El} is the capacity of hydrogen electrolyzer.

The hydrogen stored can be represented by eq. (4.9).

$$H_{2_t}^{\text{stored}} = H_{2_{t-1}}^{\text{stored}} + H_{2_t}^{\text{in}} - H_{2_t}^{\text{out}} - H_{2_t}^{\text{loss}} \tag{4.9}$$

where $H_{2_t}^{\text{stored}}$ represents the state of the charge or the Level of Hydrogen (LOH), $H_{2_t}^{\text{in}}$ is the input for hydrogen storage, $H_{2_t}^{\text{out}}$ is the output from hydrogen storage, $H_{2_t}^{\text{loss}}$ is the hydrogen lost in hydrogen storage. The hydrogen losses can be represented by eq. (4.10).

$$H_{2_t}^{\text{loss}} = H_{2_t}^{\text{stored}}\, \Theta_{\text{H}} \tag{4.10}$$

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where Θ_{H} is the co-efficient of loss for hydrogen storage. The hydrogen storage model constraints are given by eq. (4.11-4.16).

$$H_{2_t}^{\mathrm{stored}} \leq Cap_{\mathrm{H}} \tag{4.11}$$

$$H_{2_t}^{\mathrm{stored}} \geq Cap_{\mathrm{H}}\, \rho_{\mathrm{LOH}}^{\mathrm{min}} \tag{4.12}$$

$$H_{2_t}^{\mathrm{in}} \leq Cap_{\mathrm{H}}\, \varphi_{\mathrm{char}}^{\mathrm{max}} \tag{4.13}$$

$$H_{2_t}^{\mathrm{out}} \leq Cap_{\mathrm{H}}\, \varphi_{\mathrm{dis}}^{\mathrm{max}} \tag{4.14}$$

$$H_{2_t}^{\mathrm{in}} \leq H_{2_t}^{\mathrm{XOR}}\, N \tag{4.15}$$

$$H_{2_t}^{\mathrm{out}} \leq (1 - H_{2_t}^{\mathrm{XOR}})\, N \tag{4.16}$$

where Cap_{H} is the capacity of the hydrogen storage, $\rho_{\mathrm{LOH}}^{\mathrm{min}}$ is the minimum level of hydrogen, $\varphi_{\mathrm{char}}^{\mathrm{max}}$ is the maximum charging rate of the hydrogen storage, $\varphi_{\mathrm{dis}}^{\mathrm{max}}$ is the maximum discharging rate of the hydrogen storage, $H_{2_t}^{\mathrm{XOR}}$ is the binary input for avoiding simultaneous charging and discharging of hydrogen and N is an arbitrary large number.

The hydrogen storage output can be used by the hydrogen fuel station to be supplied to the hydrogen fleet vehicles. $H_{2_t}^{\mathrm{out}}$ can be represented by eq. (4.17).

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$$H_{2_t}^{\text{out}} = H_{2_t}^{\text{fleet}} \tag{4.17}$$

where $H_{2_t}^{\text{fleet}}$ is the hydrogen fuel demand required by the hydrogen fleet.

The electricity provided by the solar PV technology is given by eq. (4.18).

$$E_t^{\text{solar}} = Cap_{\text{PV}}\, PV_t^{\text{performance}} \tag{4.18}$$

where E_t^{solar} is the electricity provided by solar PV technology, Cap_{PV} is the capacity of solar PV technology and $PV_t^{\text{performance}}$ is the normalized solar PV performance at the location.

The wind power is modeled as discrete technology unlike the hydrogen electrolyzer, hydrogen storage and solar PV technologies, which are modeled as continuous technologies. It is due to the fact that wind power units are available in specific unit capacities with specific dimensions commercially, thus it requires to model wind power technology in discrete steps of its unit capacity. Therefore, the optimal wind power capacity is a discrete function of a wind power unit available commercially. The electricity provided by wind power can be represented by eq. (4.19).

$$E_t^{\text{wind}} = Wind_{\text{PQ}}\, Wind_t^{\text{potential}} \tag{4.19}$$

where E_t^{wind} is the electricity provided by the wind power technology, $Wind_{\text{PQ}}$ is the wind power unit purchase quantity and $Wind_t^{\text{potential}}$ is the wind power unit potential.

The higher level energy balance equation for the overall model is given by eq. (4.20).

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$$E_t^{\text{load}} + E_t^{\text{El}} = E_t^{\text{grid}} + E_t^{\text{solar}} + E_t^{\text{wind}} \tag{4.20}$$

where E_t^{load} is the electrical load demand associated with the hydrogen dispensing pumps and E_t^{grid} is the electricity purchased from electric grid.

4.3 Case Study

This section includes the details and the approach of designing the real case study for a small-scale hydrogen filling station as part of extending the existing microgrid testbed in Wieselburg, Austria. It also includes the time series data analysis, the technical and economical details of the technologies, assumptions and the optimization strategy.

4.3.1 Extension of the Microgrid Testbed at Wieselburg

The microgrid testbed at Wieselburg is the first microgrid research lab in Austria that integrates renewable energy, utility electricity, heat technologies, biomass technologies, electro-mobility, storage technologies, building control as well as smart network communication that allows for multiple MILP based model predictive control strategies.

The existing infrastructure at the microgrid testbed mainly consists of solar PV, battery storage, electric vehicle charging station, emergency diesel generator, point of common coupling for utility electricity import/export, biomass boilers, heat storage, absorption cooling and compression cooling technologies distributed in the three main buildings of the site. These technologies are responsible for achieving a balance of sources and loads in the multi-energy system concept (electricity, heating and cooling) of a microgrid. The

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new infrastructure required for the production, storage and use of the hydrogen fuel contains more solar PV, wind power, water electrolyzer, hydrogen seasonal storage tank and hydrogen fuel dispensers with fuel pumps. These technologies are optimized with the optimization framework given in section 4.2. This research work chooses alkaline electrolyzer for the current case study but modeling of PEM electrolyzer is also present in our MILP optimization framework and can also be used as an alternative to alkaline electrolyzer if different case study requires to choose PEM electrolyzer. The existing and optimized additional infrastructure of the microgrid testbed is shown in Figure 4.1. The production mode of the solar PV is DC followed by a DC-to-AC inverter and the production mode of the wind power is AC followed by an AC-to-AC converter. The DC-to-AC inverter efficiency for the solar PV and AC-to-AC converter efficiency for the wind power are already considered in the optimal planning methodology. The transmission mode of the complete electrical power flow is AC. However, the inverter and converter which make the power flow to be AC are not shown in the Figure 4.1, but as already mentioned, the conversion efficiencies are considered in the optimal planning methodology.

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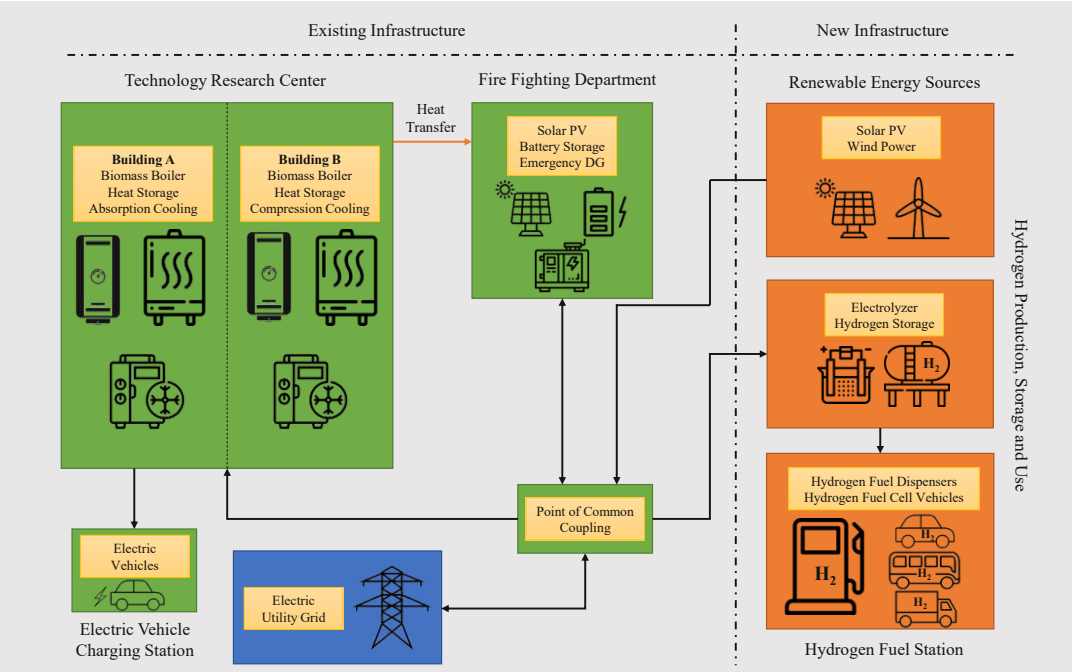

FIGURE 4.1: The extension of the microgrid testbed at Wieselburg, Austria.

4.3.2 Time Series Input Data Analysis and Assumptions

The hydrogen fleet consists of Fuel Cell Electric Vehicles (FCEVs), Fuel Cell Electric Busses (FCEBs) and Fuel Cell Electric Trucks (FCETs). The FCEBs are based on the real schedule of the conventional fuel busses in the region [114]. The FCEVs and the FCETs are based on the average annual mileage of the conventional fuel passenger cars and trucks in the region [115]. The FCETs are further divided into three sub groups based on the distance covered as small, medium and large FCETs. The corresponding single trip distance radius showing the reach of the hydrogen fleet is shown in Figure 4.2.

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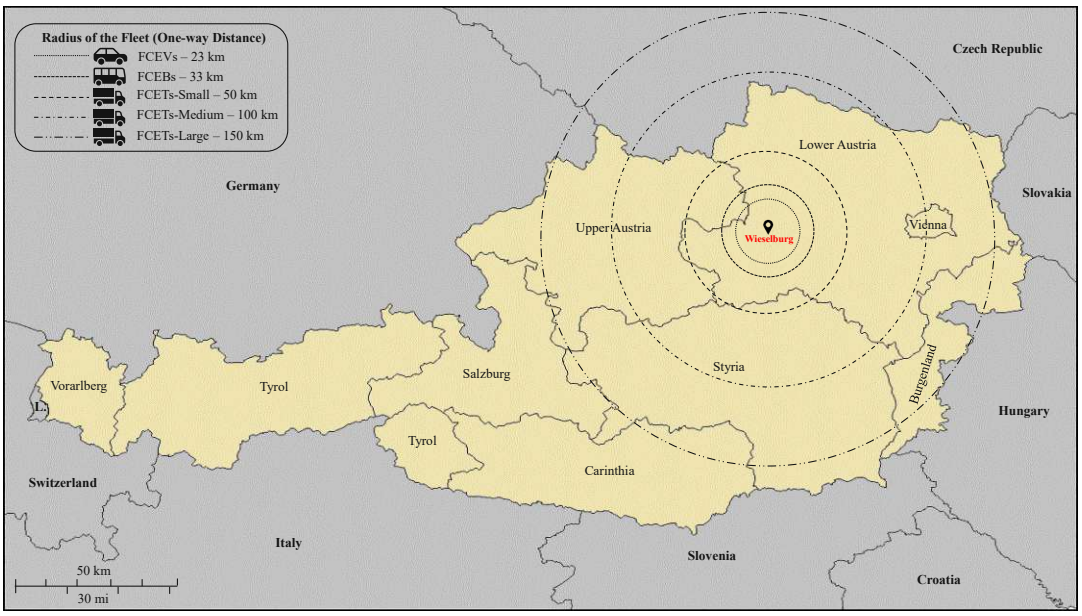

FIGURE 4.2: The reach of the entire hydrogen fleet for the case study.

The fleet covers most of the major cities in the center of Austria for transporting the goods via FCETs while the regional passenger transport demand of lower Austria is satisfied by the FCEVs and FCEBs. The design parameters of the already available hydrogen FCEVs [116], FCEBs [117] and FCETs [118] in the European market are given in Table 4.1.

Fleet	Fuel	Output [kW]	Consumption [kgH_2/100 km]	Max. Tank Capacity [kg]	Max. Range [km]	Average Speed [km/h]	Approx. Unit Cost [€]	Manufacturer
FCEV	Hydrogen (700 bar)	114	0.76	5	500	100	78,600	TOYOTA
FCEB	Hydrogen (350 bar)	180	6	37.5	400	40	620,000	CAETANOBUS
FCET	Hydrogen (350 bar)	250	8	31	400	70	302,000-334,000	ESORO

TABLE 4.1: The design parameters of the entire hydrogen fleet [116, 117, 118].

The trip distance and the weekly frequency for the FCEBs is according to the real weekly schedules of the busses in the Wieselburg region. The trip distance and the weekly frequency of the FCEVs and FCETs is taken as assumption so that the annual average mileage per vehicle remains in the range of the actual annual average mileage. The trip distance and the weekly fueling frequency of the entire hydrogen fleet are given in the Table 4.2. The hourly schedules of the week and weekend days for FCEBs are adopted according to

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the real schedule of the busses. The hourly schedules of the week and weekend days for FCEVs and FCETs are taken as assumption by not violating the annual average mileage limit. The hourly schedules for FCEVs, FCEBs and FCETs are multiplied with the respective round trip distance to obtain the total annual distance demand of the hydrogen fleet. The percentage share of the total annual distance demand by each fleet type is such that FCEVs, FCEBs and FCETs constitute 7%, 31% and 62% of the total annual distance demand respectively.

Fleet Type	Fleet Details	Single Trip [km]	Round Trip [km]	Fueling Frequency Mon	Tue	Wed	Thu	Fri	Sat	Sun
FCEVs	Passenger Cars	23	46	8	8	8	8	8	4	0
FCEBs	Wieselburg-Petzenkirchen-Ybbs/Donau (Route-5)	7.3	14.6	12	12	12	12	12	0	0
	Wieselburg-Gresten (Route-667)	25.5	51	10	10	10	10	10	5	0
	Wieselburg-Erlauf-Poechlarn (Route-670)	14.5	29	3	3	3	3	3	0	0
	Wieselburg-Gumprechtsfelden (Route-674)	5.3	10.6	6	6	6	6	6	0	0
	Wieselburg-St Georgen/Leys (Route-675)	20	40	7	7	7	7	7	0	0
	Wieselburg-Ruprechtshofen-Kilb (Route-685)	33	66	8	8	8	8	8	0	0
FCETs	Small Distance Trucks	50	100	3	3	3	3	3	0	0
	Medium Distance Trucks	100	200	5	5	5	5	5	0	0
	Large Distance Trucks	150	300	7	7	7	7	7	0	0

TABLE 4.2: The trip distance and the weekly fueling frequency of the entire hydrogen fleet.

The hydrogen fuel consumption is obtained by multiplying the mileage consumption in kgH_2/km as given in Table 4.1 with the distance demand for each fleet type. This is done in accordance with not violating the maximum tank capacity and maximum range of each fleet type. The hourly hydrogen demand of the entire hydrogen fleet on working and weekend days is shown in Figure 4.3. This hydrogen fuel consumption in kgH_2 is then converted into hydrogen energy demand in kWh (1 kgH_2 is equivalent to 33.33 kWh of energy content [119]) and is treated as the final hydrogen energy demand for the optimization problem. Together with the hydrogen fuel, it is also important to consider the electric consumption of the hydrogen fuel pumps required for dispensing the fuel. This electric consumption is considered as 1.1 kWh per kgH_2 dispensed as given in [120]. The yearly profiles of the hydrogen energy demand in kWh and the electric energy consumption of hydrogen dispensing pumps in kWh are constructed by extrapolating the respective hourly

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demand profiles of the week and weekend days. The maximum energy demand in an hour for the hydrogen fuel and hydrogen dispensing pumps is around 2034 kWh and 67 kWh respectively in the whole year.

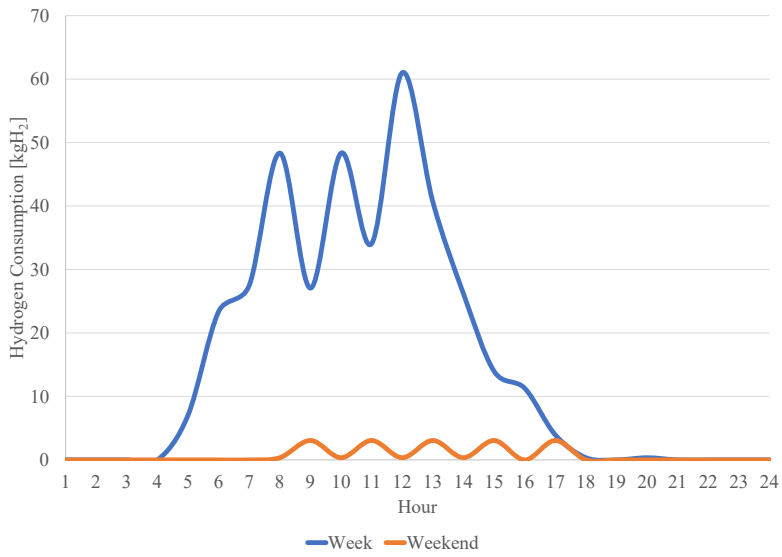

FIGURE 4.3: The hourly hydrogen demand of the entire fleet.

The required time series input data also includes the hourly solar PV performance and the wind power potential at the site. As discussed in the section 4.2 that the wind power is modeled as a discrete technology so it is required to select a wind power unit with a specific power output and hourly wind potential profile. After conducting a preliminary analysis by taking into account the location constraints of the microgrid lab, the Enercon E48 800 Model [121] has been selected for this case study as the wind power unit in the optimization. The technological and economical parameters of the solar PV and wind power unit are addressed in sub-section 4.3.3. The solar PV performance is retrieved from the Meteonorm [110] while the wind power potential is retrieved from the Renewable Ninja [122] for the same Enercon E48 800 Model with hourly time horizon. These data are shown in Figure 4.4 and Figure 4.5 for solar PV and wind power respectively.

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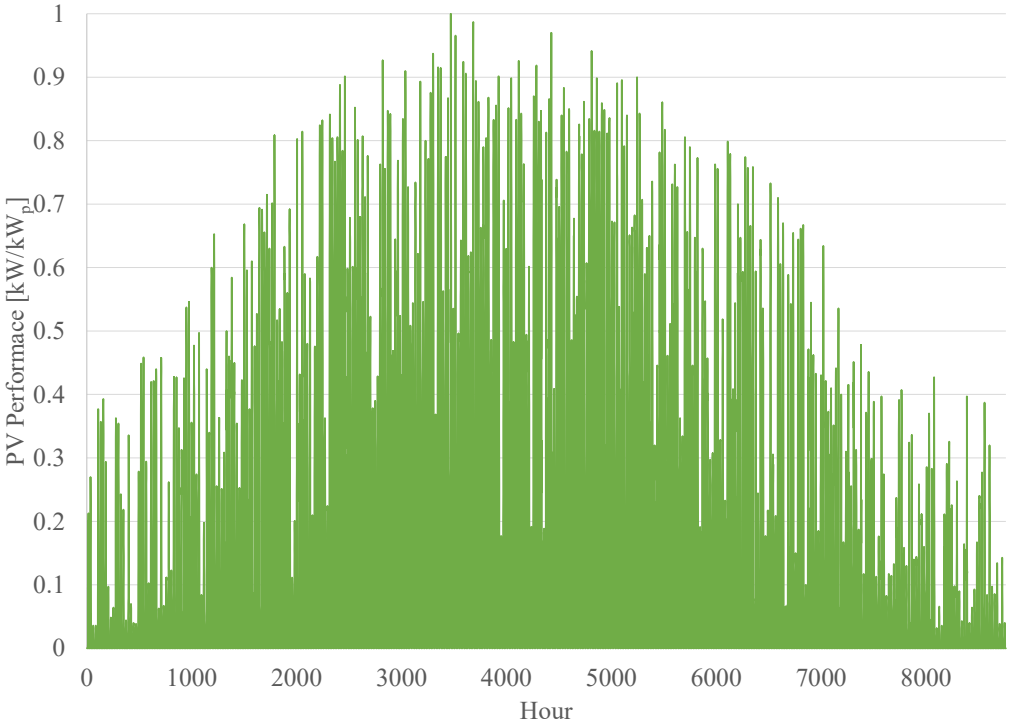

FIGURE 4.4: The solar PV performance on hourly basis at Wieselburg site [110].

