Faculty of Engineering Technology (ET)
Paul Scherrer Institut

Integration of Biomass Conversion into an Energy System Optimization Tool

Master Thesis

202000249 - Graduation ME

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Date:
24th August 2022

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Duration: 30 weeks (45EC)

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Abstract

A recommender tool for energy systems is developed in Python and tested on the energy system of canton Nidwalden in Switzerland. Nidwalden has 180 GWh of available biomass per year in the form of wood, animal manure, green waste and sewage sludge. For the conversion of these types of biomass, eighteen different biomass conversion technologies are investigated. The technologies are integrated in the model and tested in four different scenarios: the current situation of the canton (scenario A), a scenario where technologies for biomethane production are installed (scenario B), a scenario where technologies for electricity and heat production are installed (scenario C) and a scenario were biomethane producing technologies are combined with solar energy (scenario D). In this scenario (D), the possibility of seasonal electricity storage by using power-to-gas is evaluated. The biomethane production of both scenario B and D cover more than the gas load of 72 GWh. In scenario C, 3 times the heat load of 15 GWh and 10% of the electricity load of 330 GWh is produced. In scenario D, the surplus of electricity produced by the 19.2 MWp PV-panels during summer can be used for the methane deficit during winter. The costs of the suggested installed units are calculated per scenario and it was found that scenario C is economically the most feasible. However, the solutions of scenario B and D are energetically more interesting, especially in times of unstable and expensive gas supply. The model is tested on sensitivity and is publicly available. It is explained how the code works and how it can be adapted.

Acknowledgements

During the period of 30 weeks, I researched the possibilities of integrating biomass conversion technologies in recommender models. It was an exciting period, since it was my first time living abroad. Doing the master thesis taught me a lot. Of course on a technical level because of the research, but also being responsible for a planning and dealing with problems. I want to thank a few people for helping me throughout this period.

First of all, thanks to Yashar and Hossein for arranging the thesis with me. I already know Yashar for a while because of previous work, but it was great that we could organize the thesis with Hossein. Hossein, thank you for the help and discussions! We had contact a few times per week and it always felt like I could come to you with anything. I also want to thank Artur for the feedback he gave me before and during the green light meeting in the holiday season.

Besides my supervisors, I want to thank the colleagues at the office of PSI. Especially my office partner Tilman for the input in discussions and Julian for driving together a lot of times.

Next to everyone from PSI, I also want to thank Vannessa and Gillianne from WSL. Because of joint discussions, way more data could be gathered.

Lastly I want to thank all the study friends, family and friends that helped me throughout this period with both thesis related things as well as other things.

Luc van Dijk
24th August 2022

Contents

Nomenclature

General

€	Euro
AM	Animal Manure
BFE	Bundesamt für Energie
CAPEX	Capital expenses
chem	chemical
CHF	Swiss Franc
cons	Consumption
DSM	Demand Side Management
Eff	efficiency
elec	electrical
ENVEX	Total annual carbon dioxide emissions
FOM	Facilities Operations and Maintenance
GW	Green Waste
IEA	International Energy Agency
Inv. Cost	Investment cost
JASM	Joint Activity Scenarios and Modelling
LBK	Bioenergy and Catalysis Labaratory
LCA	Life-Cycle Analysis
LCOE	Levelized Cost Of Energy
LHV	Lower Heating Value
LP	Linear Programming
MILP	Mixed-Integer Linear Programming
nbr	number
Nid	Nidwalden
NLP	Non-Linear Programming
OPEX	Operating annual expenses
prod	Production
PSI	Paul Scherrer Institut

PV	Photovoltaic
r	Resources
RP	Rappen
SCCER BIOSWEET	(BIOmass for SWiss EnErgy Future, Swiss Competence Center for Energy Research)
SFF	Swiss Future Farm
SNG	Synthetic Natural Gas
SS	Sewage Sludge
SWEET EDGE	SWiss Energy research for the Energy Transition, Enabling Decentralized renewable GEneration in the Swiss cities, midlands, and the Alps
TCP	Thermochemical Processes
therm	thermal
TOTEX	Total annual expenses
u	Units
USA	United States of America
UT	University of Twente
WO	Wood
WSL	Forschungsanstalt für Wald, Schnee und Landschaft

