Identification of a Validation Method for Open Source Simulation Tools and Application of Said Method to the MVS

Multi-Vector Simulator
Sector Coupled Systems

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Sector Coupled Systems

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SUMMARY

Traditionally, the different energy sectors, such as electricity and heat, are planned and operated separately and independently from each other. In the 1990s, electricity generation in Europe was dominated by conventional fuel sources like coal and oil, followed by gas. Due to the eventual depletion of those sources, and to escape from the dependence on them, renewable energy technology was promoted and brought into the energy mix. With the progress in decarbonizing the electricity sector, the importance of decarbonizing other energy sectors, like heat and transport, increased. Sector coupling is introduced as a new energy paradigm in order to curb climate change and overcome its vagaries. Modernized energy networks are considered as highly complex systems and as a result, modelling and simulation of energy systems has become invaluable and fundamental for their development and implementation. A simulation model is often a replication of a real life system, therefore a model is abstract by nature. Implementing a model then using it without validation may cast wrongful solutions due to improper assumptions. This thesis identifies a validation scheme for open source multi-energy vector simulation tools.

There are two steps to judge whether a model is correctly representing the problem of interest: the first ascertains that the model is implementing the theories and assumptions accurately, and the second determines whether the model's output is reasonable with respect to the real system. Those two processes are known as verification and validation respectively. This study identifies three methods to validate simulation tools for sector coupled systems: conceptual model validation, model verification and operational validity. Each method uses several techniques to assess the model and its output behaviour. The thesis also underlines the importance of validating a model using a real world problem. This derived methodology is applied to the Multi-Vector Simulator (MVS), a tool developed under the Horizon 2020 project E-Land. The MVS is open source which is why it is important to validate all its features using various techniques in order to increase its credibility and potential. The validation tests' results show that the basic functionalities of the MVS work without fault. Still, some areas in which the MVS can be improved were identified by running a number of simulations. However, there is a lack of compatibility when comparing some scenario results to HOMER. The discrepancies can be explained by the different definitions of certain indicators but also by the difference in modelling some components. This means that HOMER cannot completely validate the MVS. Lastly, the MVS is applied and validated using a case study based on a pilot project in E-Land. This part of the thesis played a crucial role in the validation process and shed light on the importance of having real life case studies to validate a model.

The verification and validation method is dependent on the simulation model in question. Other tools may require additional validation techniques. Further research can thus be addressed to real life case studies and comparison to other validated models.

Preface

Growing up in Lebanon with a never-ending electricity problem, as fuel shortages and daily power cuts became a normal life routine due to corruption, mismanagement and lack of expertise, made me acknowledge the necessity for alternative energy sources. The country actually has a vast renewable energy potential which could be harnessed to carve a path to a just energy transition. I enrolled in the Master of Science in Sustainable Energy Technology at the Technical University of Delft in order to understand how this could possibly be realized. This program highlighted the importance of overturning the anthropogenic climatic impacts and expounded the "energy trilemma" idea – the interactions between cost, reliability and the environment. Integrating economic and societal aspects into sustainable energy projects, innovation processes, policies and transitions is indeed a path towards a cleaner and greener energy future.

This thesis applies the acquired knowledge from the course and seeks to identify a validation method for open source simulation tools for sector coupled systems. It includes a case study around a pilot site from the Horizon 2020 project E-Land. Thereupon, I would like to thank Reiner Lemoine Institut and the Offgrid team for this opportunity that allowed me to write my master's thesis with a practical/application orientation approach. Special thanks to Martha who continuously supported me and guided me throughout, this could not have been achieved without her. I would like to express my gratitude for Dr. Milos Cvetkovic who patiently provided me with feedback as well as unwavering guidance and support.

Ursula El Mir
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Acronyms

AIAA American Institute of Aeronautics and Astronautics

ASME American Society of Mechanical Engineers

BDEW Bundesverband der Energie- und Wasserwirtschaft

BOS Balance of System

CCHP Combined Cooling Heat and Power

CHP Combined Heat and Power

CO_2 Carbon Dioxide

COE Cost of Electricity

COH Cost of Heat

COH2 Cost of Hydrogen

COP Coefficient of Performance

CRF Capital Recovery Factor

DHC District Heating and Cooling

DHI Diffuse Horizontal Irradiance

DMSO Defense Modeling and Simulation Office

DNI Direct Normal Irradiance

EC European Commission

ECMWF European Centre for Medium-Range Weather Forecasts

EDI Dutch Energy Delta Institute

EHMS Energy Hub Management Systems

EU European Union

EVs Electric Vehicles

FIT Feed-In Tariff

GGE Gasoline Gallon Equivalent

GHI Global Horizontal Irradiance

GKO Gebietskörperschaften, Kreditinstitute und Versicherungen

HOMER Hybrid Optimization of Multiple Electric Renewables

HRE Heat Roadmap Europe

HVACR Heating Ventilation Air Conditioning and Refrigeration

ICSTM Institute of Multidisciplinary Research for Science and Technology

ICT Information and Communications Technology

IEEE Institute of Electrical and Electronics Engineers

IPCC Intergovernmental Panel on Climate Change

IRENA International Renewable Energy Agency

IRR Internal Rate of Return

JOSS Journal of Open Source Software

KPIs Key Performance Indicators

LCOE Levelized Cost of Energy

LP Linear Programming

MES Multi-Energy System

MVS Multi-Vector Simulator

NPC Net Present Cost

NZEB Net-Zero Energy Building

O&M Operation and Maintenance

oemof Open Energy Modelling Framework

PV Photovoltaic

REmap Renewable Energy Road-maps

RLI Reiner Lemoine Institut

ROE Return on Equity

SOC State of Charge

TES Thermal Energy Storage

UVTgv Valahia University of Targoviste

WACC Weighted Average Cost of Capital

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1

Introduction

This chapter introduces the subject, scope and goals of the thesis and provides some sort of map to the overall research. The first section presents the background and motivation for this thesis, followed by a section that sets the research objective. The research questions are then provided for a better overview of the topic, split between the general (or main) question and the sub-questions with more detail. In the last section, the rest of the chapters are outlined to depict the comprehensive approach to the thesis.

1.1. Background and Motivation

The year 2020 was set out as a major critical key year for climate change by most of the international organizations as it is expected to involve a higher worldwide ambition aiming to change - and perhaps reverse - the pattern of impacts [25]. Considering how clean, cheap and inexhaustible renewable energy is, it is said to play a significant and indispensable role in achieving that “inflection” point by reshaping the energy sector. The past decade has seen great integration of renewable energy, but the continuously increasing energy demand is shadowing its true effect on the trend and diminishing its full capacity. This introduction of renewable energy technology was, and still is, an actuator in the chain of improvement of other parts of the energy sector, be it a component, a system solution or a business model. Together, these novel advancements are capable of reducing a considerable amount of the anthropological footprint.

Sustainable energy technology has proven itself, for some time now, to be pivotal for the low carbon, green energy transition and reduction of Carbon Dioxide (CO_2) emissions. Nonetheless, the stochasticity feature of solar and wind power introduces a clear level of uncertainty to the supply side of the energy system. A crucial necessity today is a shift from a demand-led energy system to one in which both supply and demand are controlled [26]. In 2018, the share of renewable energy in the European Union (EU) was 18.9% while the binding Union targets are 20% for 2020 and at least 32% for 2030 [27].

1

The increased share of variable renewable energy, and thus the volatility of generation, highlight the pressing need for modern energy management systems to optimize assets capacity and dispatch. Such systems require improved forecasts and interoperability, which lead to the upgrade from the aging, one-way interaction energy infrastructure to smart grids with two-way dialogue enabling the exchange of electricity and information. Through bidirectional communication, demand flexibility can be harnessed, implying that the electricity consumption can be shifted across the hours of the day to allow the penetration of a larger share of variable renewable energy and decrease curtailment [28].

According to the European Commission (EC), buildings in the EU consume 40% of the energy produced and contribute to 36% of the CO_2 emissions [29]. This stresses on the need to focus on improving energy efficiency in order to meet the national and international set goals. One way to accomplish this is through decentralized energy generation, which reduces transmission losses indeed, but also allows the integration of co-generation or trigeneration units, such as Combined Heat and Power (CHP) and Combined Cooling Heat and Power (CCHP), respectively [26]. The latter is a technology that produces electricity and captures the heat that is usually wasted in conventional power plants. In turn, this thermal energy could be used for heating, cooling, hot water or even industrial processes [30].

Furthermore, the interactions of different energy components like power and gas were relatively unexplored in the past and controlled independently. In 2017, the natural gas and renewable energy shares for heat production were 39.2% and 26.5% respectively [31]. The current trend is to introduce sector coupling by interconnecting the energy-intensive sectors with electricity mainly produced from renewables, making it the default form of energy. This link is considered particularly promising taking into consideration the low costs of electricity generation. In the context of smart grids, power systems are also coupled with the Information and Communications Technology (ICT) domain [32]. An example of an integrated energy system based on renewable energy power-to-heat, power-to-gas and power-to-mobility is shown in Figure 1.1.

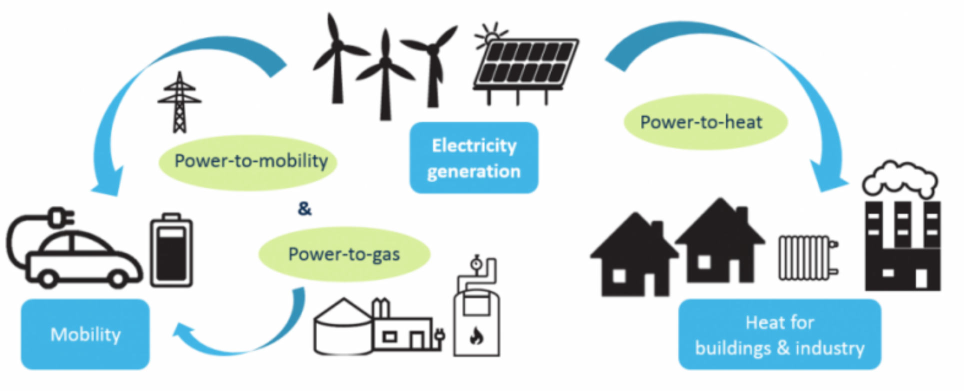

Figure 1.1: An Integrated Energy System Based on Renewable Energy [3]

Reshaping the energy system would then foster enhanced adequacy, stability and reliability and decrease the costs of decarbonization [33]. With the high penetration of renewable energy and as these energy system supply networks become more coupled, understanding the exchanges between them is integral to a successful holistic management system. A multi-energy vector framework is thus needed to create a dynamic and flexible energy system allowing the interactions between its different constituents [34]. In 2014, the Intergovernmental Panel on Climate Change (IPCC) expounded that an energy system "comprises all components related to the production, conversion, delivery, and use of energy" [35]. With that in mind, energy systems are becoming more and more complex and one way to study them is through modelling and simulation. Therefore, the adoption of a multi-energy vector simulation tool stems from the necessity of (1) having a tool that can deal with such complexity and (2) achieving synergy between all sorts of energy carriers in the system.

This thesis is part of the development of the Multi-Vector Simulator (MVS) tool[1] at Reiner Lemoine Institut (RLI) within the scope of the Horizon 2020 project E-Land[2]. The concept is to develop an integrated local management system for Energy-isLANDs by delivering a toolbox with "a modular set of methodologies and ICT tools to optimize and control multi energy islands and isolated communities" [36]. By offering a solution for energy security and decarbonization, the project supports the EU energy policy and contributes to 2030 Climate and Energy objectives[3]. The MVS is open source and has three features: it can create and analyze an energy system techno-economically based on the components costs and performance parameters, then optimize the assets' capacities, dispatch and investments by minimizing the cost of electricity generation, heat and/or hydrogen and finally it can simulate more sustainable energy transformation scenarios for the future (e.g., 100% renewable energy supply).

1.2. RESEARCH OBJECTIVE

Most of the energy system models and modelling frameworks are viewed as black boxes but the past years have seen several public releases, listed on the Open Energy Platform [37]. The building process and stages of the energy model should be open and transparent [2], as shown in Figure 1.2. The MVS is a multi-energy vector simulation tool for sector coupled systems that uses the library *oemof-solph* from the Open Energy Modelling Framework (oemof) [4], which is a *Python* toolbox for energy system modelling and optimization. The idea of having an open source simulation tool instead of a proprietary software is to make source codes available for everyone to use, enhance or even learn from. From an end-user perspective, such an availability saves considerable acquisition costs.

The open source code movement has been on for decades now and with it, the question of reliability and robustness. A primary means to assess the accuracy of simula-

[1] https://github.com/rl-institut/mvs_eland
[2] https://elandh2020.eu
[3] https://ec.europa.eu/clima/policies/strategies/2030_en#tab-0-0
[4] https://oemof.org

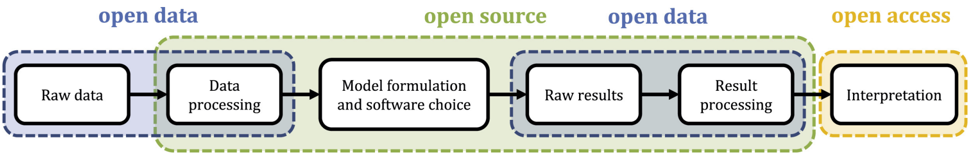

Figure 1.2: Open Source Energy Model Stages [4]

tion models is through verification and validation procedures which would very much improve the credibility of the engineered system, even under different conditions and drastic scenarios. Although the terminology used to define verification and validation might not be totally uniform, the concepts behind both remain the same. Verification is technically the task of identifying and discerning the correctness of the model, and validation determines the level of accuracy of the simulation model vis-à-vis the real-life system [38].

1.3. RESEARCH QUESTIONS

The following study focuses on identifying a validation method for multi-energy vector simulation tools. With the relevant context and research, several techniques are explored in order to develop the right and most convenient method that is applicable to the MVS. To further validate the tool, this thesis also looks into the energy system of one pilot project under E-Land, the campus of Valahia University of Targoviste (UVTgv), optimizes its status quo and near-future investments. The last part evaluates future scenarios that aim at higher sustainability goals through the integration of a bigger share of renewable energy technology. The goal is captured as a whole in the main research question, which in turn, is divided into three sub-questions to depict the flow of the work.

1.3.1. MAIN QUESTION

This thesis' main research question is:

How can an open source simulation tool for sector coupled energy systems be validated and put to use to optimize the energy system of UVTgv campus?

1.3.2. SUB-QUESTIONS

The work flow is divided into the following three sub-questions:

1. *What are the advantages of sector coupled systems and what is the role of multi-energy vector modelling and simulation in achieving energy efficiency and sustainability?*

2. *What is the required methodology to validate an open source simulation tool and increase its credibility? How can this be applied to the specific multi-energy vector simulation tool "MVS"?*

3. *Which role can an extensive case study play in the validation process? What are the possible energy supply scenarios for the exemplary pilot project UVTgv campus?*

1.4. THESIS OUTLINE

Chapter 2 provides a comprehensive and rigorous literature review and introduces the context of the thesis. Chapter 3 focuses on the verification and validation of simulation models, and identifies the applicable tests upon which a validation scheme for the MVS tool is proposed. Chapter 4 describes the implementation of this validation method by types and techniques. Chapter 5 formulates a case study around UVTgv campus' energy system by looking into the current scenario and investigating a possible, but more sustainable, future one. Finally, Chapter 6 discusses the outcomes of the validation tests and method as well as the MVS application and limitations to conclude the study with suggestions for further improvements and research.

2

Literature and Context

This chapter covers the thorough literature review with a focus on the necessary information for this research in order to shape the context of the thesis as presented in the first chapter. Section 2.1 looks into sector coupled systems and their advantages with regard to the energy transition. Section 2.2 builds on the previous one to reveal the need of multi-energy system modelling and simulation in order to account for the different energy carriers in the coupled systems. Lastly, Section 2.3 introduces the pilot project considered for this study.

2.1. Sector Coupled Systems

The period for energy transition to curb climate change has already started and the reduction of CO_2 emissions is at its heart. The prioritized target worldwide is to deep-cut emissions in the power sector, which is currently on track and likely to achieve the set goals. These efforts should be sustained, yet the perspective should widen to come to grips with a greater focus on the systems of the entire energy sector. This means that the transition should go beyond the power sector and span other sectors too [6]. To address that challenge, electrification through renewables should broaden to the energy-intensive sectors such as heating, cooling and transport. This interconnection bringing clean electricity to other end-use sectors is called sector coupling.

2.1.1. Renewable Energy in the Heat Sector

In 2017, 19.5% of the total energy used for heating and cooling in the EU was generated from renewable sources, which marks a significant growth from 10.4% in 2004 [5]. The percentage share for each EU country is shown in Figure 2.1. “Currently, demand for heating in buildings and industry outweighs demand for cooling” [39]. However, the demand for air conditioning and refrigeration is growing so fast that it is catching up to the heating demand. In 2030, it is expected that the demand for cooling increases by 72% while the demand for heating drops by 30% in the EU [40]. In general, the projections for the global energy demand for heating divulge an increase until 2030 followed by a stabilisation [39].

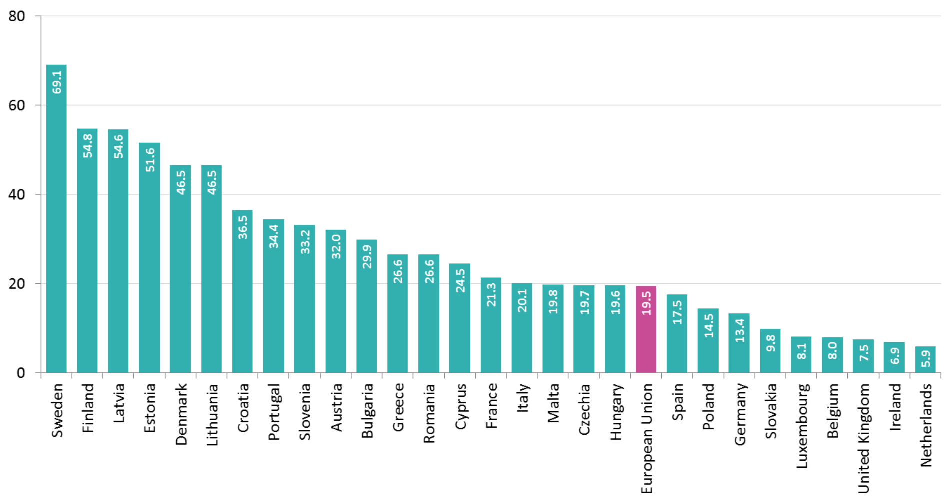

Figure 2.1: Share of Total Energy Used for Heating and Cooling Coming from Renewable Sources in 2017 [5]

Based on the Renewable Energy Road-maps (REmap) for 2050 of the International Renewable Energy Agency (IRENA), the final use of renewables would be fourfold what it was back in 2017. Figure 2.2 shows that the power and heat sectors would consume respectively about 40% and 44% of the total renewable energy production [6].

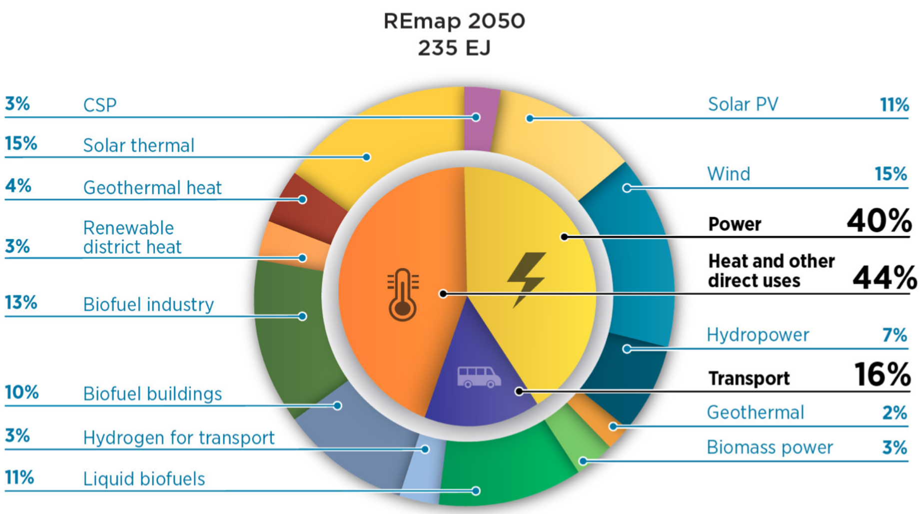

Figure 2.2: Renewable Energy Share by Sector and Technology in 2050 [6]

2

IRENA's findings reveal that "renewable energy and energy efficiency measures can potentially achieve 90% of required carbon reductions" and that "the share of renewable energy must meanwhile rise from around 15% of the primary energy supply in 2015 to around 65% in 2050" [6]. This gain includes end-use sectoral approaches, in Electric Vehicles (EVs) and heat pumps for instance, which would have already gathered momentum by then. The current share of electricity is one-fifth of the total energy consumption and it is estimated to increase up to 30% in 2050 by means of sector coupling with renewable power [6]. Examples of that would be the rise in number of EVs, as well as the introduction of innovative solutions for other activities in transport such as shipping. As for cities and buildings, new designs and constructions should be of the highest efficiency and allow the integration of renewable energy, while existing premises should be restored and reconditioned to the most achievable energy-efficient state.

With that comes the role of the countries and governments in facilitating the adoption of such technologies by enabling the right infrastructure (e.g., electric charging stations and smart grids). This kind of major transformation of the energy sector requires long investment cycles along a sufficient time period to fulfill the needs of innovation and not delay its start and progress. Each process would involve increased investments to adopt new solutions and allow technology transfer, complemented by new market designs, policies, financing mechanisms and business models [6]. At the moment, renewable energy deployment in sectors other than electricity is still lagging but with the right adaptation measures, a boost is to be expected. For instance, Germany is considered a pioneer in renewable energy and a front-runner with respect to wind and solar energy use [41]. In the early 1990s, electricity consumption from renewable energy sources was about 3% while by the end of 2016, it amounted to 32% approximately. In contrast, the renewable share fulfilling the heating and cooling demand was 2% in 1990 and 13% in 2016 [42]. The aforementioned values are for Germany but comparable statistics can be discerned in other industrialized countries [10].

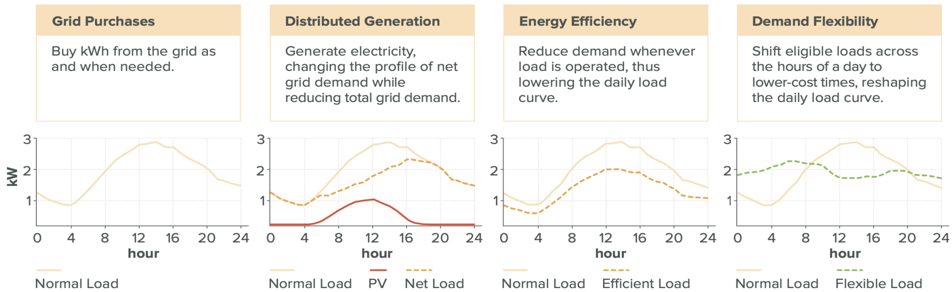

Figure 2.3: Load Improvements in Different Scenarios [7]

Figure 2.3 portrays the changes in a load profile due to the introduction of a innovative technologies or concepts. It considers three scenarios, distributed generation, energy efficiency and demand flexibility, and compares the new load to the normal load fulfilled from grid purchases. Each example merely shows the improvements and gains from the different pathways. Those positive impacts accentuate on the bigger picture, the need of a new energy paradigm to attain nation-wide and global sustainable development of energy systems.

2.1.2. DEMAND FLEXIBILITY

Future power systems operation is becoming more complex with the high penetration of renewable energy, together with distributed energy generation and sector coupling. Since the integration of some renewables comes with uncertainty and intermittency, opting for a new mitigation strategy is attractive. Accordingly, demand response is introduced, which is "the ability to control electrical energy consumption based on power grid incentives," or in other words "attuning energy consumption to energy generation" [9]. Flexible demand expands on the traditional demand response to enable the adaptation to the continuously changing market conditions through ICT tools. Demand flexibility is said to play a key role in this energy transition as it can create great economic and environment incentives [43]. Previously, the topic of demand flexibility hit the spotlight with the decarbonization of the transport sector, but the most recent research extends that boundary to include buildings and District Heating and Cooling (DHC). A simple way to represent the benefits of demand flexibility in a system is shown in Figure 2.4.

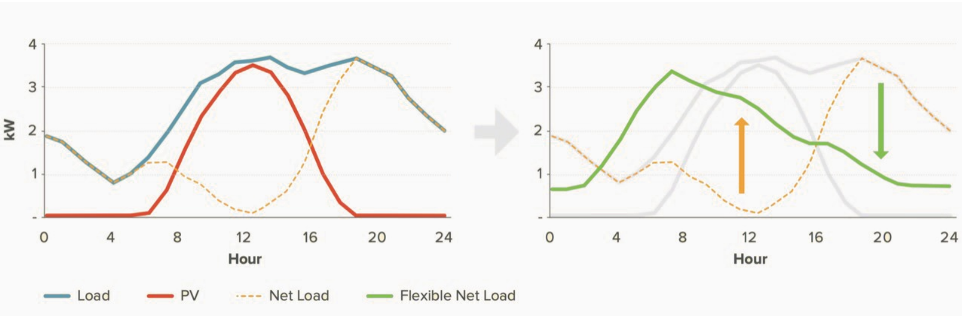

Figure 2.4: Simple Example of Demand Flexibility [7]

With the power sector coupling with heating and cooling, an example of demand response would be adjusting the operation of heat pumps to fit a flexible schedule that takes into account the "peaks or dips in electricity supply in combination with cold or heat storage" [6], such as their total shut down during peak load thus contributing to its reduction. The DHC network is seen as a promising technological solution as it operates like a smart thermal grid. It can even offer more flexibility with the addition of thermal storage. The excess electricity generation from renewables can thus be used to make liquid fuels. A study by the Dutch Energy Delta Institute (EDI) finds that "abandoned oil and gas platforms in the North Sea can be profitably converted into production and storage units that convert electricity from offshore wind farms into hydrogen and synthetic gas" [44]. Another study being a simulation for a sustainable future power system in Texas, relying on a high share of renewables, shows that "using demand flexibility in eight common end-use loads to shift demand into periods of high renewable availability can increase the value of renewable generation, raising revenues by 36% compared to a system with inflexible demand" [45].

2

Nevertheless, the feasibility of heating flexibility is questionable taking into consideration the welfare of the households. In order to make this more acceptable, each technology should be equipped with another solution to keep the same level of ease. As a result, domestic hot water would require thermal storage to reshape demand, compared to central gas boilers per se [46]. In 2013, it was estimated that "around 1.4 million GWh per year could be saved - and 400 million tonnes of CO_2 emissions avoided - in the building and industrial sectors by more extensive use of heat and cold storage" [47]. With the heating sector being the largest consumer of gas, such technologies face barriers, cost being the major one, but at the micro and macro scales today, the need for them amplifies, giving them more potential in the market.

2.1.3. POWER-TO-HEAT

Although some countries already started using renewable resources for space heating and cooling, most of the heating demand worldwide is still met through the use of fossil fuels such as natural gas, propane and fuel oil. Using green power for heating and cooling purposes contributes to the decarbonization of the relative sector and allows the integration of a bigger share of variable renewable energy (and reduces curtailment). Systems like this would also make place for greater flexibility, which is why they became somehow a precondition to achieve the ambitious climate goals. Increasing attention has thus been given to heat generation from electricity, combined with a heat storage system [10]. There are two ways to generate heat from renewable energy: the first one relies on a direct conversion from renewables to heat like solar thermal applications, and the second one, known as renewable power-to-heat, uses the electricity produced from renewables to deliver heat via heat pump technology or electric boilers. Power-to-heat is an enabling technology that puts to use heat pumps and boilers to convert electric power to efficient heating and cooling, and in order to make sector coupling easier and more flexible, thermal energy storage is usually added to the system [8].