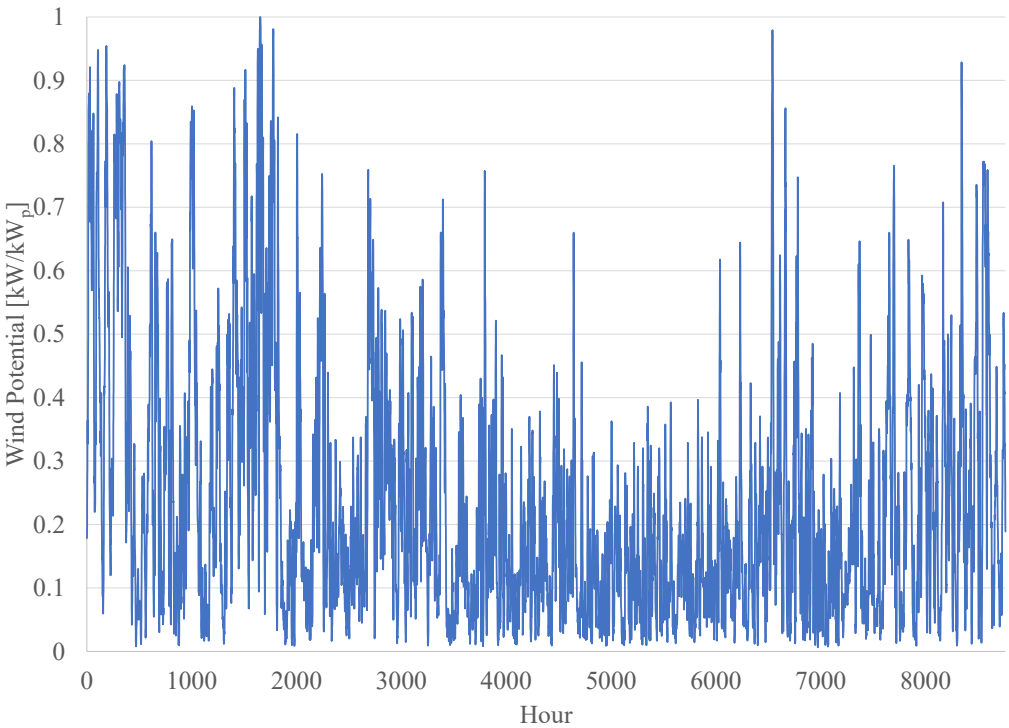

FIGURE 4.5: The wind power potential on hourly basis at Wieselburg site [122].

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4.3.3 Techno-Economical Parameters

The economical parameters for the solar PV, wind power, alkaline electrolyzer and hydrogen storage tank include the investment parameters like fixed capital costs, variable capital costs, operation & maintenance costs and lifetime. These parameters are given in Table 4.3 [70, 123, 124, 125]. In the Table 4.3, the fixed costs represent the fixed capital expenditure (Fixed CAPEX), the variable costs represent the variable capital expenditure (Variable CAPEX) and the operation & maintenance costs represent the operation expenditure (OPEX) of the technologies. The variable capital costs vary with the amount of capacity that is invested, while the fixed capital costs are independent on the size of the technology and can cover engineering costs. The fixed capital costs of the considered technologies are zero as per the cited sources [70, 123, 124, 125] because these costs are almost negligible as compared to the variable capacity investment costs of the technologies. The additional equipment such as inverter, converter, control and monitoring devices are considered in the optimal planning of this case study through the costs (CAPEX and OPEX) associated with the main technologies as well as their efficiencies and conversion curves where needed. The interest rate is considered as 3% which is needed for the calculation of the annuity rate for each technology. The electricity rate for the microgrid in Wieselburg is 11.5 cents€/kWh and is constant for the entire year. There are no monthly or daily demand rates currently enforced by the utility grid side in the region so these are not considered in this study for the purchase of utility electricity.

Technology	**Fixed Capital Costs (Fixed CAPEX)** [€]	**Variable Capital Costs (Variable CAPEX)** [€/kW or kWh]	**O&M Costs (OPEX)** [€/kW or kWh] per year	**Lifetime** [Years]
Solar PV	0	842	9	25
Wind Power	0	1,247	48	15
Alkaline Electrolyzer	0	920	19	25
Hydrogen Storage	0	14	0	30

TABLE 4.3: The economic parameters of the microgrid technologies [70, 123, 124, 125].

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The technical parameters for the alkaline electrolyzer and hydrogen storage include the efficiency of the electrolyzer, the efficiency of the pressurizer, the maximum charge and discharge rates of the hydrogen storage and the decay/losses in the hydrogen storage tank. The efficiency of the pressurizer for compressing the output of the electrolyzer to 350 bar and 700 bar is assumed to be the same. These parameters are given in Table 4.4 [70, 126, 127].

Parameter	**Value**
Efficiency of Electrolyzer [%]	70
Efficiency of Pressurizer [%]	90
Minimum Level of Hydrogen [%]	0
Maximum Charge Rate [%]	100
Maximum Discharge Rate [%]	100
Losses in Hydrogen Storage [% per hour]	0.04

TABLE 4.4: The technical parameters of the the microgrid technologies [70, 126, 127].

To assess the CO_2 emissions correctly, the CO_2 content of the purchased utility electricity also needs to be considered. The marginal CO_2 emissions rate in kg/kWh of the utility electricity purchased is considered in this study and and is shown in Figure 4.6 [128] on hourly basis for the whole year. The marginal CO_2 emissions rate is based on the Austrian-mix and import-mix electricity sources. The marginal CO_2 emissions only consider the direct emissions of the fuel while generating the electricity and do not include the indirect emissions related to the fuel production and transportation.

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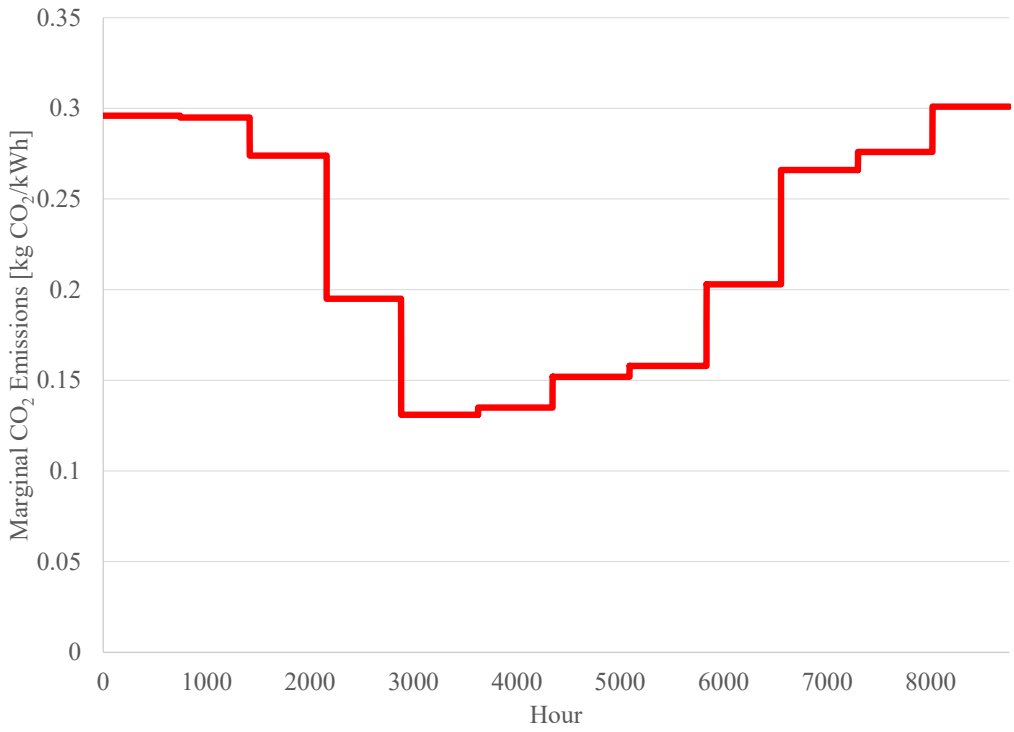

FIGURE 4.6: The hourly marginal CO_2 emissions of the utility electricity [128].

4.3.4 Optimization Framework and Strategy

The case study considers two reference cases *i.e.* the diesel basecase and the utility basecase. The diesel basecase satisfies the mobility demand by the diesel fuel. The total annual energy costs and the total annual CO_2 emissions are calculated using the Well-to-Wheel (WTW) carbon emissions, fuel mileage and WTW fuel costs given in Table 4.5 [129, 130].

Fleet Type	WTW Carbon Emissions [$kgCO_2$/km]	Fuel Mileage [litre/100 km]	WTW Fuel Costs [€/litre]	Annual Equivalent Distance of Fleet [km]
Passenger Cars	0.2445	7	1.22	105,248
Busses	1.0425	33	1.22	440,648
Trucks	0.5972	19.6	1.22	884,000

TABLE 4.5: The design parameters for the calculation of the total annual energy costs and the total annual CO_2 emissions for the diesel basecase [129, 130].

The utility basecase satisfies the mobility demand by only considering the electricity purchase from the grid using the technical and economical parameters reported in sub-section 4.3.3. In the utility basecase, the hydrogen is

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produced through electrolysis, stored and used to satisfy the mobility demand. For the utility basecase, the total annual energy costs and the total annual CO_2 emissions are calculated through the cost minimization of the optimization model. Therefore, the annual energy costs for the utility basecase include the investment costs related to the electrolyzer and hydrogen storage together with the electricity purchase costs. The annual CO_2 emissions for the utility basecase include the total marginal carbon emissions of the electricity purchase from the utility.

After setting up the reference cases, the investment optimization is performed relative to each reference case through sensitivity analyses. In each optimization scenario of the investment case, the total annual CO_2 emissions are minimized by keeping the limit on the total annual energy costs given by the cost constraint parameter γ. The results include the optimal sizing and the full-year operational dispatch of the technologies. The results also include the comparisons with the reference cases in terms of the CO_2 savings, the total annual energy costs, the total annual carbon dioxide emissions, H_2-Diesel cost gap and carbon prices to close that H_2-Diesel cost gap. The optimization framework and strategy is shown in Figure 4.7. The optimality gap of the optimization solver was set to 0.2% for all scenarios. The MILP optimization was performed on a server with a Common KVM processor CPU 3.7 GHz and 224 GB of RAM.

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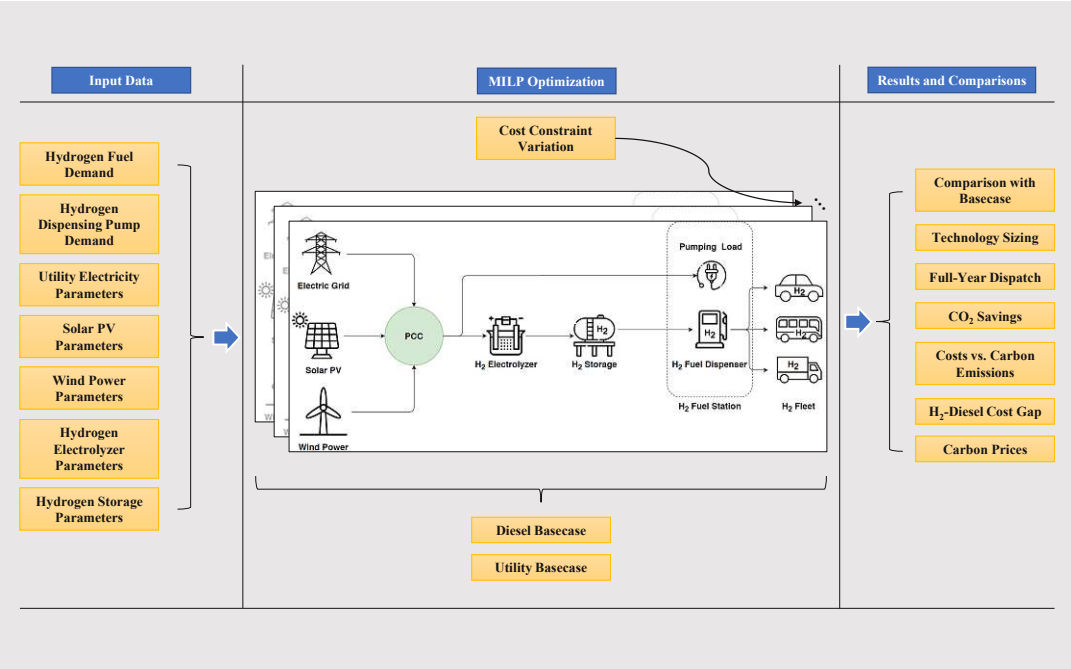

FIGURE 4.7: Overview of the optimization framework and strategy.

4.4 Results

This section provides the results of the reference cases and the corresponding investment optimization scenarios based on the variation in the cost constraint. The variation in the cost constraint is introduced by changing the γ parameter in the steps of $\pm 10\%$ and $\pm 25\%$ for the costs of each reference case. The plus sign indicates a percentage increase in the reference costs and negative sign indicates a percentage decrease in the reference costs. The total annual energy costs and the total annual CO_2 emissions of the diesel basecase and the utility basecase are given in Table 4.6. For the diesel basecase, these are calculated based on Table 4.5 given in sub-section 4.3.4 and for the utility basecase, these are calculated through minimization of the cost objective function.

The utility basecase has 65% higher total annual energy costs and 17% higher total annual carbon dioxide emissions as compared to the diesel basecase.

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Reference Case	Total Annual Energy Costs [k€]	Total Annual CO_2 Emissions [tonne-CO_2]
Diesel Basecase	397.78	1,013.03
Utility Basecase	656.10	1,181.64

TABLE 4.6: The total annual energy costs and the total annual CO_2 emissions of the reference cases.

Therefore, the diesel basecase is much cheaper and generate less CO_2 emissions than that of the utility electricity-based hydrogen. The results of the investment optimization scenarios are provided in the next sub-sections for each of the reference case.

4.4.1 Sensitivity Analysis for the Diesel Basecase

The investment optimization scenarios compared to the diesel basecase are infeasible for all the negative cost constraint variations and also for the positive cost constraint variations of +10%, +20% and +25%. The investment optimization becomes feasible for the cost constraint variation greater than or equal to +30%. Thus, an optimization solution is not possible unless the costs are increased at least 30% relative to the diesel basecase costs. The total annual energy costs and the total annual CO_2 emissions of the investment optimization scenarios compared to the diesel basecase are shown in Figure 4.8. The CO_2 savings of the investment optimization scenarios compared to the diesel basecase are shown in Figure 4.9.

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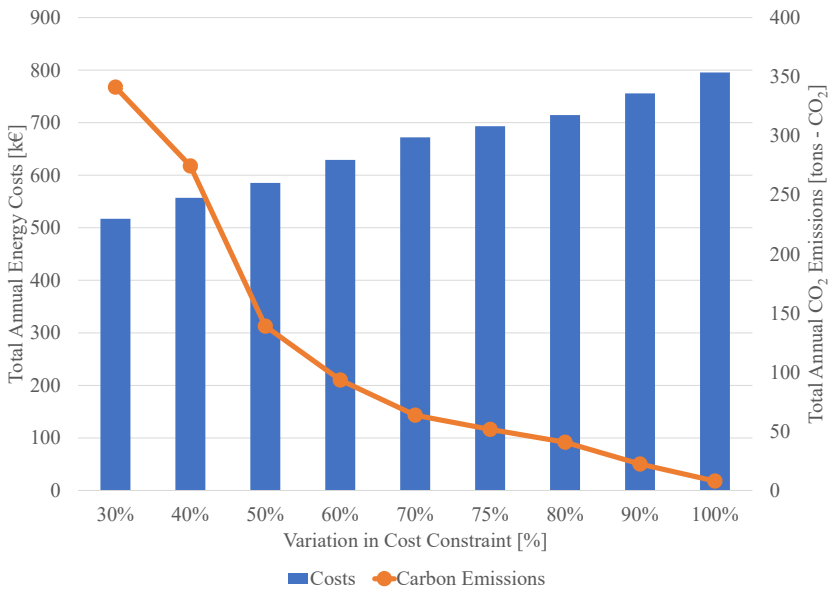

FIGURE 4.8: The total annual energy costs and the total annual CO_2 emissions of the investment optimization scenarios compared to the diesel basecase.

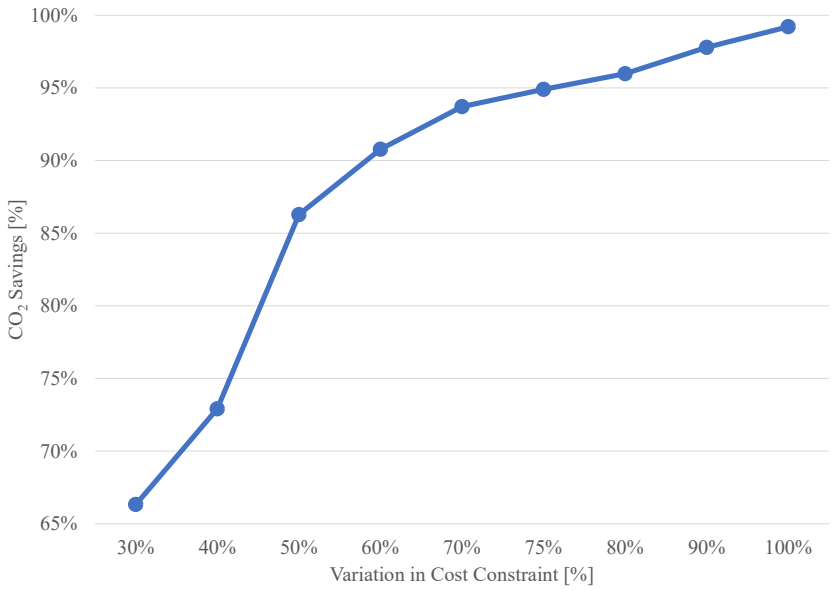

FIGURE 4.9: The CO_2 savings of the investment optimization scenarios compared to the diesel basecase.

These results show that with 30% more annual energy costs, the CO_2 emissions are reduced by 66.32%. As the cost constraint is relaxed further, the CO_2 emissions are drastically reduced by 86.28% at 50% more annual energy costs and then slowly reduced when reaching more than 90% CO_2 savings. The

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maximum CO_2 savings of almost 100% are achieved at twice the costs of the diesel basecase. The optimal capacity decisions for the solar PV, wind power, hydrogen electrolyzer and hydrogen seasonal storage are given in Table 4.7 together with the total annual energy costs, the total annual CO_2 emissions and the CO_2 savings for the investment optimization scenarios compared to the diesel basecase. The capacities are increasing with the increasing investment costs and also the CO_2 savings are increasing with larger capacities of the technologies. The evident increase in the investment of the technologies ultimately increases the on-site production of the renewable energy and the seasonal hydrogen storage.

γ [%]	Solar PV [kW]	Wind Power [kW]	Electrolyzer [kW]	Hydrogen Storage [kWh]	Total Annual Energy Costs [k€]	Total Annual CO_2 Emissions [tonne-CO_2]	CO_2 Savings [%]
−10%	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
0%	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
+10%	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
+20%	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
+25%	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
+30%	1,876	800	1,524	40,890	517.11	341.16	66.32%
+40%	2,207	800	1,734	97,556	556.89	274.47	72.91%
+50%	1,330	1,600	1,638	115,093	585.43	138.99	86.28%
+60%	1,643	1,600	1,814	169,001	629.14	93.41	90.78%
+70%	1,882	1,600	1,948	215,763	672.00	63.67	93.71%
+75%	1,983	1,600	2,005	238,742	693.24	51.69	94.90%
+80%	2,081	1,600	2,060	261,432	714.43	40.76	95.98%
+90%	2,265	1,600	2,164	304,729	755.77	22.36	97.79%
+100%	2,421	1,600	2,251	347,141	795.55	7.99	99.21%

TABLE 4.7: The capacity decisions together with the total annual energy costs, the total annual CO_2 emissions and the CO_2 savings for the investment optimization scenarios compared to the diesel basecase.