Biomass Conversion Paths

GADUP	Green Waste Anaerobic Digestion Upgrading
GADUP1	Green Waste Anaerobic Digestion Upgrading 1
GADUP2	Green Waste Anaerobic Digestion Upgrading 2
GHYGUP	Green Waste Hyrothermal Gasification Upgrading
MADICE	Manure Anaerobic Digestion Internal Combustion Engine
MADUP	Manure Anaerobic Digestion Upgrading
MADUP1	Manure Anaerobic Digestion Upgrading 1
MADUP2	Manure Anaerobic Digestion Upgrading 2
MHYGUP	Manure Hyrothermal Gasification Upgrading
SADICE	Sewage Sludge Anaerobic Digestion Internal Combustion Engine
SADUP	Sewage Sludge Anaerobic Digestion Upgrading
SADUP1	Sewage Sludge Anaerobic Digestion Upgrading 1

SADUP2	Sewage Sludge Anaerobic Digestion Upgrading 2
SHYGUP	Sewage Sludge Hyrothermal Gasification Upgrading
WCHP	Wood Combined Heat and Power
WGEM1	Wood Gasification Electrolysis Methanation 1
WGEM2	Wood Gasification Electrolysis Methanation 2
WGICE	Wood Gasification Internal Combustion Engine
WGM1	Wood Gasification Methanation 1
WGM2	Wood Gasification Methanation 2

Symbols

η	Efficiency
$\sum_u$	Sum of all installed units
τ_u	Annualization factor
c_r^{buy}	Import costs for a technology per kWh
c_r^{sell}	Export income for a technology per kWh
c_u^{mult}	Multiplication factor for an installed unit
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
E_{grid}^{+r}	The amount of energy of an exported resource
E_{grid}^{-r}	The amount of energy of an imported resource
H_2	Hydrogen
H_2O	Water
M	Molar Mass
S_u	Specific costs of an installed unit

1 Introduction

The climate is changing and this has catastrophic effects. Parts of the world are already experiencing more biodiversity loss, more extreme weather and ecosystem degradation [1]. If humans do not reduce their emissions, the mentioned events will happen on a larger scale and more frequently. The Paris climate agreement says that the earth's temperature cannot change more than 1.5 degrees Celsius compared to pre-industrial temperatures (1850-1900) [1]. All sectors of all countries have to improve on the topic of sustainability to minimize the effects of climate change. One of the fields that should improve, is the energy production field. Currently, energy production is strongly relying on fossil fuels, but it is important to change to renewable energy. One of the renewable energy sources is energy from biomass. There are various techniques to get energy from biomass. The best conversion path for a case depends on the available biomass type, the required output, the efficiency, the price, etc.

In Switzerland, energy from biomass has been researched before. There is an extensive overview of the available biomass in the country. This contains information about the amounts, the types and the regions of Switzerland in which they are available. A Swiss project called the SWEET EDGE project, is intending to expand and update the existing knowledge about the different biomass technologies. Multiple parts of this big research project are done by the Paul Scherrer Institute (PSI). One of the tasks is to focus on developing the design and evaluating the operation of local energy systems (in urban neighbourhoods), and then look into three technologies in particular: the role of storage, electric vehicles and biomass technologies. The focus of this thesis will be on the biomass technologies. In order to do this, an open-access recommender tool will be created that allows any other (urban) neighbourhood to evaluate its design and operation options for such systems. Eventually this will be a highly renewable multi-energy system, but the focus will be on biomass energy first.

At PSI, research has already been done on an optimizer tool for 'Swiss Future Farms'. These results and models can be used as an input for the new optimizer tool, which will be more general and can be used for multiple cases. To test the optimizer tool, different cases will be investigated. These cases will have different inputs and loads. Additionally, background research is necessary for the values of all the different technologies.

1.1 PSI and SWEET EDGE

PSI is the biggest research institute of Switzerland, with approximately 2100 employees. Because of the size of the institute, many research topics are covered by different research groups. This thesis will be performed in the Bioenergy and Catalysis Laboratory (LBK) at the Thermochemical Processes (TCP) subgroup. The group is focusing on biomass processes, methanation technologies, power-to-x, hydrogen use, etc. [2]. The Thermal Engineering group of the University of Twente (UT) is starting projects in collaboration with the TCP group at PSI. This thesis is the first collaboration between the two groups.