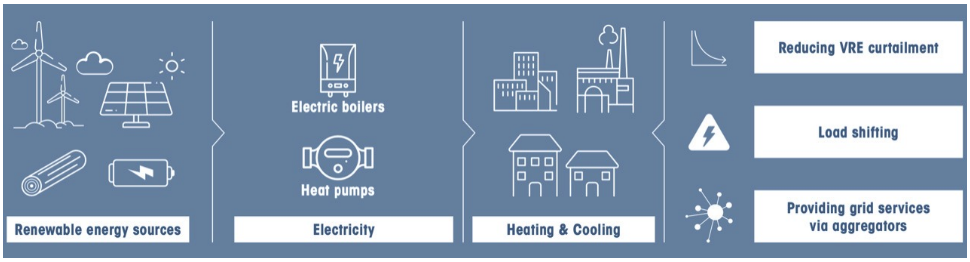

Figure 2.5: Solar and Wind Power-to-Heat System and Benefits [8]

HEAT PUMPS

Heat pumps use electricity to heat or cool buildings and spaces from surrounding air, water or ground. The heat transfer is done by using the heat available in those heat sources, which become the primary energy source, together with a small quantum of auxiliary energy in order to drive the process [8]. Typically, a heat pump draws about 66-80% of the energy required from ambient sources and the remaining 20–33% from direct electricity [48]. The Heat Roadmap Europe (HRE) estimates that by 2050, there is a potential increase for district heating up to 50% of the entire heat demand, with 25% to 30% of it being supplied through large-scale electric heat pumps [49]. The latter bring several advantages, such as resilience to the electric and thermal grids, especially by operating on an intermittent basis with more low spot price electricity from renewables to generate heat in the energy system. Introducing such a technology uses the surplus of the produced electricity and helps shaving the peak with the appropriate installed capacity [49], [50].

In 2016, the building and industry sectors relied on 20 million and 0.2 million heat pumps respectively. IRENA's analysis reveals that "heat pumps will play a critical role in the building sector" and projects a growth in their deployment "to over 250 million units by 2050, supplying 27% of the heat demand," compared to 80 million in the industry sector [8]. Denmark's national political goal is to have 100% renewable energy supply by 2050. A study shows that introducing large-scale electric heat pumps in Denmark would result in 100 M€/year benefits in 2025 [51].

Whilst heat pumps seem to be a major element for the energy transition from a socio-economic perspective, they still face some barriers that need to be overcome. The main barrier for the spread of heat pumps does not seem to be technological; it is however related to policy limitation. The lack of financial incentives for using heat pumps compared to other technologies slows their breakthrough down. One could also raise the question on tax exemption which would require bigger investments for installing heat pumps rather than other competitive technologies [49].

BOILERS

Electric boilers on the other hand, use electricity to heat water, which in turn is either circulated via pipes, or disseminated with fan coils to provide space heating, or stored in hot water tanks for later use [8]. About half of the EU's existing buildings have individual boilers installed before 1992, with an efficiency of 60% or less [1]. Table 2.1 shows the existing boiler types and their share of boilers older than their technical life.

Table 2.1: Share of Boilers Older Than Their Technical Lifetime [1]

Type of Boilers	**% Share**
Individual gas boilers	22%
Direct electric heaters	34%
Oil boilers	47%
Coal boilers	58%

In The Netherlands, the main heating mechanism in most of the buildings, be it residential, private offices, or public, is through natural gas boilers [52]. Meanwhile, Sweden and Norway rely on electric boilers in for district heating [53]. To increase flexibility, electric boilers are usually coupled with thermal storage, which gives them advantage over heat pumps [54]. Besides the mentioned types, boilers can use renewable energy (e.g. biomass) instead of the conventional energy sources to generate low supply heat temperatures in district heating [55].

It is evident that countries would need electric boilers to drive the transition and produce heat economically, especially when the electricity price is lower than fuel or gas [50]. Regulatory barriers, such as the energy tax structure, may hinder the potential realizable benefits from such systems. A study in Denmark shows that "the choice of technologies for heat generation is mainly driven by outdated policies and tax conditions that create barriers for additional flexibility in the overall energy system" [56]. One way that could reverse this is through balancing markets (also known as real-time markets) which might introduce more electric boilers to balance supply and demand [56].

THERMAL STORAGE

Thermal storage systems can store energy for short or long periods, which helps coping with seasonal variability of supply and consumption. This is particularly beneficial for countries and regions that have significant changes in heating and cooling demands with the changing weather. The major opportunity for using thermal storage in DHC set-ups is the disassociation (or decoupling) of heat and cold production from consumption. The excess heat generated with renewable energy in the summer can be stored and used again in winter times to fulfill the heat demand, thereby reducing the need for non-renewable energy sources during peak times. A forthcoming reference by IRENA will proclaim that thermal storage can also be used in a reversed way: it can store natural cold in winter to cool the space during summer. Some key technologies deployed for seasonal storage are aquifers or other forms of underground thermal energy storage [8].

A technical demonstration project among the The Drake Landing Solar Community, in Alberta, Canada, uses a district heating scheme composed of solar thermal energy and seasonal underground thermal storage. The aim is to store energy during summertime and use it to provide heat for 52 residential houses. "In the 2015-2016 winter season, the community supplied all of its heating needs from stored thermal energy; it supplied more than 90 percent of heating needs this way over each of the last five winters" [57]. Therefore, the project proves that with the right effective energy storage, it is possible to resolve the seasonal heat mismatch between supply and demand. IRENA adds to that one other result: each household would then decrease CO_2 emissions by 5.5 times every year [8].

Power-to-heat together with thermal energy storage form an effective means to increase flexibility and security of supply. The benefits of such a combination are numerous. Some examples are the increase of energy efficiency in the system and reduction of greenhouse gases emissions, both in the heating and cooling sector. Most importantly, it makes the supply of heat available at peak times at a relatively low cost [58]. Finck *et al.* illustrate a simple schematic of the flow in a building heating system as seen in

Figure 2.6. The power-to-heat part is represented by the heat pump and the additional electrical serving and the source of flexibility is the Thermal Energy Storage (TES) [9]. Thermal storage could face a couple drawbacks related to the efficiency and losses of the system [58].

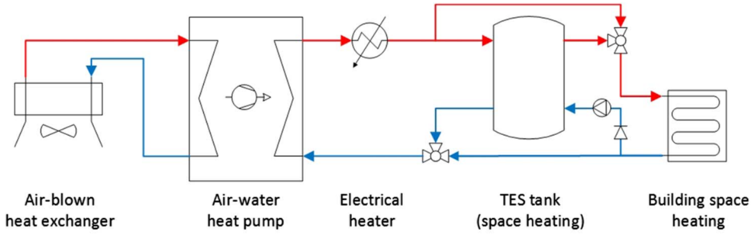

Figure 2.6: Simple Schematic of a Building Heating System [9]

2.1.4. CENTRALIZED VS. DECENTRALIZED

Power-to-heat systems can be centralized or decentralized. A centralized approach has electricity converted into heat directly from the main grid, which might be distant from the actual demand, and distributes heat via the (district) heating network. This approach might also include electricity from fossil fuel generation. In contrast, a decentralized heating system uses small heat pumps and electric boilers to generate heat or cold right at or very close to the demand [8], [10]. In this case, it is possible to benefit from rooftop solar Photovoltaic (PV) installations for instance. Decentralized systems do not necessitate a heat network infrastructure, unlike centralized systems. They are implemented directly at the consumption point which minimizes maintenance costs and distribution losses [8]. These aspects are all portrayed in Figure 2.7 for residential heating.

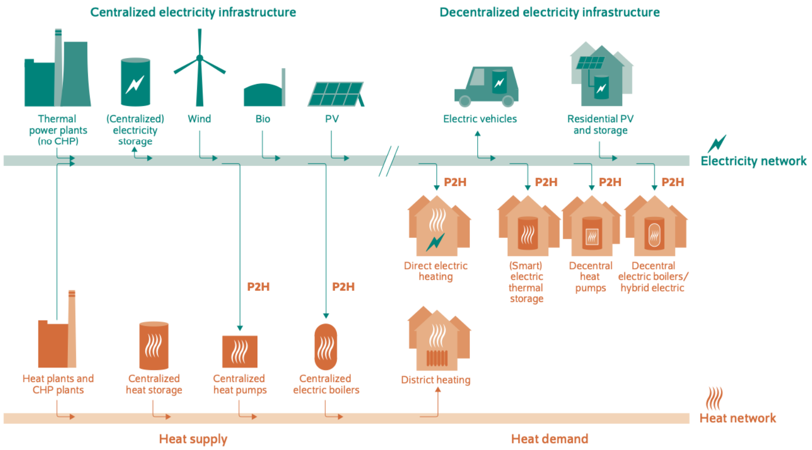

Figure 2.7: Centralized vs. Decentralized Power-to-Heat Systems [10]

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Industrial heating applications make for about 20% of the global energy demand, while space heating and cooling, as well as water heating in buildings, account for about 15% of the global energy consumption [8], [59]. Industries are usually based on decentralized heating systems in which the produced waste heat is recovered and upgraded using heat pumps cited by [8]. Figure 2.8 compares decentralized heating systems for buildings and industries.

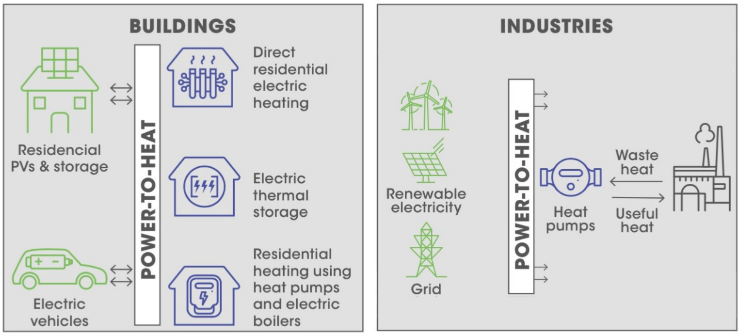

Figure 2.8: Decentralized Power-to-Heat Systems for Buildings and Industries [8]

2.2. MULTI-ENERGY VECTOR MODELLING AND SIMULATION

As showcased in the previous section, decarbonization of the electricity sector and its uses is just a part of the entire overturn of climatic vagaries. Countries have been growing recognition of the attention needed by the end-use energy sectors to allow further innovative grid transformations, streaming towards the future low-carbon energy system promised by the transition. In this context, the concept of a Multi-Energy System (MES) was put forward and has been gaining momentum ever since. The aim is to understand how the energy systems, traditionally operated independently, can be integrated to enable new services and value streams and improve their collective performance, be it technical, economic or environmental [12]. This leaves space to two main questions: what is the optimal combination of assets and how to determine it. Indeed, the answer is more complicated than it was historically, especially with the increased number of different constituents of the energy system and their interactions.

2.2.1. HOLISTIC MODELLING

There are two angles to the problem that, more or less, complement each other: the first one represents the options that suit the energy users (of electricity and other sectors) in terms of cost, reliability and comfort, and the second one denotes the energy producers' course of action to meet the energy demand, which also includes the bulk of planning and operation of the varied infrastructure. Given the big number of choices and dependencies between the energy sectors - and vectors -, there is a need to tackle the problem holistically, which leads to modelling the energy model as a whole [12]. This model should be built in such a way to overcome the computational obstacles, had it not been available. Moreover, it should be able to deal with various scenarios, such as large penetration of renewable energy with low marginal cost and high investment costs, low capacity factor and increased generation variability and uncertainty, integration of emerging technologies for demand flexibility, building resilience against climatic variables, etc. [12].

Kriechbaum *et al.* attempt to generalize the definition of a MES: it is an approach that "requires holistic consideration of an energy system, covering the energy stages from the extraction and treatment (e.g. gas well, coal mine, sun) to the services (e.g. heating, illumination, transport), while also considering the different carriers (e.g. electricity, natural gas, oil, coal)" [2]. The different stages and processes of the energy system, energy sector, energy end-use and energy services are schematically illustrated in Figure 2.9. In the United Kingdom, new energy vectors were introduced "such as CO_2 emerging as a tradable and transportable commodity and non-conventional gas displacing use of natural gas in the system," which require "the application of methods that account for their interdependences and the roles and interactions of the actors who participate within the network" [13].

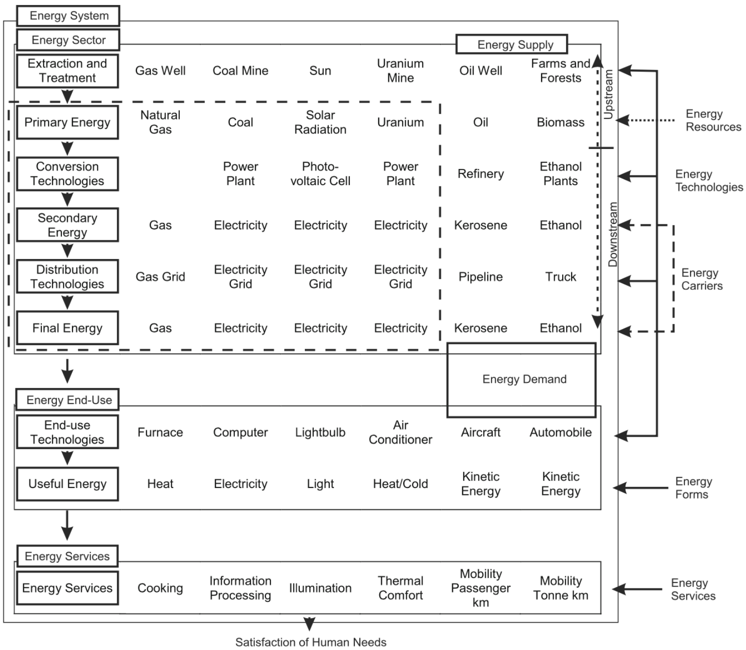

Figure 2.9: Schematic of a Multi-Energy System [2], [11]

2.2.2. APPROPRIATE FRAMEWORKS

Conventional single-energy vector systems are currently dominating the market. In order to welcome the multi-energy approach, it is important to acknowledge the barriers and provide appropriate frameworks and "sufficient value to potential market participants and innovators" to ensure "long-term stability for large-scale investments" for instance [34]. Such innovative models could be attractive to energy business actors seeking new lucrative cases. One example would be the multi-energy providers retailers who would try to devise a strategy to maximize profits by hedging and optimizing their asset portfolio, considering a favourable regulatory framework [60]. Saint-Pierre and Mancarella propose that a novel framework for active distribution system management can "facilitate the transition from distribution network operators to distribution system operators and their interaction with transmission system operators" [61]. As such, distribution system operators can benefit from multi-energy models by exploiting the flexibility aspect in the other energy sectors [62].

A study on the transition pathways for the Scottish energy system concluded that local solution are only able to solve local problems but today's issues are faced by the national and regional systems, and accordingly, there must be national and regional frameworks and new regulatory approaches to initiate, support, guide, coordinate and manage the key developments for energy system transition [13]. From that perspective, energy network regulators, policy makers and governments' involvement is crucial for the paradigm shift. Another analytical report suggests that public funding agencies should focus more on multi-energy vector integration by providing support and demonstration activities, as well as developing and testing solutions for the non-technical challenges (e.g., business models, remuneration structures, etc.) [34].

2.2.3. STATE OF THE ART AND ENERGY HUBS

A simple conceptual example of an of integrated energy system modelling and its potential uses is sketched in Figure 2.10, adapted from [12] and [2]. The purpose is to shed light on on the interactions between resources, technology and investment, economy and society and environment. The very first energy models were created circa 1970 and were used extensively to explore the most economical options for transitioning to a low carbon energy future, based on the standards and requirements back then [63]. In the past, energy systems were simplified to dispatchable generators (or purely sinusoidal voltage sources) and linear resistive loads, which is why an energy-based perspective was sufficient to build a model. However, this has definitely changed over the past two or three decades, which have witnessed the variability of renewable energy sources and the increased use of nonlinear electrical apparatus, leading to a necessary shift to a power-based perspective for future energy systems [64].

Traditionally, energy services focused mainly on the supply-side and single energy domain approach [65], while future networks will be mostly based on the the optimal integration of different energy carriers to achieve energy efficiency needs, and ensure sustainability and a more rational use of energy [66]. New business cases and scenarios will require demand-side actions and a multi-energy approach i.e. a multi-source multi-product energy system, which in turn require synergy among energy carriers (electrical, thermal, chemical, etc.). This adds degrees of freedom (decision variables) to the entire system, on the demand and supply sides. The concept of energy hub was developed and

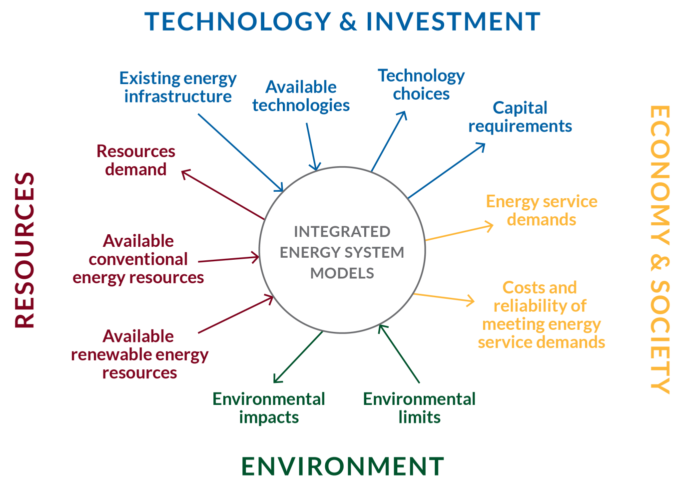

Figure 2.10: An Example of Integrated Energy System Modelling. Adapted from [12], [2]

adopted accordingly, in the context of integrated energy systems, to suitably represent the interactions between the multiple energy carriers/vectors [14], [66]. A hub is defined as a centre of an activity or network; thus, an energy hub is this interface in which a number of energy activities, generation, conversion and storage, effectively take place to feed the connected loads [14], [66], [13].

Figure 2.11 demonstrates the possibility of integrating non-dispatchable renewable energy sources Re_i and a storage system S_i with a hub model H_i and its throughput. The input vector to the hub is represented by P_i and the sum of the energy import from the rest of system is denoted by $F_{\alpha i}$. The electricity output is L_i and feeds the demand D_i directly [13]. The interactions among different energy networks take places at the node α, which could be a real physical node or a virtual one, aggregating energy devices to exchange/generate/convert different forms of energy [66].

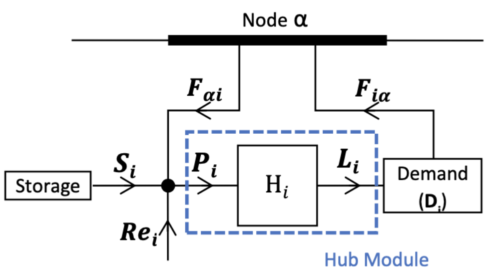

Figure 2.11: Energy Hub Example With Renewable Energy Sources and Local Storage [13]

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The idea is to obtain the best network configuration, which is known to be the optimal economical solution. Best means "better energy services, fewer environmental costs, improvement in the utilization of resources, suitable voltage profiles, etc." [66]. As mentioned, there are two perspective in an energy system. The customer's objective is to minimize their electricity costs, whereas the utilities are not only concerned about costs, but also about numerous issues such as load shape, peak load or even quality of service. Coupling of power systems with advanced ICT tools introduced a novel concept in smart grids referred to as Energy Hub Management Systems (EHMS). It allows customers to manage their energy demand, production, storage and exchanges with the external grid in real-time [67]. The EHMS is based on a two-tier hierarchical scheme to account for objectives of the customers as well as the utility. Figure 2.12 distinguishes two levels: the micro hub level and the macro hub level, each with the objective of optimizing the energy consumption from the end-user's and the utility's point of view respectively.

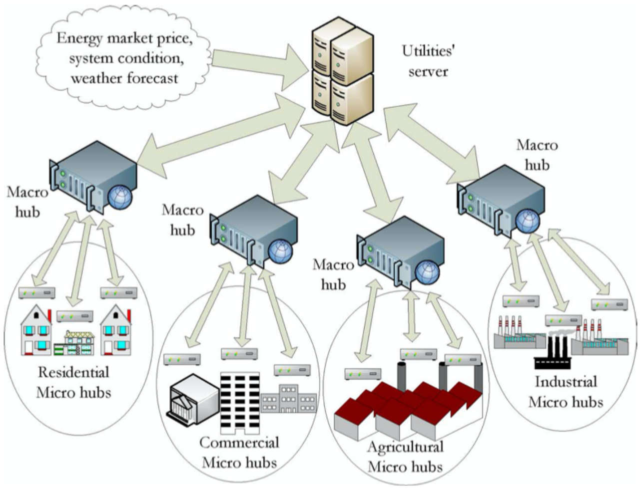

Figure 2.12: Overall Energy Hub Management System [14]

2.2.4. OPEN SOURCE ENERGY MODELS

It is estimated that by 2040, 63% of the world population would be living in cities [68], which underlines the need for a more dynamic, flexible and sustainable energy system, and gives extra motivation for the rationale for multi-energy vector modelling and simulation. Energy system modelling is also a decision-making tool, not only meant for the computation of precise numbers but also for gaining insight into any complex system [69]. Mathematical methods were, and are still, used "to create models which allowed the formalisation of scattered knowledge about complex interactions in the energy sector and helped analysts to understand a sector that had become complex" [2].

Pfenninger *et al.* list four main advantages of open source energy models: improved quality of science in terms of transparency, peer review, reproducibility and traceability, more effective collaboration with better policy outcomes, increased productivity due to the avoidance of unnecessary duplication, and profound relevance to societal debates [70]. A couple of years ago, the open source code movement received a lot of skepticism regarding its viability. However, some fundamental changes have been put in place to win the prospects in the market [71]. There are certain criteria to be met to get under the open source license. The point is to develop technologies collaboratively and allow the creative of derivative works [72]. As such, the shared research on open source energy models become a driving force that facilitates global coordination on climate action and engages more decision-makers [70].

Bloess *et al.* [10] structure a comprehensive table of reviewed papers, which include numerous models for power-to-heat applications with details on the objective, mathematical method and problem formulation, provided in Appendix A. Furthermore, Kriechbaum *et al.* compare three MES open source modelling frameworks: *Calliope*, *oemof* and *urbs*. The source codes for each are hosted on *github* and are continuously being updated. As mentioned in Chapter 1, the MVS tool is based on the *oemof-solph python* library. It is therefore interesting to note the similarities and differences between the three models in terms of features and characteristics, summarized in Table 2.2.

MODELLING ASPECTS

The features and characteristics used to assess the three frameworks are defined and explained here below [2]:

- Modelling scope distinguishes between two types of models: planning and operational. The first one is used to study long-term evolution of energy systems by taking into consideration the investment costs and decisions, as well as any future variability of certain assets' availability and/or prices. The second type of models examines the operational feasibility of a scenario as there is constant dynamics between supply and demand.
- Model formulation determines how the model equations are brought to a mathematical tractable problem formulation.
- Spatial coverage means that the MES can range from a single building to districts, cities or whole countries.
- Time horizon defines the time planning considered in the model (e.g., a day, a year or 50 years).
- Assessment criteria is the evaluation scope that looks into performance indicators such as technical, economic, environmental, etc.
- MES approach represents the way the energy flows in the networks, energy storage and the energy conversion between networks is modelled. The two approaches are the integrated approach and model linkage (also known as co-simulation).
- Energy sectoral coverage determines the sectors span by the MES model.

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- Spatial resolution specifies the dimensions taken by the model as most of the time, energy supply and demand do not occur at the same location.
- Time resolution determines whether the framework covers a wide range of time scales, from microseconds to hours for instance.
- Load flows classifies the energy transmission either as network or power flow models. The first type is considered as a black-box and the second one as grey- or white-box. Type I network flow models assume energy transmission without losses, while type II network flow models include the losses as a function of the corresponding flow, which makes the model more accurate.
- Unique features are the distinguishable features of each modelling framework.

Table 2.2: Characteristics and Features Comparison of Three Open Source Modelling Frameworks [2]

Feature	**Calliope**	**oemof**	**urbs**
Modelling scope	Operational, planning	Operational, planning	Operational, planning
Model formulation	Linear	Linear and mixed integer	Linear
Spatial coverage	Local to countries	Local to countries	Local to countries
Time horizon	Short and long	Short and long	Short and long
Assessment criteria	Economic	Economic	Economic, with environmental auxiliary constraints
MES approach	Energy hub	Energy hub	Energy hub
Energy sectoral coverage	Electricity, gas, heat	Electricity, gas, heat, transport	Electricity, gas, heat
Spatial resolution	Single- and multi-region	Single- and multi-region	Single- and multi-region
Temporal resolution	Low and high	Low and high	Low and high
Load flows	Network flow type II	Network flow type II	Network flow type II
Unique features	Ramp rates, multi-scenario	Ramp rates for storage, up and down times	Demand response, multi-scenario

FRAMEWORK COMPARISON

As can be concluded from Table 2.2, the three modelling frameworks share the same modelling scope, as they are based on both models, operational and planning. Since the two modes are incorporated, then high time resolutions and long-term investigation periods are supported. The model formulation is also the same, bringing the equations and constraints to a liner programming problem. Only *oemof* can accept binary variables and create a mixed integer linear programming problem. The main objective function for the models is to minimize the cost of production, given a specific scenario. Thus the economic assessment is common among the three frameworks. *urbs* has a more sophisticated and advanced economic analysis. It also includes an extra assessment feature based on the CO_2 emissions as an auxiliary constraint.

All of the modelling frameworks are based on the energy hub concept (as previously introduced), which is "a generic approach for steady state modelling and optimisation of future interconnected multi-energy networks" [2]. They all cover the electricity, heat and gas sector but *oemof* stands out with the transport sector option. The energy transmission is described by the type II network flow models. Even though the basic characteristics and functionalities of the tools are quite similar, they also happen to have some unique features. *Calliope* and *urbs* both support multi-scenario evaluation, *urbs* provides demand response, and *oemof* allows the implementation of down-times for converters.

In general, the three frameworks are well structured and developed. *urbs* has a couple more advanced features and application possibilities, yet a considerable advantage for *oemof* is the code's clear and modular structure that makes it easily adaptable.

2.3. PILOT PROJECT - UVTGV CAMPUS

With the urgent call from the United Nations to take action in combating climate change [73], several universities are working nowadays towards carbon neutrality. One successful initiative and example is the EUREF campus in Berlin that relies on "a climate-neutral energy supply, an intelligent energy grid, [and] energy-efficient buildings" [74].

UVTgv campus is situated in the centre of Romania and spans an area of 140,000 m^2. This location is known for large temperature differences between seasons with heavy rain and high winds. The campus is currently supplied by the national electrical and natural gas grids and a diesel generator. Besides the use of conventional energy sources, UVTgv produces its own local energy from five PV systems, five wind turbines and one solar thermal plant, with battery and TES systems respectively [36]. The MVS tool helps the university campus decarbonize their sector coupled energy system with its multi-vector approach. It also enables the campus to become its own energy island by making complex energy mix less challenging to simulate and optimize.

2.3.1. ENERGY SYSTEM UNDER INVESTIGATION

The considered energy system for this study is the Institute of Multidisciplinary Research for Science and Technology (ICSTM)[1], which extends over two buildings (~2,240 m^2). The research institute is built of the east-west axis and is operational with building-integrated PV and stationary storage, solar thermal with storage, coupled with an adsorption chiller and a Heating Ventilation Air Conditioning and Refrigeration (HVACR) system. Additionally, there is a microgrid system that provides electrical security in case

[1] https://916.icstm.ro/

of situations with critical loads. There are also three small rooftop wind turbines in hybrid connection with the different PV systems but they are currently dysfunctional. Figure 2.13 is a picture of the research institute showing the different renewable energy systems integrated with the building, while Figure 2.14 portrays the energy system schematic that is assumed for the rest of the application and in such a way that the MVS recognizes the components and is able to run the simulation.

Figure 2.13: UVTgv-ICSTM Renewable Energy Systems

In fact, four *Solph* components are used in the representation of UVTgv-ICSTM's energy system: source, sink, storage and transformer. These components are connected together with flows and buses. It is important to note that *oemof-solph* cannot identify and model a hybrid inverter nor a heat pump as the flow of energy is bidirectional. For that reason, such components are represented by two transformers instead, and are highlighted by the dotted enclosure as one technical unit. It is possible to spot the point of sector coupling in Figure 2.14; it is represented by the two flows from the AC electricity bus into the heat pump. The electricity required to heat or chill is also indicated in the schematic. Those values - 218.18 and 229.64 kW - are quite large which is why the heat sector generally makes use of gas as an energy input rather than renewable energy.