The optimal costs of the hydrogen fuel consumption (€/kgH_2) and the hydrogen energy (€/kWh) are shown in Figure 4.10 and Figure 4.11 respectively. The hydrogen fuel consumption costs in Figure 4.10 are compared with the current market costs of the hydrogen fuel in Austria (9 €/kgH_2 [131]). The current market costs of the hydrogen fuel are mainly based on the centralized hydrogen production via fossil fuels. The hydrogen energy costs in Figure 4.11 are compared with the current market costs of the diesel fuel energy in Austria (0.12 €/kWh [130]).

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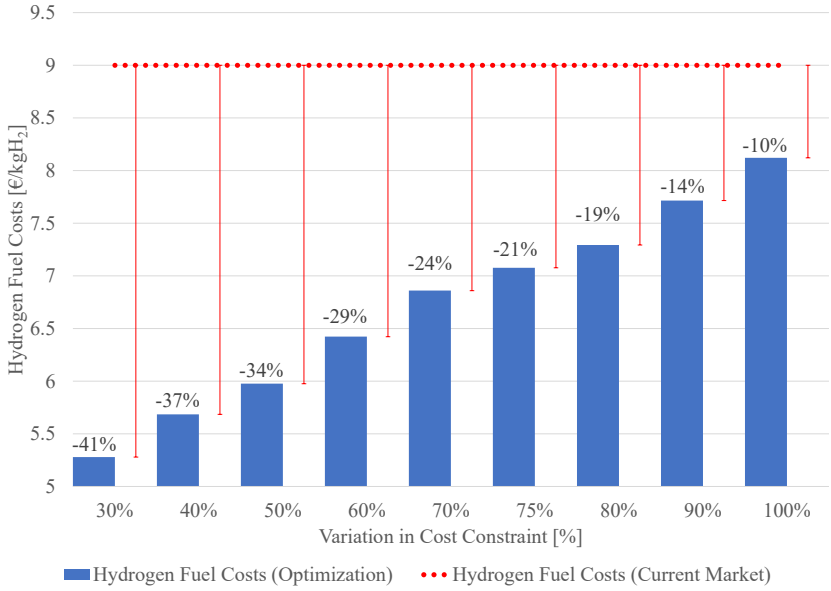

FIGURE 4.10: Hydrogen fuel consumption with the current market costs of hydrogen (red dotted lines) in Austria for the investment optimization scenarios as compared to the diesel basecase.

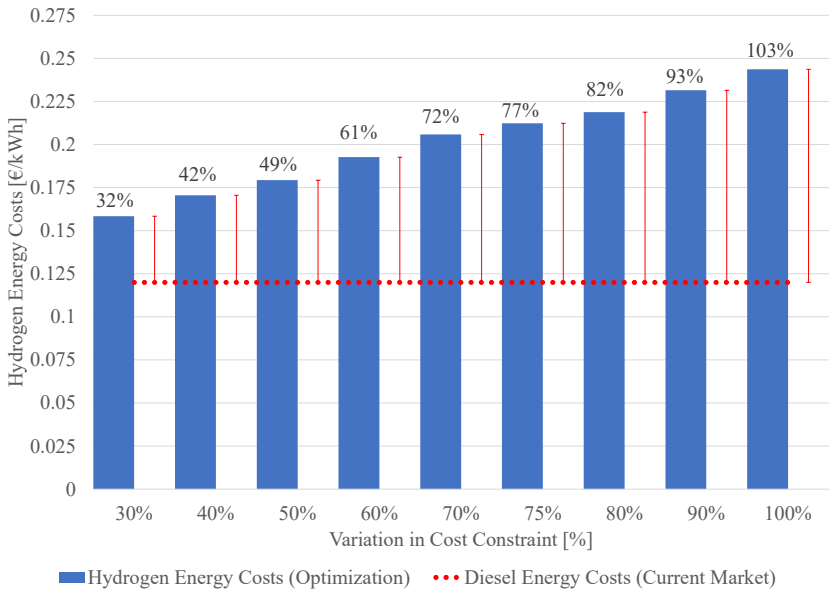

FIGURE 4.11: Hydrogen energy costs with the current market costs of diesel fuel (red dotted lines) in Austria for the investment optimization scenarios as compared to the diesel basecase.

Figure 4.10 shows that the optimized hydrogen fuel costs can be 41% lower as

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compared to the current market costs of the hydrogen fuel. As the cost constraint is relaxed further, the gap between the optimal hydrogen fuel costs and the market costs of the hydrogen fuel is decreased. This gap is just 10% when the total annual energy costs of the optimization are double as compared to the reference costs of the diesel basecase, but still lower than the current hydrogen costs.

On the other hand, Figure 4.11 shows that the optimized hydrogen energy costs are always higher than the current market costs of the diesel fuel in all investment optimization scenarios. The optimized hydrogen energy costs are at least 32% higher as compared to the market costs of the diesel fuel. The difference between the optimized hydrogen energy costs and the market costs of the diesel fuel increases as the cost constraint is relaxed further. The optimized hydrogen energy costs are slightly more than double as compared to the market costs of the diesel fuel when the total annual energy costs of the optimization are increased by 100% as compared to the reference costs of the diesel basecase.

Even though the optimal costs of the hydrogen fuel consumption are lower than the current hydrogen fuel costs in all investment scenarios, the optimal hydrogen energy costs are always higher than the current diesel energy costs. These costs would be much larger if the hydrogen production and storage are not considered close to the point of delivery of the fuel due to the transportation and other delivery related costs of the system. This shows the benefit of using renewable energy based microgrids and distributed hydrogen energy systems over the conventional fossil fuel based centralized hydrogen energy systems. The difference between the optimal hydrogen energy costs and the current diesel energy costs can be compensated by introducing carbon prices, subsidies and cheaper costs of the solar PV, wind power, hydrogen electrolyzer and hydrogen storage technologies. The introduction of the

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carbon price as an emission tax for the diesel fuel is considered in this study to close the H_2-Diesel cost gap shown in the Figure 4.11. The carbon price increases the diesel fuel costs and reduces the current difference of the costs between hydrogen fuel and diesel fuel. This can enable the transition of shifting the high energy costs of the hydrogen fuel to the same energy costs as the diesel fuel but with a system that can decarbonize the mobility sector. The sub-section 4.4.3 provides further details on how the H_2-Diesel cost gap can be closed by the introduction of carbon prices.

The detailed dispatch graphs of the hydrogen storage together with the monthly energy shares of the solar PV, wind power and utility electricity are shown in Figure 4.12 for the investment optimization scenarios compared to the diesel basecase. Figure 4.12 shows that as the variation in the cost constraint parameter increases from +30% to +100%, the share of the renewable energy sources increases because of the increase in the investment decisions and also the size of the hydrogen seasonal storage increases. Thus, making it desirable for catching the seasonality of the solar PV and wind power technologies. This seasonal behaviour of the hydrogen storage is evident from its dispatch throughout the year. The corresponding share of the utility electricity decreases and the CO_2 savings increase.

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FIGURE 4.12: Detailed dispatch graphs of the investment optimization scenarios as compared to the diesel basecase.

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4.4.2 Sensitivity Analysis for the Utility Basecase

The investment optimization scenarios compared to the utility basecase can be considered as a subset of the diesel basecase optimization scenarios because the utility basecase costs are higher than that of the diesel basecase costs. Therefore, the variation in the cost constraint parameter can be considered in both positive and negative directions. The optimization scenarios for the negative cost constraint variations are feasible until the utility basecase costs are lowered by more than 20% and the investments are infeasible below that point. The total annual energy costs and the total annual CO_2 emissions of the investment optimization scenarios compared to the utility basecase are shown in Figure 4.13. The CO_2 savings of the investment optimization scenarios compared to the utility basecase are shown in Figure 4.14. The optimal capacity decisions for the solar PV, wind power, hydrogen electrolyzer and hydrogen storage are reported in Table 4.8 together with the total annual energy costs, the total annual CO_2 emissions and the CO_2 savings for the investment optimization scenarios compared to the utility basecase.

γ [%]	Solar PV [kW]	Wind Power [kW]	Electrolyzer [kW]	Hydrogen Storage [kWh]	Total Annual Energy Costs [k€]	Total Annual CO_2 Emissions [tonne-CO_2]	CO_2 Savings [%]
−25%	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
−20%	2,002	800	1,604	54,363	524.88	312.77	73.53%
−10%	2,371	800	1,838	140,485	590.49	245.56	79.22%
0%	1,765	1,600	1,882	192,823	650.37	78.09	93.39%
+10%	2,108	1,600	2,075	267,884	720.52	37.79	96.80%
+20%	2,389	1,600	2,233	338,458	787.32	10.85	99.08%
+25%	2,514	1,600	2,304	372,972	820.13	0.23	99.98%

TABLE 4.8: The capacity decisions together with the total annual energy costs, the total annual CO_2 emissions and the CO_2 savings for the investment optimization scenarios compared to the utility basecase.

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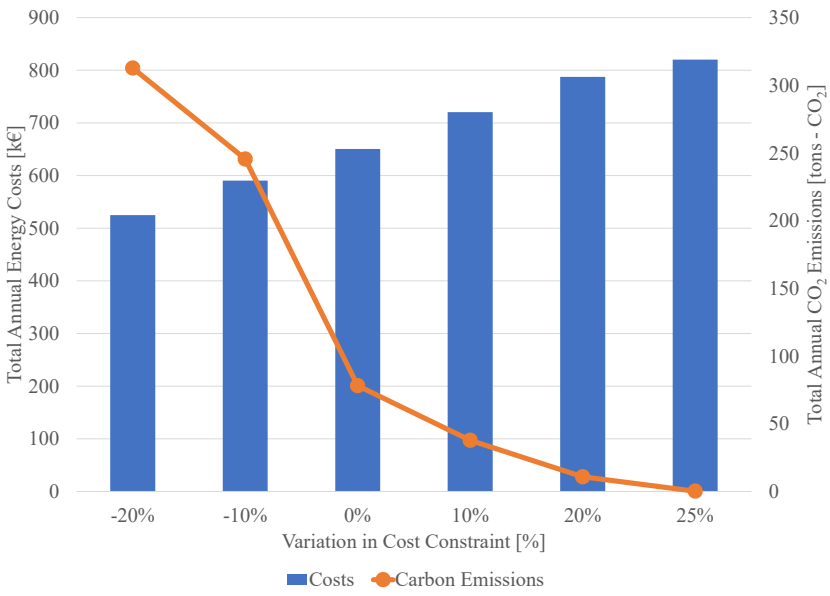

FIGURE 4.13: The total annual energy costs and the total annual CO_2 emissions of the investment optimization scenarios compared to the utility basecase.

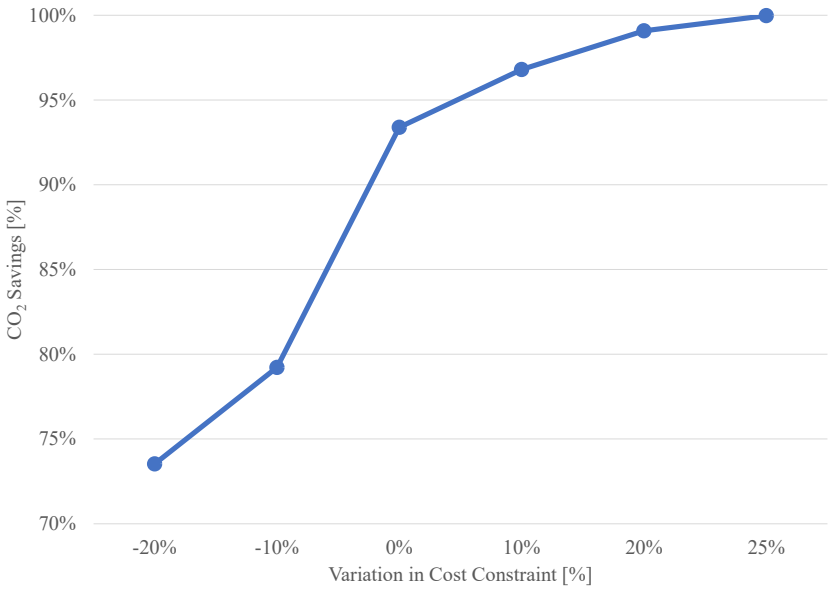

FIGURE 4.14: The CO_2 savings of the investment optimization scenarios compared to the utility basecase.

Without any further relaxation or limitation in the reference costs of the utility basecase (0% point in Table 4.8), the investment decisions consider the renewable energy sources which significantly reduce the share of the utility electricity and achieve the CO_2 savings of around 94%. Before touching the

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infeasibility boundary, the investment decisions still provide around 74% of the CO_2 savings at 20% lower annual energy costs relative to the utility basecase costs. This use case validates that at least 74% decarbonization of the mobility sector can be achieved by microgrids at costs lower than that of the utility electricity based hydrogen energy systems which do not consider microgrids. The results also show that with just 25% more annual energy costs than the utility basecase costs, a 100% decarbonization of the mobility sector is possible by the renewable energy based microgrid solution.

The optimal costs of the hydrogen fuel consumption (€/kgH_2) and the hydrogen energy (€/kWh) are shown in Figure 4.15 and Figure 4.16 respectively. In this sensitivity analysis, the results of the hydrogen fuel costs and hydrogen energy costs show the similar behavior to the sensitivity analysis for the diesel basecase. Also in this case, carbon prices, subsidies and cheaper costs of the technologies are required to make the hydrogen energy costs competitive with the current market costs of the diesel fuel. The subsection 4.4.3 provides further details to close the H_2-Diesel cost gap shown in the Figure 4.16 by the introduction of carbon prices.

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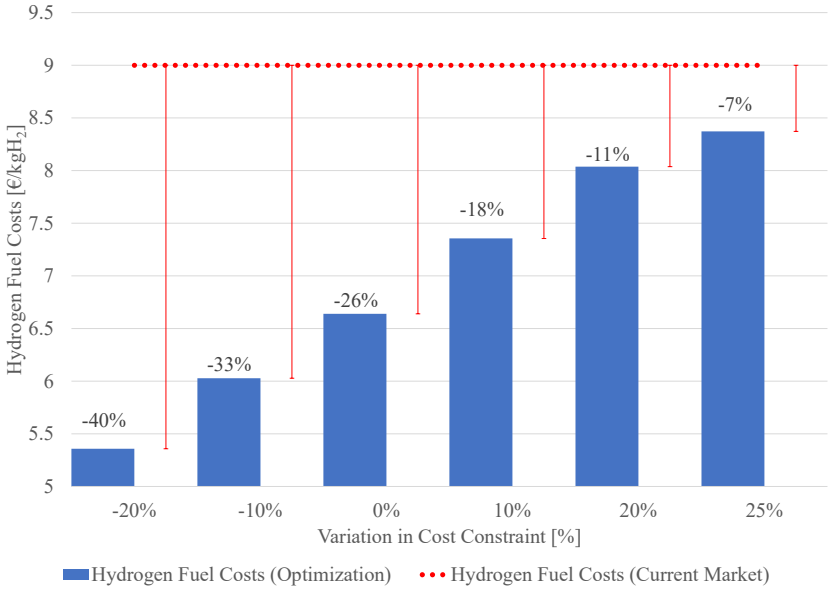

FIGURE 4.15: Hydrogen fuel consumption with the current market costs of hydrogen (red dotted lines) in Austria for the investment optimization scenarios as compared to the utility basecase.

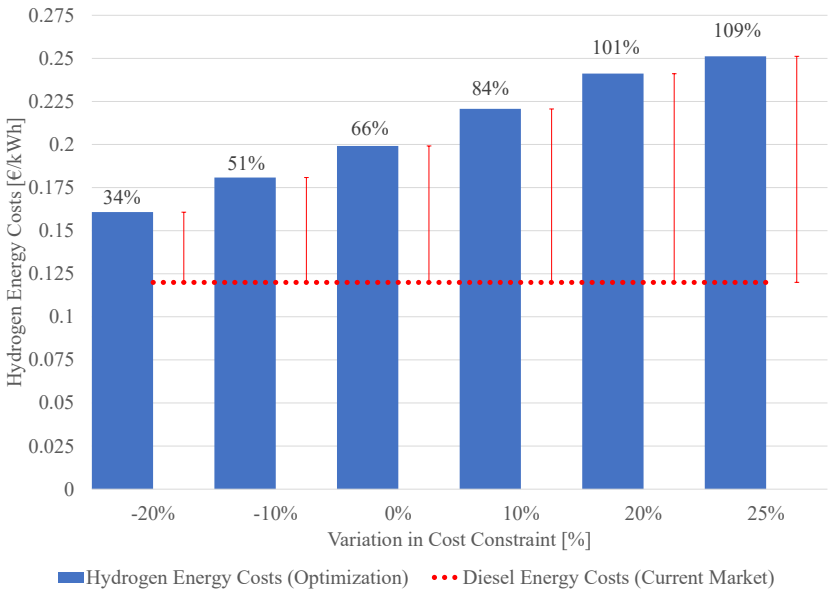

FIGURE 4.16: Hydrogen energy costs with the current market costs of diesel fuel (red dotted lines) in Austria for the investment optimization scenarios as compared to the utility basecase.

The detailed dispatch graphs of the hydrogen storage together with the monthly energy shares of the solar PV, wind power and utility electricity are shown in

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Figure 4.17 for the investment optimization scenarios compared to the utility basecase. Figure 4.17 shows that the seasonal behavior of the hydrogen storage becomes evident as the share of the renewable energy sources increases.

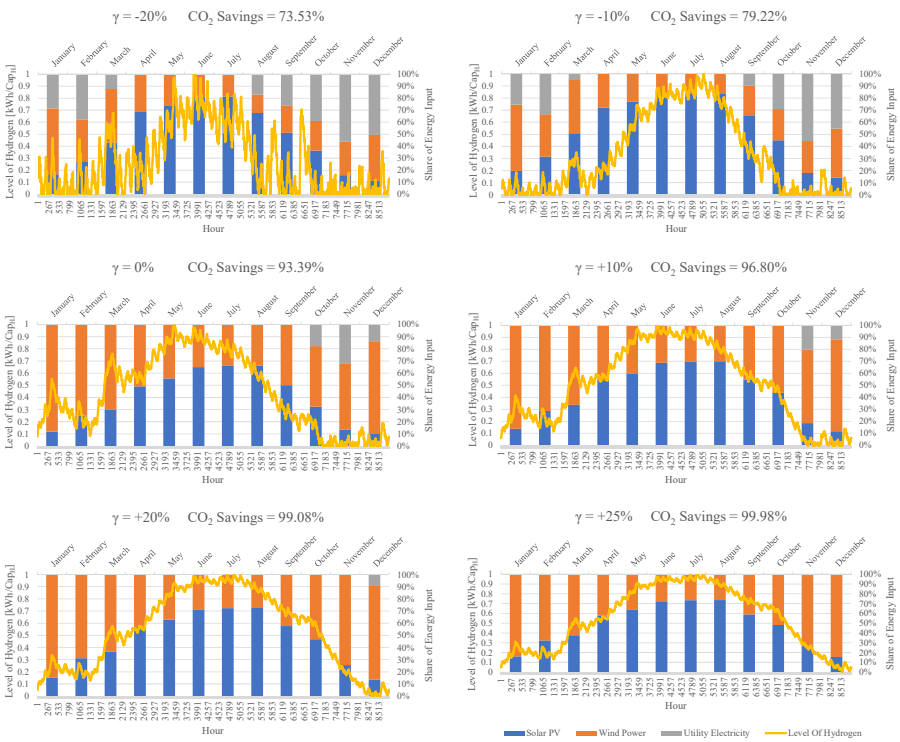

FIGURE 4.17: Detailed dispatch graphs of the investment optimization scenarios as compared to the utility basecase.

4.4.3 Carbon Prices to close the H_2-Diesel Cost Gap

This sub-section provides a detailed methodology and results of the carbon prices that can vary the diesel fuel costs and close the H_2-Diesel cost gap. By using the design parameters given in Table 4.5, the carbon emissions per unit diesel fuel consumption (kg-CO_2/litre) and the diesel fuel demand share (%) for each fleet type are calculated and are given in Table 4.9.