2.3.2. INPUT DATA

Most of the input data is extracted from the datasheets of the components and the locally-available monitoring system. However, the building heating and cooling demands as well as the solar thermal generation profile are not available. Other parameters, such as the efficiency of storage and some transformers, are assumed based on the online information on the types of products. Efficiency for storage is defined as the ratio of the energy it can provide to the energy needed to charge it; it accounts for the energy loss during the charging/discharging periods. A typical lead-acid battery has an energy efficiency of 85% [75], [76], while TES can have an efficiency between 50% to 90% [77].

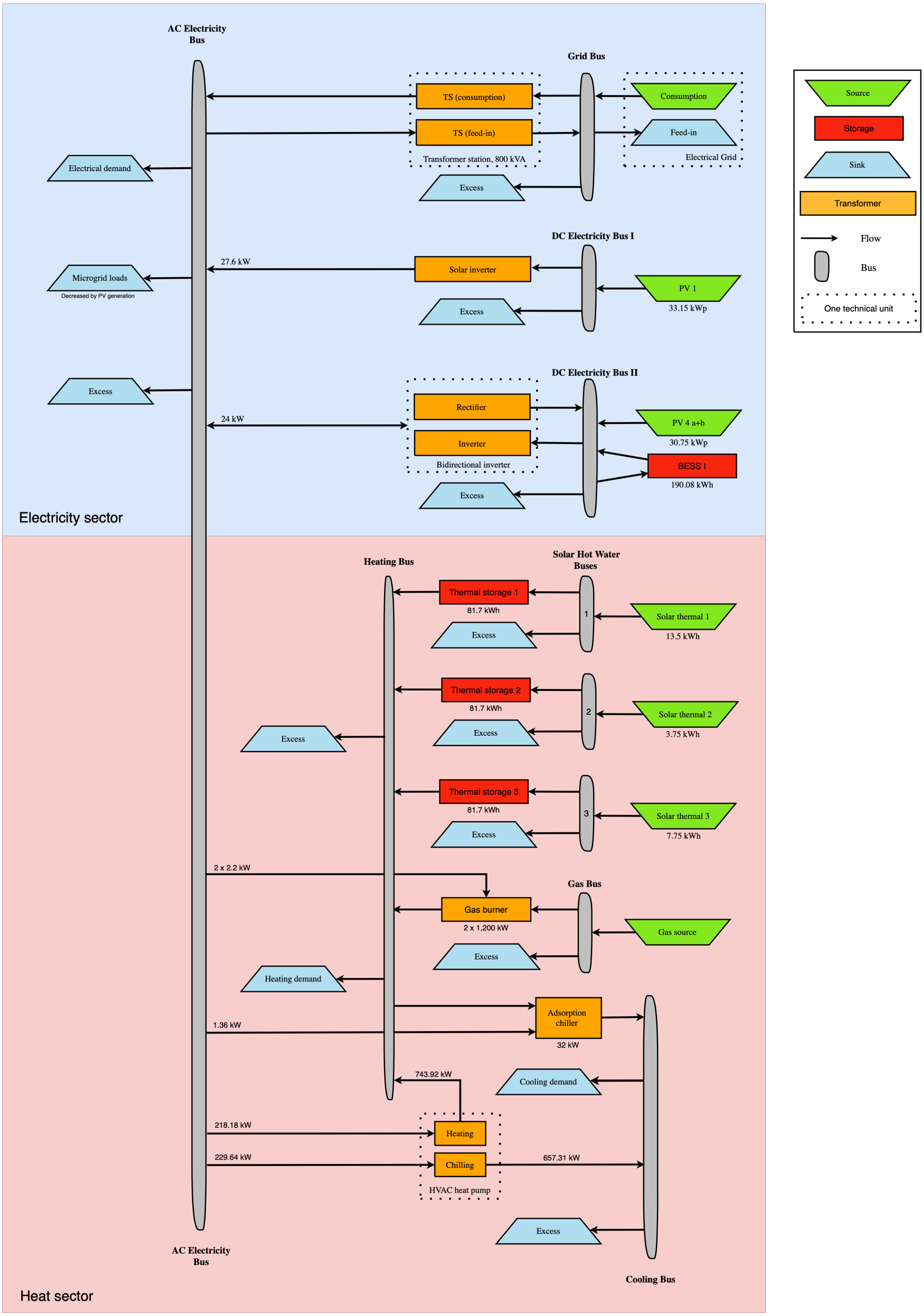

Figure 2.14: Energy System Schematic of UVTgv-ICSTM

The chosen value is 70%. The energy efficiency for the transformer station is extracted from [78] in which the overall energy efficiency of distribution transformers for the EU-25 countries is demonstrated.

The solar thermal generation time series is created using the *oemof-thermal* package, a model for thermal energy components. The weather data, Global Horizontal Irradiance (GHI), Diffuse Horizontal Irradiance (DHI) and ambient temperature, is downloaded from ERA5 using *python* with the site's coordinates. ERA5 is the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate. The assumptions made to calculate the collectors' heat are the following:

- The collectors' inlet temperature is 20°C.
- The temperature difference between the collectors' inlet and mean temperature is 10°C.
- The azimuth is 190°C.
- The total losses amount to 35% (15% heat transfer, 15% peripheral losses and 5% storage losses) based on [79].

The Direct Normal Irradiance (DNI) is calculated using a function within *oemof-thermal*. The GHI and DNI are both plotted against the third solar thermal collector in Figure 2.15, respectively from left to right.

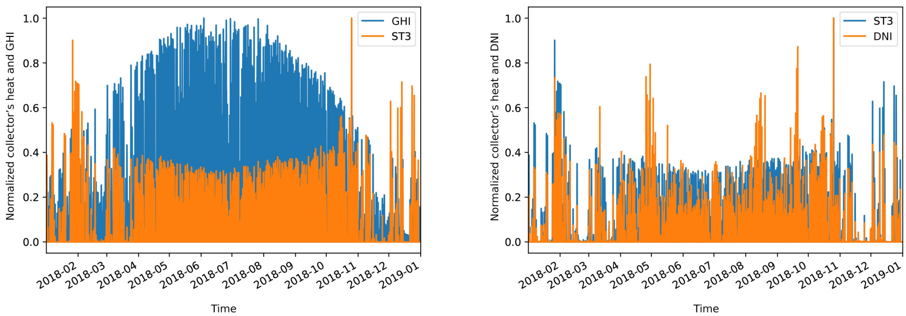

Figure 2.15: Global Horizontal Irradiance and Direct Normal Irradiance Plots

Another attempt at generating those time series for the three solar thermal system uses the ambient temperature profile provided by the university, which was measured locally using the available sensors on the rooftop. Some of the temperatures were missing, and were thus corrected by just filling in the same temperature at the previous timestamp. The ambient temperature plot and the corrected/processed one are shown in Figure 2.16, and the final plots for the three collectors' heat are shown in Figure 2.17.

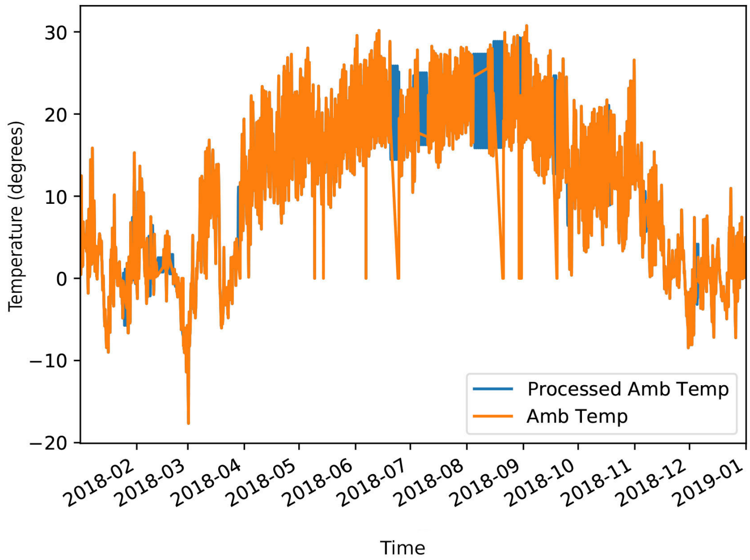

Figure 2.16: Ambient Temperature Final Plot

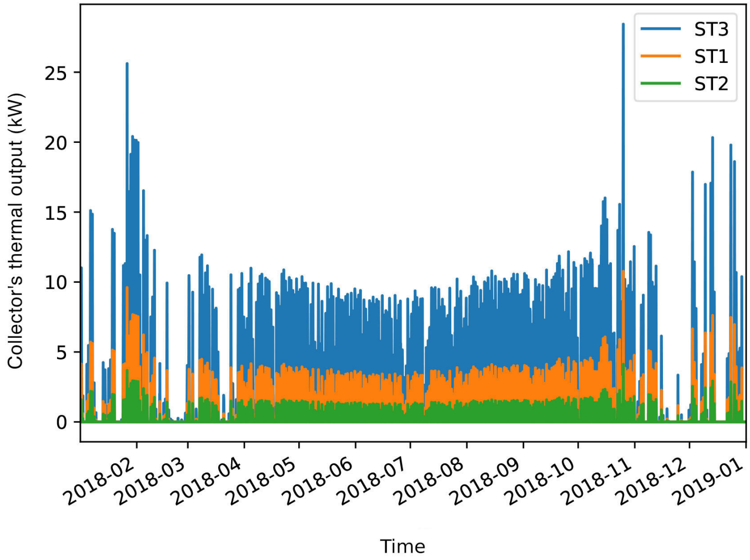

Figure 2.17: Solar Thermal Collectors' Heat Plot

2

As for the heat demand, it is estimated using *oemof-demandlib* and the available profiles from the Bundesverband der Energie- und Wasserwirtschaft (BDEW) - Federal Association of Energy and Water Management. The same weather data from ERA5 is used. The time series is based on the profile type Gebietskörperschaften, Kreditinstitute und Versicherungen (GKO) - local authorities, credit institutions and insurance companies - [80], and the total gas consumption and boiler efficiency provided by the university. The heat demand plot over a year is shown in Figure 2.18.

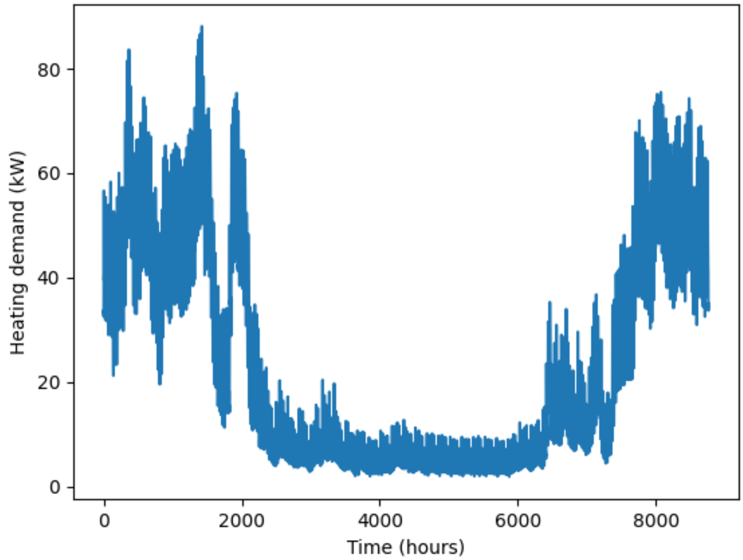

Figure 2.18: Heat Demand Plot

Since there is no data whatsoever provided for the cooling demand, an internal code developed at RLI is used to generate a cooling profile for UVTgv-ICSTM. It is mainly based on the total cooling demand (kWh/year) and a base temperature for cooling, assumed by RLI to be 23 degrees Celsius, and the same ambient temperature time series provided by the university. In order to calculate the total cooling demand, the specific cooling demand for service sector for Romania (kWh/m^2) is used from the STRATEGO project, supported by the Intelligent Energy Europe Programme [81]. This value is equal to 119 kWh/m^2 and the area of the ICSTM building is 2,240 m^2. Therefore, the total cooling demand is estimated to be equal to 266,560 kWh/year. A plot of that demand is shown in Figure 2.19.

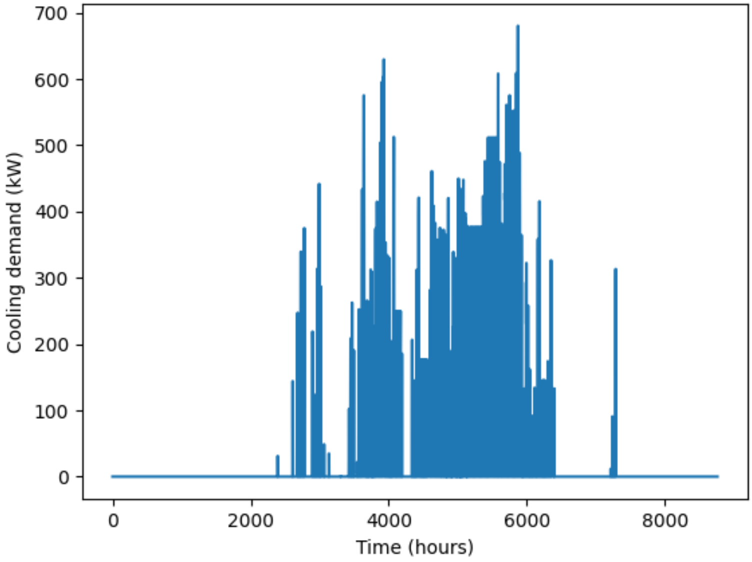

Figure 2.19: Cooling Demand Plot

3

Methodology

The goal of the thesis is to identify a validation method for an open source multi-vector simulation tool. This chapter starts by defining verification and validation for simulation models, then introduces the entire validation approach based on thorough literature review. Superposing research with the model at hand, the validation method is narrowed down to the techniques that are applicable to the MVS. The chapter converges towards the chosen methodology to validate the MVS with little mention of potential pitfalls.

3.1. Verification and Validation of Simulation Models

Modernized energy networks are considered as highly complex systems: they encompass several sets of modular active power electronics and ICT tools to enable interactions with the traditional grid. Moreover, these systems are designed in such a way to allow a big(ger) penetration of renewable energy and controllable loads [32]. As a result of such technological advances, modelling and simulation of energy systems has become invaluable and fundamental for their development and implementation; it fulfills the need to understand current states and predict future ones by evaluating the operation, behavior and performance of each component in the system under normal and emergency situations. Therefore, simulation models ought to deliver "correct" results, and if they are open source, this feature becomes even more indispensable. This concern of whether a simulation model is credible or not, is addressed through model verification and validation - conducted during its development – and has always received significant research attention. Implementing a model without validation may cast wrongful solutions due to improper assumptions.

The first attempt at formally defining verification and validation was done by the Institute of Electrical and Electronics Engineers (IEEE) in 1984. Howbeit, those definitions were found to be somehow limited. Consequently, the United States Department of Defense, and later both the American Institute of Aeronautics and Astronautics (AIAA) and the American Society of Mechanical Engineers (ASME) improved those definitions [38]. Attempting to briefly showcase this enhancement in wording, Figure 3.1 portrays a short timeline with examples of definitions for both verification and validation with reference to Latuszynska [82].

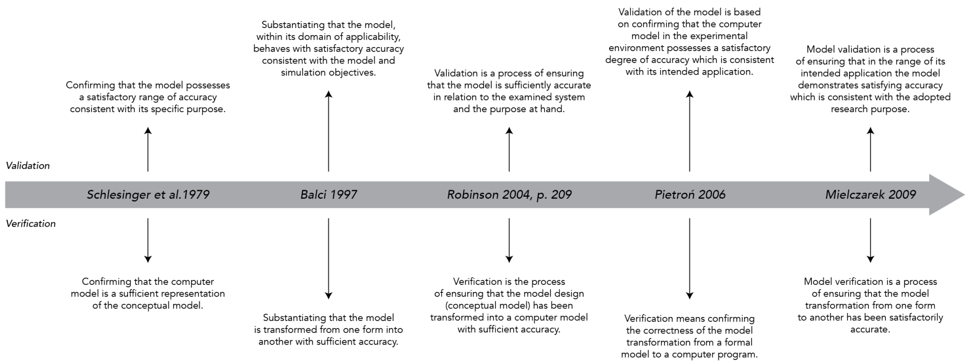

Figure 3.1: Validation and Verification Definition Examples - Own Figure, Inspired by [15], [16], [17], [18], [19]

Nowadays, the definitions of verification and validation can be found in abundance in different words and structures, yet aiming at the same concept. Both are processes with ascertainment purpose and are defined as follows: verification is the assurance that the model accurately reflects the developer's conceptual problem entity, while validation is the degree to which the model's behavior is a reasonable representation of the real system [83], [22], [21].

The most adopted "precisely targeted" definitions according to Oberkampf and Trucano [38] are printed here below:

> *Verification*: "The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model."
>
> *Validation*: "The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model."

Because the terms "verification" and "validation" are often confused, it is important to underline the fact that one does not imply the other. Yet, in practice, the two processes are often blended when modelling a system due to their interrelation [84]. This will be further explained in the next sections.

3.2. VALIDATION APPROACH

There are two basic ways for evaluating a model: the first one relies on the development team and the second assigns the task to an "independent" third party. For the purpose of

3

the thesis, the validation method is presented from the model development perspective and is considered to be the same for an open source simulation tool. Sargent [83] discusses four approaches to assess model validity which will be elaborated in the following section: data validity, conceptual model validity, model verification, and operational validity. Data validity ensures that the model is implemented, run and tested on the necessary adequate and reasonable data. Conceptual model validation establishes that the conceptual model's theories and assumptions are reliable and correct and the problem of interest is properly emulated for the intended use of the model. Model verification assures that the programming and construction of the conceptual model is accurate. Operational validation determines that the model's output behavior is satisfactory and involves sufficient accuracy [83].

This whole substantiation process is actually a constitutive part of the entire development of the simulation model as seen in the simplified version by Sargent [20] depicted in Figure 3.2. A multi-energy vector simulation tool unfolds into this simplified modelling which resolves into the following: the problem entity is basically the real-life energy system to be modelled, the conceptual model is the mathematical equations forming together a holistic logical representation of that same system, and the computerized model is the coded version of the conceptual model implemented (in the MVS, it is in *python*). The details on the interrelations between the three cores for the implementation of the model are omitted and the focus will be solely on the validation process.

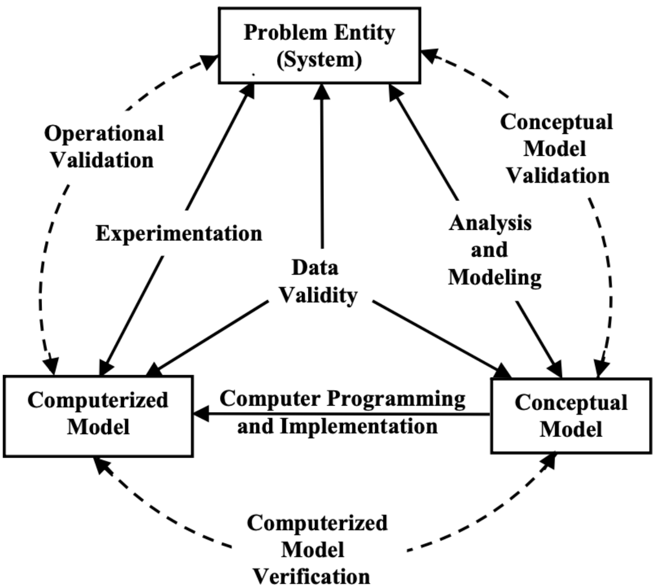

Figure 3.2: Simplified Version of the Modelling and Validation Processes [20]

First, the conceptual model is derived from the stated real-life system followed by conceptual model validation until the causal relations and formulas underlying the model are acceptable. The second step is to mimic this logical mathematical structure onto the computer and start model verification to reach the required adequacy. Operational validity comes right after and is conducted on the computerized model. This validation process is iterative and repeated as many times as necessary in order to meet the requisite accuracy. Changes might be needed at different stages either in the conceptual model or in the computerized model. Finally, data validity is common among all the processes of model development: it is the core of the entire scheme - with no proper inputs, outputs become futile. Most of the time, data validity is not considered as part of the model validation [20]. In the MVS case, data is variable and dependent on the user, yet there is internal validation of the input data - whether it is acceptable or not - as will be seen in the second block of Figure 4.3. Hence, data validity will not be studied further in the next chapter.

It is important to notice the double-headed arrows, which underline the exchange and readjustments between the elements, meaning the processes are not completely separate or independent and some steps should be conducted simultaneously. Figure 3.3 also shows this iterative process in which "juggling" between the real system, conceptual model and computerized model is necessary through several validation methods.

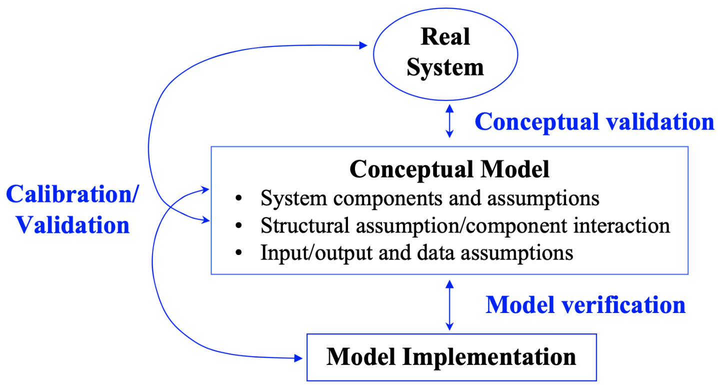

Figure 3.3: Iterative Validation Process [21]

3.3. VALIDATION TECHNIQUES

Simulation models differ from conventional software systems in their behavior: while general software systems should generate utterly predictable outcomes for a set of test data, simulation models have an expected output that could vary depending on the system configuration and input data, and subsequently require additional testing to verify and validate the model [21]. Most of the time, a model is designed for a particular application; thus, its validation should ensue from that same purpose and within an acceptable range of accuracy. The latter is usually determined prior to the development process or at its early beginning. The standard for the level of credibility is set quite high today given the increased responsibility of simulation models [38], wherefore the choice of a validation approach becomes even more important.

Sargent [83] presented various validation techniques that are commonly adopted, including tests. Some of them involve subjective analyses while other ones are based on totally objective decisions, generally requiring the use of confidence intervals or external models for instance. All the methods and techniques depicted by Sargent [83] can be used for the validation of simulation models and submodels for sector coupled systems depending on the context, requirements and data availability. Nevertheless, not all of them are applicable to the MVS case. In fact, some of them entail the availability of a certain set of data or even type of problem, and a couple of them are intentionally excluded as other methods fulfill the same attribute. Table 3.1 lists some of the aforementioned techniques and the decision on whether they will be used for the validation of the MVS tool or not.

3.3.1. FACE VALIDITY

Conceptual model validation determines that the conceptual model's fundamental theories and assumptions are reliable and correct and the problem of interest is properly emulated for the intended use of the model [20]. Such an evaluation is usually performed by individuals who have knowledge on the subject and can thus assess the behavior of the model. This is known as face validity or expert intuition, which is the prime validation technique for the conceptual model. High face validity means a high degree of realism [85]. The examination is expected to be led by an individual other than the modeller, with expertise in the system rather than in the model. This part of the validation process could also involve potential users to test the output reasonableness. Inspection of the output could span from reviewing the basic underlying theories to studying the flowchart or graphical model. In the MVS' case, face validity consists of reviewing the set of model equations and tracing the model flow to identify deficiencies.

3.3.2. STATIC TESTING

Model verification assures that the programming and construction of the conceptual model is accurate. "The fundamental strategy in verification is to identify, quantify, and reduce errors caused by the mapping of the conceptual model to a computer code" [38]. Since the model is implemented using a high level programming language, verification in this case is only concerned with determining the correctness of the simulation functions. This can be executed by either static testing or dynamic testing. Dynamic testing is mostly done through traces, which monitor the program execution and record the code line by line. This method is avoided, and instead, static testing of individual functions is used through proof of correctness techniques. These correctness proofs validate the consistency of an output "assertion" with respect to an input specification (particular values of variables) [86].

Table 3.1: Validation Techniques and Applicability to MVS

Validation Techniques	**Applicability to MVS**
Animation - Graphical Displays	Yes - graphical displays are used to make subjective interpretation and decisions on output behaviour
Benchmark Tests	Yes - those simple tests assess the performance of the model by assessing the outputs, which should remain valid in its future versions
Comparison to Other Models	Yes - this mainly focuses on reproducing an energy system using a different validated model and comparing the outputs
Degenerate Tests	No - the model does not include a total degenerate problem, however extreme input parameters are accounted for in the extreme condition tests
Event Validity	No - the model does not include event or hazardous occurrences, but the model is tested for sudden changes of input parameters
Extreme Condition Tests	Yes - these will be used to make sure that the outputs are still plausible during any unlikely event
Face Validity	Yes - this ensures a high degree of verisimilitude
Historical Data Validation	No - historical data is not available
Historical Methods	No - historical methods are omitted as more detailed and robust methods will be used
Internal Validity	No - the model does not involve internal stochasticity or a large amount of variability
Multistage Validation	No - this validation technique is based on the historical methods that is not used for the MVS validation
Operational Graphics	No - the model does not run through time, instead graphical displays are used to interpret the results
Parameter Variability - Sensitivity Analysis	Yes - the model's output transformations are tested for different input parameters. However, the model does not involve any internal parameters that need fine-tuning
Predictive Validation	No - forecasts on the system's behaviour are not used as other methods do evaluate the output without field experiments
Static Testing/Dynamic Testing	Yes - only static testing is used for model verification. However, input-output relations are investigated through other chosen techniques
Traces	No - traces are not used, instead the flowchart is examined and static testing is used
Turing Tests	No - this is somehow infeasible as the real system is not totally in place. The applicable alternative is the face validity technique

3.3.3. GRAPHICAL DISPLAYS

One primary testing mechanism, common among various type of models, is graphical displays. This method is also referred to as animation. Since the MVS does not run through time, the terminology "graphical displays" is adopted instead. The functionality is inferred by the literal meaning of these two words: "the model's operational behaviour is displayed graphically" [20], making space for informal subjective interpretation and decisions. This technique is an integral part of operational validity. It allows the exploration of a model's behaviour for different sets of experimental data to determine whether the model has sufficient accuracy.

The most useful types of graphs in such simulations are scatter plots, bar graphs or histograms, pie charts, and Cartesian graphs. Important values for validating the model like the mean, variance, extrema, etc. can be deduced from such plots. Moreover, graphs can be used in combination with face validity or other validation techniques to evaluate the output behaviour.

3.3.4. COMPARISON TO OTHER MODELS

Comparison to other models is a validation technique applicable to operational validity. The main idea is to compare the results of the simulation to the ones of other valid models. The comparison is done in two ways: "(1) simple cases of a simulation model are compared to known results of analytic models, and (2) the simulation model is compared to other simulation models that have been validated" [20]. The first part (analytic models) is omitted for the MVS and the focus is on the second part which aims at reproducing one case using an optimization model with different component structure.

There are three ways to compare the simulation model's output to the one of the real-life system or another valid model through the use of graphs, confidence intervals, or hypothesis tests. The last two approaches help in making objective decisions, yet they are not very practicable as they are based on a big number of statistical assumptions and data, the lack of which would lead to unsatisfying results. Hence, the most common tool would be the use of graphs for such comparisons [20]. The results would be undeniably questionable if any of the models used for comparison is not a valid representation of the real system. Therefore, this method should be carefully applied [84].

3.3.5. SENSITIVITY ANALYSIS

Sensitivity analysis studies input-output transformations; it highlights the effects on the outputs when changing the values of inputs. Since the model is a map of the real system, then the correlations and changes should be the same in both worlds. Another feature of the sensitivity analysis technique is the possibility to fine-tune internal parameters by also looking at the model's behaviour with respect to their variability. However, the MVS does not involve such specific values and thus the sensitivity analysis in this case focuses on input-output relationships. That way, it is possible to determine the input parameters that are sensitive and may cause significant changes in the results [20].

Most of the time, simulations models are abstract replicas of what could be real life systems. Such models are thought to be "function generators" as they produce output values when given certain inputs. According to Hillston [84], those generated functions are expected to be continuous, meaning it is unlikely to "anticipate that a slight change in an input value will result in very large changes in the corresponding output value." By running the simulation model for different input values, it is possible to draw conclusions on the smoothness of the function and major changes would be an indication of a prospected error. As such, sensitivity analysis takes part in the operational validation process.