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Fleet Type	Carbon Emissions [kg-CO_2/litre]	Fuel Demand Share (FDS) [%]
Passenger Cars	3.49	7%
Busses	3.16	31%
Trucks	3.05	62%

TABLE 4.9: The carbon emissions per unit diesel fuel consumption and fuel demand share for each fleet type.

The H_2-Diesel cost gap is shown in Figure 4.11 and Figure 4.16 for each investment optimization scenario in €/kWh. This H_2-Diesel cost gap is converted into €/litre for diesel fuel. The H_2-Diesel cost gap is given cumulatively for all the fleet types by each investment optimization scenario. Therefore, it is necessary to take into account the carbon emissions and the fuel demand share of each fleet type given in Table 4.9 to calculate the carbon price (€/kg-CO_2) in each investment optimization scenario by using eq. (4.21).

$$CarbonPrice_{\gamma} = \frac{H_2DieselCostGap_{\gamma}}{(CO_{2\text{cars}}\,FDS_{\text{cars}}) + (CO_{2\text{busses}}\,FDS_{\text{busses}}) + (CO_{2\text{trucks}}\,FDS_{\text{trucks}})} \tag{4.21}$$

The resulting carbon prices for all the investment optimization scenarios relative to the diesel basecase and utility basecase are given in Table 4.10 and Table 4.11 respectively.

As the cost constraint parameter is relaxed, the H_2-Diesel cost gap is increasing and the resulting carbon price is also increasing. With a CO_2 saving of around 66%, the carbon price on the diesel fuel is estimated to be around 124 €/tonne-CO_2 to close the H_2-Diesel cost gap. These results show that the carbon price is estimated to be more than 400 €/tonne-CO_2 to make the hydrogen costs competitive with the diesel costs and achieve almost 100% CO_2 savings.

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γ [%]	H_2-Diesel Cost Gap [€/kWh]	[€/litre]	Carbon Price [€/kg-CO_2]	[€/tonne-CO_2]	CO_2 Savings [%]
+30%	0.0384	0.384	0.1233	123.3	66.32%
+40%	0.0506	0.506	0.1624	162.4	72.91%
+50%	0.0593	0.593	0.1905	190.5	86.28%
+60%	0.0727	0.727	0.2335	233.5	90.78%
+70%	0.0858	0.858	0.2757	275.7	93.71%
+75%	0.0923	0.923	0.2966	296.6	94.90%
+80%	0.0988	0.988	0.3174	317.4	95.98%
+90%	0.1115	1.115	0.3581	358.1	97.79%
+100%	0.1237	1.237	0.3973	397.3	99.21%

TABLE 4.10: Carbon prices to close the H_2-Diesel cost gap for the investment optimization scenarios compared to the diesel basecase.

γ [%]	H_2-Diesel Cost Gap [€/kWh]	[€/litre]	Carbon Price [€/kg-CO_2]	[€/tonne-CO_2]	CO_2 Savings [%]
−20%	0.0408	0.408	0.1309	130.9	73.53%
−10%	0.0609	0.609	0.1955	195.5	79.22%
0%	0.0792	0.792	0.2544	254.4	93.39%
+10%	0.1007	1.007	0.3234	323.4	96.80%
+20%	0.1211	1.211	0.3892	389.2	99.08%
+25%	0.1312	1.312	0.4214	421.4	99.98%

TABLE 4.11: Carbon prices to close the H_2-Diesel cost gap for the investment optimization scenarios compared to the utility basecase.

4.5 Resume

This chapter investigates the optimal planning of microgrids including the hydrogen energy system through mixed-integer linear programming model. A real case study is analyzed by extending the only microgrid lab facility in Austria. The case study considers the hydrogen production via electrolysis, seasonal storage and fueling station for meeting the hydrogen fuel demand of fuel cell vehicles, busses and trucks. The optimization is performed relative to two different reference cases which satisfy the mobility demand by diesel fuel and utility electricity based hydrogen fuel production respectively. The key results indicate that the low emission hydrogen mobility framework

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is achieved by high share of renewable energy sources and seasonal hydrogen storage in the microgrid. The investment optimization scenarios provide at least 66% and at most 99% carbon emission savings at increased costs of 30% and 100% respectively relative to the costs of the diesel reference case.

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Chapter 5

Mixed-Integer Linear Programming based Optimization Strategies for Renewable Energy Communities

5.1 Introduction

This chapter aims to assess, investigate and solve the Research Question 3. A renewable energy community is modeled using mixed-integer linear programming methodology for contributing towards the clean energy transition set by the Clean Energy Package (CEP) of the European Commission. The behavior of the renewable energy community based mechanism is quantified in terms of renewable energy sharing among community participants which consider multiple energy tariffs and mixture of prosumers and consumers in the multi-nodal microgrid structure.

The rest of this chapter is structured as follows. Section 5.2 describes the formulation of the optimization problem. Section 5.3 provides the detailed information of the case study and its testing, including pre-processing and analytics of data. Section 5.4 discusses the detailed results followed by the resume in Section 5.5.

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5.2 Formulation of Optimization Problem

The methodology considers an optimization model using a MILP framework based on the Distributed Energy Resources - Customer Adoption Model (DER-CAM) [37] and further developed within this research to include the additional decision variables for the surplus energy at a single node, the energy transfer between multiple nodes with the corresponding financial constraints and different electricity tariff scenarios with a yearly time horizon. A major difference to the existing literature is the new option for the renewable energy transfer between the nodes (community members) combined with the newly introduced node-specific time-of-use electricity rates using a full-scale optimization horizon (i.e. a full linked year). With this time horizon, volatile energy supply systems as well as seasonal energy transfer can be considered directly and hourly based electricity rates can be considered in the optimization. Therefore, this MILP framework considers the full-scale optimization *i.e.* 8760-hours by extending the previously MILP framework (with time series in terms of 24-hours based three representative daytypes for each month) having months $m \in \{1, 2, \ldots, 12\}$, daytypes $d \in \{1, 2, 3\}$ and hours $h \in \{1, 2, \ldots, 24\}$ [35] with $t \in \{1, 2, \ldots, 8760\}$.

5.2.1 Objective Function

The MILP optimization framework minimizes the total energy costs, the total CO_2 emissions of a REC and it can consider different utility rates of the individual participants. In this case, the optimization is performed from the perspective of the operator of a REC and thus according to the community total costs. The simplified objective function related to the total annual energy costs C can be represented by eq. (5.1).

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$$C = \sum_{\mathrm{n}} C_{\mathrm{n}} = \sum_{\mathrm{n}} \left(\sum_{\mathrm{tech}} DER_{\mathrm{invest}} + \sum_{t} C_{\mathrm{utility}} + \sum_{t} C_{\mathrm{O\&M}} \right) \tag{5.1}$$

where C_{n} is the annual energy cost per node, DER_{invest} is the annualized investment cost per technology *tech* and C_{utility} is related to the electrical purchase minus sales to the utility grid or to the community members. The $C_{\mathrm{O\&M}}$ variable is related to the operation and maintenance costs.

DER_{invest} can be further described as shown in eq. (5.2) and eq. (5.3).

$$DER_{\mathrm{invest}} = \sum_{\mathrm{tech}} (C_{\mathrm{up}}\, \Pi_{\mathrm{tech}}) \tag{5.2}$$

$$C_{\mathrm{up}} = VarC_{\mathrm{tech}}\, Cap_{\mathrm{tech}} + FixC_{\mathrm{tech}} \tag{5.3}$$

where C_{up} are the upfront capital costs of the technology, Π_{tech} is the annuity rate of the technology, which gives the present value of the technology in terms of the annuity, the interest rate, and the number of annuities *i.e.* lifetime of the technology, $VarC_{\mathrm{tech}}$ are the variable capital costs of the technology, Cap_{tech} is the technology capacity to be invested and $FixC_{\mathrm{tech}}$ are the fixed capital costs of the technology. The variable capital costs vary with the amount of capacity that is invested, while the fixed capital costs are independent on the size of the technology and can cover engineering costs.

To accurately reflect the additional cost possibilities for the renewable energy transfer within a REC, two new cost variables have been added to the total C_{utility} costs, which are further described in eq. (5.4). Furthermore, all electricity rates related to the utility purchase are node-specific in this model, so that different tariff scenarios for each node and customer can be tracked explicitly.

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$$\sum_{\mathrm{n,t}} C_{\mathrm{utility}} = \sum_{\mathrm{n,t}} E_{n,t}^{\mathrm{UtPur}}\, \zeta_{\mathrm{n,t}}^{\mathrm{UtPur}} - \sum_{\mathrm{n,t}} E_{n,t}^{\mathrm{UtExp}}\, \zeta_{\mathrm{t}}^{\mathrm{UtExp}} + \sum_{\mathrm{n}} C_{\mathrm{n}}^{\mathrm{UtFix}} + \sum_{\mathrm{n,t}} E_{\mathrm{n,t}}^{\mathrm{UtMax}}\, \zeta_{\mathrm{n,t}}^{\mathrm{UtMax}} + \sum_{\mathrm{n,t}} E_{n,t}^{\mathrm{RecPur}}\, \zeta^{\mathrm{RecPur}} - \sum_{\mathrm{n,t}} E_{n,t}^{\mathrm{RecExp}}\, \zeta^{\mathrm{RecExp}} \tag{5.4}$$

where $E_{n,t}^{\mathrm{UtPur}}$ is the purchased electricity from the utility at node n, $\zeta_{\mathrm{n,t}}^{\mathrm{UtPur}}$ is the node-specific TOU-rate for the electricity purchase from the utility, $E_{n,t}^{\mathrm{UtExp}}$ is the exported electricity to the utility at node n and $\zeta_{\mathrm{t}}^{\mathrm{UtExp}}$ is the rate for the electricity export. $C_{\mathrm{n}}^{\mathrm{UtFix}}$ is the yearly utility fee at node n, $E_{\mathrm{n,t}}^{\mathrm{UtMax}}$ is the maximum purchased electricity from the utility during the whole year at node n and $\zeta_{\mathrm{n,t}}^{\mathrm{UtMax}}$ is the node-specific yearly power demand rate. Note that the REC-based electricity purchase and export prices are different as described in the case study addressed in sub-section 5.3.

$E_{n,t}^{\mathrm{RecPur}}$ is the newly introduced purchased electricity from other REC members at node n, ζ^{RecPur} is the energy community rate for the REC-based electricity purchase defined by the community operator, $E_{n,t}^{\mathrm{RecExp}}$ is the exported electricity to the REC at node n and ζ^{RecExp} is the defined rate for the electricity export to the REC.

Furthermore, in order to avoid higher individual costs for each participant (node) in a community setup, the total annual energy costs per node C_{n} can also be limited in the optimization by the cost constraint of C_{n}^{lim} according to the eq. (5.5) and eq. (5.6) so that the individual costs per node/client in the REC are not exceeding the individual reference costs.

$$C_{\mathrm{n}}^{\mathrm{lim}} = (1+\gamma)\, C_{\mathrm{n}}^{\mathrm{ref}} \tag{5.5}$$

$$C_{\mathrm{n}} \leq C_{\mathrm{n}}^{\mathrm{lim}} \tag{5.6}$$

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where $C_{\mathrm{n}}^{\mathrm{ref}}$ are the costs associated with the reference case at node n and γ is the cost constraint parameter responsible for limiting the total annual energy costs per node.

The simplified objective function related to the total annual carbon dioxide emissions can be represented by eq. (5.7). It is the summation of the carbon dioxide emissions occurred in providing the electricity from the grid at each node n. Carbon dioxide emissions from other technologies such as a combined heat and power system running on natural gas can be considered in principle, but only electricity from grid is considered as a source of carbon dioxide emissions in this study.

$$CO_2 = \sum_{n,t} CO_{2\mathrm{grid}} \tag{5.7}$$

5.2.2 Technology Constraints

The case study addressed in sub-section 5.3 considers mainly two distributed energy technologies for the production and storage of renewable energy shared within the REC, including the photovoltaic (PV) technology and the energy storage system (ESS), since this is the major focus of the current legislation.

The electricity provided by the PV technology is given by eq. (5.8).

$$E_{n,t}^{\mathrm{solar}} = Cap_{\mathrm{n}}^{\mathrm{PV}}\, PV_{n,t}^{\mathrm{perf}} \tag{5.8}$$

where $E_{n,t}^{\mathrm{solar}}$ is the electricity provided by the solar PV technology at node n, $Cap_{\mathrm{n}}^{\mathrm{PV}}$ is the capacity of the solar PV technology at node n and $PV_{n,t}^{\mathrm{perf}}$ is the normalized solar PV performance at the corresponding location, which depends on the location, orientation, temperature and panel types.

The energy storage system (ESS) can be represented by eq. (5.9).

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$$ESS_{n,t}^{\text{stored}} = ESS_{n,t-1}^{\text{stored}} + ESS_{n,t}^{\text{in}} - ESS_{n,t}^{\text{out}} - ESS_{n,t}^{\text{loss}} \tag{5.9}$$

where $ESS_{n,t}^{\text{stored}}$ represents the State of Charge (SoC) of the ESS at node n, $ESS_{n,t}^{\text{in}}$ is the input for ESS, $ESS_{n,t}^{\text{out}}$ is the output from the energy storage, $ESS_{n,t}^{\text{loss}}$ is the energy lost in the ESS. The energy losses can be represented by eq. (5.10).

$$ESS_{n,t}^{\text{loss}} = ESS_{n,t}^{\text{stored}}\,\Theta_{\text{ESS}} \tag{5.10}$$

where Θ_{ESS} is the co-efficient of loss for the ESS. The energy storage constraints are given by eq. (5.11-5.16).

$$ESS_{n,t}^{\text{stored}} \leq Cap_{\text{n}}^{\text{ESS}} \tag{5.11}$$

$$Cap_{\text{n}}^{\text{ESS}}\,\rho_{\text{SoC}}^{\text{min}} \leq ESS_{n,t}^{\text{stored}} \leq Cap_{\text{n}}^{\text{ESS}}\,\rho_{\text{SoC}}^{\text{max}} \tag{5.12}$$

$$ESS_{n,t}^{\text{in}} = E_{n,t}^{\text{ESSin}}\eta_{\text{char}} \leq Cap_{\text{n}}^{\text{ESS}}\,\varphi_{\text{char}}^{\text{max}} \tag{5.13}$$

$$ESS_{n,t}^{\text{out}} = E_{n,t}^{\text{ESSout}}\,1/(\eta_{\text{dis}}) \leq Cap_{\text{n}}^{\text{ESS}}\,\varphi_{\text{dis}}^{\text{max}} \tag{5.14}$$

$$ESS_{n,t}^{\text{in}} \leq ESS_{n,t}^{\text{XOR}}\,N \tag{5.15}$$

$$ESS_{n,t}^{\text{out}} \leq (1 - ESS_{n,t}^{\text{XOR}})\,N \tag{5.16}$$

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where $Cap_{\mathrm{n}}^{\mathrm{ESS}}$ is the capacity of the ESS at node n, $\rho_{\mathrm{SoC}}^{\mathrm{min}}$ and $\rho_{\mathrm{SoC}}^{\mathrm{max}}$ are the minimum and maximum SOCs of the ESS, η_{char} and η_{dis} are the charging and discharging efficiencies of the ESS, $\varphi_{\mathrm{char}}^{\mathrm{max}}$ and $\varphi_{\mathrm{dis}}^{\mathrm{max}}$ are the maximum charging and discharging rates of the ESS, $ESS_{n,t}^{\mathrm{XOR}}$ is the binary input for avoiding simultaneous charging and discharging of the ESS at node n and N is an arbitrary large number.

5.2.3 Energy Balance and Constraints

In a REC constellation the electricity provided by the solar PV technology at node n $E_{n,t}^{\mathrm{solar}}$ can be divided into three PV electricity components, corresponding to three decision variables given by eq. (5.17)

$$E_{n,t}^{\mathrm{solar}} = E_{n,t}^{\mathrm{onsite}} + E_{n,t}^{\mathrm{UtExp}} + E_{n,t}^{\mathrm{RecExp}} \tag{5.17}$$

where $E_{n,t}^{\mathrm{onsite}}$ is the onsite usage of the electricity provided by the PV technology at node n, which can be used to satisfy the demand or charge the onsite battery at node n if one exists. $E_{n,t}^{\mathrm{ExpUt}}$ is the exported PV electricity to the utility and $E_{n,t}^{\mathrm{RecExp}}$ is the exported PV electricity to the REC participants at node n when there is a demand for electricity.

The constraints given by eq. (5.18) and (5.19) serve to prevent simultaneous import and export to/from the utility if a grid connection exists, i.e. binary parameter $\delta^{\mathrm{gc}} \neq 0$, otherwise both $E_{n,t}^{\mathrm{UtPur}}$ and $E_{n,t}^{\mathrm{UtExp}}$ will be fixed at zero.

$$E_{n,t}^{\mathrm{UtPur}} \leq \left(\delta_{n,t}^{\mathrm{ps}}\, \delta^{\mathrm{gc}}\right) N \tag{5.18}$$

$$E_{n,t}^{\mathrm{UtExp}} \leq \left(\left(1 - \delta_{n,t}^{\mathrm{ps}}\right)\, \delta^{\mathrm{gc}}\right) N \tag{5.19}$$

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where $\delta^{\text{ps}}_{n,t}$ is related to the binary electricity purchase or sell decision variable at node n and N is an arbitrary large number.

Moreover, the electricity which is stored and provided by the ESS technology at node n can also be divided into two ESS components, corresponding to two decision variables given by eq. (5.20)

$$E^{\text{ESSout}}_{n,t} = E^{\text{ESSons}}_{n,t} + E^{\text{ESSRecExp}}_{n,t} \tag{5.20}$$

where $E^{\text{ESSons}}_{n,t}$ is the onsite usage of the electricity provided by the ESS at node n and $E^{\text{ESSRecExp}}_{n,t}$ is the exported ESS electricity to the REC. Note that in this REC model also centralized community PV and ESS technologies are possible as long as a node n for a "centralized" technology location has been specified. Thus, the model can make decisions on decentralized individual PV and ESS technologies at each node/building and also provide electricity from PV and ESS for the entire REC in one location.

For the renewable energy transfer option within the REC a new transfer variable has been introduced given by eq. (5.21)

$$\sum_{n'} E^{\text{trans}}_{n,n',t} = E^{\text{RecExp}}_{n,t} + E^{\text{ESSRecExp}}_{n,t} \tag{5.21}$$

where $E^{\text{trans}}_{n,n',t}$ is related to the renewable energy transfer from node n to node n' and is given by the sum of the total exported electricity from the PV and ESS technology within the REC. This is also the total electricity amount that can be purchased by other community members from a node n.

The higher level energy balance equation for the overall model is given by eq. (5.22).

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$$
\begin{aligned}
&E_{n,t}^{\mathrm{UtPur}} + \sum_{n'} E_{n,n',t}^{\mathrm{trans}} + E_{n,t}^{\mathrm{onsite}} + E_{n,t}^{\mathrm{ESSons}} + E_{n,t}^{\mathrm{UtExp}} \\
&= E_{n,t}^{\mathrm{load}} + E_{n,t}^{\mathrm{ESSin}} + E_{n,t}^{\mathrm{sales}}
\end{aligned}
\tag{5.22}
$$

where $E_{n,t}^{\mathrm{load}}$ is the electrical load demand at node n and $E_{n,t}^{\mathrm{sales}}$ are the total remaining electricity sales to the utility at node n.

5.3 Case Study

This section includes the details and the approach of designing the real case study for a small-scale REC testbed with nine community participants in a village in Carinthia, Austria of which six are consumers and three are prosumers with an existing PV system. It also includes the time series data analysis, the technical and economical details of the technologies, assumptions and the optimization strategy.

5.3.1 Renewable Energy Community

The setup of the testbed is based on the characteristics of a typical REC aiming to share the renewable energy produced within the community at a local level. In addition to the necessary technical setup of the REC, the project focuses on the active participation of citizens, community and local initiatives in order to create a solution that fully exploits the positive effects of a REC.

In the municipality of this village in Carinthia, a total of nine project participants have agreed to participate in a REC consisting of the local authority, a fire department, a bank, a residential building (two households and one electrical hot water boiler profile) and three single-family households. In addition, the fire department has an existing PV system with a peak power of 17.68 $\mathrm{kW_p}$ and two of the single-family households have already a PV system with a peak power of 4.2 $\mathrm{kW_p}$ and 2.6 $\mathrm{kW_p}$, where the surplus PV electricity

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is sold to the utility at a certain feed-in tariff in the reference case. By transferring to an REC, the surplus PV electricity produced by the individual participants can be distributed to the community members (nodes) at a reduced network tariff, which means that less electricity has to be purchased from the public grid, thus saving costs and carbon emissions. Moreover, greenfield scenarios without existing PV technologies are also considered in order to find the optimal investment decisions for this REC and whether the total energy costs can be further reduced through the expansion of renewable energies. Furthermore, all participants are located on one network level (low voltage distribution network). The current network topology of the REC testbed with the existing technologies is shown in Figure 5.1. Although the investments in PV and ESS are considered in a centralized approach in this topology, further decentralized investments in PV and ESS are also possible in each individual node together with the existing decentralized technologies.

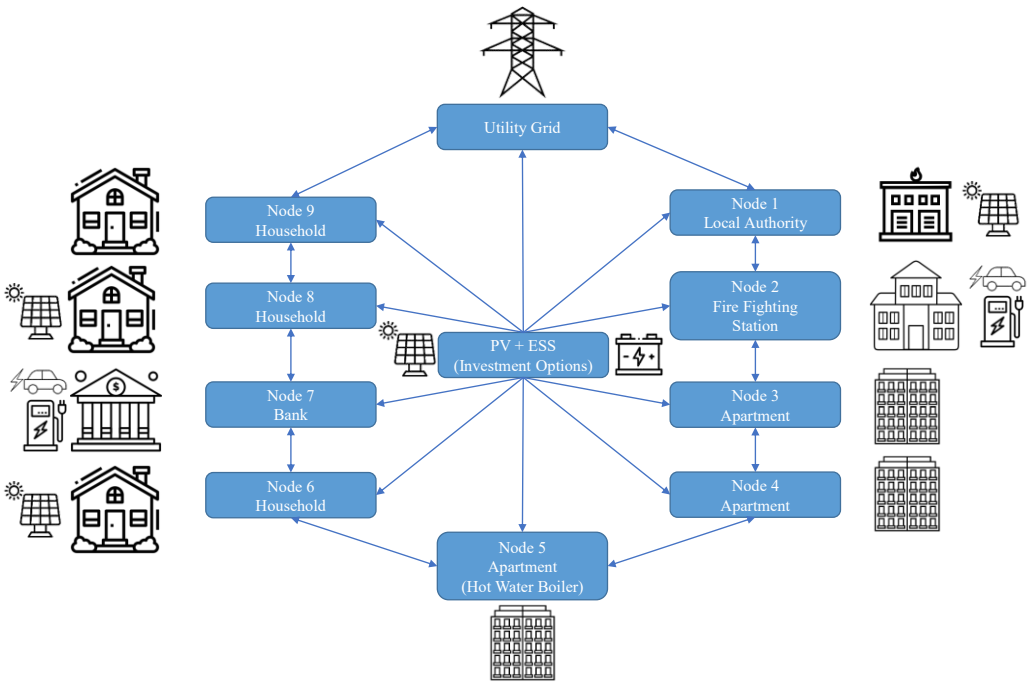

FIGURE 5.1: The network topology of the renewable energy community testbed at a village in Carinthia (Austria) with central investment options and other existing technologies.

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5.3.2 Time Series Input Data Analysis and Assumptions

The responsible Distribution System Operator (DSO) in this region is the KNG-Kärnten Netz GmbH, who are co-initiators of this REC project and provided the electrical load profile data of the community. The electrical load profiles of the individual participants are synthetically generated load profiles based on real smart-meter measurements in a 15 min time interval for a whole year. The hourly based electric load data are shown in Figures 5.2-5.3.

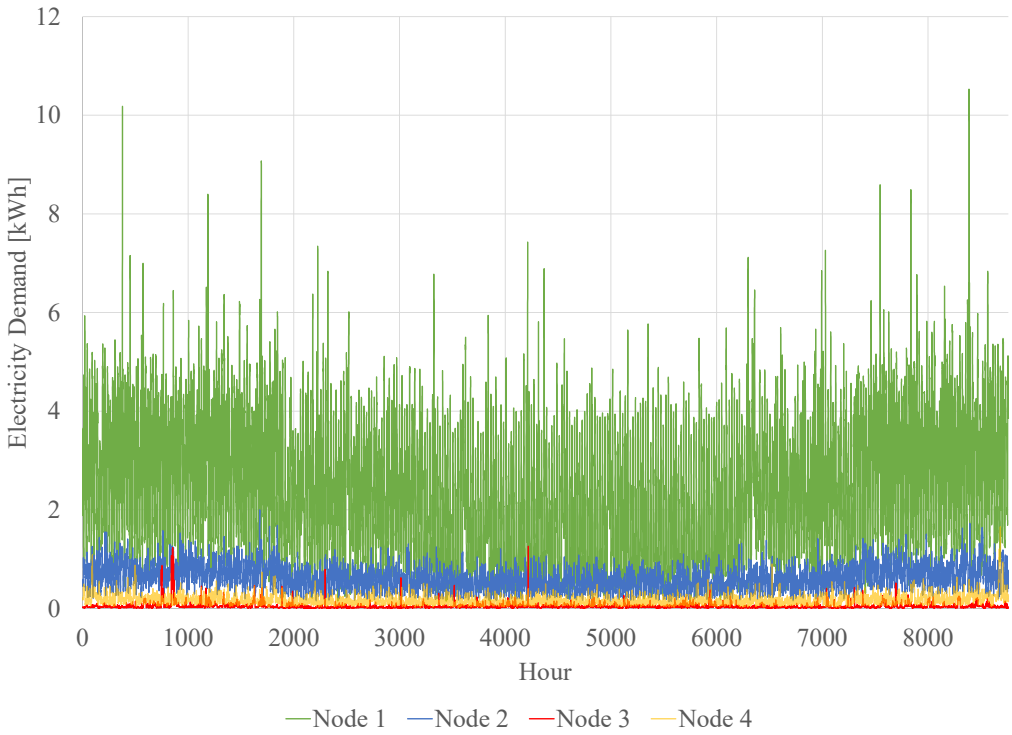

FIGURE 5.2: The hourly electrical demand profile of node 1-4.

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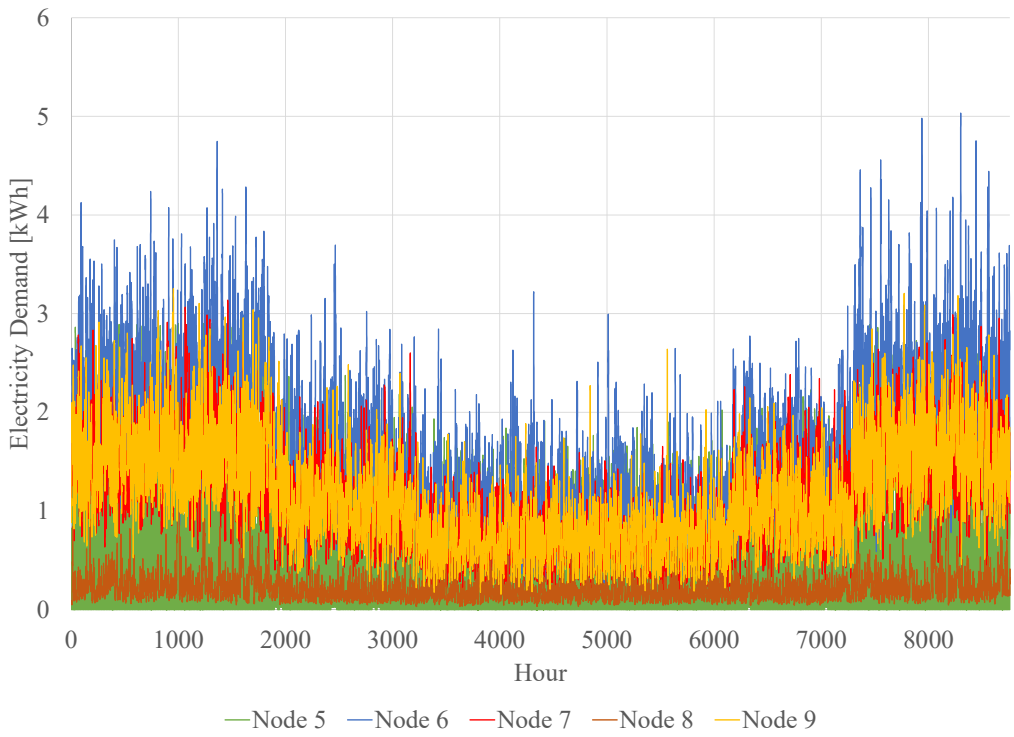

FIGURE 5.3: The hourly electrical demand profile of node 5-9.

Moreover, the corresponding histograms for each demand are shown in Figure 5.4 to provide a visual representation of the electrical load data distributions in relation to the number of hours.

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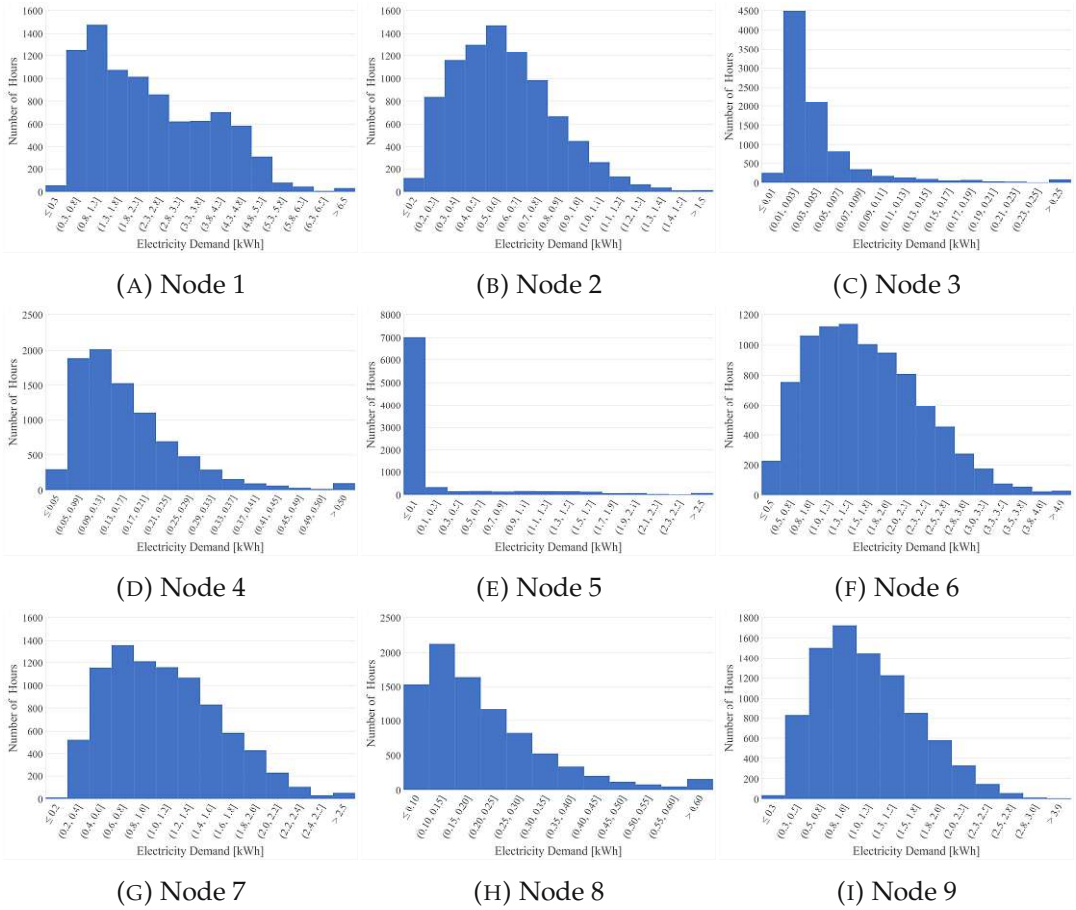

(A) Node 1 (B) Node 2 (C) Node 3

(D) Node 4 (E) Node 5 (F) Node 6

(G) Node 7 (H) Node 8 (I) Node 9

FIGURE 5.4: The corresponding histograms for each electrical demand.

Furthermore, the maximum power and yearly electricity consumption for each community participant (node) and type are reported in Table 5.1. The total annual consumption of the whole REC amounts to approximately 63,902 kWh/a with a hourly peak load of 18.32 kW_p when the individual electricity consumptions are aggregated to a total load.

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Node	Type	Maximum Hourly Power [kW]	Annual Energy [kWh] per year
1	Local Authority	10.52	19,972.69
2	Fire Fighting Station	1.98	5,171.55
3	Apartment	1.26	378.10
4	Apartment	1.65	1,395.14
5	Apartment (Hot Water Boiler)	2.84	1,816.81
6	Household	5.03	14,093.83
7	Bank	3.13	9,452.83
8	Household	2.23	1,803.63
9	Household	3.25	9,817.13

TABLE 5.1: The maximum hourly power and annual electrical load of each community participant.

For the determination of the electricity provided by the existing PV technologies at the location, the solar PV performance is required at the site. The solar PV performance is retrieved from Meteonorm [110] with an hourly time horizon. Meteonorm explicitly provides the hourly values of the PV performance of a typical medium sized plant with crystalline silicon modules and an efficient inverter for a whole year. These data are shown in Figure 5.5. The technological and economical parameters of the PV technology are addressed in sub-section 5.3.3.

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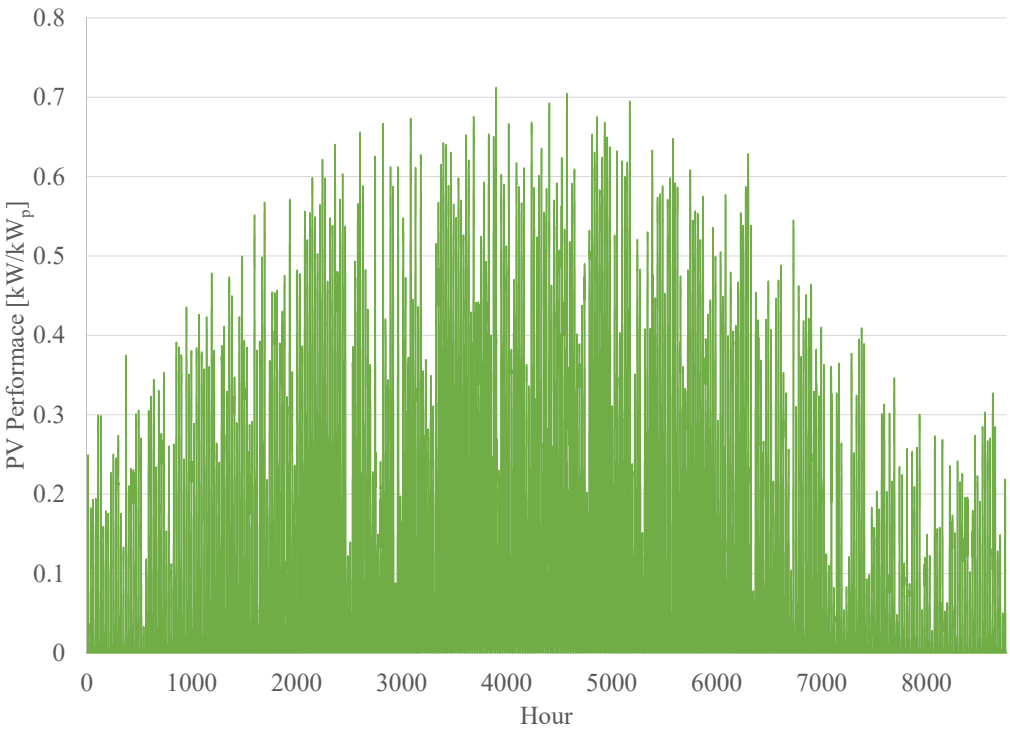

FIGURE 5.5: The solar PV performance data on hourly basis at the site [110].

In order to assess the CO_2 emissions correctly, the CO_2 content of the purchased electricity from the utility also needs to be considered. The marginal CO_2 emissions rate of the purchased electricity is considered in kg/kWh in this study and is shown in Figure 5.6 [128] on hourly basis for the whole year. The marginal CO_2 emissions rate is based on the Austrian-mix and import-mix electricity sources. The marginal CO_2 emissions only consider the direct emissions of the fuel while generating the electricity and do not include the indirect emissions related to the fuel production and transportation.

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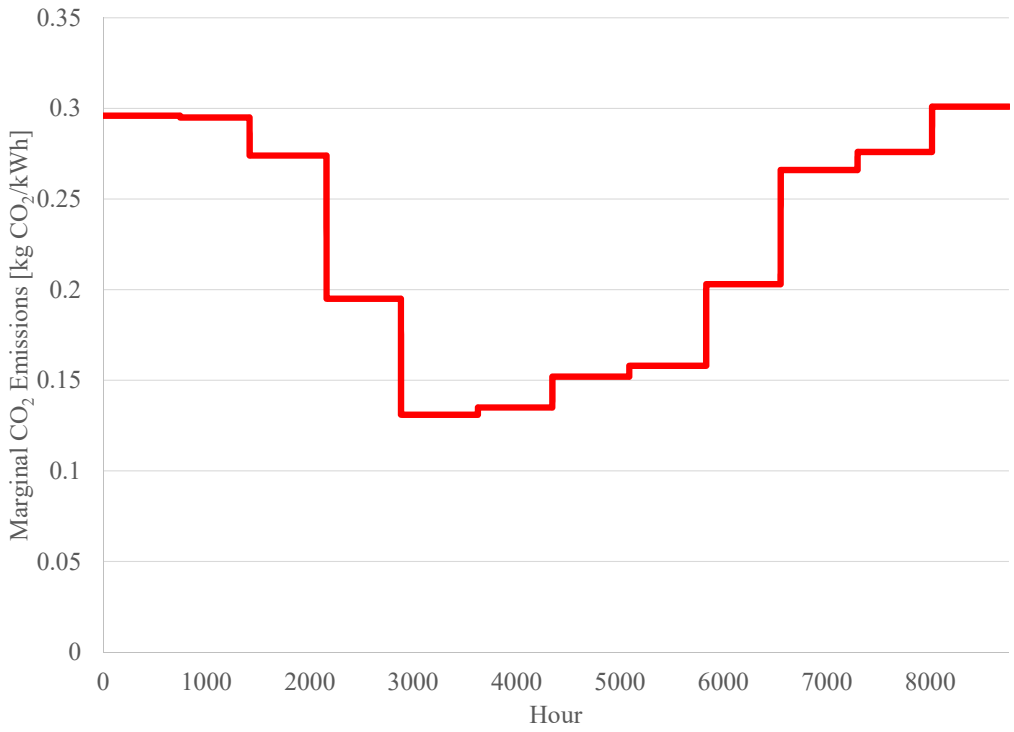

FIGURE 5.6: The hourly marginal CO_2 emissions of the utility electricity [128].

5.3.3 Techno-Economical Parameters

The economical parameters for the solar PV and ESS include the investment parameters like fixed capital costs, variable capital costs, fixed maintenance costs and lifetime. These parameters are given in Table 5.2 [58, 132]. For the ESS, a Lithium-ion based battery is considered. The lifetime of such Lithium-based batteries results from the stated manufacturer's warranty of ten years at a discharge depth of 100% [133]. In order to minimize battery degradation and prolong the usage of the stored renewable energy, the ESS is only operated in a SOC range of 20-100%, which according to [134] can increase the lifetime (more precisely the number of charge cycles) by 50%. Therefore a lifetime of 15 years is assumed for the ESS in this study. The interest rate is considered as 2% which is needed for the calculation of the annuity rate for each technology.

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Technology	Fixed Costs [€]	Variable Costs [€/kW or kWh for ESS]	Fixed Maintenance Costs [€/kW or kWh for ESS] per year	Lifetime [Years]
PV	0	842	9	25
ESS	0	434	0	15

TABLE 5.2: The economic parameters of the microgrid technologies [58, 132].