3.3.6. BENCHMARK TESTS

Benchmarking is providing a comparison of the model being validated to some other model or metric to assess its performance. The type of benchmark tests utilized vary upon on the nature, use, and type of model. Benchmarking may entail the validation of the model's outputs by comparing them to "the model's previous version, an externally produced model, a model built by the validator, other models and methodologies considered by the model developers, but not chosen, industry best practice, [or] thresholds and expectations of the model's performance" [87]. The most used benchmark approach is to compare the model's results to those of the system it is replacing. This system should have a known behavior in order to judge whether the approach is returning apt outputs.

Benchmarking also measures the outcomes of the model against those of earlier versions of that model, meaning if any changes are done to the source code, benchmark tests should still check the validity of the results. The validation is mostly leveraged on the type of model, its objective and the validator's experience. Benchmark tests for the MVS take part in the operational validity process. They cover all the aspects of the simulation and optimization model as they incorporate different constraints and components for each sector.

3.3.7. EXTREME INPUT PARAMETERS

Another important characteristic that simulation models should have is the ultimate ability to generate plausible outputs even with extreme input parameters. If it fails to do so, it loses credibility. Therefore, a model should be tested under multiple scenarios with different sets of unlikely factors such as extreme weather conditions, drastic changes in demand, long maintenance period, very high component costs or even very low component efficiency.

Another validation technique mentioned in Table 3.1 is degenerate testing, which tests the model for borderline values i.e. values at the extremities of the operating range. Although there are no such values for which the MVS become absolutely degenerate, extreme conditions can occur and accordingly the model is tested for extreme input parameters as already mentioned. This technique is part of the operational validity approach and can locate bugs that would have otherwise never been discovered [84].

3

3.4. VALIDATION HIERARCHY

Following the previous sections, it is possible to say that validation tests are quite sequential, which is why a strategy should be developed to build confidence in the model's simulation ability and performance. This is translated into a hierarchy of validation assessments as seen in Figure 3.4 [22]. The top tier represents the complete system, which is the MVS tool that includes the economic dispatch and investment models. Three more tiers are illustrated that show the decomposition of the entire complex system into a series of fundamental functions: subsystems, modules and unit problems. Usually, the number of tiers differ from one model to another, but four tiers are shown for the MVS.

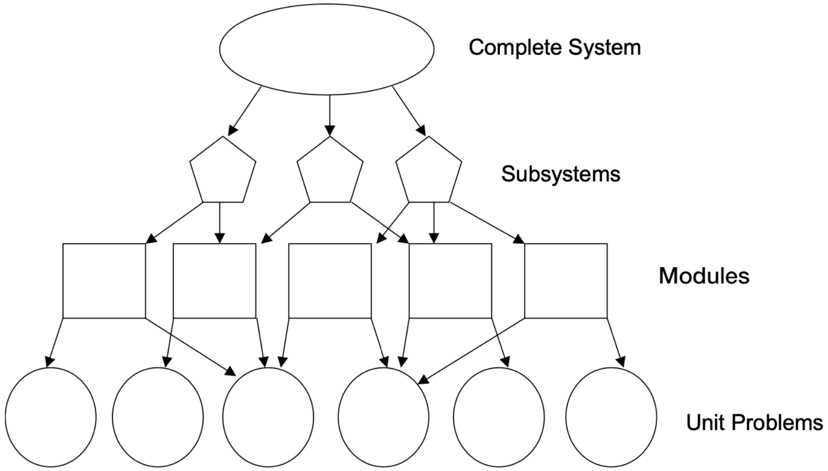

Figure 3.4: Validation Hierarchy, Adapted from [22]

The hierarchy is traversed from the bottom up: unit problems are validated first before module testing and the logic is similar for the other tiers. This reduces the number of errors in each stage of validation [22]. The choice of this validation hierarchy is of paramount importance because it segregates the characteristics of the model, but also defines its coupling and interactions from a level to another until the complete system is tested. Unit problems are basically validated by conducting unit tests on targeted single units (tackled in Subsection 4.2.1), while modules are validated by performing integration tests on entire modules or combinations of modules (tackled in Subsection 4.2.2). Subsystems represent the different functionalities and features of the MVS, which are mostly validated by the chosen techniques for operational validity in Section 4.3.

3.5. POTENTIAL PITFALLS AND RECOMMENDATIONS

Discrepancies and/or deficiencies may occur at any point during operational validation. This means that they might be caused by any previous step, be it the implementation of the model's theories, the development of the computer code or even the input of invalid data. As much as the real-life system is captured in the simulation model in terms of matching characteristics, outcomes may still differ when compared to each other. Winton [21] states that simulation models provide "surface realism," meaning that the results might be deceiving despite their realistic appearance. One way to overcome this limitation is by employing multiple validation techniques and comparing the results to real data if available.

Additionally, Sargent [83] enumerates a couple of recommendations for model validation given that many of the decisions are based on subjective interpretations:

1. Agree with the team on the validation approach with a minimum set number of validation techniques.
2. Identify the required accuracy of the model's output.
3. Analyze and test the theories and assumptions that formulate the problem.
4. Study the conceptual model as much as possible with face validity.
5. Examine the output behavior of the model using the computer version at every iteration.
6. Make comparisons with the system's behavior or other validated models with preset input values to locate the changes or errors.
7. Document this validation method and its results for future reference.

4

Implementation of the Validation Method

This chapter demonstrates the implementation of the validation method into the MVS in three sections. The first one covers conceptual model validation, the second one tackles model verification and the last one outlines the applied techniques for operational validity.

4.1. Conceptual Model Validation

According to the Defense Modeling and Simulation Office (DMSO), conceptual model validation consists of "determining that the theories and assumptions underlying the conceptual model are correct and the representation of the validated requirements is reasonable and at the correct level of abstraction" [88]. In addition, the model has to be "internally complete, consistent and correct" and its "structure, logic, mathematical and causal relations" valid [89]. Subsequently, the validation process is done in two steps: first, the set of model equations is reviewed to make sure that the appropriate relationships have been used, and second, the model's global flowchart is traced and examined. Both evaluations are carried out using the face validity technique as introduced in Subsection 3.3.1. It is worth mentioning that the MVS is planned to be submitted to the Journal of Open Source Software (JOSS) as a last step before the end of the project for further peer review to increase simulation credibility.

4.1.1. Model Equations

A Linear Programming (LP) problem is a constrained optimisation problem, in which the maximum or minimum value of a linear expression, called objective function, subject to a number of linear constraints has to be found. The optimization problem under investigation in this research is related to the design and operation of (future) power systems and contains economic dispatch, investment decisions, optimal power flow and design choices for electricity and heat for energy islands. As every optimization problem, an LP problem can be described by specifying the decision variables (optimization variables/degrees of freedom), the objective function (performance criterion), and the bounds (lower and/or upper bounds) and constraints (equality and/or inequality constraints) [90].

The common way to optimize an energy system is through a dispatch optimization based on the marginal costs of the available generating units. The MVS is based on the energy system modelling library *oemof-solph*, which, in turn, uses *Pyomo* - a Python-based open source modelling language and package with multiple optimization capabilities [91] - to create linear problems [23]. *Solph* has an added value over other models as it can provide a combined dispatch and investment optimization for power, heat and mobility [23]. An energy system with *solph*'s different network classes and structure is shown in Figure 4.1. It is possible to set up various energy systems based on *oemof-solph*'s standard asset types.

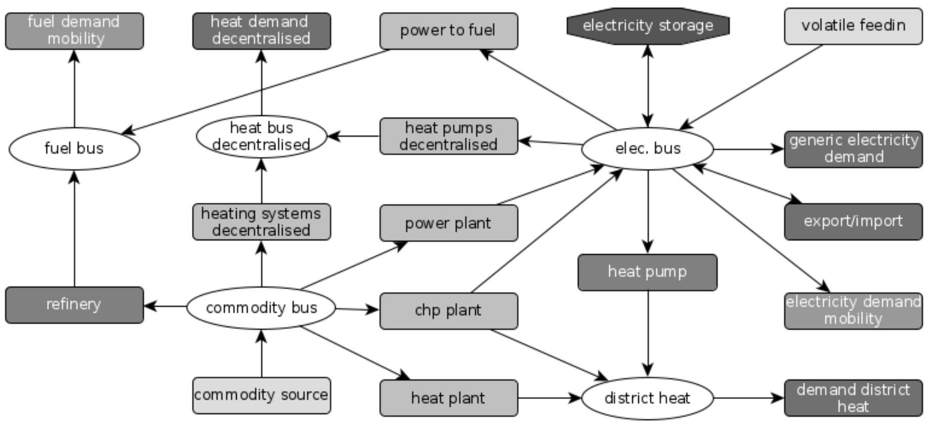

Figure 4.1: Solph Energy Model Example [23]

The economic dispatch problem has the objective of minimizing the energy production and supply costs by allocating the total demand among the generating units. The latter have different generation costs depending on the prime energy source used for electricity production. In large-scale plants for instance, the marginal costs for coal, oil or nuclear may differ considerably [92], which also applies to smaller generating units. At the same time, the investment model optimizes near-future investments in generation and storage assets to obtain the least-cost of supply for electricity and heat. By using the investment mode, it is possible to compare the reliance on the existing components only against investing in new capacities, and for that the annual savings must compensate for the new costs [93]. By using the *python* library *oemof-solph* and calling the *cbc solver*, the optimal solution - capacities and dispatch - can be determined. The objective function is then expressed as follows [90], [94], [95]:

$$\min Z = \sum_i a_i \cdot CAP_i + \sum_i \sum_t c_{var,i} \cdot E_i(t) \tag{4.1}$$

The total electricity generation cost is Z [€], and each asset i is accounted for through its annual cost, i.e. annuity, per capacity unit a_i [€/kW/year, €/kWh/year, €/kWp/year], capacity CAP_i [kW, kWh, kWp], variable operational/dispatch cost $c_{var,i}$, such as electricity [€/kWh] and fuel prices [€/L], and energy dispatch $E_i(t)$ [kWh] in time step t [h]. Both CAP_i and $E_i(t)$ are bounded solutions such that:

$$CAP_i \geq 0 \tag{4.2}$$

$$E_i(t) \geq 0 \qquad \forall t \tag{4.3}$$

4

Once the user inputs the required data, the annual cost of each asset i is calculated in the second block of Figure 4.2 and Figure 4.3 (in subsection 4.1.2), referred to as the pre-processing step. The cost function in Equation 4.4 is obtained by amalgamating information from [90] and [94]. This cost a_i takes into consideration the investment costs or capital expenditure *CapEx* [€/unit], the replacement costs as well as the residual value $c_{res,i}$ [€/unit] if existent, and the operating expenses *OpEx* [€/unit/year], which cover the Operation and Maintenance (O&M).

$$a_i = \left(CapEx_i + \sum_{k=1}^{n} \frac{CapEx_i}{(1+d)^{k \cdot t_a}} - c_{res,i} \right) \cdot CRF(T) + OpEx_i \tag{4.4}$$

The discount factor is d and its value is determined by the user. The common method is to calculate the Weighted Average Cost of Capital (WACC) and use it as discount factor. The entire project duration is T [year], which can be different from the asset's lifetime t_a [year]. The number of replacements of that asset within T is denoted by n and estimated as follows:

$$n = round\left(\frac{T}{t_a} + 0.5 \right) - 1 \tag{4.5}$$

The residual value (or salvage value) is the estimated remaining monetary value of an asset at the end of the project. In this case, a linear depreciation is considered, meaning the value is reduced uniformly each year to reach the scrap value. The latter accounts for the time value of money as seen in Equation 4.6, and the present value of the resales revenue is deducted from the assets' costs in Equation 4.4.

$$c_{res} = \frac{CapEx}{(1+d)^{n \cdot t_a}} \cdot \frac{1}{T} \cdot \frac{(n+1) \cdot t_a - T}{(1+d)^T} \tag{4.6}$$

The Capital Recovery Factor (CRF) is a ratio used for the calculation of the present value of the annuity (series of equal payments). Technically, it is the inverse of the annuity factor if known.

$$CRF(T) = \frac{d \cdot (1+d)^T}{(1+d)^T - 1} \tag{4.7}$$

As mentioned, the MVS optimization method relies on an economic dispatch problem which consists of distributing the total demand at each time step among the available generating units in such a way that the supply cost is minimized. Therefore, the idea is to keep balance between the incoming energy feeders and the outgoing ones for each bus. The balancing equation for each bus is equal to all the energy flowing from the assets to the bus E_{in} minus all the energy that the bus is feeding to other assets E_{out}. Equation 4.8 is applicable to all bus types, be it electrical (AC and DC), thermal (heat and cold) or hydrogen.

$$\sum E_{in,i}(t) - \sum E_{out,i}(t) = 0 \qquad \forall t \tag{4.8}$$

To dive deeper in the understanding of the model, UVTgv-ICSTM's energy system is considered as a case study to elaborate on the equations.

CASE STUDY: UVTGV CAMPUS - EQUATIONS AND CONSTRAINTS

The available assets forming the energy system components of the research building at UVTgv campus are listed in Table 4.1 with reference to Figure 2.14. Both grids, electrical and gas, are assumed to be available 100% of the time with no consumption limits. In addition, the MVS includes a sink component for excess energy, connected to each bus and represented by E_{ex}, in order to account for the excess energy in the system that has to be dumped.

Table 4.1: UVTgv's List of Asset Types

Asset	**Abbreviation**	**Unit**
Transformer station	ts	kVA
Electrical grid	grid	kW
Gas source	gas	kWh
Solar PV1	pv1	kWp
Solar inverter	inv,pv1	kW
Solar PV4	pv4	kWp
Battery storage BESS	bat	kWh
Inverter (DC/AC)	inv,pv4	kW
Rectifier (AC/DC)	rec	kW
Solar thermal	st	kWh
Thermal storage	tes	kWh
Heat pump - heat	hph	kWh
Heat pump - cold	hpc	kWh
Gas burner	gb	kWh
Adsorption chiller	adc	kWh

For the sake of simplicity, the subscripts indices *in* and *out* are removed from the following energy balancing equations and instead, the + or - sign, as shown in Equation 4.8, will indicate whether it is an incoming or outgoing energy flow. The electrical system has two main types of buses, AC and DC, which allow power flow, with electricity being the main energy carrier. The interactions at the AC bus are summarized in Equation 4.9.

$$\begin{aligned} E_{ts,c}(t)\cdot\eta_{ts,c} - E_{ts,f}(t) + E_{inv,pv1}(t)\cdot\eta_{inv,pv1} + E_{inv,pv4}(t)\cdot\eta_{inv,pv4} - E_{rec}(t) \\ -E_{hph}(t) - E_{hpc}(t) - E_{adc,el}(t) - E_{gb,el}(t) - E_{ex}(t) - E_{d,ac}(t) = 0 \qquad \forall t \end{aligned} \tag{4.9}$$

$E_{ts,c}$ and $E_{ts,f}$ are the transformer station consumption and feed-in from and to the AC electricity bus respectively, and $E_{d,ac}$ represents the electrical demand i.e. building loads. Some assets, like transformers, inverters, rectifiers and batteries, have an electrical conversion efficiency that would reduce the output power and is denoted by η. The adsorption chiller and gas burner both require minor auxiliary electricity denoted by *el* in Equation 4.9. It is important to acknowledge that the coupling of the electrical and heat sectors happens through the use of the HVACR system as it consumes power from the AC electricity bus to produce heat. The electrical energy required to heat and cool is E_{hph} and E_{hpc}, respectively.

4

Equation 4.10 and Equation 4.11 outline the interactions at each of the two DC electricity buses respectively, the first one connected to *pv1* and the second to *pv2*.

$$E_{pv1}(t) - E_{inv,pv1}(t) - E_{ex}(t) = 0 \qquad \forall t \tag{4.10}$$

$$\begin{aligned} E_{pv4}(t) + E_{bat,out}(t)\cdot\eta_{bat,out} + E_{rec}(t)\cdot\eta_{rec} \\ -E_{inv,pv4}(t) - E_{bat,in}(t) - E_{ex}(t) = 0 \qquad \forall t \end{aligned} \tag{4.11}$$

As for the electrical grid side, it is represented by a grid bus with a consumption source and feed-in sink, and two transformers in/out as outlet in the system, as seen in Equation 4.12. $E_{ts,c}$ and $E_{ts,f}$ are the consumption and feed-in from and to the electric grid respectively,

$$E_{grid,c}(t) - E_{grid,f}(t) + E_{ts,f}(t)\cdot\eta_{ts,f} - E_{ts,c}(t) = 0 \qquad \forall t \tag{4.12}$$

The battery model takes into consideration the minimum and maximum energy capacity that can be stored. This is rendered by the following inequality constraints in using the State of Charge (SOC), E_bat being the stored energy in the battery.

$$CAP_{bat}\cdot SOC_{min} \le E_{bat}(t) \le CAP_{bat}\cdot SOC_{max} \qquad \forall t \tag{4.13}$$

The model is also characterized by the charge $\eta_{bat,in}$ and discharge $\eta_{bat,out}$ efficiencies, decay per time step ϵ and the rate at which the battery can be charged $C_{rate,in}$ and discharged $C_{rate,out}$. All these values are expressed in [%]. The next equations require an initial storage value at *t-1*. It is important to note that these equations are only valid if the simulation is on an hourly basis, otherwise they would not add up.

$$E_{bat}(t) = E_{bat}(t-1) + E_{bat,in}(t) \cdot \eta_{bat,in} - \frac{E_{bat,out}(t)}{\eta_{bat,out}} - E_{bat}(t-1) \cdot \epsilon \qquad \forall t \qquad (4.14)$$

$$0 \leq E_{bat}(t) - E_{bat}(t-1) \leq CAP_{bat} \cdot C_{rate,in} \qquad \forall t \qquad (4.15)$$

$$0 \leq E_{bat}(t-1) - E_{bat}(t) \leq CAP_{bat} \cdot C_{rate,out} \qquad \forall t \qquad (4.16)$$

Moreover, since the PV system is not a dispatchable source, the output energy is calculated using the capacity and specific yield that the user inputs. The specific yield β_{pv} is a performance metrics, entered as a time series, measuring the generated energy per installed capacity [kWh/kWp] at each timestep *t*. Equation 4.17 is applicable for both PV systems given the user's inputs.

4

$$E_{pv}(t) = CAP_{pv} \cdot \beta_{pv}(t) \qquad \forall t \qquad (4.17)$$

Now for the thermal side of the system, the same concept is applied to the different buses. The demand is split between heating $E_{d,h}(t)$ and cooling $E_{d,c}(t)$ demands expressed in kWh (or equivalent Joules). This means that the system comprises two main buses: the heating bus and the cooling bus. The thermal storage and gas burner are assumed to have a thermal efficiency denoted by η for each. For simplicity and convenience of computability, a constant correlation between the required input electricity and heat output is assumed for the heat pump, known as Coefficient of Performance (COP). The index *hp* is used as the *COP* is the same for heating and cooling using the heat pump. The adsorption chiller is also characterized by a *COP*, which is another way to express its efficiency.

$$E_{tes}(t) \cdot \eta_{tes} + E_{gb}(t) \cdot \eta_{gb} + E_{hph}(t) \cdot COP_{hp} - E_{ads}(t) - E_{ex}(t) = E_{d,h}(t) \qquad \forall t \qquad (4.18)$$

$$E_{ads}(t) \cdot COP_{ads} + E_{hpc}(t) \cdot COP_{hp} - E_{ex}(t) = E_{d,c}(t) \qquad \forall t \qquad (4.19)$$

The thermal storage input before charging losses is equal the output of the solar thermal and the latter is a function of the irradiance on the collector after all losses and the collector efficiency, expressed as a time series in the model (more information is available in subsection 2.3.2). The solar hot water buses balance equation is found in Equation 4.20. Finally, the gas bus equation is also expressed the same way in Equation 4.21.

$$E_{st}(t) - E_{tes}(t) - E_{ex}(t) = 0 \qquad \forall t \qquad (4.20)$$

$$E_{gas}(t) - E_{gb}(t) - E_{ex}(t) = 0 \qquad \forall t \qquad (4.21)$$

4.1.2. FLOWCHARTS

When creating a simulation model, there exists a list of basic steps that are usually respected in order to achieve a successful implementation. The first steps relate to the problem definition, project planning and system identification. Right after that, model formulation comes as a fourth step, in which the requirements for a just operation of the model are determined [96]. To facilitate the understanding of the behavior of the system, a flowchart or block diagram is drawn to show the sequence of operation and the interactions and dependencies between the different variables of the model. A flowchart needs to be a clear, neat and logical graphical representation of the system and its functions. This step of model building could be the first wrench in the implementation as errors and inaccuracies may occur and should then be corrected [97]. This is done through the revision loop that is traced in conceptual model validation.

The first attempt at mapping the process flow of the MVS tool is shown in Figure 4.2, which in turn is a bit more developed to include more detail as seen in Figure 4.3. By overlapping the blocks of both, the processing logic is extracted and described as follows. The user inputs the required data through a web interface and defines the energy vectors and the techno-economic parameters that form all together the objective function with the relevant constraints. This bunch of data is then verified in the preprocessing block: if it is valid, it is then processed as inputs to the simulation, otherwise, error messages are sent to the user. The next step is the automatized generation of the *oemof-solph* model, which tacks the components and constraints and translates them to a linear system equation to be solved in the next block. The post-processing block looks into the simulation results to evaluate the system performance, after which the outputs (Key Performance Indicators (KPIs) and graphs) are provided to the user through a web interface.

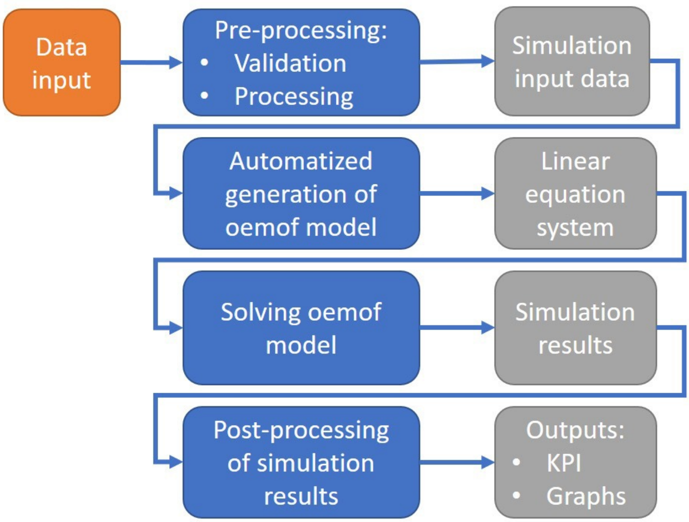

Figure 4.2: Process Flow of the MVS

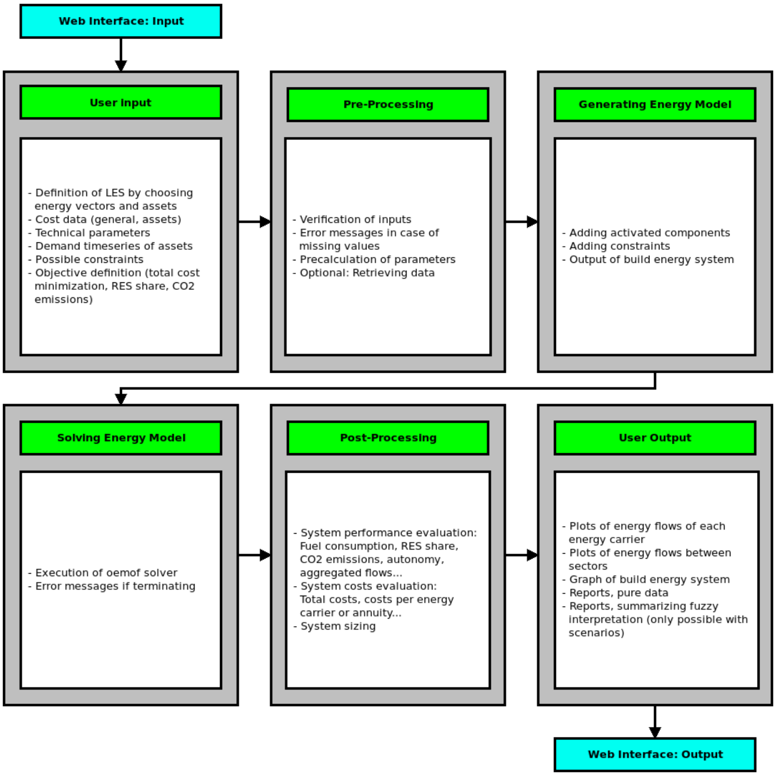

Figure 4.3: Detailed Process Flowchart of the MVS

The idea to examine the flowchart emphasizes on the importance of tracing back the functionality and operation of the MVS, be it in the components, process, system model, simulation or performance. Accordingly, a new graphical model, as seen in Figure 4.4, is created that builds on the previous two, but also focuses on the characteristics of the MVS by highlighting the inputs and the outputs. The inputs from the user are divided into four categories: project description, energy consumption, system configuration, and meteorological data. Project description includes the general information about the project, as well as the economic and financial data. The energy consumption can be expressed in three types of demand profiles, electrical, thermal and hydrogen, however, the user can input many demand time series for each demand type as a system can have several loads. In the system configuration, the user indicates the components' technical data, such as the specifications from the datasheet, and their related costs. Finally, the last category is for the meteorological data, and that one is usually for weather-dependent assets, such as solar PV or wind turbines, for which the user has to provide a time series for the calculation of the energy produced.

The middle block in Figure 4.4 represents the simulation feature of the MVS tool. The system model is based on the *oemof-solph python* library as explained in the previous

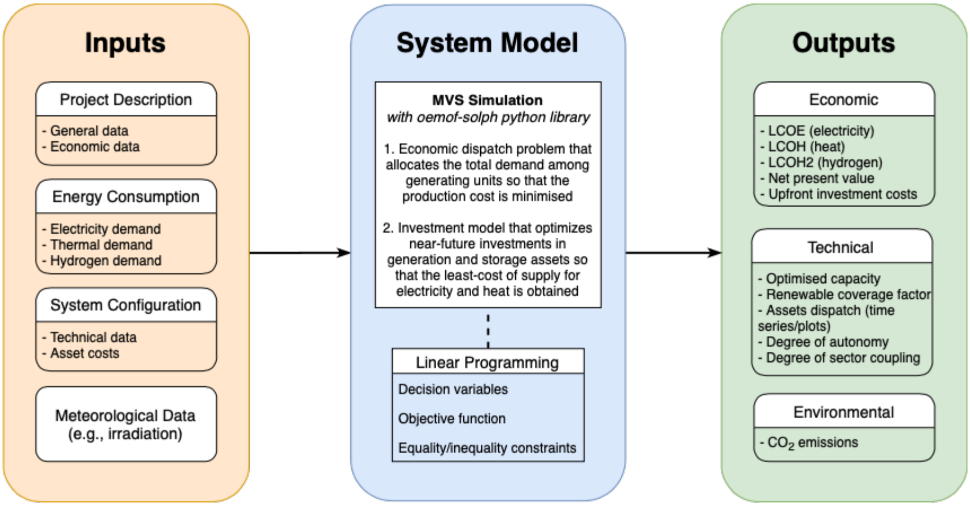

Figure 4.4: Global Flowchart of the MVS

subsection, which aggregates the components' data and constraints to formulate a linear programming problem. The optimization problem is described by the decision variables, objective function, and equality/inequality constraints. The objective function criterion in this case is to minimize the production costs by considering an economic dispatch problem. If the user chooses to enable the investment model, then the least-cost of supply of electricity, heat and hydrogen is obtained with decisions on investments in assets. The optimal solution is computed and the results are outputted to the user, sorted in three categories. The first one lists the economic/financial values, like the Levelized Cost of Energy (LCOE) of a certain energy carrier or asset, the Net Present Cost (NPC), etc., which help in the profitability evaluation. The second part of the results is related to the technical aspect of the system, in which the user can extract the optimized capacity for each asset for instance. The last one is the environmental contribution of the system, expressed in CO_2 emissions savings. All those values impart to the decision making.