The technical parameters for the energy storage system includes the charging and discharging efficiencies, the maximum charge and discharge rates, the minimum and maximum SOC and the self-discharge rate (losses) of a typical Lithium-Ion ESS. These parameters are given in Table 5.3 [133, 135].

Parameter	Value
Charging Efficiency of ESS [%]	95
Discharging Efficiency of ESS [%]	95
Maximum Charge Rate [% per hour]	34
Maximum Discharge Rate [% per hour]	34
Minimum SOC of ESS [%]	20
Maximum SOC of ESS [%]	100
Self-Discharge Rate of ESS [% per hour]	0.2

TABLE 5.3: The technical parameters of the Li-ion based ESS [133, 135].

In Austria, the total electricity tariff is divided into three main components consisting of an energy, a grid and a fees component with the last two components regulated by law and dependent on the respective region [136, 137, 138]. Furthermore, the Austrian sales tax of 20% must also be taken into account. The energy component of the electricity tariff for the utility purchase is based on the KELAG Home Basic tariff [139], which is commonly used for households (HH) at this site, and a special tariff for the local authority (LA) and the electrical hot water boiler (HWB) defined by the local energy

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supplier. Furthermore, in this case study a distinction is made between two different tariff scenarios. The first scenario refers to a pure consumption tariff without variable power demand rates for all REC members and is therefore called "Scenario Without-DR" in this study. In the second scenario there is a variable power demand rate in the grid tariff component, which refers to the yearly peak load of each REC participant, and thus is called "Scenario With-DR". The tariffs are summarized into a variable (€c/kWh), a fixed (€/a) and a peak load-related (€/kW$_p$/a) cost component for the optimization, which results in the following cost breakdown for the different tariff scenarios and participant types given in Table 5.4.

		Without-DR			With-DR		
Tariff Component	**Unit**	**HH**	**LA**	**HWB**	**HH**	**LA**	**HWB**
Energy	€/a	39	8	0	39	8	0
	€c/kWh	6.79	4.53	6.25	6.79	4.53	6.25
Grid	€/a	65.21	65.21	65.21	27.96	27.96	27.96
	€/kW$_p$/a	0	0	0	13.79	13.79	13.79
	€c/kWh	6.53	6.53	6.53	6.07	6.07	6.07
Fees	€/a	37.35	37.35	37.35	37.35	37.35	37.35
	€c/kWh	3.49	3.49	3.49	3.49	3.49	3.49
Sales Tax	%	20	20	20	20	20	20
$\zeta_{n,t}^{UtPur}$ - Variable Cost Incl. Tax	€c/kWh	20.17	17.46	19.52	19.62	16.91	18.97
$\zeta_{n,t}^{UtMax}$ - Peak Load Cost Incl. Tax	€/kW$_p$/a	0	0	0	16.55	16.55	16.55
C_n^{UtFix} - Fixed Cost Incl. Tax	€/a	169.87	131.17	121.57	125.17	87.97	78.37

TABLE 5.4: The individual and summarized electricity tariff components in the REC.

According to the current status of the negotiations surrounding the EAG, it can be assumed that the variable part of the grid component for the shared electricity within the REC will be reduced by at least 60% in order to create additional financial incentives for community members in Austria. In addition, the variable part of the fees cost component is also to be abolished. The energy price is determined by the operator of the REC or by the community

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participants. In this study energy rates of 4 €c/kWh are considered, which is equal to the fixed feed-in tariff to the utility of 4 €c/kWh and corresponds to the current community situation with the existing PV technologies. For the greenfield investment scenarios it is assumed that no energy rates have to be paid and are therefore considered to be 0 €c/kWh. The cost structure and the summarized variable energy community tariff for the purchased electricity from the REC is given in Table 5.5.

		Without-DR	**With-DR**
REC Tariff Component	**Unit**	**HH, LA, HWB**	**HH, LA, HWB**
Energy	€c/kWh	0 or 4	0 or 4
Grid	€c/kWh	2.61	2.43
Fees	€c/kWh	0	0
Sales Tax	%	20	20
ζ^{RECPur} - Variable Cost Incl. Tax	€c/kWh	3.13 or 7.93	2.92 or 7.72

TABLE 5.5: The energy community tariff components and the summarized variable cost for the purchased electricity from the REC.

In addition to the fixed feed-in tariff ζ_t^{UtExp} of 4 €c/kWh, also time-variable rates for the PV surplus electricity sales to the utility are considered in other greenfield optimization scenarios. This is significantly important to show how the REC reacts with different market signals. For this the Austrian spot market prices on an hourly basis are used. This market price history is shown in Figure 5.7 [140].

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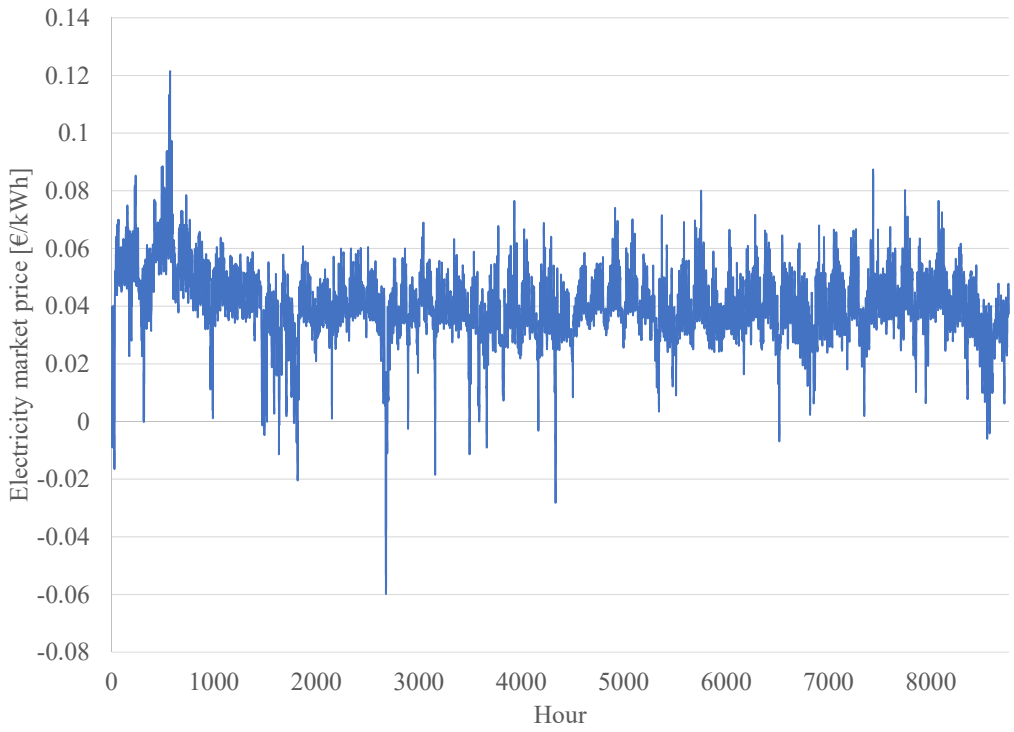

FIGURE 5.7: The hourly EPEX spot market prices for the year 2019 in Austria [140].

5.3.4 Optimization Framework and Strategy

The case study considers three different reference cases (RC) and three different optimization cases (OC) in a REC constellation related to the corresponding reference case and where the renewable energy transfer among the community participants is enabled. The different scenarios are reported in Table 5.6. For all cases, the total annual energy costs and the total annual CO_2 emissions are calculated through a cost minimization of the optimization model. The energy costs include the investment costs related to the PV and ESS technologies together with the electricity purchase or sales from the utility or the REC. The CO_2 emissions include the total marginal carbon emissions of the electricity purchase from the utility.

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Scenario	Description
RC-Without-DR-PV	Reference case: existing PV and without demand rates
RC-Without-DR	Reference case: no existing PV; only utility purchase and without demand rates
RC-With-DR	Reference case: no existing PV; only utility purchase and with demand rates
OC-Without-DR-PV	Optimization: existing PV and without demand rates; no additional investments
OC-Without-DR	Optimization: enabled investments and without demand rates
OC-With-DR	Optimization: enabled investments and with demand rates

TABLE 5.6: Different scenarios for the optimization and testing framework.

The first reference case RC-Without-DR-PV represents the current status of the participants and considers the three existing PV systems using the technical and economical parameters reported in sub-section 5.3.3. In this reference case the tariff scenario without demand rates is considered for the utility purchase, which is given in Table 5.4. Furthermore, in this reference case, the PV surplus can only be fed into the grid at a fixed feed-in tariff of 4 €c/kWh. The associated optimization case OC-Without-DR-PV determines by how much the total PV self-consumption of the REC can be increased and thus how much total annual energy costs and total annual CO_2 emissions can be saved with the prevailing tariff scenario, when the renewable energy transfer between the participants is enabled.

The second and third reference case RC-Without-DR and RC-With-DR are so-called greenfield scenarios with different tariff schemes in each case (one without and one with demand rates), where no existing PV technologies are considered. The corresponding investment and optimization cases OC-Without-DR and OC-With-DR determine how much is invested in new PV and ESS technologies and thus how much energy costs and CO_2 emissions can be saved in a REC with the optimally chosen technology capacities and enabling the renewable energy transfer. In both greenfield investment optimization cases, the spot market prices given in Figure 5.7 are used for the PV

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surplus sales to the utility. The assumptions for all optimization scenarios are summarized in Table 5.7.

Scenario	ζ^{RECPur} **- REC-Purchase** [€c/kWh]	ζ^{RECExp} **- REC-Export** [€c/kWh]	ζ_t^{UtExp} **- Utility Sales** [€c/kWh]
OC-Without-DR-PV	7.93	4	4
OC-Without-DR	3.13	0	Market Prices
OC-With-DR	2.92	0	Market Prices

TABLE 5.7: The assumptions made regarding the REC-Purchase and Utility Sales for all optimization scenarios.

For all cases, the total annual energy costs and the total annual CO_2 emissions are calculated through a cost minimization of the optimization model. The results include the optimal sizing and the full-year operational dispatch of the technologies. Furthermore, the results also include the comparisons with the reference cases in terms of the energy cost and CO_2 savings, the total annual energy costs per node and the distributed renewable energy to each node for the different tariff scenarios. The optimality gap of the optimization solver was set to 0.2% for all scenarios. The MILP optimization was performed on a server with a Common KVM processor CPU 3.7 GHz and 224 GB of RAM.

5.4 Results

This section provides the results of the reference cases and the corresponding optimization scenarios for each node based on the different electricity tariff scenarios.

5.4.1 Current Status with Existing Technologies

First, the current status of the community participants is determined with the reference case scenario RC-Without-DR-PV. For this, the total electricity

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purchase from the grid, the produced PV electricity provided by the existing PV technologies and the respective share of the onsite PV usage, the total annual energy costs and the total annual CO_2 emissions are calculated for each node through a cost minimization using the time series input data and techno-economical parameters given in sub-section 5.3.2-5.3.3.

The calculated total energy costs per node of the RC-Without-DR-PV reference case scenario are used as node-specific cost constraints for the optimization scenario OC-Without-DR-PV, where the renewable electricity transfer between the participants is possible. The REC participants who provide the renewable electricity to the REC (ζ^{RECExp}) get the same energy rate as if they sold the electricity to the grid (ζ^{UtExp}), i.e. 4 €c/kWh. This means that the participants who sell the electricity to the other community members are not economically disadvantaged in the new REC setup. The results for the whole REC obtained from the reference (RC-Without-DR-PV) and optimization scenario (OC-Without-DR-PV) are given in Table 5.8. The node-specific results are also given in Tables 5.9-5.10.

Scenario	PV	PV-Onsite	REC-Purchase	Community Energy Costs	Cost Savings	Community CO_2 Emissions	CO_2 Savings
	[kW]	[kWh/a]	[kWh/a]	[€/a]	[%]	[kg-CO_2/a]	[%]
RC-Without-DR-PV	24.48	6,648.19	-	12,976.25	-	13,879.25	-
OC-Without-DR-PV	24.48	6,648.19	9,694.71	11,843.70	8.73	11,839.45	14.70

TABLE 5.8: The results of the reference and optimization scenario (RC-Without-DR-PV and OC-Without-DR-PV) calculated through a cost minimization.

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Node	Grid-Purchase [kWh/a]	PV-Production [kWh/a]	PV-Onsite [kWh/a]	Total Energy Cost [€/a]	Total CO2 Emissions [kg-CO_2/a]
1	19,972.69	0	0	3,618.40	4,707.04
2	2,651.8	18,115.65	2,519.75 (13.9%)	1,002.63	656.19
3	378.09	0	0	246.24	88.51
4	1,395.14	0	0	451.38	326.11
5	1,816.81	0	0	476.21	437.94
6	10,736.24	4,303.49	3,357.59 (78%)	2,516.58	2,729.55
7	9,452.83	0	0	2,076.61	2,300.86
8	1,032.78	2,664.07	770.85 (28.9%)	438.09	256.31
9	9,817.13	0	0	2,150.10	2,376.74
Total	57,253.51	25,083.21	6,648.19 (26.5%)	12,976.25	13,879.25

TABLE 5.9: RC-Without-DR-PV results of each node.

Node	Grid-Purchase [kWh/a]	REC-Purchase [kWh/a]	PV-REC-Export [kWh/a]	Total Energy Cost [€/a]	Cost Savings [%]	Total CO_2 Emissions [kg-CO_2/a]	CO_2 Savings [%]
1	18,085.91	1,886.77	0	3,438.59	4.97	4,351.51	7.55
2	2,651.66	0.14	7528.05	1,002.61	0	656.16	0
3	280.49	97.61	0	2,234.29	4.85	69.46	21.52
4	1,035.99	359.15	0	407.42	9.74	257.77	20.96
5	1,362.07	454.74	0	423.51	11.07	338.53	22.70
6	9,232.4	1,503.84	632.24	2,332.51	7.31	2,362.8	13.44
7	6,985.86	2,466.96	0	1,774.66	14.54	1,785.57	22.40
8	986.87	45.91	1534.42	432.48	1.28	244.64	4.55
9	6,937.54	2,879.59	0	1,797.63	16.39	1,773.01	25.40
Total	47,558.79	9,694.71	9,694.71	11,843.70	8.73	11,839.45	14.70

TABLE 5.10: OC-Without-DR-PV results of each node.

In total, an average annual PV generation of 25,083.21 kWh/a is available for the entire REC, where the existing PV systems have an aggregated peak power of 24.48 kW_p. In the reference scenario, only 6,648.19 kWh/a of the total PV generation is used for own demand (PV-Onsite), which corresponds to an average, percentage own demand coverage of approx. 26.5%. This means that the majority of the produced PV electricity is available as surplus and in this case must be fed into the grid. Through a transition to a REC, the PV own use of the community can be further increased, since in this case, the renewable electricity transfer between the community participants is enabled.

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Figure 5.8 shows how the renewable energy is optimally distributed within the REC according to the cost minimization and how much each participant can purchase from the REC with the corresponding cost savings.

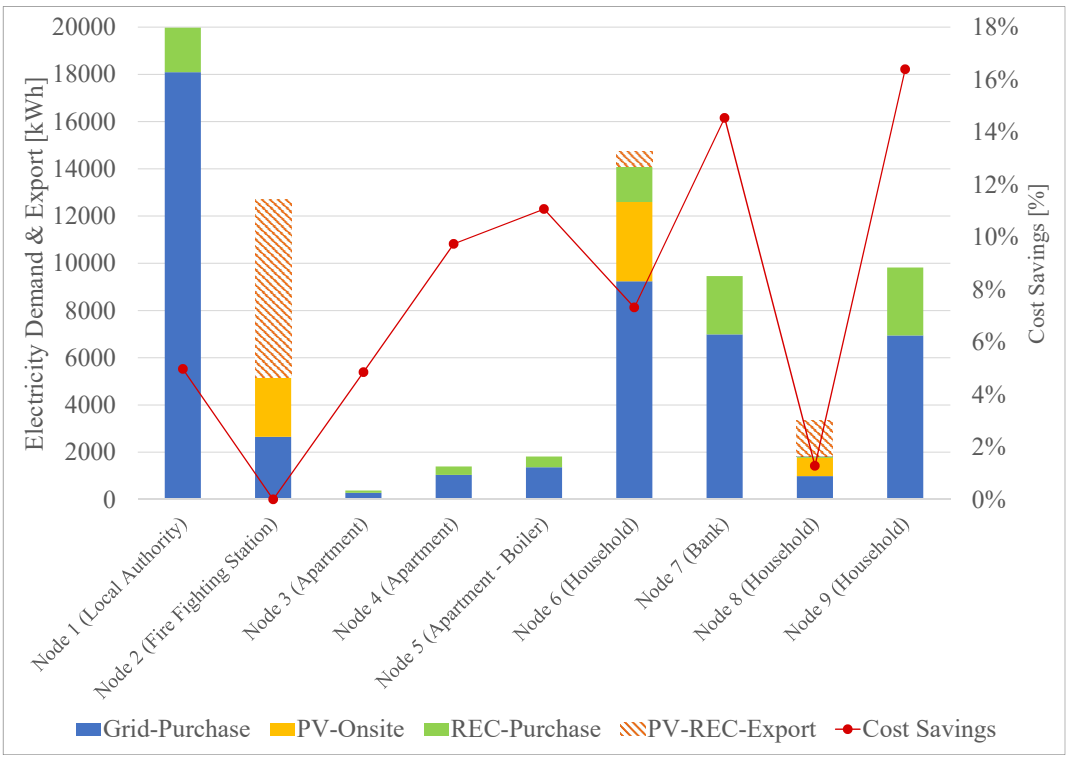

FIGURE 5.8: The annual electricity demand of each REC participant satisfied by the calculated Grid-Purchase, PV-Onsite usage and the REC-Purchase together with the cost savings for the optimization scenario OC-Without-DR-PV. The dashed bars show how much renewable PV electricity was exported to the other community participants.

The optimization results show that the total PV own use of the REC can be increased from 6,648.19 kWh/a (26.5%) to 16,342.9 kWh/a (65.2%) as a result of the additional REC-Purchase within the community. This is due to the introduced possibility of the renewable electricity transfer between nodes, so that the electricity demand of each community participant can be satisfied with the provided renewable electricity of the PV surplus. Through this additional possibility to purchase renewable electricity from the REC the total annual energy costs can be reduced by 8.73% as the renewable electricity is

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purchased at a reduced energy community tariff rate (see Table 5.5). Moreover, since renewable electricity is purchased, the total annual CO_2 emissions can be reduced by 14.7% within the REC at the same time. Note that this only applies to CO_2 emissions within the local network, and not the wider distribution grid. Furthermore, it can be seen from Figure 5.8 that node 2 is exporting more PV electricity than any other node since it has the biggest PV capacity installed and, accordingly, the largest PV surplus is generated on this node, which is exported and distributed to the participants in the most cost-optimal way. Therefore, the total electricity transfer from node 2 to other nodes can be analyzed in terms of an operational dispatch through Figure 5.9.

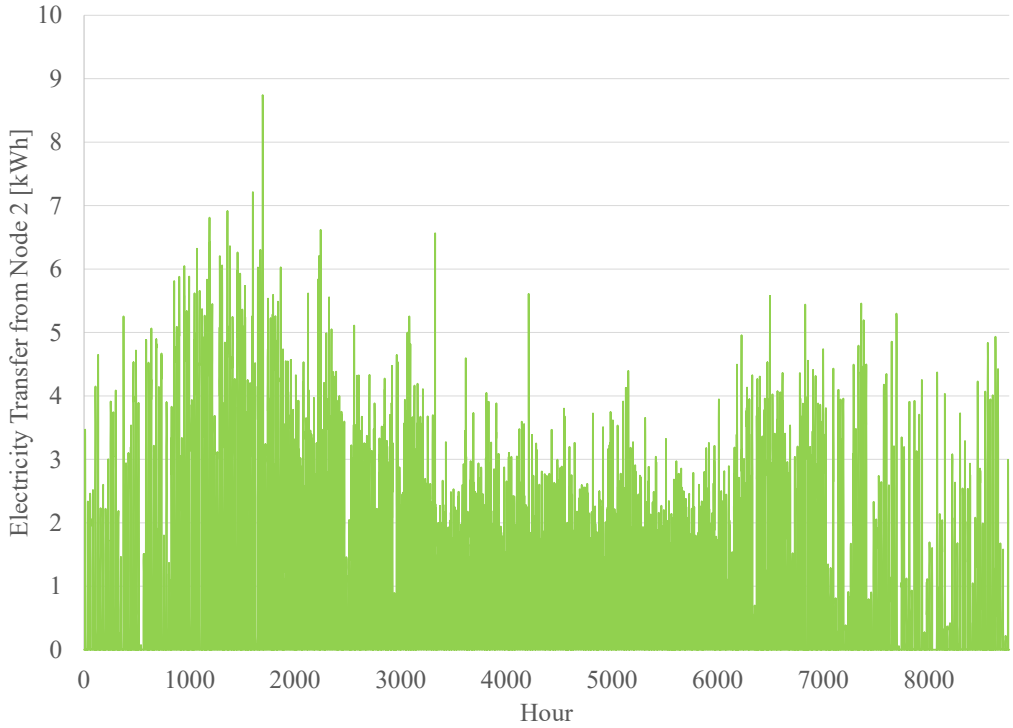

FIGURE 5.9: The total electricity transfer form the Node 2 to all other nodes for the optimization scenario OC-Without-DR-PV.

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5.4.2 Greenfield Investment Scenarios

In addition to the current community status, reference cases without existing PV technologies are also considered, i.e. RC-Without-DR and RC-With-DR. These scenarios correspond to green field scenarios, where the whole electricity demand is satisfied by the purchase from the grid with the different tariff scenarios given in Table 5.4. The calculated total energy costs per node of both RC-Without-DR and RC-With-DR reference case scenarios are again used as cost constraints for the investment scenarios OC-Without-DR and OC-With-DR, where the renewable electricity transfer among the participants is enabled if a renewable generation system is selected through the performed cost optimizations. In these optimization scenarios, investments in PV generation systems and ESS are considered in a centralized node. All the community nodes are connected with each other, also with this central investment node and utility grid for electricity sharing. The centralized investment node provides advantage over enabling the decentralized investments because the community can avoid the building retrofit costs and reduce the technology installation costs. Moreover, the centralized PV and ESS are much easier to maintain and monitor on the community level. The produced surplus electricity is sold to the utility at time-variable market prices on an hourly basis, which are shown in Figure 5.7. The total results of the reference cases (RC-Without-DR and RC-With-DR) together with the investment decisions and objective function savings obtained from the optimization scenarios (OC-Without-DR and OC-With-DR) are given in Table 5.11. The node-specific results are also given in Tables 5.12-5.14.

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Scenario	PV	ESS	REC-Purchase	Community Energy Costs	Cost Savings	Community CO_2 Emissions	CO_2 Savings
	[kW]	[kWh]	[kWh/a]	[€/a]	[%]	[kg-CO_2/a]	[%]
RC-Without-DR	-	-	-	13,778.50	-	15,281.18	-
RC-With-DR	-	-	-	13,554.91	-	15,281.18	-
OC-Without-DR	46.37	-	20,129.30	11,831.10	14.13	10,899.84	28.67
OC-With-DR	52.22	14.15	23,929.76	11,481.03	15.30	10,076.12	34.06

TABLE 5.11: The results of the greenfield reference (RC-Without-DR and RC-With-DR) and investment scenarios (OC-Without-DR and OC-With-DR) calculated through a cost minimization.

			Without-DR	With-DR
Node	**Grid-Purchase**	**Total CO2 Emissions**	**Total Energy Cost**	**Total Energy Cost**
	[kWh/a]	[kg-CO_2/a]	[€/a]	[€/a]
1	19,972.69	4,707.04	3,618.40	3,639.43
2	5,171.55	1,205.9	1,213.08	1,172.61
3	378.10	88.51	246.24	220.23
4	1,395.14	326.11	451.38	426.28
5	1,816.81	437.94	476.21	470.09
6	14,093.83	3,416.54	3,012.70	2,973.57
7	9,452.83	2,300.86	2,076.61	2,031.58
8	1,803.63	421.54	533.77	516.00
9	9,817.13	2,376.74	2,150.10	2,105.11
Total	63,901.69	15,281.18	13,778.50	13,554.91

TABLE 5.12: RC-Without-DR and RC-With-DR results of each node.

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Node	Grid-Purchase [kWh/a]	REC-Purchase [kWh/a]	Total Energy Cost [€/a]	Cost Savings [%]	Total CO_2 Emissions [kg-CO_2/a]	CO_2 Savings [%]
1	17,038.1	2,934.58	3,401.74	5.99	4,109.12	12.70
2	2,953.54	2,218.01	989.22	18.45	733.25	39.19
3	222.59	155.50	230.55	6.37	55.42	37.39
4	816.95	578.20	393.02	12.93	203.41	37.63
5	1,087.75	729.06	407.37	14.46	261.69	40.25
6	8,614.12	5,479.71	2,459.63	18.36	2,203.69	35.50
7	5,897.95	3,554.88	1,717.82	17.28	1,512.07	34.28
8	1,050.26	753.37	457.73	14.25	261.25	38.02
9	6,091.13	3,726.00	1,774.03	17.49	1,559.94	34.37
Total	43,772.39	20,129.30	11,831.10	14.13	10,899.84	28.67

TABLE 5.13: OC-Without-DR results of each node.

Node	Grid-Purchase [kWh/a]	REC-Purchase [kWh/a]	Total Energy Cost [€/a]	Cost Savings [%]	Total CO_2 Emissions [kg-CO_2/a]	CO_2 Savings [%]
1	16,939.24	3,033.44	3,403.20	6.49	4,090.04	13.11
2	2,374.73	2,796.82	934.93	20.27	606.58	49.70
3	128.04	250.05	180.60	18.00	31.77	64.11
4	598.89	796.26	340.76	20.06	151.78	53.46
5	425.97	1,390.84	328.56	30.11	101.61	76.80
6	8,211.39	5,882.44	2,475.52	16.75	2,145.4	37.21
7	5,217.33	4,235.49	1,680.29	17.29	1,366.73	40.60
8	859.62	944.01	415.86	19.41	219.35	47.96
9	5,216.71	4,600.42	1,721.31	18.23	1,362.86	42.66
Total	39,971.92	23,929.76	11,481.03	15.30	10,076.12	34.06

TABLE 5.14: OC-With-DR results of each node.

Based on the obtained results given in Table 5.11, it can be seen that for both optimization scenarios, the cost minimization invests in PV technologies. In the OC-With-DR scenario the PV capacity is being selected even larger than in the OC-Without-DR scenario. This is due to the fact that in this OC-With-DR scenario, investments are also made in a ESS technology, which means that additional PV electricity can be stored, resulting in a larger PV capacity investment and allowing more renewable electricity to be shared within the REC. Moreover, the reason for also investing in an additional ESS in the OC-With-DR scenario is that power demand rates are considered in this scenario

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and that power peaks can be absorbed by the use of ESS (peak-shaving) resulting in lower peak load-related costs for each community participant. This is illustrated in Figure 5.10, where the optimized electricity purchase of the first 10 days is shown. Figure 5.10 shows that the Grid-Purchase is cut off by the REC-Purchase and thus flattened.

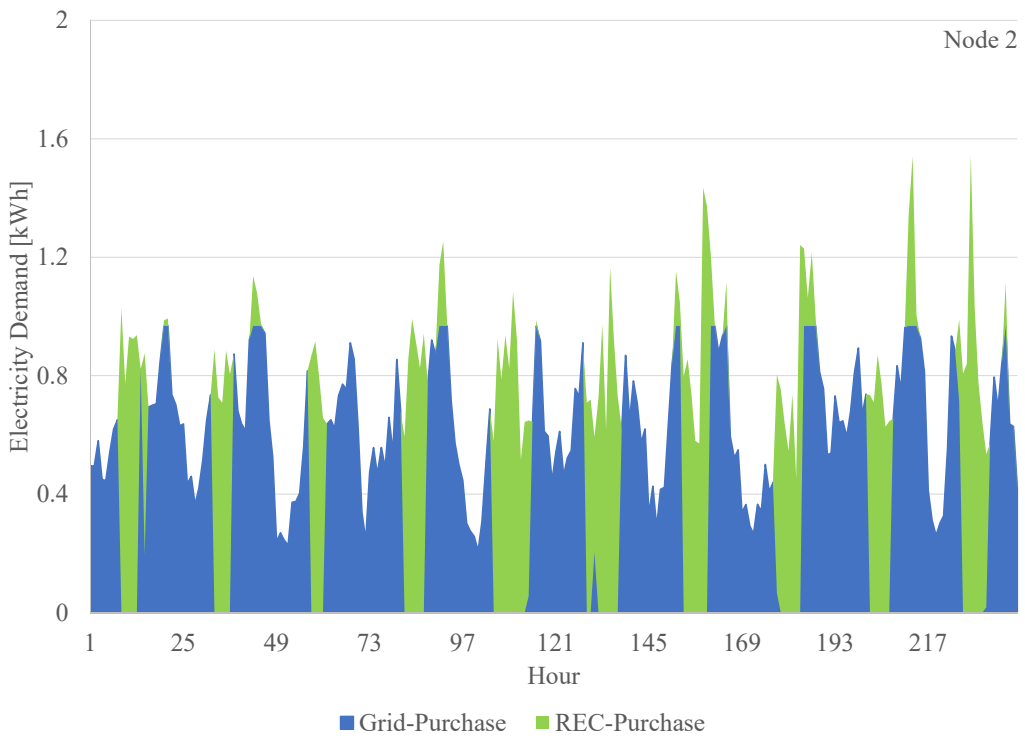

FIGURE 5.10: The calculated electricity purchase from the grid and the REC of Node 2 determined via the optimization scenario OC-With-DR.

In this study, the annualized investment and maintenance costs are allocated to the community participants weighted by the amount of electricity purchased from the REC per node. This means that if a participant purchases more electricity relative to the total REC-Purchase, its investment and maintenance cost share in the technologies will also be correspondingly higher. The optimization results of each node together with the objective function savings obtained from the investment scenarios OC-Without-DR and OC-With-DR are shown in Figure 5.11 and Figure 5.12 respectively.

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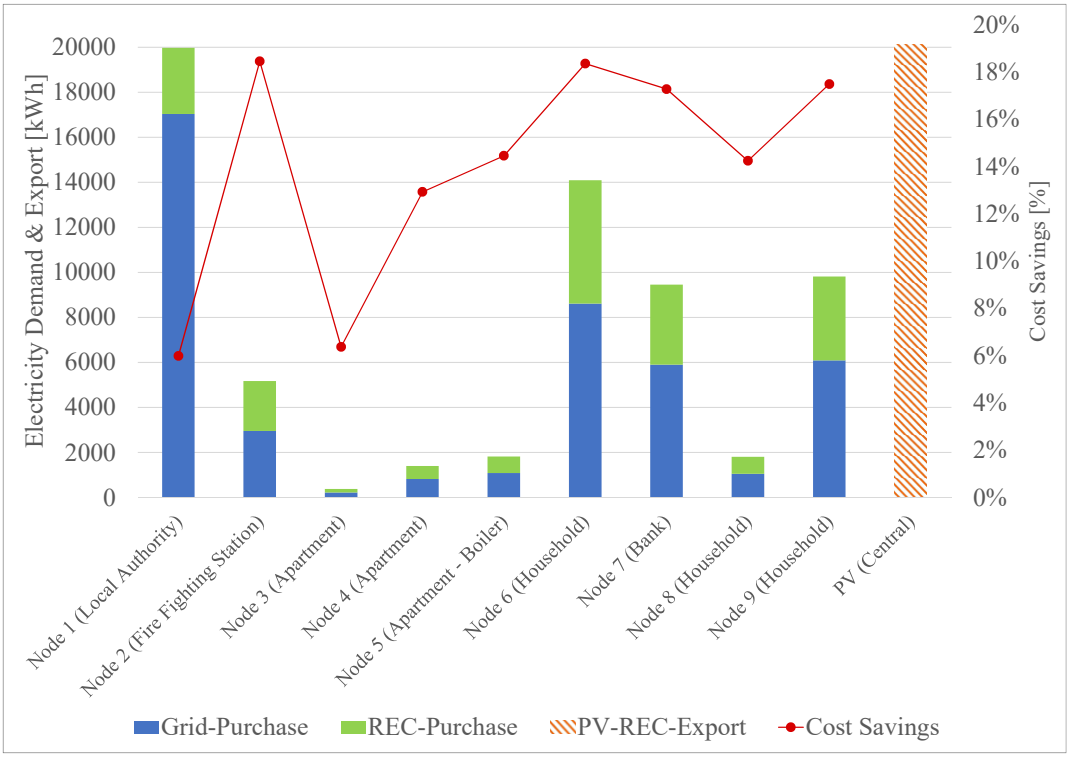

FIGURE 5.11: The annual electricity demand of each REC participant satisfied by the calculated Grid-Purchase and the REC-Purchase together with the cost savings for the optimization scenario OC-Without-DR.

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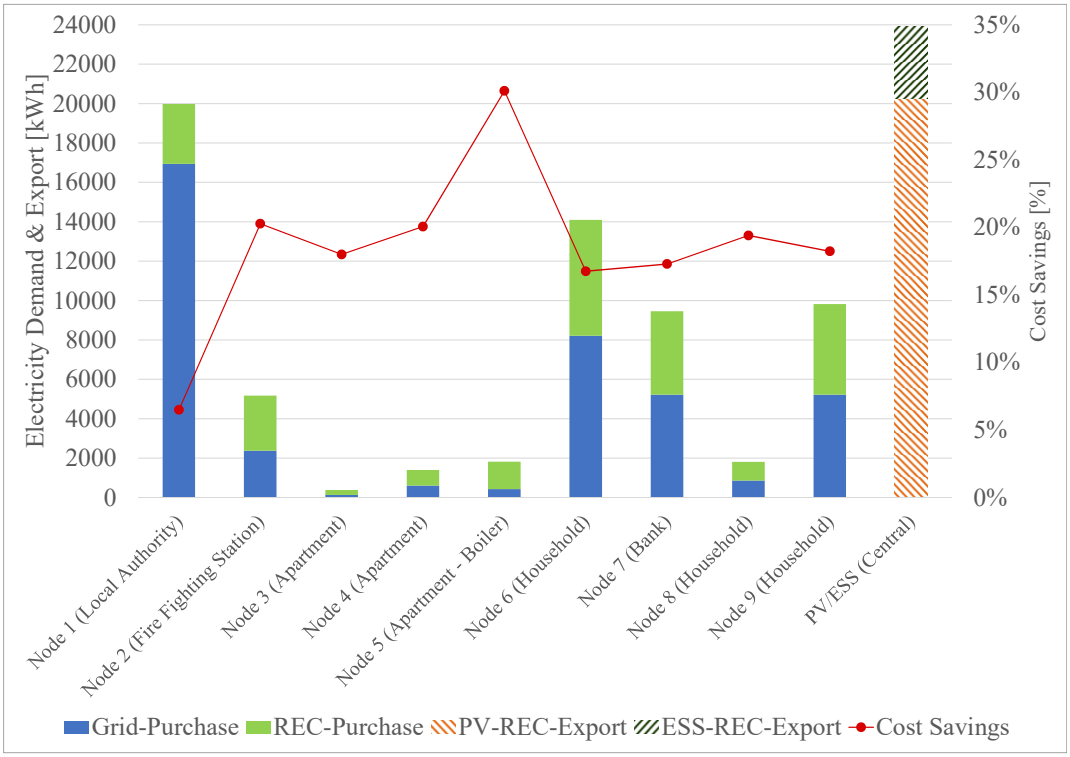

FIGURE 5.12: The annual electricity demand of each REC participant satisfied by the calculated Grid-Purchase and the REC-Purchase together with the cost savings for the optimization scenario OC-With-DR.

The calculated results show that with the invested technologies, the total annual community energy costs can be reduced by 14.13% and the total annual CO_2 emissions can be reduced by 28.67% within the REC in the OC-Without-DR investment scenario. Moreover, they show that each participant in a REC constellation can benefit with a significant cost reduction of at least approx. 6% to a maximum of over 18%. In the OC-With-DR scenario with demand tariffs, the optimization results show an even higher total energy cost reduction of 15.3% and total annual CO_2 reduction of 34.06% within the community. This is due to the larger capacity of the invested PV technology and the additional ESS where the PV electricity can be stored, allowing more renewable electricity to be shared within the REC. This ESS allows to reduce the peak load-related costs in a targeted manner through the additional, time-limited renewable power supply of the community participants from the ESS

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(peak-shaving), when demand rates are used. Furthermore, this additionally increases the total renewable share in the overall electricity supply of the REC, which leads to even lower CO_2 emissions, when investing in a ESS. Thus, the results show that renewable energy communities can significantly reduce both energy costs and CO_2 emissions with the presented MILP-based planning approach, especially when demand-based tariffs are used for the utility purchase.

5.5 Resume

Local and renewable energy communities show a high potential for the efficient use of distributed energy technologies at regional levels according to the Clean Energy Package of the European Union. However, until now there are only limited possibilities to bring such energy communities into reality because of several limitation factors. Challenges are already encountered during the planning phase since a large number of decision variables have to be considered depending on the number and type of community participants and distributed technologies. This research overcomes these challenges by establishing a mixed-integer linear programming based optimal planning approach for renewable energy communities. A real case study is analyzed by creating an energy community testbed with a leading energy service provider in Austria. The case study considers nine energy community members of a municipality in Austria, distributed photovoltaic systems, energy storage systems, different electricity tariff scenarios and market signals including feed-in tariffs. The key results indicate that renewable energy communities can significantly reduce the total energy costs by 15% and total carbon dioxide emissions by 34% through an optimal selection and operation of the energy technologies. In all the optimization scenarios considered, each community participant can benefit both economically and ecologically.

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Chapter 6

Discussion and Synthesis of the Thesis

This chapter provides the discussion and synthesis of the results obtained in this thesis work. In particular, Section 6.1 elaborates on the findings referring to the research questions defined in Section 1.2. Furthermore, Section 6.2 presents the strengths and the limitations of proposed methodology. Finally, Section 6.3 provides suggestions for amendments in future regulation and policymaking based on the results of Chapters 3-5.

6.1 Findings referring to the Research Questions

The main objective of this thesis work is to develop the optimization framework that can decarbonize the multi-energy system microgrids, addressing the research questions defined in Section 1.2. The investigations and results in Chapter 3, Chapter 4 and Chapter 5 provide answers to three research questions respectively and these findings are presented as follows.

Research question 1: *How can we effectively model optimal planning and operation dispatch of a thermal seasonal storage taking into account its non-linear cost vs. capacity relationship using the linear programming models? Also, how do the different temporal resolutions affect the system and the run-time of the optimization models?*

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Chapter 3 considers the development of two different optimization models *i.e.* Opt-3D and Opt-8760 with a different time horizon using MILP modeling framework. The first model uses the time series aggregation methods to reduce the yearly data into three different representative daytypes. The second model considers the full scale time horizon for the same data. The MILP framework considers the minimization of the total annual energy costs and the total annual CO_2 emissions of a thermal energy system having central heating, solar thermal and heat storage as technologies for a case study comprising of eight different scenarios. The non-linear costs related to the technology investments for solar thermal and heat storage technologies are linearized into piecewise affine (PWA) cost functions by using linear fit process and convex combination model. Both of the optimization models consider the fixed linear (Non-PWA) cost functions as well as PWA cost functions for solar thermal and heat storage technologies in all scenarios. A detailed testing and validation of the Opt-3D and the Opt-8760 models have been presented by assessing the accuracy of the time series aggregation methodology and comparing the investment decisions, the objective function savings, the objective function difference and the run time of both models in all scenarios using fixed linear (Non-PWA) cost functions as well as PWA cost functions.