4.2. MODEL VERIFICATION

Model verification attempts to determine that a simulation model is conforming with the conceptual/mathematical model upon which it is based. The goal is to establish that the computational model contains no logic or coding errors, including any algorithm being used for the integration and operation of the model [98]. In simpler words, "Verification is like debugging—it is intended to ensure that the model does what it is intended to do [84]," and goes beyond that as verification data generation might be needed in some steps for comparison with expected values [21]. To demonstrate the accuracy of the model, unit tests and integration tests are written with a static-analysis method approach as mentioned in subsection 3.3.2. These tests are automated using *python*, and this practice is used to avoid repetitive manual checks to verify whether the model is working correctly.

4.2.1. UNIT TESTS

Unit testing is a method that conducts tests on a targeted single unit such as an individual component, source code, or any function or sub-function [99], [100]. A unit test is a verification test, composed of a function that compares an input-output pair through the assertion method and returns a Boolean value - *True* or *False*. If the result is *True*, then the code is behaving as intended, otherwise, a *False* indicates that it is not and accordingly, the code should be reviewed [101]. Unit tests help detect the bugs in the model and thus fixing them in the early phases of development [100]. A framework for functional testing known by *Pytest* is adapted to write the test codes using *Python*. *Pytest* is simple and easy to use in terms of syntax as only plain *assert* statements are used. When a test method is executed, the check is done through an assertion that returns the status as mentioned. Using this framework is advantageous as it can run specific tests, subsets of tests, and tests in parallel, and can even skip tests, but most importantly with regards to the MVS, it is open source [102]. An example of an implemented unit test is the verification of whether the MVS is correctly calculating the CRF. In order to do so, values for d and T are assumed and the CRF is calculated separately and compared to the MVS' result. Other functions are not as simple and require the assumptions of more values of different types such as dictionaries, which include several keys and attributes to represent all the energy vectors in the system. A code example is given in Listing 4.1.

Listing 4.1: Unit Test to Check the Addition of All Cost Parameters

```
def test_all_cost_info_parameters_added_to_dict_asset():
    """Tests whether the function get_costs is adding all the calculated costs to
    dict_asset."""
    E2.get_costs(dict_asset, dict_economic)

    # Note: The valid calculation of the costs is tested with test_benchmark_KPI.py and
    # Test_Economic_KPI.test_benchmark_Economic_KPI_C2_E2()
    for k in (
        COST_DISPATCH,
        COST_OM,
        COST_TOTAL,
        COST_OPERATIONAL_TOTAL,
        ANNUITY_TOTAL,
        ANNUITY_OM,
    ):
        assert k in dict_asset
```

4.2.2. INTEGRATION TESTS

Integration tests target more general parts of the code such as entire modules, test the chunks as a group and verifies that the result of a combination of the different modules of the application is still correct [99]. In literal meaning, this method checks integration between various modules. This part of model verification is performed after unit testing is complete and is considered as a kind black box testing [100], which means that errors are harder to find at this point. The MVS source code is based on six main modules: initialization, input data parsing, data processing, modelling and optimization, evaluation, and output. Some of the modules also include sub-modules with different functionalities. Integration tests for all the modules and sub-modules are performed. Since the modules are interdependent in the simulation, it might be needed to run them sequentially to obtain the output of a module and the one after it and asses the results according to what is expected. For instance, the evaluation module and sub-modules are set to append the results of the simulation and optimization to the dictionary including all the energy vectors. To test this, it is important to understand the content of the dictionary before the previous module, modelling and optimization, to be able to assert that the right keys and attributes were properly added to it. A sub-module testing example in shown in detail in Appendix B. To monitor which parts of the code have been executed with respect the source code and which have not been exercised by tests, coverage measurement is used to gauge and assess the effectiveness of the unit tests and integration tests [103]. This makes explicit how well a module is covered by its own set of tests [104].

4.3. Operational Validity

As mentioned, operational validation determines that the model's output behavior is satisfactory and involves sufficient accuracy [20]. This part involves most of the testing and evaluation and any encountered inadequacy could be originated in either previous validation steps. All the validation techniques listed in Table 3.1 can be used in this step, yet the focus is on the ones that are applicable. For the operational validity of the MVS, benchmark tests and extreme input scenarios are developed to assess its quality and performance. Sensitivity analysis cases are also studied in order to pinpoint the effects on the outputs when changing the values of some inputs. Lastly, the MVS results are compared to the results of another validated optimization model with different component representation.

4.3.1. Benchmark Tests

A benchmark is known to be a metric or a point of reference against which it is possible to compare results to assess the quality of the system in question. Benchmark testing in the case of the MVS would basically measure a repeatable set of quantifiable results to compare the present and future releases with their respective benchmarks [105]. In other words, the MVS is run for a known (simple) system or given case (in terms of behavior) to produce results that would demonstrate the performance of the tool. If any changes are done to the source code, benchmark tests check if the results are different or not as the MVS should be able to reproduce the same expected results even with new and potentially better functions. The benchmark tests for the MVS tools are meant to cover all its functionalities. The implemented tests are summarized in Table 4.2. The left column of the table describes the components and constraints combination for the test and the right side defines the expected results for each case with the assertion equation used. These tests are implemented in a way to read the output files and values, and by the use of equations and the assertion method, they make sure that the results are as expected. Many more tests still need to be conducted to try to cover all the MVS' aspects.

SIMPLE CASE ELECTRICITY BUS

The first two simple tests results are shown in Figure 4.5 and Figure 4.6. As stated in the expected results in Table 4.2, the total excess energy in the second scenario with battery (purple curve in Figure 4.6) is less than that of the system without battery (red curve in Figure 4.5) and that is because the battery is being charged (blue curve in Figure 4.6). The assertion equations are translated into the language used in the previous section on model equations and are also shown in Table 4.2. The equation condition for *A+B* makes sure that the balancing equation is met while the equation condition for *A+B+E* evaluates that the total excess energy in case *A+B* (which is grid + PV) is greater than the total excess energy in case *A+B+E* (which is grid + PV + battery).

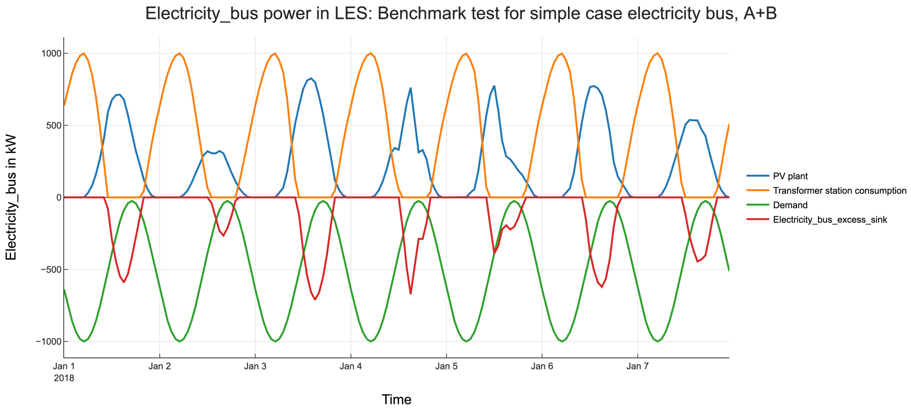

Figure 4.5: Electricity Bus Plots for Simple Electricity Bus Scenario I

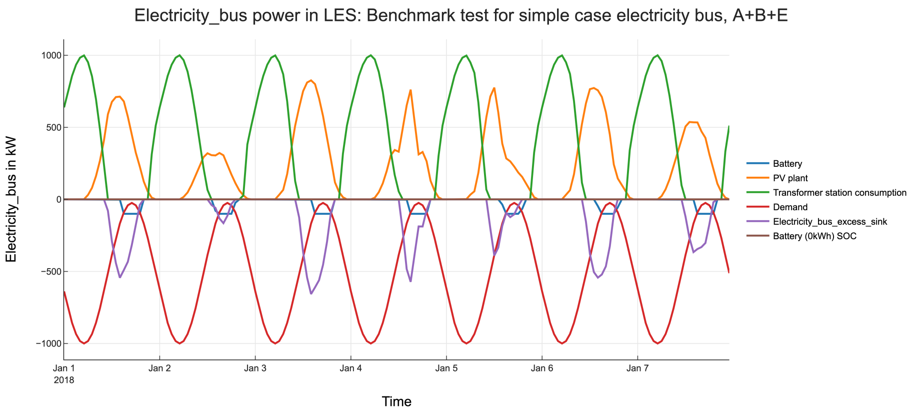

Figure 4.6: Electricity Bus Plots for Simple Electricity Bus Scenario II

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Table 4.2: MVS Benchmark Tests

Case	Component and constraint combination	Expected results and assertion equations
A+B	Grid + PV	Maximised PV use to feed the load and the rest is supplied from the grid $assert \quad E_{PV}(t) + E_{grid}(t) - E_{d,ac} - E_{ex} == 0 \qquad \forall t$
A+B+E	Grid + PV + battery	Reduced excess energy compared to grid + PV scenario as the surplus energy is used to charge the battery $assert \quad \sum E_{ex,AB}(t) > \sum E_{ex,ABE}(t) \qquad \forall t$
A+D	Grid + diesel generator	Only use diesel generator if its LCOE is less than the grid price $assert \quad LCOE_{diesel} < electricity\_price$ $assert \sum E_{diesel}(t) == \sum E_{d,ac}(t) \qquad \forall t$
A+E	Grid + battery	Battery is never used, only the electricity from the grid is used to feed the load $assert \sum E_{bat}(t) == 0 \qquad \forall t$
A+E+PDP	Grid + battery + peak demand pricing	- Battery is charged starting at a previous time step when grid is supplying peak demand but demand is smaller $if \quad E_{grid}(t) == peak\_demand \& \quad E_{d,ac}(t) > E_{grid}(t)$ $\& \quad E_{grid}(t-1) > E_{d,ac}(t-1), assert \quad E_{bat,in}(t-1) > 0$ - Battery is also charged when grid is supplying peak demand but demand is smaller $if \quad E_{grid}(t) == peak\_demand \& \quad E_{d,ac}(t) < peak\_demand$ $assert \quad E_{bat,in}(t) > 0 \qquad \forall t$ - Battery is discharged when grid is supplying peak demand and demand is bigger $if \quad E_{grid}(t) == peak\_demand \& \quad E_{d,ac}(t) > peak\_demand$ $assert \quad E_{bat,out}(t) > 0 \qquad \forall t$
A+F+G	Grid price time series + heat pump + heat grid	Only use heat pump when electricity_price/COP is less than heat_price $if \quad \frac{electricity\_price(t)}{\eta_{hph}} > heat\_price$ $assert \quad E_{heat,grid}(t) == E_{d,h}(t) \qquad \forall t$ $if \quad \frac{electricity\_price(t)}{\eta_{hph}} < heat\_price$ $assert \quad E_{hph}(t) == E_{d,h}(t) \qquad \forall t$

Benchmark tests *A+D* and *A+E* are also part of the simple case electricity bus scenarios. The logic behind the assertion equations and results interpretation can be thought similar and therefore, the results are not included to avoid redundancy.

Peak Demand Pricing

The results of the peak demand pricing scenario are shown in Figure 4.7. In fact, this figure includes all the power flows to and from the electricity bus. It is possible to distinguish the three peak demand pricing periods in orange, green and red. The expected behaviour of the battery can be interpreted from the plot: when the electrical grid is supplying peak demand (orange curve, around 250 kW), the battery is charged (blue curve) as the demand (purple curve) is lower than the peak demand consumption from the grid (orange curve). When the demand (purple curve) reaches approximately 300 kW, the battery is discharged and used to compensate for the difference between the grid and the demand. The battery discharge is not plotted in this version of the MVS. It is also possible to notice that the battery is charged (blue curve) at instances before peak demand (orange curve). All those conditions are also translated into assertion equations as seen in Table 4.2.

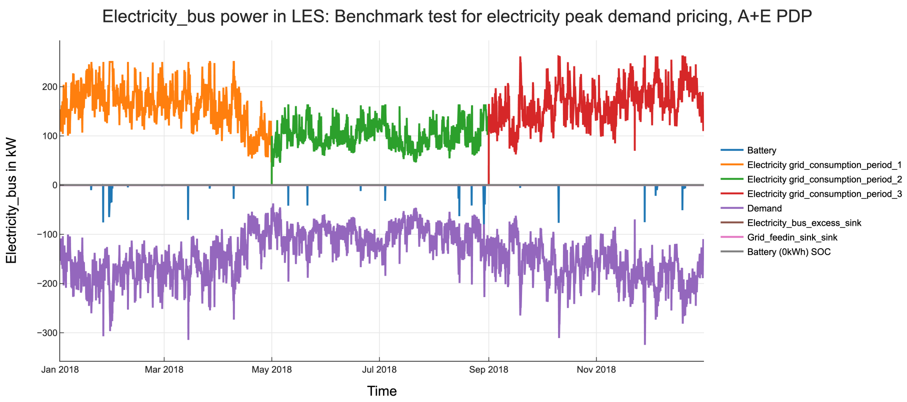

Figure 4.7: Electricity Bus Plots for Peak Demand Pricing Scenario

Sector Coupled System and Electricity Price Time Series

The last benchmark test results are plotted in Figure 4.8. It is clear that there are several switches between the use of the heat pump (red curve) and the heat grid (purple curve) to feed the demand (green curve). This is due to the input time series (cyan curve) which provides an intermittent value for the grid energy price 0.1,0.3. When the electricity price divided by the COP is less than the heat grid price, the heat pump is put to use as it is more economical. The COP is assumed to be equal to 3.5. Two assertion equations are used for this benchmark test as stated in Table 4.2.

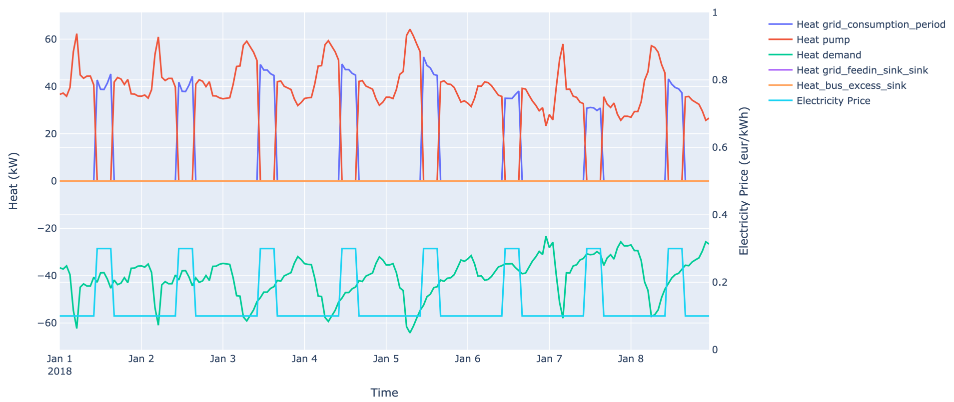

Figure 4.8: Heat Bus Flow for Sector Coupled System and Electricity Price Time Series

4.3.2. EXTREME SCENARIOS

Extreme condition tests or extreme scenarios are commonly used as a validation method for simulation models. By exposing those models to extreme conditions/input parameters, one can verify whether the model is providing reasonable outputs or not [106]. As such, those tests form some kind of qualitative validation to make sure that the model structure and outputs are still plausible under those unlikely factors [83]. By creating those cases, several MVS features are tested too such as the investment model. The list of extreme scenario cases is found in Appendix C. The following tests are quite similar and the results can be analogous. Therefore, only the results for the second tests in *High Component Cost* are shown in detail. As previously mentioned, the interpretation of the results is done through the graphs and qualitative analysis.

HIGH COMPONENT COST

Two simple tests are run to determine whether the MVS is investing in the cheapest component. The first tests includes the national grid, supposedly cheap, and a PV system with an LCOE made larger than the grid price. When the investment model is turned on, the MVS does not invest in this PV system and uses the national grid instead to supply the load. This is checked by looking at the *Optimized Additional Capacity* value for PV, which should be null. The second test is somehow similar, yet it compares two exactly similar assets, *PV1* and *PV2*, with one having a slightly higher LCOE. That is done by using lower specific costs for *PV1* than *PV2*. The MVS invests in the asset with the lower LCOE with no connected costs to the one with the higher LCOE. This is validated by looking at the *Optimized Additional Capacity* for both assets in the output files, which can also be checked in Figure 4.9: the MVS only invests in *PV1*. Another way is to look at the electricity bus plots in Figure 4.10 in which *PV2* is not used.

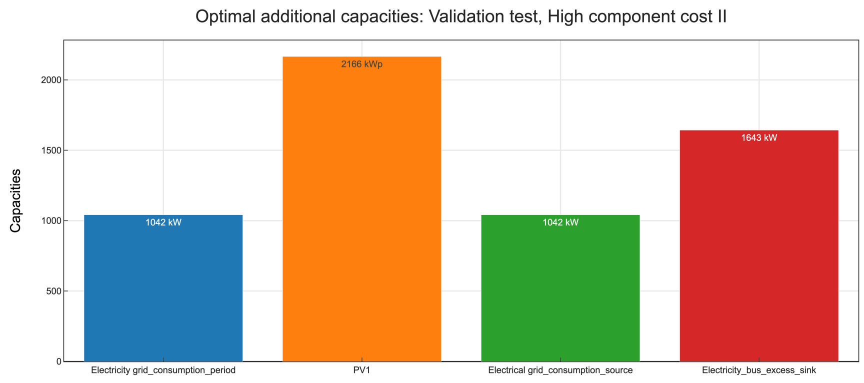

Figure 4.9: Optimal Additional Capacities for High Component Cost Scenario

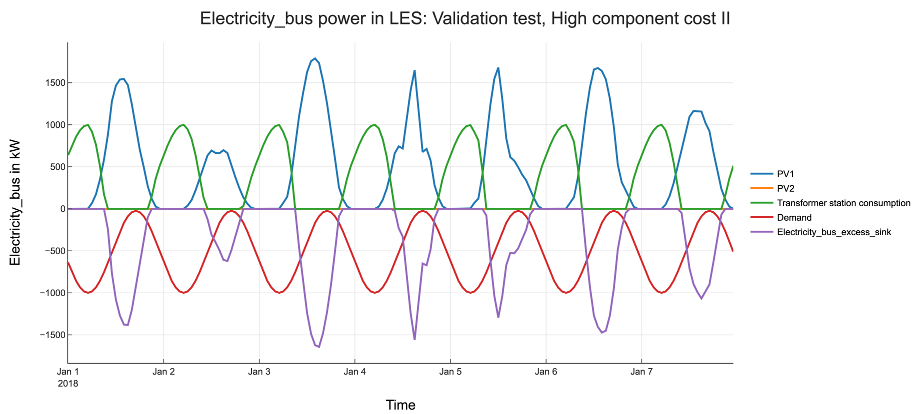

Figure 4.10: Electricity Bus Plots Showing *PV1* Use

LOW EFFICIENCY COMPONENT

For that scenario, two tests are also performed. The first one considers two comparable transformer objects with one having a slightly lower efficiency. The MVS invests in the component with a higher efficiency specification, which is checked by reading the same variable *Optimized Additional Capacity* as in the previous tests. In the second test, two energy production time series are used, one that is reduced by a factor of 10, and the MVS is expected to choose the most efficient one for supply (in other words, the one with the highest specific yield for PV for instance). The results show that no cost is connected to the one with the lowest or least efficient time series.

VERY BAD WEATHER

The following two tests assess the results of the MVS when the weather is bad. For the purpose of the tests, a PV system with a low irradiation time series is chosen. If renewables (in this case PV) are optimized, investments into renewables will be avoided and the grid is chosen for supply. If renewables are not optimized, the system uses renewables to decrease internal demand and supply the rest with the grid. In both tests, renewables do not incur any new or additional costs to the system.

4.3.3. SENSITIVITY ANALYSIS

4

Sensitivity analysis is part of the model validation scheme as it is an attempt to assess the appropriateness of a particular model specification and is particularly useful in gaining confidence in the results. Sensitivity analysis quantifies the uncertainty of the outputs with respect to the uncertainty or fluctuations of the input parameters. By exploring those relationships, it is possible to identify errors in the model that implicate the modelling and development process [107]. The intended sensitivity analyses are also shown in Appendix C. So far, only one case has been implemented, which is developed here below.

One interesting case to investigate is the investment model behavior when comparing the LCOE of an asset to the set Feed-In Tariff (FIT). In the previous validation tests, the LCOE of an asset was compared to the electricity price and if the latter is smaller than the former, then the MVS does not invest in the asset. To further analyze investment decisions, input files for a scenario with an electric grid and a PV system are created. The PV system specifications are assumed in such a way that the grid electricity price is much higher than the LCOE of the PV. An primitive excel sheet with the details of the calculations is found in Appendix D and results in an LCOE of 0.157 €/kWh. This LCOE is calculated within the MVS using the annuity method $\frac{NPC \cdot CRF}{generation}$, which also results in 0.157 €/kWh. Both LCOE calculation methods can lead to each other, and the fact that there is no discrepancy between the calculation sheet and the MVS validates this result. The grid price is set to 0.3 €/kWh, and this means that the model should invest in PV since the LCOE of PV is less than the grid price.

The next step is to run a sensitivity analysis around the FIT value. When the FIT is still less than the LCOE of the PV, the MVS should slowly invest in some additional capacity of the asset as the FIT increases. Once the FIT value crosses the LCOE of the asset, it should invest in the specified maximum capacity to benefit totally from that difference. Figure 4.11 shows three comparable simulations, with different maximum capacities for PV. It is clear that:

- When the maximum capacity is set to 500 kW, the system reaches this maximum capacity when the FIT is somewhere around 0.14 €/kWh.
- When the maximum capacity is set to 1,000 kW, the system invests in PV slowly and right around 0.16 €/kWh, the MVS invests in the entire PV capacity of 1,000 kW.

- When the maximum capacity is set to 1,500 kW, the resulting curve of the sensitivity analysis follows the exact same trend as the previous two cases. However, it makes a higher jump around 0.16 €/kWh in order to invest in the entire allowed PV capacity and increase the earnings from the grid.

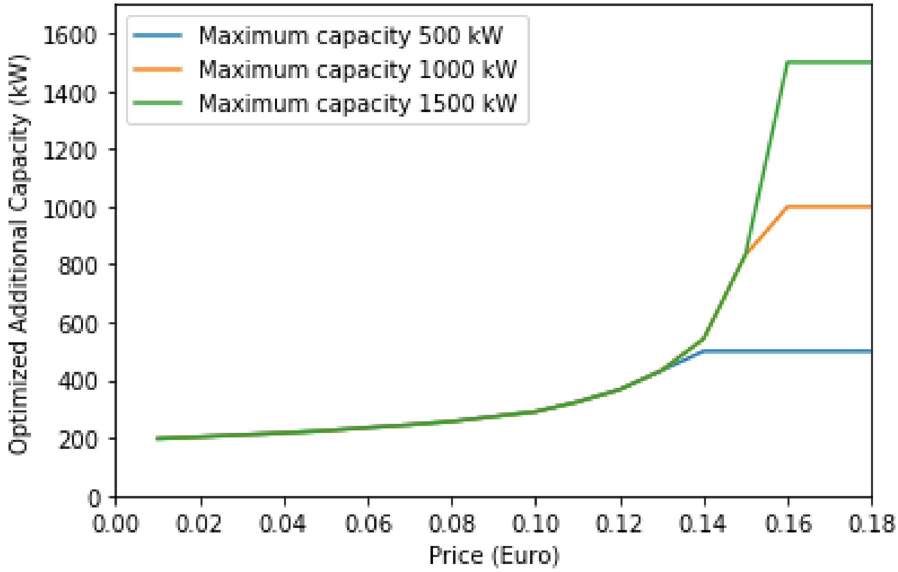

Figure 4.11: Asset LCOE vs. Feed-in Tariff

4.3.4. HOMER REPRESENTATION

According to the DMSO, "there is no such thing as an absolutely valid model, credibility can be claimed only for the intended use of the model or simulation and for the prescribed conditions under which the model or simulation has been tested" [108]. This is why the emphasis should be more on model testing, which means confidence should be built on the appropriateness of a model vis-à-vis the purpose. Moreover, comparing two models and saying one is better or has a higher degree of authenticity than the other can sometimes be irrelevant [109]. Yet, comparison to other models is still a validation technique in practice and therefore, outputs of the MVS are compared to those of another valid model.

HOMER MODEL DESCRIPTION

The proprietary software Hybrid Optimization of Multiple Electric Renewables (HOMER) is a global tool used for decision making in the microgrid and distributed energy resource space. Its overall function is described quite well by the meaning of HOMER. Its design is founded on a production cost simulation engine within an optimization algorithm and sensitivity analysis function as seen in Figure 4.12. From a programming perspective, it is technically a set of nested loops; the inner loop dispatches the generation assets and manages storage to meet the load in every simulation time step to keep energy balance. It then optimizes the design at hand by simulating numerous configurations and ranking them by NPC or other criteria, which defines what is best for this particular scenario. HOMER also includes sensitivity cases that evaluate the results of individual optimization.

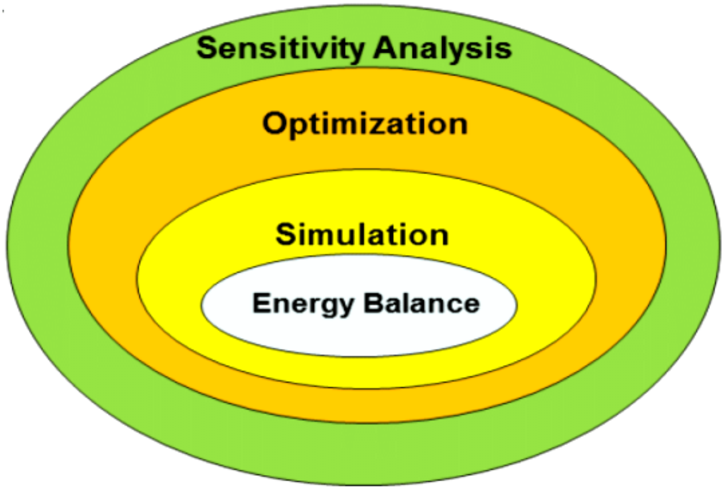

Figure 4.12: Homer Design Philosophy and Conceptual Relationship of Analysis [24]

OUTPUT RESULTS COMPARISON

A rather simple sector coupled system is created using HOMER Pro Microgrid Analysis Tool 3.14.2. In this simulation however, the two considered sectors are electricity and hydrogen. The discount rate is set to 8% and the project lifetime to 25 years. Commercial loads (electrical and hydrogen) are chosen from the standard loads available on HOMER and their key values are summarized in Table 4.3 and their plots are drawn in Figure 4.13. The system is connected to the local grid with a power price of 0.5 $/kWh and selling electricity at a FIT of 0.05 $/kWh.

Table 4.3: Electric and Hydrogen Loads

Metric	Electric	Hydrogen
Average/day	2,426.4 kWh/day	165.59 kg/day
Average	101.1 kW	6.9 kg/hr
Peak	405.71 kW	23.31 kg/hr
Load factor	0.25	0.3

PV is included as a renewable energy source in the system with a capital cost of 1,300 $/kW and O&M of 10 $/kW/year. In order to interconnect the two sectors, an electrolyzer is added in such a way that it takes power from the electricity bus to feed the hydrogen bus. The electrolyzer's capital costs are set to 300 $/kW, O&M costs to 20 $/kW/year, and efficiency to 85% . A generic reformer is added to the system at the hydrogen side as HOMER cannot find a feasible solution due to the unmet hydrogen load. The chosen fuel is biodiesel with a price of 0.62 $/L. The reformer's O&M costs are 30 $/kW, its lifetime is 25 years and its efficiency is 68.6%. The system's schematic is shown in Figure 4.14.