In summary, the Opt-3D and the Opt-8760 models provide comparable results in cost minimization by both using Non-PWA and PWA cost functions for Scenario-1 and Scenario-2 respectively. The investment decision results for CO_2 minimization using Non-PWA cost functions for the Opt-3D model in scenario-1 and scenario-3 are well aligned with the investment decision results for CO_2 minimization using Non-PWA cost functions for the Opt-8760 model in scenario-2 and scenario-4 respectively. However, these investment decisions vary significantly when considering the CO_2 minimization using

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PWA cost functions in scenario-1 to scenario-4 with Opt-8760 model performing better than the Opt-3D model by providing bigger investments in solar thermal and heat storage technologies, thus contributing to a maximum of 76.6% CO_2 savings. In all the scenarios, the Opt-3D model has significant run time savings as compared to the Opt-8760 model because of its lower time resolution. This can be considered a positive result for the cost minimization in scenario-1 and scenario-2 and also in the CO_2 minimization in scenario-1 to scenario-4 using Non-PWA cost functions, since the results do not deviate significantly in terms of objective function difference. But, for scenario-3 and scenario-4, better results are observable at the cost of bigger run time by using the Opt-8760 model. Furthermore, the run time is higher for the optimization runs in all scenarios using PWA cost functions as compared to that of using Non-PWA cost functions due to additional decision variables in both optimization models.

Research question 2: *What is the impact of renewable based hydrogen energy systems in decarbozining the mobility sector using microgrids and how it is compared with the state-of-the-art diesel fuels? Also, how can we drive the paradigm shift from conventional to renewable hydrogen based mobility using carbon prices and policy framework?*

Chapter 4 helps in addressing the urgent and vital issue of the decarbonization in the mobility sector. It considers a regional case study having a real microgrid testbed in Wieselburg, Austria. The main emphasis is to highlight the importance of the renewable energy based hydrogen production, hydrogen seasonal storage and its use by considering a MILP based optimization framework in a microgrid perspective. The investment optimization has a multi-objective setting which considers the CO_2 minimization scenarios with the cost limitations. The case study considers sensitivity analyses relative to two different reference cases *i.e.* the diesel basecase and the utility

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basecase. The diesel basecase considers the conventional diesel fuel and the utility basecase considers the utility electricity based hydrogen fuel. The results include the optimal investment decisions and the operational dispatch of the technologies. A comparison is made between the economic viability, assessed in terms of costs per unit hydrogen fuel consumption and the environmental impact, assessed in terms of CO_2 savings. An economic assessment is performed by comparing the optimization results with the current market costs of the diesel fuel as well as hydrogen fuel in Austria. The H_2-Diesel cost gaps are identified for all the investment optimization scenarios and the carbon prices are calculated to close the H_2-Diesel cost gaps.

With respect to the diesel basecase, the investment optimization results of the energy system are infeasible unless the investment costs are increased by at least 30% relative to the diesel basecase costs. From 30% to 100% increase in the diesel basecase costs, the investment optimization provides a minimum CO_2 savings of 66.32% and a maximum CO_2 savings of 99.21%. These results show that the renewable energy sources, if penetrated highly into the microgrids, can significantly reduce the carbon footprint and make use of the renewable hydrogen fuel to enable the decarbonized energy transition in the mobility sector. Evidently, the seasonal hydrogen storage has an important role in this decarbonized energy transition as it captures the seasonal variability of the renewable energy sources. With respect to the utility basecase, the investment optimization results can be considered as a subset to that of the diesel basecase. The variation in the cost constraint also provides feasible results if the costs are decreased by 20% relative to the utility basecase costs. The most interesting outcome in the utility basecase is that at no further costs, the renewable energy based sources and the hydrogen seasonal storage in the microgrid can provide CO_2 savings of around 94%. At 20% reduced costs, the microgrid still constitutes a large share of renewable energy

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that provides significant CO_2 savings of around 74%. Thus, renewable energy based microgrids are highly desirable as compared to the utility based hydrogen energy systems for the decarbonization of the mobility sector.

From an economic point of view relative to both reference cases, the optimal hydrogen fuel costs (€/kgH_2) are lower than the current market costs of the hydrogen fuel. This difference could be due to not considering the costs related to the delivery of the hydrogen fuel since the hydrogen production, storage and distribution are assumed to be close to the fueling station in this microgrid. Therefore, the hydrogen fuel is considered to be cheaper if it is produced by renewable energy based microgrids close to the point of delivery of the fuel. The optimal hydrogen energy costs (€/kWh) are higher than the current diesel fuel costs in all investment optimization scenarios. These costs would be much larger if the hydrogen production and storage are not considered close to the point of delivery of the fuel due to the transportation and other delivery related costs of the system. This shows the benefit of using renewable energy based microgrids and distributed hydrogen energy systems over the conventional fossil fuel based centralized hydrogen energy systems.

This work provides a trade-off between mitigating the environmental impact by the CO_2 savings and assessing the economical viability in terms of the energy system costs. The trade-off indicates that if the mobility sector has to be decarbonized completely by hydrogen, the current costs of this decarbonization are doubled as compared to the current diesel fuel based mobility framework. Surprisingly, this decarbonization can still provide at least a CO_2 saving of around 66% if the difference of the costs between hydrogen fuel and diesel fuel is only 32%. This draws an attention to make the hydrogen energy price competitive with the diesel fuel price. The introduction of the carbon price as an emission tax for the diesel fuel is considered in this study to close

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the H_2-Diesel cost gaps. The carbon price increases the diesel fuel costs and reduces the current difference of the costs between the hydrogen fuel and the diesel fuel if applied in the policy framework. For achieving a CO_2 saving of around 66%, a carbon price of around 124 €/tonne-CO_2 is estimated on the diesel fuel to make the hydrogen and the diesel fuel costs competitive with each other. For achieving almost 100% CO_2 savings, a carbon price of more than 400 €/tonne-CO_2 is estimated on the diesel fuel to close the H_2-Diesel cost gap.

Research question 3: *How can renewable energy based microgrids contribute towards the clean energy transition set by Clean Energy Package (CEP) of European Commission using Renewable Energy Community (REC) concept? Also, how would a REC based mechanism behave in terms of renewable energy sharing, multiple energy tariffs and mixture of prosumers and consumers in the multi-nodal microgrid structure?*

Chapter 5 addresses the decarbonization of the regional sector via targeted, MILP based optimal planning of renewable energy communities in a microgrid constellation, where the renewable energy can be transferred between nine community participants. It examines and analyzes a real case study, where an energy community testbed was created by a leading Austrian energy service provider in a village in Carinthia, Austria. The study considers the development of a MILP-based optimization framework, where distributed PV generation systems, energy storage systems, different electricity tariff scenarios and market signals are taken into account, so that a real REC setup can be mapped mathematically accurately and optimally planned. The case study considers in total three different reference cases and three corresponding optimization and investment scenarios in a REC setup, where the renewable energy transfer between the participants is enabled.

The first reference case RC-Without-DR-PV represents the current status of

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the participants and considers the three existing PV systems where the PV surplus can only be fed into the grid. The associated optimization case OC-Without-DR-PV determines by how much the total PV self-consumption of the REC can be increased and thus how much total annual energy costs and total annual CO_2 emissions can be saved with the prevailing tariff scenario, when the renewable energy transfer between the participants is enabled. The second and third reference case RC-Without-DR and RC-With-DR are greenfield scenarios with different tariff schemes in each case (one without and one with demand rates), where no existing PV technologies are considered. The corresponding investment and optimization cases OC-Without-DR and OC-With-DR determine how much is invested in new PV and ESS technologies and thus how much energy costs and CO_2 emissions can be saved with the optimally chosen technology capacities. For all cases, the total annual energy costs and the total annual CO_2 emissions are calculated through a cost minimization of the optimization model.

In summary, the optimization results of the first OC-Without-DR-PV case show that the total PV own use of the REC can be increased from 26.5% to 65.2% only by enabling the renewable electricity transfer between the participants. Through the additional possibility to purchase renewable electricity from the REC at a lower tariff, the total annual energy costs can be reduced by 8.73% and the total annual CO_2 emissions can be reduced by 14.7% within the REC at the same time. For the greenfield optimization scenario OC-Without-DR, the cost minimization only invests in central PV technologies, resulting in total annual energy cost savings of 14.13% and total annual CO_2 savings of 28.67%. However, the greatest savings are achieved in the greenfield optimization scenario OC-With-DR with demand rates. In this case, investments are also made in central ESS technologies, which are primarily used for peak

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shaving and thus further reducing the peak load-related costs for each community participant. Here the optimization results show a total energy cost reduction of 15.3% and total annual CO_2 reduction of 34.06% within the community.

Overall, the key results of this work indicate that REC can significantly reduce the total energy costs and CO_2 emissions through an optimal selection and operation of the distributed energy technologies if the renewable energy is transferred and shared between the community participants. Moreover, all optimization scenarios performed via the presented MILP-based planning approach show that each community participant can benefit both economically and ecologically with the optimal sizing and full-year operational dispatch of the corresponding technologies, regardless of the electricity tariff scenario selected. However, the greatest cost benefit can be achieved if investments in additional technologies or energy storage systems are enabled. This allows to reduce the peak load-related costs in a targeted manner through the additional, time-limited renewable power supply of the community participants from the ESS (peak-shaving), when demand rates are used.

6.2 Strengths and Limitations of the Proposed Methodologies

The field of modeling a microgrid based energy system is actually complex and depends upon various factors such as quality of data, detail of the model, assumptions and their impact on the real-world examples. Like any other research work, the modeling framework proposed in this thesis to address the research questions has some strengths and limitations which are summarized below.

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Overall, all of the three models that are developed in Chapter 3 to 5 are mixed-integer linear programming based. These models have been developed using practical assumptions and have been applied to different case studies having real-world applications. Even though, there exists non-linear relationships between different variables of the considered technologies in real-world, the models are linearized and complexity as well as computational effort are reduced. From the system perspective, these models can be adapted and used for a case study in any other country. Therefore the transferability of the modeling framework across different countries is also a strength of the proposed methodologies.

The time-series data for the electrical and thermal loads, mobility demand, production from DER technologies, utility tariffs and marginal CO_2 emissions from the utility are considered to be perfect foresight based on authentic references. This perfectly foresighted time-series data is deterministic in nature and does not involve uncertainties. This is a limitation of the developed models which can be avoided by considering the stochastic parameters using probabilities to model uncertainties.

In Chapter 3, the model uses the PWA technique to convert the non-linear cost vs. capacity relationship of thermal storage and solar thermal. Although the linear segments are fitting over non-linear relationship with minimal residual errors, this methodology uses binary variables which increase the computational run time as compared to not using the binary variables in a mixed-integer linear programming models. Even though the Opt-3D model does not consider the connectivity between different daytypes, its optimization results are aligned with those of Opt-8760 model for cost minimization runs and significantly lower computational time is observed as compared to that of Opt-8760. But, the CO_2 minimization runs of Opt-8760 with PWA are better than that of Opt-3D because of the connectivity throughout the year

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and at the same time the computational time is significantly higher as compared to Opt-3D. This is a limitation of Opt-3D model where connectivity can be considered at the cost of model complexity and higher computation run time.

In Chapter 4, the hydrogen demand for the overall fleet is designed based on the weekly fueling frequency and then extrapolated to the yearly time-series data. This extrapolation to the yearly time-series is a limitation because the demand can change based on the monthly and seasonal variation. The hydrogen production, storage and distribution are assumed to be close to the fueling station in this microgrid. This neglects the cost of hydrogen delivery which can impact the overall hydrogen optimal costs and its comparison to diesel fuel costs.

In Chapter 5, the model considers energy transfer among multiple nodes of the microgrid in a community setting. Even though the model is quite complex considering various decision variables for solar PV and ESS transfer between nodes, it is limited in not considering the losses incurred during energy transfer and the infrastructure of distribution network such as cables and transformers etc. Also, the power flow can be considered for the energy transfer among nodes of the community. This can impact on the total energy being transferred in the community and change the total objective function savings. Additionally, The model does not consider any distribution algorithm by which the total annual energy cost savings and total annual carbon dioxide emission savings of the community can be distributed among all participants as a result of their participation.

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6.3 Suggestions for Amendments in Future Regulation and Policymaking

The energy storage technologies play an important role in the renewable energy based microgrids. Energy storage technologies including battery storage, thermal storage and hydrogen storage provide flexibility when used in the renewable energy based microgrids. In heating sector, the thermal energy storage can make use of the seasonality behavior and significantly reduce the total energy costs and total annual carbon emissions if deployed correctly. It is crucial and important to realize for policy makers to pursue a path of moving away from fossil fuels while still satisfying the heating demand across the EU to achieve the goals of the "Clean Energy for All Europeans" package [80].

The regulation and policy should emphasize on the initial potential assessment of thermal seasonal storage demonstration projects across the EU countries and communicate the potential benefits to the prosumers as well as commercial end-users. The current barriers for the thermal energy storage are the high upfront capital costs and gradual uptake of the renewable heating technologies. These barriers need to be overcome by regulating the costs of the thermal storage technologies and making a policy for awareness in the society to drive the use of it. One possible way to show the benefits of the seasonal thermal storage is to increase the number of demonstration projects and provide deployment support in terms of incentives for the new customers in terms of subsidized technology costs and time-of-use or price signals for the use of district heating which can cause the time shifting usage and most likely drive the use of renewable energy based heating sources together with both the short-term and the long-term seasonal thermal energy storage.

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The production, storage and use of hydrogen fuel can decarbonize the mobility sector when it is produced via renewable energy based electrolysis process, but only 4% of the current global production of hydrogen is electrolysis based, and not all of its production is via renewable energy at the moment. This imposes a need to create a policy that can drive the use of electrolysis using renewable energy sources. This will also drive to achieve the targets of the "Net Zero by 2050" roadmap [141] not only in the mobility sector but also in other sectors where electricity can not meet the end-user demand. Currently, the manufacturing capacity of electrolyzers is one of the key barriers that needs to be addressed. The technology costs of electrolyzers need to lowered down by the introduction of regulation and rolling-out of electrolyzers and successful deployment has to be managed by strong policymaking strategies.

The most important barrier for the hydrogen fuel in the mobility sector is its overall cost of usage at the demand side. It is significantly higher than the conventional fossil fuels and the regulation needs to be introduced to make it competitive with the market prices of fossil fuels for its successful deployment. This thesis provides the necessary policy framework to introduce the carbon prices or carbon tax on the use of fossil fuels to drive the usage of hydrogen over the conventional fossil fuels in order to decarbonize the mobility sector. This policymaking strategy needs to be implemented and regulated throughout the EU countries in order to give boost to the process of achieving net zero by 2050 targets. Also, the standards of hydrogen production, storage and usage need to be harmonized across the sectors and countries. This can reduce the complexity of using hydrogen based energy systems in microgrids if regulated using harmonized standards.

Although the Directive 2018/2001 [81] defines the renewable energy communities for the EU, different countries have different strategies and timelines to

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actually implement the aspects of renewable energy communities in their legislation due to different national regulation and policymaking. This is causing delay in the deployment of the renewable energy sharing concept among different participants of the community and therefore, facing potential challenges from system implementation aspects. For Austria, the energy communities framework is defined by the Erneuerbaren Ausbaugesetzes (EAG) [84] and is in the process of legal implementation.

The regulation needs to be introduced in making it possible for the prosumers to share the energy with other participants of the community with transparent and legally binding energy contracts, either in terms of peer-to-peer transactions or incentives from the utility companies. Furthermore, the demonstration projects need to be established for analyzing the potential of energy communities using renewable energy sources and the outcomes need to communicated with potential prosumers with transparency. Policymakers need to define different tariff schemes for energy sharing among participants. These tariffs can be classified into different types based on the technologies used to transfer the energy and the amount of energy sharing. Finally, the social welfare or the overall savings in terms of energy costs and emissions needs to be distributed in fair, transparent and systematic ways in order to keep the competition of energy sharing among different participants.

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Chapter 7

Conclusion and Future Outlook

The increasing global energy demand, increasing carbon footprint, depletion of conventional energy sources and the conventional grid infrastructure call for the need of urgent and strong actions to provide solutions to the world's energy problem. While there are many other strategies to contribute to the solution of these problems, renewable energy based microgrids are on the rise. The main goal of this thesis is to provide the optimal planning and operation strategies that can decarbonize the multi-energy system based microgrids.

Microgrids have the capability to provide the flexibility to the grid by using distributed energy resources close to the end-user demand and increase the reliability of the energy supply as well as the efficiency of the overall system if designed and implemented correctly. Therefore, optimization techniques are required to design the microgrids with respect to planning and operation. This thesis uses mixed-integer linear programming framework to develop three different optimization models that consider various distributed energy resources in different energy sectors and are applied to different case studies in Austria. The modularity of the models developed in this research work enables them to be used for similar case studies across other countries and possibly extend them by including new technologies and sector coupling for future implications.

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The modelling of thermal energy storage system with seasonal behavior is important for microgrids as it can provide significant flexibility and utilize maximum surplus of the solar thermal energy. This thesis develops two different optimization models, Opt-8769 model has full scale yearly time-resolution of 8760-hours and Opt-3D model has lower time resolution based on 3 representative days in each month of the year. These models investigate the challenges of seasonal thermal energy storage in microgrids. Moreover, the non-linear cost vs. capacity behavior of thermal energy storage is linearized using piecewise affine functions to correctly reflect the costs of the storage relative to its size. The results show that the seasonal behavior of thermal energy storage in a microgrid can have a significant effect when considering the full scale optimization modeling using piecewise affine cost functions, but the computational run time for solving the optimization model can be significantly larger. Therefore, further work is necessary to develop an understanding on how the optimal seasonal storage planning and operation can be achieved by using models like the Opt-3D, but with connected day-types, and present a comparison between the optimal sizing and dispatch of technology portfolio, objective function accuracy and computational resources. Also, the water heating demand can be considered together with space heating demand depending upon the application of the system under study. Furthermore, the uncertainties can be introduced to the load and the weather input data and modeled using stochastic techniques to realize the dynamic effect of the inputs on the results. This can increase the computational effort for both models because of the additional model variables and equations.

The real deployment of the hydrogen electrolyzer, hydrogen seasonal storage, and hydrogen use in the mobility sector have been modeled, investigated and analyzed in this thesis work by possible extension of the only

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microgrid test facility in Lower Austria. The model is based on the mixed-integer linear programming based optimization technique that considers solar PV and wind power as renewable energy sources in combination with utility electricity. The end-user demand of the hydrogen fleet consisting on three different types of mobility is created from the combination of real schedules and the yearly statistics of the transport sector in the region. The framework considers multi-objective optimization where total annual CO_2 emissions are minimized by keeping a limit on the total annual energy costs of the microgrid system. The main goal is to investigate the scenarios for the decarbonization of mobility sector using the developed model and analyze the hydrogen fuel costs as compared to conventional diesel fuel costs. The results indicate that current costs of the complete decarbonization of the mobility sector by developed hydrogen energy system model in the microgrid are double as compared to the current diesel fuel based mobility network. This draws an attention to introduce a policy framework in terms of carbon prices or carbon tax over conventional diesel fuels to make the hydrogen fuel costs competitive with conventional diesel fuel costs if decarbonization of the mobility sector has to be achieved. Otherwise, it is not cost efficient as compared to current market situation. Therefore, carbon prices need to be introduced using future regulation and policymaking. In this context, the future work may include to explore more ways to generate hydrogen such as from biomass and compare it with conventional fuels. Also, the comparison can be made with the electric vehicles to satisfy the same mobility demand and investigate their feasibility in comparison to both electrolysis based hydrogen fuels and conventional fuels.

The concept of renewable energy sharing among community members of a microgrid shows promising potential and effective use of distributed energy

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resources. The setup of energy community with multi-nodal structure of microgrid is much more complex than a single node based microgrid system. The mechanism of energy sharing, the design of tariffs for energy sharing and overall objective function need to be modeled correctly in order to draw practical analysis for successful deployment of renewable energy communities. This thesis develops a mixed-integer linear programming model for the optimal planning and operation dispatch of renewable energy community testbed in Austria having nine different participants. The distributed energy resources include solar PV and battery energy storage system. Different electricity tariff scenarios are considered together with market signals. The results of the optimization scenarios indicate that each community participant can significantly benefit form the energy sharing mechanism in terms of both cumulative annual energy costs and annual carbon dioxide emissions savings. The future work may include the distribution of these savings among different community participants based on their extent of participation and cooperation via game-theoretic techniques having fair, transparent and regulated scheme. This will also help energy system planners to consider various energy sharing strategies in the field of cooperative optimization.

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