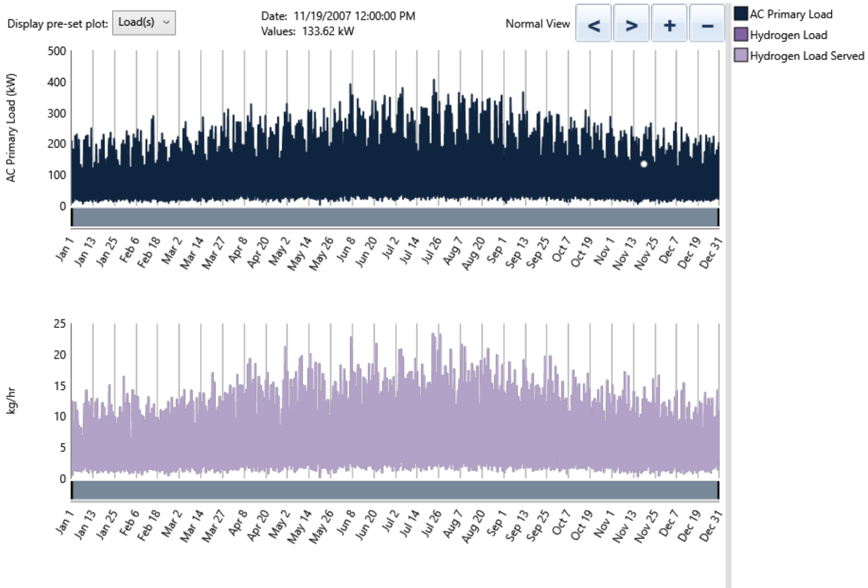

Figure 4.13: Electric and Hydrogen Loads Plots

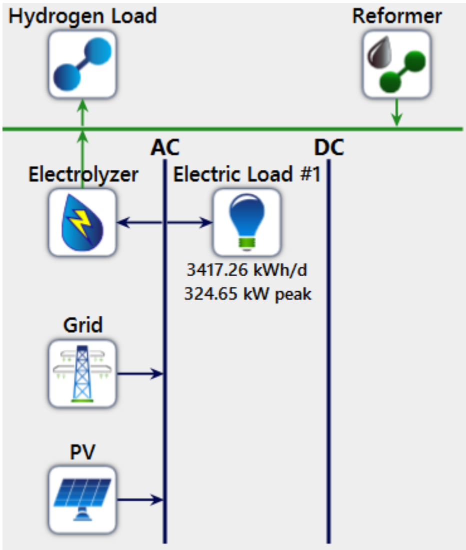

Figure 4.14: Energy System Homer Schematic

No Pre-Installed Capacities The first test considers no pre-installed capacities for the assets. Once the button *calculate* is hit, HOMER simulates hundreds, and sometimes thousands, of solutions and classifies them as feasible and infeasible. The results are extracted from HOMER and the time series for the electric load, hydrogen load and PV production are inputted into the MVS. In turn, the same system is replicated in the MVS v0.4.1 with the same component specifications and the optimization model is run. The energy system graph plotted through the MVS is shown in Figure 4.15.

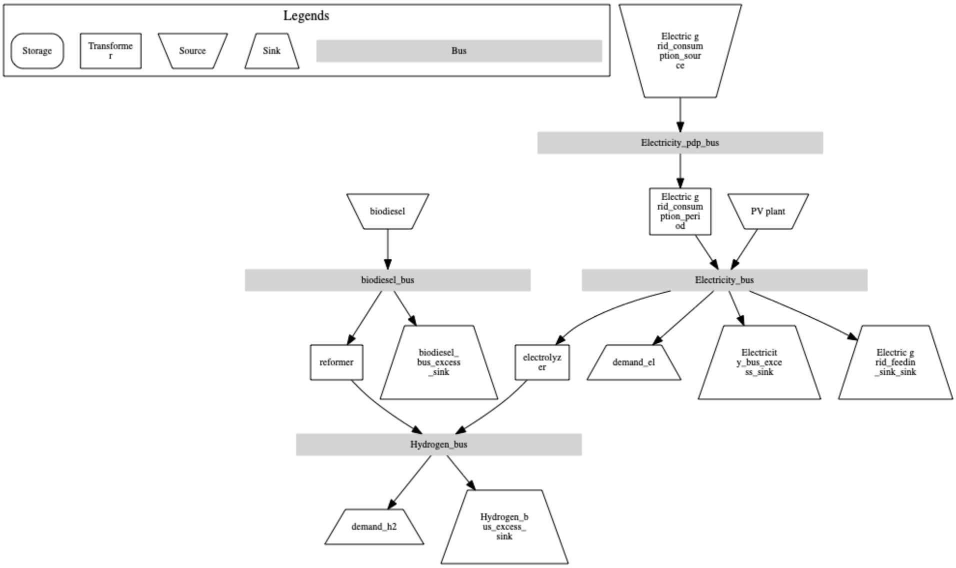

Figure 4.15: MVS Energy System Graph

Table 4.4: Optimization Results Without Pre-Installed Capacities

	HOMER	MVS
PV capacitiy (kWp)	859.56	904.08
Electrolyzer capacity (kW)	0	17.56
Reformer output (kg/yr)	60,442	103.06
Grid consumption (kWh/yr)	311,595	351,431
Grid sales (kWh/yr)	635,506	667,000
Excess electricity (kWh/yr)	0	0
Excess hydrogen (kg/yr)	0	0
Renewable energy share electricity (%)	79.5	78.3
Renewable energy share hydrogen (%)	0	0
NPC ($)	4,640,500	2,803,389
Levelized Cost of Electricity (COE) ($/kWh)	0.286	0.091
Levelized Cost of Hydrogen (COH2) ($/kg)	7.19	0.003
CO_2 Emissions (kg/yr)	196,928	TBD

As the system is made as a green field and the LCOE of the PV system made smaller than the electric grid price (0.5 $/L), it is expected that both models invest in PV. The LCOE of PV is calculated through the MVS, HOMER and the Excel spreadsheet in Appendix D, which all result in 0.09365 $/kWh. In addition, since the electrolyzer is cost-effective, and since $\frac{grid\_price}{electrolyzer\_efficiency} < \frac{biodiesel\_price}{reformer\_efficiency}$, it is also expected that the optimization models invest in some electrolyzer capacity. HOMER and the MVS both invest in a large PV capacity but surprisingly, only the MVS invests in an electrolyzer capacity. The results of this simulation are shown in Table 4.4 and the time series plots in Figure 4.16 in which it is possible to see that there is no presence for the electrolyzer in HOMER's results and that the reformer alone is used to feed the hydrogen load. On the contrary, the MVS plots at the hydrogen bus are drawn in Figure 4.17 to show the use of the electrolyzer (blue curve) and reformer (orange curve).

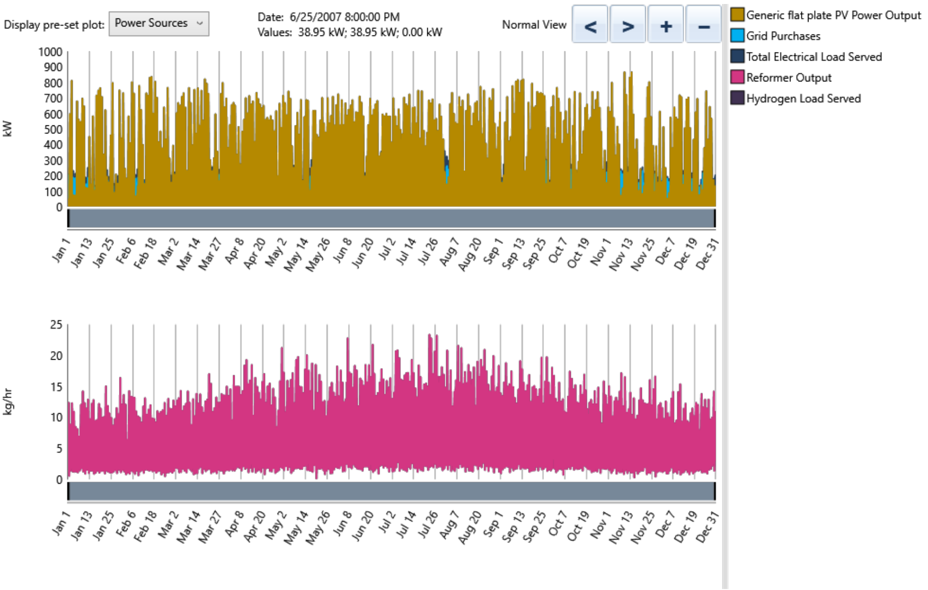

Figure 4.16: HOMER Plots of Time Series Without Use of Electrolyzer

It seems that HOMER and the MVS invests in a comparable PV capacity with about 44 kWp more for the MVS. On the other hand, the MVS invests in 17.56 kW capacity of electrolyzer compared to nothing for HOMER. The MVS also calculates the LCOE of the electrolyzer and it is equal to 0.014 $/kW. The grid consumption is in the same range for both models, with a slightly higher value for the MVS. This could be justified by the presence of an electrolyzer in the system which uses electricity to generate hydrogen. Both systems have no excess on all the buses and instead they benefit from the FIT. The grid sales are also in the same range; the MVS sells more because it invests in a higher PV capacity. The renewable energy share for electricity is very close, 1.15% higher for HOMER. The renewable energy share for hydrogen accounts for the share of renewable energy electricity used to cover for the hydrogen load (not through the electrolyzer in this case).

It is zero in both systems as no renewable source is directly feeding the hydrogen bus. The NPC in the HOMER simulation is 1.65 times bigger than that of the MVS. This can be explained by the higher O&M costs for the reformer (as the reformer output is much larger for HOMER).

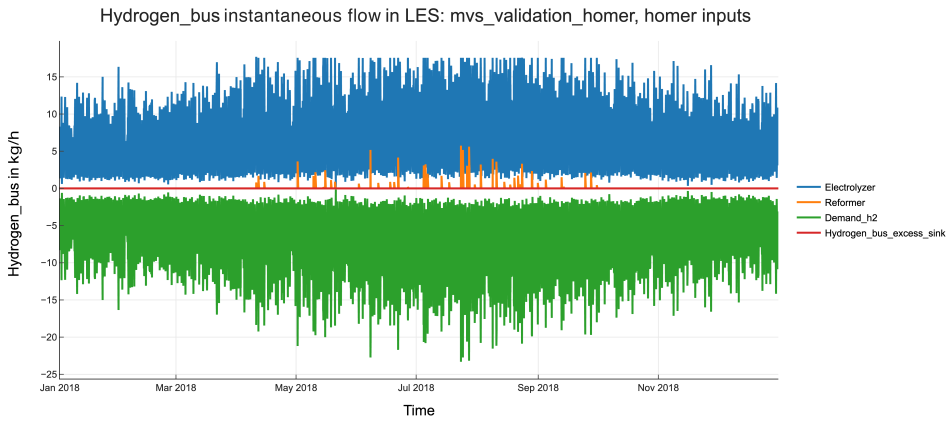

Figure 4.17: MVS Plots of Time Series at Hydrogen Bus

The Levelized COE and Levelized COH2 are way apart for both models. The definitions are compared in order to understand the difference. HOMER divides the annualized cost of producing electricity and/or hydrogen, which is equal to the total annualized cost minus the cost of serving the thermal load, by the total useful electric and hydrogen energy production. The MVS however, uses another method which aggregates the costs of energy supply and distributes them over the total energy demand supplied. The latter is calculated by weighting the energy carriers according to their energy content (Gasoline Gallon Equivalent (GGE)). This conversion factor for hydrogen is 32.87 kWh electricity per kilogram of hydrogen. This could explain the difference in the levelized COH2 in both models (HOMER does not convert hydrogen to equivalent electricity). As for the levelized COE, the difference is due to the lower NPC, which when multiplied by the CRF, results in the annualized cost.

Adding Optimization Constraints The next step is to force HOMER to invest in the electrolyzer. Therefore, a minimum capacity optimization constraint of 100 kW is added for the electrolyzer component in HOMER while an installed capacity of 100 kW is added as a constraint for the electrolyzer in the MVS as this is the only way to have this emulated. The winning system architecture in HOMER includes this time all five components. The same comparison is drawn between the two models in this scenario in Table 4.5 and the time series from HOMER are plotted in Figure 4.18.

Table 4.5: Optimization Results With Pre-Installed Capacity for the Electrolyzer

	HOMER	MVS
PV capacitiy (kWp)	796.36	904.08
Electrolyzer capacity (kW)	100	100
Reformer output (kg/yr)	60,442	0
Grid consumption (kWh/yr)	320,871	351,553
Grid sales (kWh/yr)	328,221	667,000
Excess electricity (kWh/yr)	0	0
Excess hydrogen (kg/yr)	4,905	0
Renewable energy share electricity (%)	77.7	78.3
Renewable energy share hydrogen (%)	0	0
NPC ($)	4,784,434	2,813,532
Levelized COE ($/kWh)	0.369	0.092
Levelized COH2 ($/kg)	6.86	0.003
CO_2 Emissions (kg/yr)	202,790	TBD

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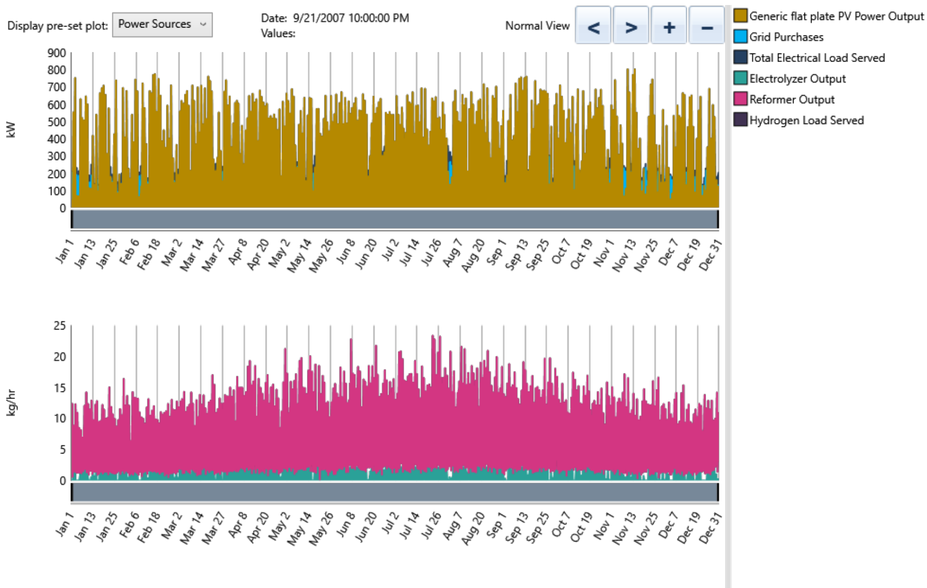

Figure 4.18: HOMER Plots of Time Series With All Five Assets

Obviously, the MVS does not use the reformer at all since the installed capacity for the electrolyzer together with the PV generation cover for the hydrogen load. This can be seen in Figure 4.19 and Figure 4.20. Technically, the MVS uses almost the same system as in the previous case, the only difference is the electrolyzer capacity, which affects the NPC, and the reformer output. HOMER however, invests in 100 kW of electrolyzer as this is a capacity constraint and the electricity used to produce hydrogen is actually sent to the excess hydrogen sink and the reformer is solely used again to feed the hydrogen load. The levelized COE is higher in HOMER than the previous simulation due to the rise in costs. There is a drop in the levelized COH2 because the hydrogen energy production is now higher due to the 4,905 kg of excess.

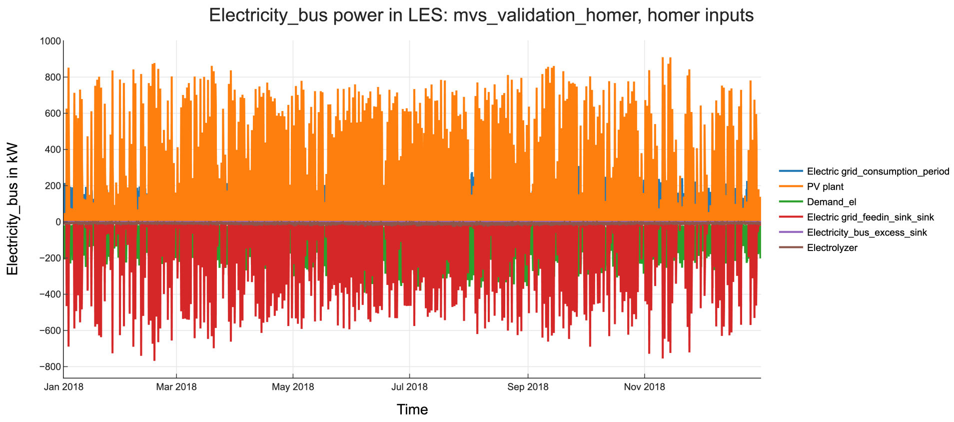

Figure 4.19: MVS Plots of Time Series at Electricity Bus

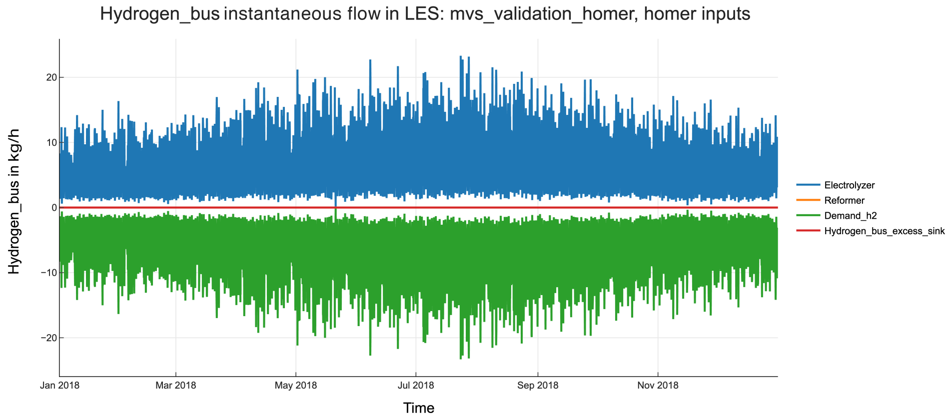

Figure 4.20: MVS Plots of Time Series at Hydrogen Bus Without Use of Reformer

Unrealistic Scenarios Since the results still seem cumbersome, a third test is run in such a way that the capital cost of the reformer is made equal to 100,000 $/kW, its efficiency to 0.01% and the biodiesel fuel price to 100 $/L, which are all unreasonable values but worth the try for verification purposes. The results for the MVS are practically the same since it already stopped using the reformer in the optimization with 100 kW of electrolyzer, but still HOMER's results came odd: the reformer is supplying the hydrogen load while the electrolyzer output produces a larger hydrogen excess within the system than in the previous case. The results are shown in Table 4.6. HOMER invests in a larger PV capacity in order to increase the sales over the project lifetime, but the levelized COE and COH2 are exorbitant.

Table 4.6: Optimization Results With Unreasonable Values for the Reformer

	HOMER	MVS
PV capacitiy (kWp)	1,011	904.08
Electrolyzer capacity (kW)	100	100
Reformer output (kg/yr)	60,442	0
Grid consumption (kWh/yr)	293,736	351,553
Grid sales (kWh/yr)	567,059	667,000
Excess electricity (kWh/yr)	0	0
Excess hydrogen (kg/yr)	5,690	0
Renewable energy share electricity (%)	79.8	78.3
Renewable energy share hydrogen (%)	0	0
NPC ($)	2.29E+12	2,813,532
Levelized COE ($/kWh)	147,365	0.091
Levelized COH2 ($/kg)	3,237,175	0.003
CO_2 Emissions (kg/yr)	477,229	TBD

One last simulation is performed by taking the same previous case and adding smaller capacity optimization constraints in HOMER for the reformer and electrolyzer. The winning system architecture includes 20 kg/hr reformer and 10 kW electrolyzer yet, the electrolyzer is barely used in HOMER unlike the MVS which totally invests in the cheapest asset.

To conclude on this techno-economic modelling comparison, HOMER cannot really be used to validate the MVS or assess the degree of realism of the MVS. It may seem that some values are similar or close, especially on the electrical side, like the LCOE of PV for instance and the renewable shares. Nonetheless, when it comes to sector coupled systems, it seems like the MVS looks for the least-cost solution while HOMER looks for the more reliable but also cheap solution, which is less dependent on the variability of renewable energy sources. More insights are discussed in the last chapter.

5

APPLICATION TO UVTGV CAMPUS

This chapter looks into one E-LAND H2020 pilot project, UVTgv Campus, and takes its research institute ICSTM as a case study which could be replicated onto the other buildings. This part aims at bridging the gap between the theories and application of model verification and validation and the simulation problem-solving practice. A description of the studied energy system is provided in Section 2.3, which allows the investigation into this energy system through the use of the MVS. The application of said tool is done in three steps. The first one is a simulation of the status quo, the second one is a techno-economic study of the optimization of the current energy scenario and assets in terms of dispatch and capacity, and the last one is a further dig into a possible future net-zero building with near-future investments in other assets.

5.1. CURRENT ENERGY SCENARIO

Before optimizing an existing energy system, it is important to understand its current behaviour. Therefore, as a first step, UVTgv-ICSTM's energy system is simulated for a year, in an hourly step and without optimization of current assets. This part of the study does not really look into the deep economic part of the existing system, but rather in its operational side. The energy system graph generated by the MVS is shown in Figure 5.1. It is similar to the energy system schematic in Figure 2.14 and the same component names are adopted. It can be spotted that the MVS creates an excess sink at every bus in the system, which is mentioned in Subsection 4.1.1. As previously explained, the system is composed of three main buses: the AC electricity bus, the heating bus and the cooling bus. DC electricity bus II is also important as it is connected to the battery storage system. In this simulation, BESS I is rarely charged or discharged, as most of the PV production is used to feed the AC loads. The highest SOC reached is 0.418, which is a change of only 0.018 from the minimum SOC.

Since the assets are already installed, the MVS would make use of them to feed the different loads. At the AC electrical bus side, the two PV systems are able to produce around

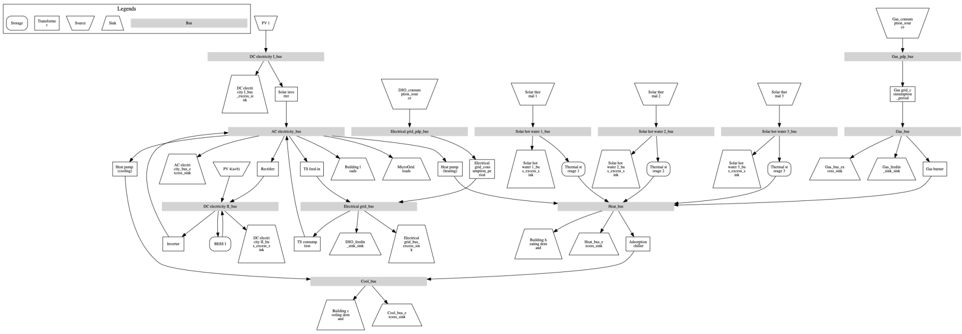

Figure 5.1: UVTgv-ICSTM Energy System Graph

66,000 kWh through the inverters, which directly feed the building and microgrid loads, and the rectifier is never used to charge the battery storage directly from the grid. There is no excess nor feed-in in the system. The consumption from the electrical grid amounts to ~308,520 kWh as it does not only compensate for the difference with the electrical demand (244,214 kWh), but electricity is also used to heat and cool the building. This is obvious in the AC electricity bus power plots in Figure 5.2.

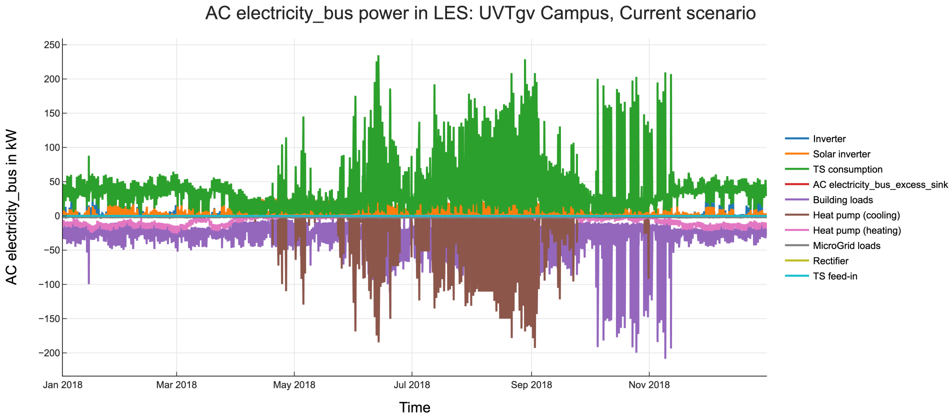

Figure 5.2: Status Quo AC Electricity Bus Plots

In fact, the electricity price and gas price used are 0.494 RON/kWh and is 0.16 RON/kWh, extracted from [110] and [111] respectively. At the heat bus side, the gas burner is not used at all, and the reason for that is that the electricity price divided by the transformer station efficiency (assumed 96%) and the heat pump COP (3.41) is actually less than the gas price ($\frac{0.494}{0.96 \times 3.41} < 0.16$). The three thermal energy storage systems are used to supply the building heating demand. Thermal storage 3 is contributing the most compared to the other two systems as it is fed by the third solar thermal system which has the highest generated output time series. The adsorption chiller also uses some energy from the heat bus to feed the building cooling demand. The latter is mainly met through the heat pump as it is much more efficient than the adsorption chiller. The instantaneous heat flows at the heating and cooling buses are shown in Figure 5.3 and Figure 5.4 through which the same observations could be made.

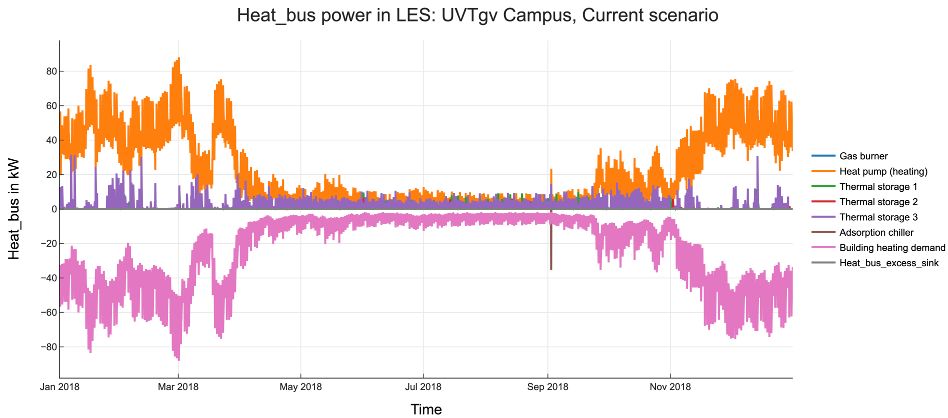

Figure 5.3: Status Quo Heating Bus Plots

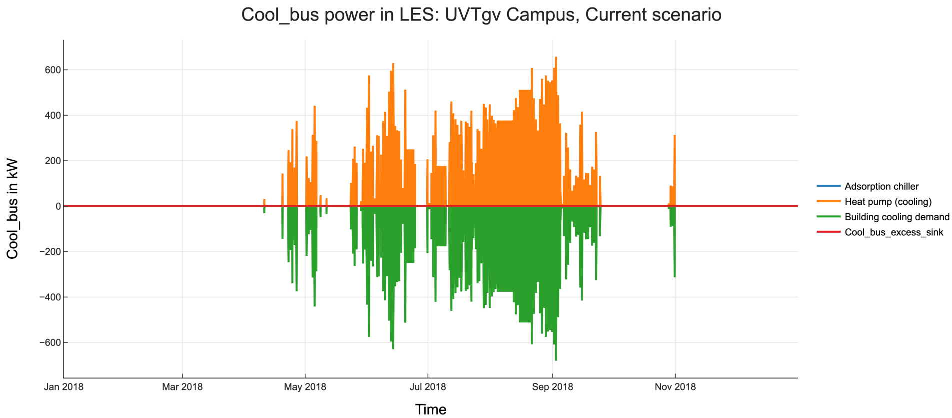

Figure 5.4: Status Quo Cooling Bus Plots

It is important to mention that the lifetime chosen for the PV systems and transformer objects is equal to the project lifetime. This means that the system does not incur any replacement costs for those assets. However, only the storage systems (battery and thermal) have a lifetime that is less than the project lifetime. Consequently, the system requires their replacement after their designated lifetime, which means that there are extra costs associated to the storage systems throughout the lifetime of the project. The annuity costs are shown in Figure 5.5 in which it can be seen that the electrical grid has the highest associated share, meaning that the system still heavily relies on imports from the grid.

The renewable energy share for electricity is 17.61% and that of heat is 100%. The renewable share for heat is whole because the gas burner is not used and the three solar thermal systems are renewable sources directly feeding the heat load. The total renewable energy share for the current system is 21.81%. The renewable energy share is calculated by taking the renewable generation used in a sector and dividing it by the total generation including the consumption from the grid. Also, each generation unit output is scaled to its energy content, which the MVS refers to as the weights of the different energy carriers (explained earlier in Subsection 4.3.4). The levelized COE is 0.3577 RON/kWh and the levelized Cost of Heat (COH) is also 0.3577 RON/kWh thermal. The reason for that is the choice of weight for the thermal energy (heat). At the moment it is assumed that 1 kWh thermal is equivalent to 1 kWh electricity. The levelized cost of a certain energy carrier is based on distributing the system's NPC over the weighted energy demand in such a way that the attributed costs are weighted and multiplied by the CRF and then divided by the total energy demand of the carrier.

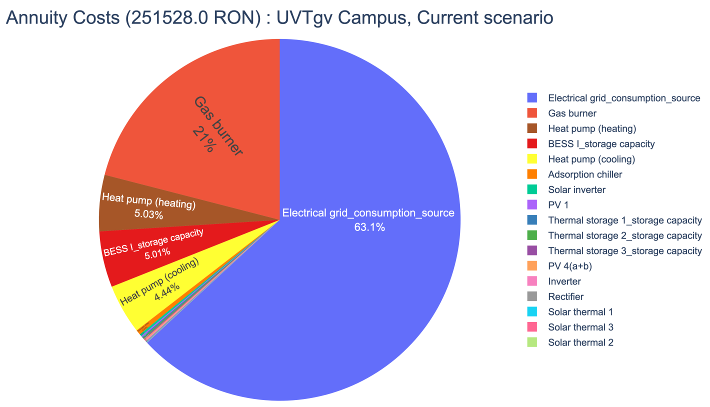

Figure 5.5: Status Quo Annuity Costs

However, the university confirms that the gas burner is mostly used for heating and that the heat pump is usually used for cooling purposes. The reason is that the gas price that is used is actually a price found online while in real life, the campus might be paying less for gas as an educational institution. In order to simulate this, the gas price is changed arbitrarily to 0.14 RON/kWh to make sure that it is cheaper than the use of electricity through the heat pump. The heat bus plots are shown in Figure 5.6 in which it is clear that the gas burner (blue curve) is used to supply the entire heating demand (pink curve). The heat pump is now only used for cooling and contributes to 99% of the cooling load (the rest is covered by the adsorption chiller).

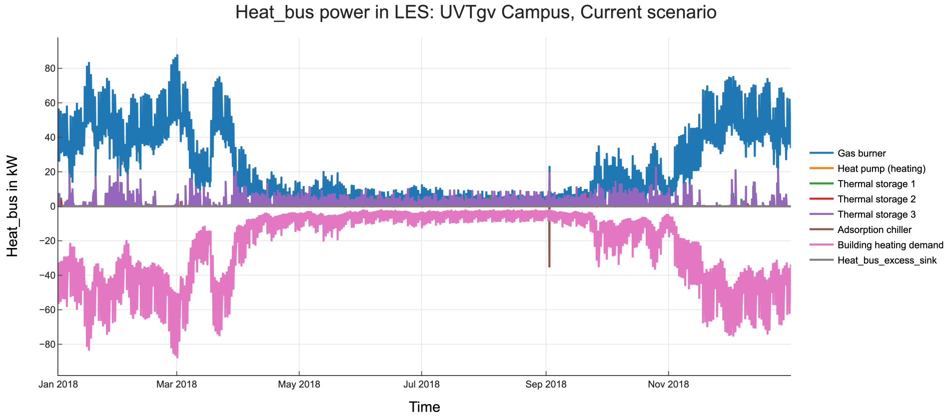

Figure 5.6: Current Heating Demand Covered by Gas Burner

The KPIs comparison is drawn in Table 5.1. Since the gas burner is used instead of the heat pump, the renewable share for heat dropped from 100% with only solar thermal production to 10.13% that includes the gas burner as a non-renewable energy technology. Besides, the renewable share for electricity increased to 20.45% because the PV generation is now used to supply the electrical load and thus there is less consumption from the the electrical grid (~256,391 kWh compared to ~308,520 kWh). The total renewable energy share thus decreased to 16.5% and the annuity share for the electrical grid from 63.1% to 52.6%. The slight change in the levelized costs of the two energy carriers (0.0011) is due to the difference in NPC.

Table 5.1: KPI Comparison For Different Gas Price

Gas price (RON/kWh)	0.16	0.14
Renewable energy share electricity (%)	17.61	20.45
Renewable energy share heat (%)	100	10.13
Total renewable share (%)	21.81	16.51
NPC (RON)	2,685,006	2,677,124
Levelized COE (RON/kWh)	0.3577	0.3566
Levelized COH (RON/kWh)	0.3577	0.3566

5.2. CURRENT ENERGY SCENARIO OPTIMIZATION

In this section, the same assets and capacities are used for the economic dispatch but this time, the investment model is enabled for all the assets and the simulation optimizes the entire system. This part of the study relies heavily on the economic parameters for the project and each asset. It is important to mention that the cost values for each asset were not provided by the university and instead, they are estimated, calculated or approximated based on sources found online as it is quite challenging to have exact and non-variant data.

5.2.1. ECONOMIC PARAMETERS

The discount rate is set to 8% and the project duration to 25 years. The assets share two main common assumptions: 1- they have no associated development costs as this is quite a variant and is ignored for the time being, and 2- no dispatch costs are associated to any of the existing assets (dispatch costs are usually present in the case of fuel sources such as diesel generators). For the two PV system modules, a specific cost of 1,500 RON/kWp is assumed based on data from [112] and the O&M costs are assumed to be 8 RON/kWp/year as PV panels are almost maintenance free. The prices for the rectifier and inverter are set to 2,860 RON/kW while the price for the solar inverter is set to 1,230 RON/kWp and those values are inspired by [113], [114] and [115]. The O&M costs are set to 20 and 17 RON/kW/year respectively. As for BESS I, it is a system of lead-acid batteries and the costs are estimated from [116]: the battery specific cost is 1,020 RON/kWh and the O&M costs are 40 RON/kWh/year from [117]. The efficiency is set at 85% and the minimum SOC to 40%, which are both also taken from [116].

5

As for the heat sector assets, the gas burner specific costs are retrieved from [118] and are equal to 1,214 RON/kWth while its O&M costs are estimated at 22 RON/kWth/year. The heat pump price is also taken from the same source and is set to 1,550 RON/kWth for both heating and cooling and the O&M costs to 17 RON/kWth/year. For the adsorption chiller, the specific costs are approximated at 2,500 RON/kWth from [119] and [120] and the O&M costs are assumed to be 35 RON/kWth/year. The solar thermal panels prices are inspired from [121] and set to 1,700 RON/kWh and their O&M costs at 8 RON/kWh/year. Finally, the thermal storage tanks' costs are estimated to be 120 RON/kWh and 6 RON/kWh/year according to [122] and [123] respectively.

5.2.2. OPTIMIZATION RESULTS USING SAME EXISTING ASSETS

Once the MVS is run with those specific parameters and all the existing assets are optimized, it looks for the least supply cost of electricity and heat. The first interesting values to read are the additional optimized capacities for the assets which are displayed in Figure 5.7. It seems that the MVS invests in both available PV systems (PV1 76.09 kWp and PV4(a+b) 47.75 kWp), their corresponding inverters (34.7 kW and 2.67 kW respectively), and solar thermal 3 (9.94 kWh) as it has the highest performance. It also seems that the system now has dumped the extra energy produced from PV in the excess sinks connected to the DC buses (31,013 kWh for DC bus I and 13,896 kWh for DC bus II). This can be explained by the absence of a FIT, but also by the fact that investing in a bigger storage or inverter capacity could be more expensive and therefore, the MVS allocates this extra energy to the excess sinks. There is also some excess energy at the solar thermal 3 bus. The system does not have excess energy at the other buses. There is no additional capacity connected to other components, however the dispatch capacities are revisited.

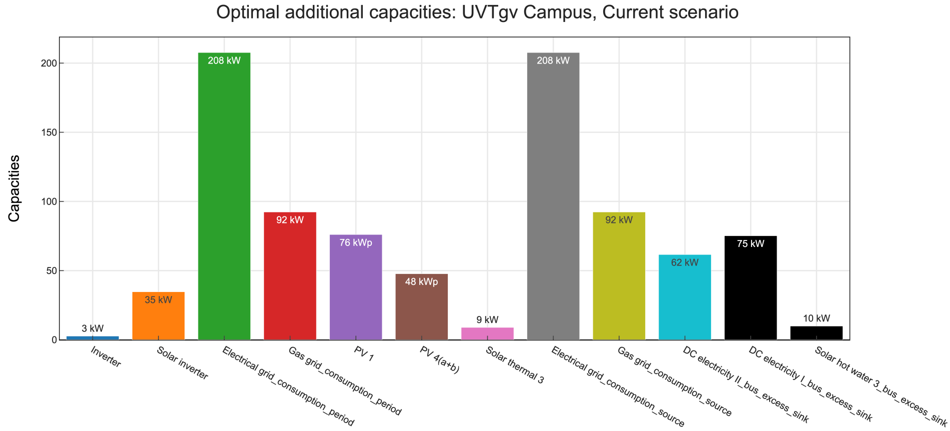

Figure 5.7: Optimized Current Scenario Additional Optimal Capacities

Table 5.2 shows the results of the simulations with and without optimization. The grid consumption has massively dropped in the optimized case (by 83 MWh). The battery storage system is finally put to use. On the heat side, the heat pump is now used for both heating and cooling but mostly for cooling. The gas burner is still used but less than in the non-optimized case, and same for the adsorption chiller but it is a bit more used in the optimized case.

Table 5.2: Output Comparison Between Optimized and Non-Optimized Scenarios

Scenario	Non-optimized	Optimized
Grid consumption (kWh/yr)	256,391	172,934
Grid sales (kWh/yr)	0	0
Rectifier (kWh/yr)	0	1,184
Battery (kWh/yr)	0	31,741
Heat pump (heating) (kWh/yr)	0	27,868
Gas burner (kWh/yr)	177,763	145,040
Thermal storage (kWh/yr)	14,706	19,615
Heat pump (cooling) (kWh/yr)	266,506	266,470
Adsorption chiller (kWh/year)	54	89

The upfront investment costs are shown in Figure 5.8. As previously mentioned, the storage systems have a shorter life than that of the project and consequently they all have associated costs as they need to be replaced. The other costs cover the optimized added capacities for the previously mentioned assets. The annualized cost shares are shown in Figure 5.9. It is clear that the reliance on the electric grid dropped (grid consumption became 172,934 kWh) as the grid cost share decreased by 15%.

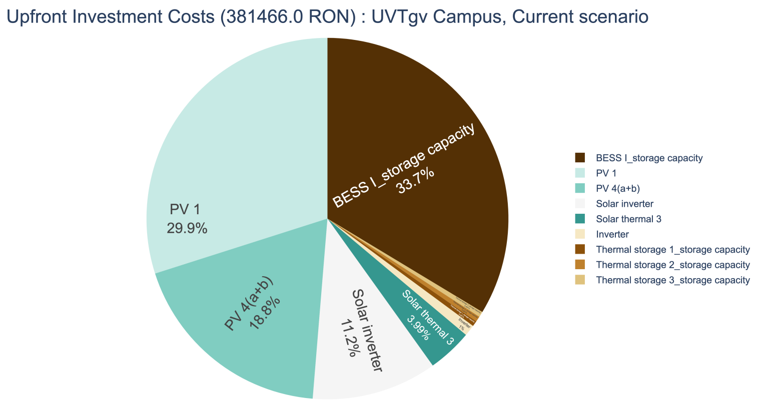

Figure 5.8: Optimized Current Scenario Upfront Investment Costs

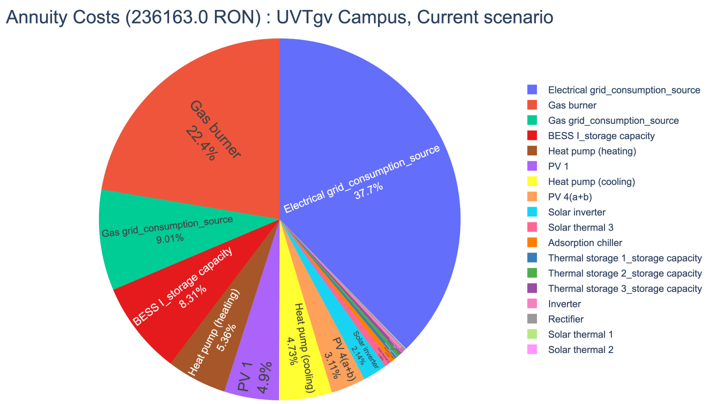

Figure 5.9: Optimized Current Scenario Annuity Costs

The KPIs comparison is drawn in Table 5.3. The renewable energy share increased for both sectors, but majorly for electricity, bringing the total renewable energy share up by 26%. The rest of the indicators are close to the ones from the non-optimized scenario; the difference in the levelized costs is about 0.021 RON/kWh, which means that the non-optimized system is a cheap solution yet not optimal and less sustainable.

Table 5.3: KPI Comparison Between Optimized and Non-Optimized Scenarios

Scenario	Non-optimized	Optimized
Renewable energy share electricity (%)	20.45	54.71
Renewable energy share heat (%)	10.13	15.58
Total renewable share (%)	16.51	42.52
NPC (RON)	2,677,124	2,520,986
Levelized COE (RON/kWh)	0.3566	0.3358
Levelized COH (RON/kWh)	0.3566	0.3358

5.3. POSSIBLE FUTURE ENERGY SCENARIO

The idea in this section is to investigate a possible future energy scenario for UVTgv-ICSTM, which is the Net-Zero Energy Building (NZEB). An NZEB is a residential or commercial building that produces enough renewable energy to meet its own annual energy consumption [124]. According to the EU, this type of building should have a very high energy performance and should balance off all its energy needs from renewable energy technologies on-site or nearby [125], [126]. This can be simulated in the MVS by using the minimum renewable energy share constraint and setting it to 100%. This feature requires the capacity and dispatch optimization of the MVS to reach at least this minimum renewable share defined by the user. It is applied to the entire sector coupled system, hence the energy carrier weighing factors are also included in the calculations, which may lead to unexpected results. The equation for the minimum renewable energy constraint min_RE is written explicitly in Equation 5.1, in which RE_gen and non_RE_gen are the renewable and non-renewable energy generation and w is the corresponding weighting factor for each energy carrier.

$$min\_RE \leq \frac{\sum RE\_gen \cdot w}{\sum RE\_gen \cdot w + \sum non\_RE\_gen \cdot w} \tag{5.1}$$

5.3.1. ADDITIONAL ASSETS

In order to look into this sustainable future energy scenario, more green assets are considered. The campus has already five small wind turbines installed: three of them are on the rooftop and two of them are on the ground level with 20 meters height. However, these wind turbines are currently non-operational or defected. Taking into consideration that the university already explored this renewable energy solution and that the campus is located in Romania, small wind turbines are included as an additional asset in the input files. They can be placed on-site or even off-site as long as they are feeding the grid as much as the campus is consuming from it. An hourly times series for small scale wind turbines power output at 30 meters is generated using Renewables.ninja tool[1]. This scientific-quality weather data is still a rough estimate and can be ameliorated if data can be extracted from the sensors and monitoring system on campus. Based on [127] and [128], the specific costs are set to 13,800 RON/kW and the O&M to 280 RON/kW/year.

The second asset considered is a small biogas plant, which has a high untapped potential in Romania. Biogas is almost climate neutral and can be used to generate electricity, heat or even co-generate both. The feedstock for biogas has three main sources: agricultural waste, wastewater and biogenic landfill waste [129]. To incorporate this asset, a biogas fuel source is created with a dispatch price of 1.64 RON/m^3 [130] and a biogas turbine as a transformer component connected to the heat bus. The turbine costs 2,400 RON/kW and its O&M costs are 32 RON/kW [128]. Its efficiency is also taken from [128] but is multiplied by the weighting factor for biogas considered in the MVS in order to convert cubic meter to kW. The calculations lead to an efficiency of 240% (0.45 * 5.38 kWh electricity per m^3 = 2.4).

5.3.2. 100% RENEWABLE ENERGY SCENARIO RESULTS

With all the data for the assets put in place, the MVS is run and the minimum renewable share factor is set to 1. The optimal additional capacities are shown in Figure 5.10 and summarized in Table 5.4.

Table 5.4: Optimal Additional Capacities for 100% Renewable Energy

Asset	**Optimal Additional Capacity**
PV1	788.53 kWp
Solar inverter	94.52 kW
PV4 (a+b)	441.69 kWp
Inverter	167.77 kW
Rectifier	17.86 kW
BESS I	1,875.81 kWh
Wind turbine	82.83 kW
Biogas	22.41 m^3
Biogas turbine	53.77 kW

The model invests in large PV capacity as it seems to be the most economical. The inverter capacities are smaller than expected (with respect to design: Pnom = 1.25), which explains the high excess at both DC buses. DC electricity bus II has a smaller excess as seen in Figure 5.10 and the reason for that is the investment in a large battery capacity. The MVS also invests in the two added assets, the wind turbine and biogas plant. The capacities are smaller than PV as the latter is more economical but also performant. The distribution of the extra energy at the electrical grid bus is allocated to the excess sink as

[1] https://www.renewables.ninja

there is no FIT assumed in the system. If the MVS is run again for the same input parameters and the transformer station efficiency is assumed to be 100%, this energy will be allocated randomly between the excess and feed-in sinks. There is also some excess energy at the solar hot water buses and that is because investing in a bigger thermal storage capacity is more expensive than this solution.

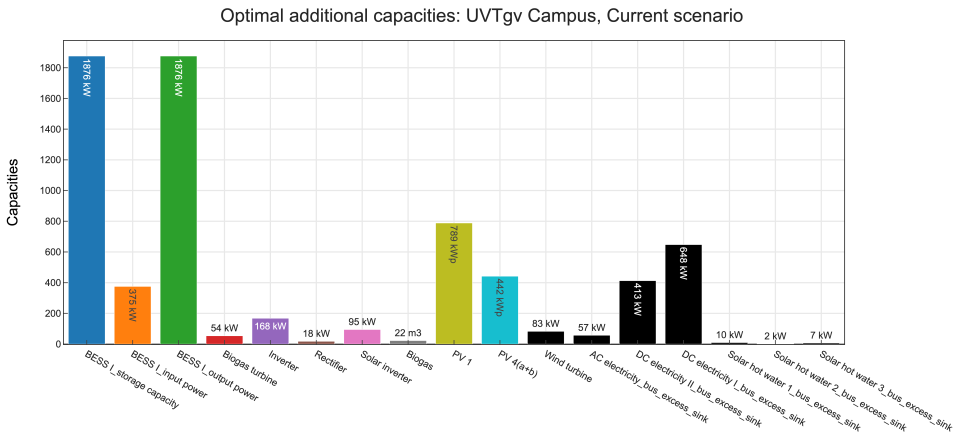

Figure 5.10: Future Scenario Additional Optimal Capacities

The energy system graph including the two new assets is shown in Figure 5.11. It shows that the wind turbine is directly connected to the AC loads while the biogas plant is connected to the heat bus through the biogas turbine. The wind turbine is feeding 298,596 kWh to the AC electrical bus. The instantaneous power flows at the electricity bus are shown in Figure 5.12. It is possible to spot the contribution of solar (orange and blue curves) and wind (red curve) power to the demand, the heat pumps consumption (pink and grey curves) and the excess energy (purple curve). There is no grid consumption at all.

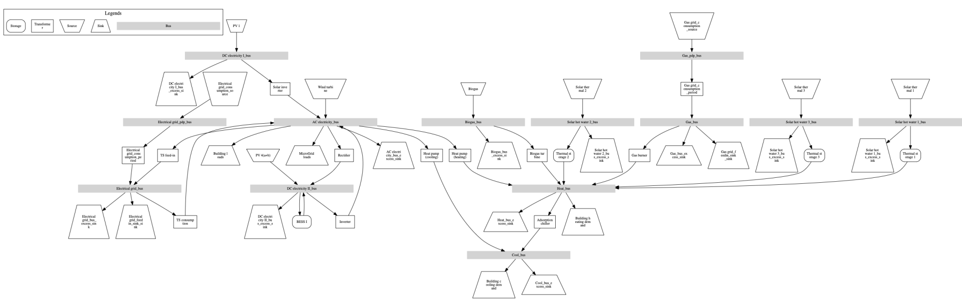

Figure 5.11: Energy System Graph for 100% Renewable Share

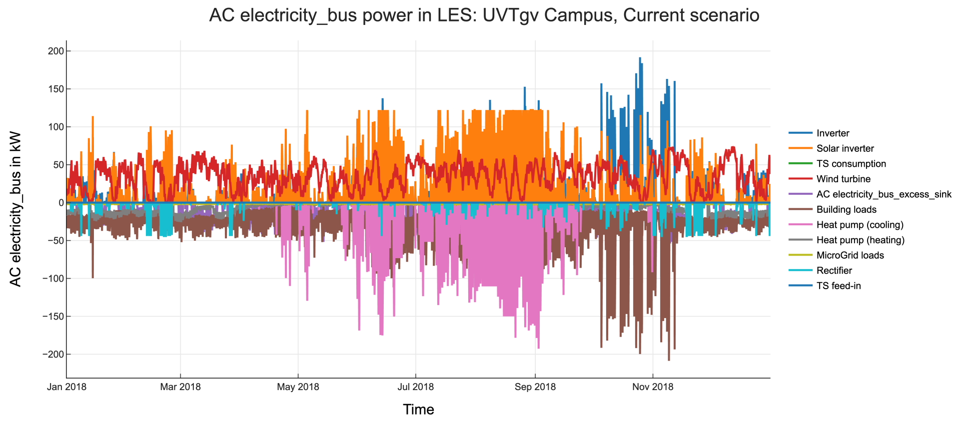

Figure 5.12: Electricity Bus Plots With 100% Renewables Scenario

At the heat bus in Figure 5.13, it is obvious that the heat pump (green curve) is covering for most of the thermal load, yet there is some contribution from the biogas turbine (blue curve) and thermal storage systems (red, purple and brown curves). There is some consumption from the adsorption chiller (pink curve) to feed the cooling load and the gas grid is not used. The plots at the cool bus are shown in Figure 5.14. It is not possible to see the contribution of the adsorption chiller, which is 706.5 kWh as its efficiency is 65% only. Most of the cooling demand is supplied from the heat pump (orange curve).

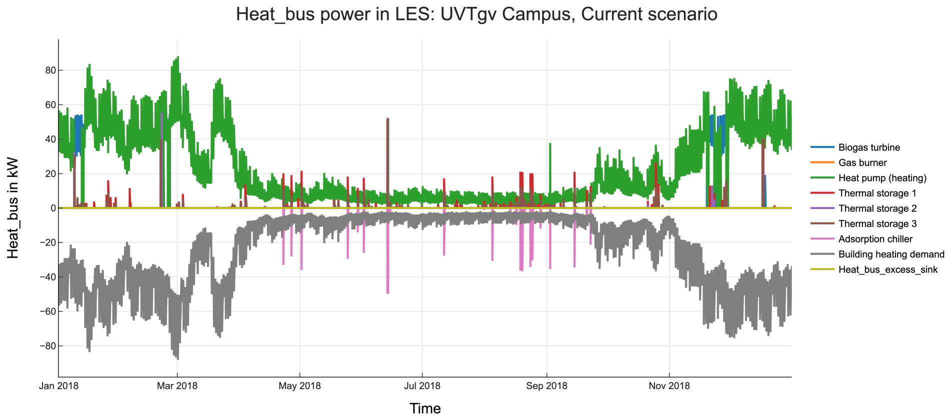

Figure 5.13: Heat Bus Plots With 100% Renewables Scenario

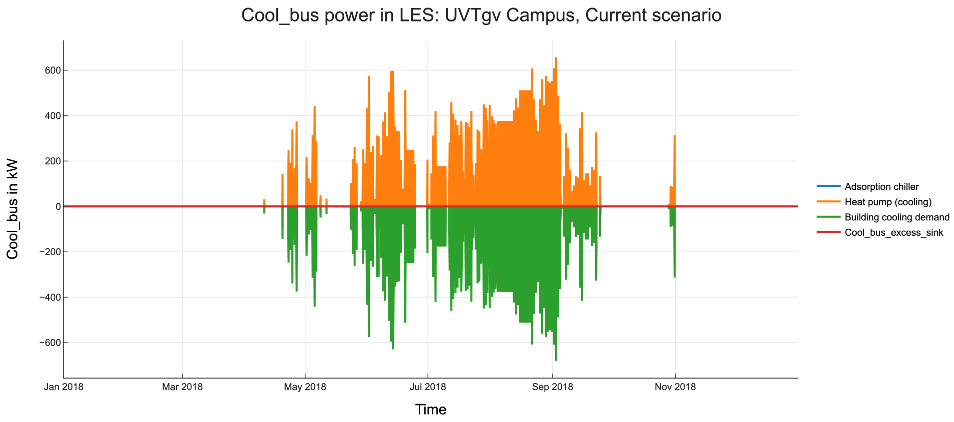

Figure 5.14: Cool Bus Plots With 100% Renewables Scenario

Lastly, Table 5.5 summarizes the KPIs values for this simulation. As expected, the renewable energy share for each sector and the total renewable share are 100%. The NPC and levelized COE and COH can all be lower if a FIT were present in the system. Another 100% renewable energy case can be simulated for the campus but this time including run-of-the-river hydroelectricity; there is a close by river and it can potentially be harnessed to serve the university loads.

Table 5.5: Future Energy Scenario KPIs

Renewable energy share electricity (%)	100
Renewable energy share heat (%)	100
Total renewable share (%)	100
NPC (RON)	9,072,582
Levelized COE (RON/kWh)	1.2087
Levelized COH (RON/kWh)	1.2087

6

Discussion and Conclusion

This is a concluding chapter discussing the outcomes of the implementation of the validation method and the application of the MVS to the extensive case study on UVTgv campus. The second section highlights the limitations of the MVS and the last section presents some suggestions for possible future research in order to further validate multi-energy vector simulation tools.

6.1. Outcomes of Validation

The purpose of the thesis is to identify a validation method for multi-energy vector simulation models which can be transferred to any similar tool. Chapter 4 demonstrated the implementation of this validation method into the MVS. As seen, the validation scheme is split in three main parts: conceptual model validation, model verification and operational validity. The conceptual model's theories and assumptions were validated by reviewing the set of equations underlying the tool as well as tracing back the flowchart by covering all the aspects of the model. The next step was to verify that those concepts were properly implemented in the MVS by writing unit tests and integration tests. Those two stages of model validation required a deep knowledge of the energy system to study whether the model's output behavior is reasonable. Some verification was also done using external methods such as the Excel spreadsheet for the asset LCOE calculation. The results from conceptual model validation and model verification were satisfactory and involved a sufficient level of accuracy.

Several validation techniques were used for operational validity. In fact, this stage of model validation is broad and can involve various and varied techniques to study the degree to which a multi-energy vector simulation tool is an accurate representation of the real world problem. In the case of the MVS, the first three techniques applied were benchmark tests, extreme scenarios and sensitivity analysis and the results were all adequate: the model was behaving as expected. Since the tool includes many features, more tests can be written with different constraints, components, sectors, etc. Below are some examples on more tests that could be explored:

- Sensitivity analysis to check the random supply of load between grid and diesel generator when $\frac{fuel\_price}{\eta_{generator}} = \frac{grid\_price}{\eta_{transformer}}$
- Sensitivity analysis to verify when a diesel generator replaces the consumption from the electrical grid if the $dispatch\_price \leq peak\_demand\_charge$
- Benchmark tests for investment model
- Benchmark tests for component with two input sources

The last technique used for operational validity is the comparison to other models, which was HOMER for the case of the MVS. This part of the thesis showed that comparing two models to assess if one is better than the other or has a higher degree of authenticity can be inapt. The two models behave differently for sector coupled systems. HOMER always sets a base case which is the system with the lowest initial capital cost and compares it economically to the winning architecture which is the system with the lowest NPC. It seems that the MVS is able to operate without the use of the reformer at all while HOMER cannot. If researched furthered, one could consider different system configurations and for instance evaluate the addition of a hydrogen storage to store the excess which makes the system more reliable and robust. It may also be that the electrolyzer is modelled differently in each optimization tool. In addition, the two models calculate the levelized cost of an energy carrier using different methods, which make the results incomparable. For all the listed reasons, HOMER cannot merely validate the MVS with the few simulations presented in Subsection 4.3.4. More scenarios can be created, starting by simulating each sector alone, then combining electricity and heat or electricity and hydrogen by using different component specifications and adding/removing storage, etc.

As for the extensive case study on UVTgv campus' energy system, the different energy scenario simulations helped in validating the tool in question by using a real life example. The problem of interest was properly represented in the MVS. Another main validation point that was tackled in this part is the importance of reasonable data, especially the cost assumptions for optimization. In fact, numerous simulations were run in order to understand the sensitivity of input-output transformations and have acceptable results. Most importantly, Chapter 5 sheds light on the role that an extensive case study plays in the validation process and underlines the need for further application of the MVS to real life projects, like the other three pilot sites, with more accurate data, especially in terms of costs.

6.2. MVS LIMITATIONS

The MVS release used in this thesis is v0.4.1. Running simulations using a non-finalized version of the MVS has shown some limitations of the tool, which are described and discussed in this section. Looking back at the set of model equations derived in Subsection

Section 4.1.1, and keeping in mind that *oemof-soplh* is a model generator for linear energy system modelling and optimization, some real life constraints were not taken into consideration in the set of model equations. For instance, the battery storage system generally works on a bidirectional flow basis. In fact, it is not possible to charge and discharge the battery at the same moment t. This also means that the inverter and rectifier cannot be working at the same moment t. Again, the inverter and rectifier are actually one component in real life, but it cannot be represented by a *soplh* component as one unit (previously explained in Section 2.3). Consequently, the two equation constraints Equation 6.1 and Equation 6.2 are not incorporated in the model as the problem would become a non-linear one, with non-linear constraints. To avoid confusion, error messages should be sent to the user in case those equations were not met in an iteration.

$$E_{inv,pv4}(t) \cdot E_{rect}(t) = 0 \qquad \forall t \tag{6.1}$$

$$E_{bat,in}(t) \cdot E_{bat,out}(t) = 0 \qquad \forall t \tag{6.2}$$

It is also the same for consuming from or feeding the grid.

$$E_{dso,c}(t) \cdot E_{dso,f}(t) = 0 \qquad \forall t \tag{6.3}$$

Furthermore, the MVS accounts for excess energy E_{ex} in the system but not for the shortage E_{sh} (the grid is always available to compensate). Yet, if this were to be included, it would have also fallen under the previous problem with non-linear constraints as deduced from Equation 6.4.

$$E_{sh}(t) \cdot E_{ex}(t) = 0 \qquad \forall t \tag{6.4}$$

The MVS simplifies the modelling of an asset. For instance, a diesel generator is implemented without its efficiency curve and turbines without ramp rates, thermal storage is implemented like battery storage, etc. Moreover, degradation over the lifetime of PV is also excluded. In fact, all production assets are expected to have the same generation profile for the lifetime of the project, which is not the case in real life. From the economic/financial point of view, inflation is not considered unless the user accounts for it in the discount factor. In addition, the tool is generic when it comes to costs and does not comprise all the Balance of System (BOS). Still the project planner can include those costs in the specific costs but that would become a rough estimation. All the above mentioned limitations have impact on the decision variables. The current version of the MVS does not output important values like CO_2 emissions or the amount of CO_2 omitted, the Internal Rate of Return (IRR), Return on Equity (ROE) and payback.

Another issue encountered was the cost of a hybrid inverter and heat pump as they are modelled by two separate transformers. The decision was to divide the costs by two even though this is technically wrong. There is however a plan in place to introduce a new constraint that links the two twin transformers together in terms of capacity and costs. Furthermore, when there is over generation in the system and no FIT, the MVS distributes the extra energy randomly between the excess and feed-in sinks as seen in the future energy scenario simulation for UVTgv. When running the simulation again, this excess energy can be allocated differently.

From another feature perspective, the MVS has perfect foresight over the study-period, meaning the system is optimized with complete knowledge of the parameters. For instance, the MVS knows when it should charge a battery in order to use it in the next time steps when there is not enough production, which is not the case in a real system. Perfect foresight is not an error, it is sometimes a convenient theoretical assumption to support investment decisions in models. A perfect foresight approach can lack realism but can also be beneficial compared to myopic strategies.

Finally, the calculation of the renewable energy share for sectors other than electricity is calculated based of the generation that is supplied directly from renewable sources. In other words, there should be renewable energy assets directly feeding the heat or hydrogen bus in order to have a renewable energy share different from zero (e.g., solar thermal). Hence, using components that allow sector coupling and the use of renewable energy electricity to serve other sectors is not accounted for in the share. This was encountered in the HOMER and UVTgv simulations. Another common method to calculate the share of renewables could use the share of energy consumption supplied from renewable sources. This renewable energy share can be improved by including the additional renewable energy captured by heat pumps from ambient heat.

The last limitation is the current weighting factor between an energy sector and electricity. At the moment, the MVS assumes a factor of one to convert heat to electricity which makes the levelized cost of both sectors equal in any simulation including both. This conversion factor could be reviewed. The same weighting factors are also used in the minimum renewable energy share constraint. Other methods could be investigated and compared to the MVS outputs.

6.3. Conclusion

This thesis aimed to identify a validation method for open source simulation tools for sector coupled systems, which was transferred to the MVS and formed a kind of application exercise. The techniques used for conceptual model validation and model verification validated the conceptual model and the computerized model respectively. Most of the techniques for operational validity also validated the output of the simulation model except for using HOMER as the two optimization tools are quite different. Indeed, a lot more tests can be run within the three validation methods to further assess the problem of interest and make sure that it is properly represented with respect to the developer's conceptual description of the model. The last part of the thesis used an extensive case study built around UVTgv pilot project from E-Land H2020. This application of the MVS to a real world system contributed to the validation the tool. When simulating this sector coupled energy system, many issues were encountered, comprehended and fixed only then. It is possible to further improve the MVS in the development and validation aspects as previously presented.

Just like the MVS, other open source simulation tools can also benefit from the derived validation methodology in Chapter 3. Running more real life case studies can validate the MVS or similar tools to a greater extent. Comparing the MVS to other open source models like *urbs* and *Calliope* could be favourable. Another proprietary optimization software like HOMER can also be explored for results comparison. Further research can be done on other verification and validation techniques for simulation models to propose a larger framework.

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Appendix A
List of Power-to-Heat Models

Paper		General method	Type of program	Model name	Time resolution	Endogenous investments	Explicit formulations	
							P2H	Heat storage
Arteconi et al. 2016	[27]	Cost minimization	MILP	–	Hourly, one year	–	(✓)	(✓)
Bach et al. 2016	[28]	Cost minimization	LP	BALMOREL	Hourly, 12 weeks	–	–	–
Barton et al. 2013	[29]	Scenario assessment	n/a	FESA	Hourly, one year	–	–	–
Bauermann et al. 2014	[30]	Cost minimization	Stochastic LPs	E2M2, HeatSyM	Time steps (days, hours)	Power, heat	–	–
Blarke 2012	[31]	Cost minimization	MILP	COMPOSE	Hourly, one year	–	–	–
Böttger et al. 2014	[32]	Analysis of potentials	n/a	–	Hourly, one year	–	–	–
Böttger et al. 2015	[33]	Cost minimization	MILP	MICOES-Europe	Hourly, one year	–	✓	✓
Chen et al. 2014	[34]	Minimization of residual demand variability	QP	–	Hourly, one year	–	✓	✓
Connolly et al. 2016	[35]	Simulation	n/s	EnergyPLAN	Hourly, one year	–	–	–
Cooper et al. 2016	[36]	Building simulation	n/s	–	1 min, (90 days)	–	–	–
Dodds 2014	[37]	Cost minimization	LP	UK MARKAL	72 time slices	(Power,) Heat	–	–
Ehrlich et al. 2015	[38]	Cost minimization	LP	–	Hourly, one year	–	✓	✓
Fehrenbach et al. 2014	[39]	Cost minimization	LP	TIMES	Time slices	Power, heat	–	–
Georges et al. 2014	[40]	Flexibility maximization	MILP	–	15 min, 3.5 days	–	✓	✓
Hedegaard et al. 2012	[41]	Simulation	n/s	EnergyPLAN	Hourly, one year	–	✓	✓
Hedegaard, Balyk 2013	[42]	Cost minimization	LP	BALMOREL, building add-on	Hourly, 4 weeks	Power, heat	✓	✓
Hedegaard, Münster 2013	[43]	Cost minimization	LP	BALMOREL, building add-on	Hourly, 5 weeks	Power, heat	–	–
Heinen et al. 2016	[25]	Cost minimization	LP	–	Hourly	Power, heat	✓	✓
Henning, Palzer 2014	[44,45]	Iterative heuristic calibration	n/a	REMod-D	Hourly, one year	–	✓	✓
Hughes 2010	[46]	Data analyses, heuristic simulation	n/a	–	Hourly, one year	–	–	–
Kirkerud et al. 2014	[47]	Cost minimization	LP	BALMOREL	1768 time slices, 52 weeks	–	–	–
Kiviluoma, Meibom 2010	[48]	Cost minimization	LP	BALMOREL	Hourly, 26 weeks	Power, heat	–	–
Li et al. 2016	[49]	Cost minimization	NLP	–	Hourly, one year	–	✓	✓
Liu et al. 2016	[50]	Welfare maximization	LP	–	15 min, 2880 h	–	–	–
Lund et al. 2010	[51]	Simulation	n/s	EnergyPLAN	Hourly, one year	–	–	–
Mathiesen, Lund 2009	[52]	Simulation	n/s	EnergyPLAN	Hourly, one year	–	–	–
Merkel et al. 2014	[53]	Cost minimization	MILP	TIMES, customized	Hourly, 48 h	Heat	–	✓
Merkel et al. 2017	[54]	Cost minimization	MILP	TIMES-HEAT-POWER	6048 h (heat), 48 time slices (system)	Power, heat	–	–
Münster et al. 2012	[55]	Cost minimization	LP	BALMOREL	n/a	Power, heat	–	–
Nielsen et al. 2016	[56]	Cost minimization	MILP	–	Hourly, 24 h	–	✓	✓
Østergaard et al. 2010	[57]	Simulation	n/s	EnergyPLAN	Hourly	–	–	–
Østergaard, Andersen 2016	[58]	Dispatch simulation	n/a	EnergyPRO	Hourly, one year	n/s	(✓)	(✓)
Østergaard, Lund 2011	[59]	Simulation	n/s	EnergyPLAN	Hourly, one year	–	–	–
Papaefthymiou et al. 2012	[60]	Cost minimization	Stochastic MILP	PowerFys	Hourly, one year	–	✓	✓
Patteeuw et al. 2015	[61]	Cost minimization	MILP	–	Hourly, 48 h	–	✓	✓
Patteeuw et al. 2015	[62]	Cost minimization	MILP	–	Hourly, 48 h	–	✓	✓
Patteeuw et al. 2015	[63]	Cost minimization	MILP	–	Hourly, one year	(Power, heat)	–	–
Patteeuw, Helsen 2016	[64]	Cost minimization	MILP	–	Hourly, one week	(Power, heat)	✓	✓
Patteeuw et al. 2016	[65]	Cost minimization	MILP	–	Hourly, one year	–	✓	✓
Pensini et al. 2014	[66]	(Heuristic) Cost minimization	n/a	–	Hourly, 4 years	Heat	–	–
Petrović, Karlsson 2016	[67]	Cost minimization	LP	TIMES-DK	Time slices	Power, heat	–	–
Salpakari et al. 2016	[68]	Minimization of residual load	MILP	–	Hourly, 24 h	–	✓	✓
Schaber et al. 2013	[69]	Cost minimization	LP	URBS-D	Hourly, 6 weeks	Power, heat	–	–
Teng et al. 2016	[70]	Cost minimization	MILP	ASUC	Hourly, one year	–	–	–
Waite, Modi 2014	[71]	Dispatch simulation	n/a	–	Hourly, one year	(Pre-optimization)	✓	–

Notes: Parentheses indicate a secondary consideration. *Abbreviations:* LP: linear program; MILP: mixed integer linear program; NLP: non-linear program; n/a: not applicable; n/s: not specified; QP: quadratic program.

Appendix B
Example of Module Testing

Listing B.1: Sub-Module E2 Economics Tests

```
import pandas as pd
import pytest

import src.C2_economic_functions as C2
import src.E2_economics as E2

from src.constants_json_strings import (
    UNIT,
    FLOW,
    CURR,
    DEVELOPMENT_COSTS,
    SPECIFIC_COSTS,
    DISPATCH_PRICE,
    DISCOUNTFACTOR,
    ANNUITY_FACTOR,
    VALUE,
    LABEL,
    INSTALLED_CAP,
    LIFETIME_SPECIFIC_COST,
    CRF,
    LIFETIME_SPECIFIC_COST_OM,
    LIFETIME_PRICE_DISPATCH,
    ANNUAL_TOTAL_FLOW,
    OPTIMIZED_ADD_CAP,
    ANNUITY_OM,
    ANNUITY_TOTAL,
    COST_TOTAL,
    AGE_INSTALLED,
    COST_OPERATIONAL_TOTAL,
    COST_DISPATCH,
    COST_OM,
    LCOE_ASSET,
    ENERGY_CONSUMPTION,
    ENERGY_CONVERSION,
    ENERGY_PRODUCTION,
    ENERGY_STORAGE,
    INPUT_POWER,
    OUTPUT_POWER,
    STORAGE_CAPACITY,
    TOTAL_FLOW,
    SPECIFIC_REPLACEMENT_COSTS_INSTALLED,
    PROJECT_DURATION,
    SPECIFIC_REPLACEMENT_COSTS_OPTIMIZED,
)
```

```
dict_asset = {
    LABEL: "DSO_feedin_sink",
    DISPATCH_PRICE: {VALUE: 0.4, UNIT: "currency/kWh"},
    SPECIFIC_COSTS: {VALUE: 0, UNIT: "currency/kW"},
    INSTALLED_CAP: {VALUE: 0.0, UNIT: UNIT},
    DEVELOPMENT_COSTS: {VALUE: 0, UNIT: CURR},
    SPECIFIC_REPLACEMENT_COSTS_INSTALLED: {VALUE: 0, UNIT: CURR},
    SPECIFIC_REPLACEMENT_COSTS_OPTIMIZED: {VALUE: 0, UNIT: CURR},
    LIFETIME_SPECIFIC_COST: {VALUE: 0.0, UNIT: "currency/kW"},
    LIFETIME_SPECIFIC_COST_OM: {VALUE: 0.0, UNIT: "currency/ye"},
    LIFETIME_PRICE_DISPATCH: {VALUE: 5.505932460595773, UNIT: "?"},
    ANNUAL_TOTAL_FLOW: {VALUE: 0.0, UNIT: "kWh"},
    OPTIMIZED_ADD_CAP: {VALUE: 0, UNIT: "?"},
    FLOW: pd.Series([1, 1, 1]),
}

dict_economic = {
    CURR: "Euro",
    DISCOUNTFACTOR: {VALUE: 0.08},
    PROJECT_DURATION: {VALUE: 20},
}

dict_economic.update(
    {
        ANNUITY_FACTOR: {
            VALUE: C2.annuity_factor(
                project_life=dict_economic[PROJECT_DURATION][VALUE],
                discount_factor=dict_economic[DISCOUNTFACTOR][VALUE],
            )
        },
        CRF: {
            VALUE: C2.crf(
                project_life=dict_economic[PROJECT_DURATION][VALUE],
                discount_factor=dict_economic[DISCOUNTFACTOR][VALUE],
            )
        },
    }
)


dict_values = {
    ENERGY_PRODUCTION: {
        "PV": {ANNUITY_TOTAL: {VALUE: 50000}, TOTAL_FLOW: {VALUE: 470000}}
    },
    ENERGY_CONVERSION: {
        "inverter": {ANNUITY_TOTAL: {VALUE: 15000}, TOTAL_FLOW: {VALUE: 0}}
    },
    ENERGY_CONSUMPTION: {
        "demand": {ANNUITY_TOTAL: {VALUE: 0}, TOTAL_FLOW: {VALUE: 40000}}
    },
    ENERGY_STORAGE: {
        "battery_1": {
            "input_power": {ANNUITY_TOTAL: {VALUE: 1000}, TOTAL_FLOW: {VALUE: 1000}},
            "output_power": {
                ANNUITY_TOTAL: {VALUE: 30000},
                TOTAL_FLOW: {VALUE: 240000},
```

```
            },
            "storage_capacity": {
                ANNUITY_TOTAL: {VALUE: 25000},
                TOTAL_FLOW: {VALUE: 200000},
            },
        },
        "battery_2": {
            "input_power": {ANNUITY_TOTAL: {VALUE: 1000}, TOTAL_FLOW: {VALUE: 1000}},
            "output_power": {ANNUITY_TOTAL: {VALUE: 30000}, TOTAL_FLOW: {VALUE: 0}},
            "storage_capacity": {
                ANNUITY_TOTAL: {VALUE: 25000},
                TOTAL_FLOW: {VALUE: 200000},
            },
        },
    },
}

exp_lcoe_pv = 50000 / 470000
exp_lcoe_demand = 0
exp_lcoe_battery_1 = (1000 + 30000 + 25000) / 240000


def test_all_cost_info_parameters_added_to_dict_asset():
    """Tests whether the function get_costs is adding all the calculated costs to dict_asset."""
    E2.get_costs(dict_asset, dict_economic)

    # Note: The valid calculation of the costs is tested with test_benchmark_KPI.py,
    # Test_Economic_KPI.test_benchmark_Economic_KPI_C2_E2()
    for k in (
        COST_DISPATCH,
        COST_OM,
        COST_TOTAL,
        COST_OPERATIONAL_TOTAL,
        ANNUITY_TOTAL,
        ANNUITY_OM,
    ):
        assert k in dict_asset


def test_calculate_costs_replacement():
    cost_replacement = E2.calculate_costs_replacement(
        specific_replacement_of_initial_capacity=5,
        specific_replacement_of_optimized_capacity=10,
        initial_capacity=1,
        optimized_capacity=10,
    )
    assert cost_replacement == 5 * 1 + 10 * 10


def test_calculate_operation_and_management_expenditures():
    operation_and_management_expenditures = E2.calculate_operation_and_management_expenditures(
        specific_om_cost=5, installed_capacity=10, optimized_add_capacity=10
    )
    assert operation_and_management_expenditures == 100


def test_calculate_total_asset_costs_over_lifetime():
```

```python
    total = E2.calculate_total_asset_costs_over_lifetime(
        costs_investment=300, cost_operational_expenditures=200
    )
    assert total == 500


def test_calculate_costs_upfront_investment():
    costs = E2.calculate_costs_upfront_investment(
        specific_cost=100, capacity=5, development_costs=200
    )
    assert costs == 700


def test_calculate_total_capital_costs():
    total_capital_expenditure = E2.calculate_total_capital_costs(
        upfront=300, replacement=100
    )
    assert total_capital_expenditure == 400


def test_calculate_total_operational_expenditures():
    total_operational_expenditures = E2.calculate_total_operational_expenditures(
        operation_and_management_expenditures=100, dispatch_expenditures=500
    )
    assert total_operational_expenditures == 600


asset = "an_asset"
flow = pd.Series([1, 1, 1])


def test_calculate_annual_dispatch_expenditures_float():
    dispatch_expenditure = E2.calculate_dispatch_expenditures(
        dispatch_price=1, flow=flow, asset=asset
    )
    assert dispatch_expenditure == 3


def test_calculate_annual_dispatch_expenditures_pd_Series():
    dispatch_price = pd.Series([1, 2, 3])
    dispatch_expenditure = E2.calculate_dispatch_expenditures(
        dispatch_price, flow, asset
    )
    assert dispatch_expenditure == 6


def test_calculate_annual_dispatch_expenditures_else():
    with pytest.raises(TypeError):
        E2.calculate_dispatch_expenditures([1, 2], flow, asset)


def test_all_list_in_dict_passes_as_all_keys_included():
    """Tests whether looking for list items in dict_asset is plausible."""
    list_true = [ANNUAL_TOTAL_FLOW, OPTIMIZED_ADD_CAP]
    boolean = E2.all_list_in_dict(dict_asset, list_true)
    assert boolean is True
```

```
def test_all_list_in_dict_fails_due_to_not_included_keys():
    """Tests whether looking for list items in dict_asset is plausible."""
    list_false = [AGE_INSTALLED, OPTIMIZED_ADD_CAP]
    with pytest.raises(E2.MissingParametersForEconomicEvaluation):
        boolean = E2.all_list_in_dict(dict_asset, list_false)
        assert boolean is False


def test_calculation_of_lcoe_of_asset_total_flow_is_0():
    """Tests if LCOE is set to None with TOTAL_FLOW of asset is 0"""
    for group in [ENERGY_CONVERSION, ENERGY_STORAGE]:
        for asset in dict_values[group]:
            E2.lcoe_assets(dict_values[group][asset], group)
    assert dict_values[ENERGY_CONVERSION]["inverter"][LCOE_ASSET][VALUE] is 0
    assert dict_values[ENERGY_STORAGE]["battery_2"][LCOE_ASSET][VALUE] is 0


def test_calculation_of_lcoe_asset_storage_flow_not_0_provider_flow_not_0():
    """Tests whether the LCOE is correctly calculated for each asset in the
    different asset groups"""
    for group in [ENERGY_PRODUCTION, ENERGY_CONSUMPTION, ENERGY_STORAGE]:
        for asset in dict_values[group]:
            E2.lcoe_assets(dict_values[group][asset], group)
    assert dict_values[ENERGY_PRODUCTION]["PV"][LCOE_ASSET][VALUE] == exp_lcoe_pv
    assert (
        dict_values[ENERGY_CONSUMPTION]["demand"][LCOE_ASSET][VALUE] == exp_lcoe_demand
    )
    assert (
        dict_values[ENERGY_STORAGE]["battery_1"][LCOE_ASSET][VALUE]
        == exp_lcoe_battery_1
    )
    for component in [INPUT_POWER, OUTPUT_POWER, STORAGE_CAPACITY]:
        assert LCOE_ASSET in dict_values[ENERGY_STORAGE]["battery_1"][component]
```

Appendix C
Extreme Scenarios and Sensitivity Analyses

Validation	Case	Qualitative Expectation	Pre-calculations/Assumptions	Investment Optimization Y/N
Extreme scenarios	High component cost 1	Do not invest in component and use the cheap grid instead	$LCOE_a$ >> grid price	Y
	High component cost 2	Comparable assets (PV1, PV2), choose the cheaper one for supply	LCOE(PV2) >> LCOE(PV1)	Y
	Low efficiency 1	Comparable assets (inverter1, inverter2), choose most efficient one for supply	η(inv1) << η(inv2)	Y
	Low efficiency 2	Comparable assets (PV1, PV2), choose most efficient one for supply (better specific yield timeseries)	η(PV2) << η(PV1)	Y
	Very bad weather	If the weather is very bad and renewables are optimized, investments into renewables will be avoided and the grid is chosen for supply	Time-series with low irradiation (divided by 10 from base case timeseries)	Y
		If the weather is very bad and renewables are not optimized, the system will use renewables to decrease internal demand and supply the rest with the grid.	Time-series with low irradiation or wind speed/energy	N
Sensitivity analysis	Fuel price = grid price	Random supply of load between grid and diesel generator	Fuel price/DG efficiency = grid price/transformer efficiency	N
	Fuel price < peak price	Diesel generator replaces consumption from grid if the peak price is higher then the fuel price	specific cost DG < peak price and fuel price/DG efficiency < grid price/transformer efficiency	N
	Feed-in tariff	- If $LCOE_a$ > electricity price, don't invest in asset - If $LCOE_a$ < FIT, invest in asset and dump to grid	refer to second sheet	Y

APPENDIX D
LCOE DETAILED CALCULATION

The initial cost of investment expenditure is equal to the specific costs times the capacity. However, the capacity choice does not affect the LCOE calculation. The O&M is also just multiplied by the capacity to get the cost per year. The generated electricity is the product of the specific yield and the capacity. The LCOE is is defined as follows:

$$LCOE_a = \frac{\sum_t \frac{I_t+M_t+F_t}{(1+r)^t}}{\sum_t \frac{E_t}{(1+r)^t}} \tag{D.1}$$

where r is the discount rate and t is the year.

specific costs (eur/kWp)	1,120
capacity (kWp)	1
o&m (eur/kWp)	10
discount rate	0.15
lifetime (years)	25
specific yield (kWh/kWp)	1,163.79
degradation	0.00%

LCOE (eur/kWh/year)	0.157470592

Year	The initial cost of investment expenditures (I)	Maintenance and operations expenditures (M)	Fuel expenditures (if applicable) (F)	The sum of all electricity generated (E)	$(I_t + M_t + F_t) / (1 + r)^t$	$E_t / (1 + r)^t$
0	1,120	0	0	0.00	1,120.00	0.00
1	0	10	0	1,163.79	8.70	1,011.99
2	0	10	0	1,163.79	7.56	880.00
3	0	10	0	1,163.79	6.58	765.21
4	0	10	0	1,163.79	5.72	665.40
5	0	10	0	1,163.79	4.97	578.61
6	0	10	0	1,163.79	4.32	503.14
7	0	10	0	1,163.79	3.76	437.51
8	0	10	0	1,163.79	3.27	380.45
9	0	10	0	1,163.79	2.84	330.82
10	0	10	0	1,163.79	2.47	287.67
11	0	10	0	1,163.79	2.15	250.15
12	0	10	0	1,163.79	1.87	217.52
13	0	10	0	1,163.79	1.63	189.15
14	0	10	0	1,163.79	1.41	164.48
15	0	10	0	1,163.79	1.23	143.02
16	0	10	0	1,163.79	1.07	124.37
17	0	10	0	1,163.79	0.93	108.15
18	0	10	0	1,163.79	0.81	94.04
19	0	10	0	1,163.79	0.70	81.77
20	0	10	0	1,163.79	0.61	71.11
21	0	10	0	1,163.79	0.53	61.83
22	0	10	0	1,163.79	0.46	53.77
23	0	10	0	1,163.79	0.40	46.75
24	0	10	0	1,163.79	0.35	40.66
25	0	10	0	1,163.79	0.30	35.35
				sum	1,184.64	7,522.94
					LCOEa	0.15747

specific costs ($/kWp)	1,300
capacity (kWp)	1
o&m ($/kWp)	10
discount rate	0.08
lifetime (years)	25
specific yield (kWh/kWp)	1,407.19
degradation	0.00%

LCOE ($/kWh/year)	0.093649595

Year	The initial cost of investment expenditures (I)	Maintenance and operations expenditures (M)	Fuel expenditures (if applicable) (F)	The sum of all electricity generated (E)	$(I_t + M_t + F_t) / (1 + r)^t$	$E_t / (1 + r)^t$
0	1,300	0	0	0.00	1,300.00	0.00
1	0	10	0	1,407.19	9.26	1,302.95
2	0	10	0	1,407.19	8.57	1,206.44
3	0	10	0	1,407.19	7.94	1,117.07
4	0	10	0	1,407.19	7.35	1,034.32
5	0	10	0	1,407.19	6.81	957.71
6	0	10	0	1,407.19	6.30	886.77
7	0	10	0	1,407.19	5.83	821.08
8	0	10	0	1,407.19	5.40	760.26
9	0	10	0	1,407.19	5.00	703.94
10	0	10	0	1,407.19	4.63	651.80
11	0	10	0	1,407.19	4.29	603.52
12	0	10	0	1,407.19	3.97	558.81
13	0	10	0	1,407.19	3.68	517.42
14	0	10	0	1,407.19	3.40	479.09
15	0	10	0	1,407.19	3.15	443.60
16	0	10	0	1,407.19	2.92	410.74
17	0	10	0	1,407.19	2.70	380.32
18	0	10	0	1,407.19	2.50	352.15
19	0	10	0	1,407.19	2.32	326.06
20	0	10	0	1,407.19	2.15	301.91
21	0	10	0	1,407.19	1.99	279.55
22	0	10	0	1,407.19	1.84	258.84
23	0	10	0	1,407.19	1.70	239.67
24	0	10	0	1,407.19	1.58	221.91
25	0	10	0	1,407.19	1.46	205.47
				sum	1,406.75	15,021.40
					LCOEa	0.09365