Multiple people from the LBK group are involved in the Swiss SWEET EDGE project. It stands for SWiss Energy research for the Energy Transition, Enabling Decentralized renewable GEneration in the Swiss cities, midlands and the Alps. In this project, various institutes, universities and industries work together on tracking decentralized renewable energy in Switzerland. The goal is to ensure that by 2035 and 2050, the Swiss energy system is designed technically and economically optimal. An important part of that goal is to get high shares of locally-sourced renewable energy in different areas. Technologies like battery and thermal storage, power-to-x, private and public electric transportation and new biomass technologies in renewable energy systems for Swiss cities should be investigated more in depth. Especially the biomass technologies are interesting for this thesis [3] [4].

1.2 Problem Statement

It is known that urban areas have more difficulties to switch to renewable alternatives than rural areas. This is mostly due to the lack of space and resources. An example, there is no biomass available in the form of animal manure in urban areas and plenty in rural areas. The SWEET EDGE project needs an open-access recommender tool that allows any urban neighbourhood to evaluate its design and operation, which will be developed in this thesis. A similar kind of recommender tool has been developed already for Swiss farms [5]. Some of this work can be reused, but it needs to be extended. First of all, biomass conversion paths need to be explored. Then, they need to be integrated in a proper way in the model. Since the model needs to work for any urban neighbourhood, a test case is used. That will change the loads and demands compared to the model for farms. The input files are expanded, but also the energy balance files will be changed. The model is able to generate plots, but this will be improved so all the useful information can be shown in this report. Eventually, the model needs to be easily adaptable for different cases. In this thesis, the model will be used on a test case and optimization will be done for that case.

1.3 Research Questions and Objectives

The investigation and solving of the problem can be managed better by answering the research questions. The research is not limited to these research questions. For example, the model will also be tested with a case. Findings of the tests are also important for the thesis and future users of the model. The main research question is:

- How can the operation of local energy systems efficiently be developed and evaluated into a recommender tool with integrated biomass conversion technologies?

This main research question will be answered at the end of the thesis with the help of some sub-questions.

- What are the applicable biomass conversion pathways to electricity, heat and biomethane?
- How efficient, complex and costly are these pathways?
- To what extend can the model be used for the optimization of energy systems in urban neighbourhoods?

The aim of the thesis is to create the recommender tool and validate it with a case study. The questions will help to integrate biomass conversion technologies into the model. There are no specific research questions for the case study, since it is only defined to validate the model.

1.4 Thesis Structure

The thesis is written in a certain structure to improve readability. In this section, the background and focus of this thesis are described. For example, why is more research required on this topic and what are the research questions that can help to fill the research gap.

In the next section, **Section 2**, the results of the literature review are given. Some important articles are discussed and their topics are in a wide range. For example, there is information from articles about biomass data, but also about code development. Additionally, an extensive overview of the data collection on the biomass conversion technologies and the biomass availability are given.

In **Section 3**, the methodology is discussed. Different scenarios are given and calculations are performed to get all the necessary values for the scenarios. After that, the model is explained, as well as the model development, optimization and sensitivity analysis.

In **Section 4**, the results of the different cases are given, explained and discussed. The scenarios are reviewed on implementation of biomass technologies, but also on cost and emission perspective. This is done by analyzing and discussing the results in every results section immediately. Next to the analysis of the results, there are recommendations for future users of the model and general discussions about topics like the technologies and the limits of the model.

The last section, **Section 5**, contains the conclusions, recommendations and acknowledgments. So the research questions are answered here and a conclusion is drawn about the model. The recommendations are partly about the model, and partly about future research. After this section, the references and the appendices are given. They are both referred to throughout the report.

2 Literature Review

This section gives an overview of the literature that was found on the topic. The first part is mostly about the biomass conversion technologies, the second part is about the biomass in Switzerland and lastly some information about the model is given. In Subsection 2.1, the biomass conversion technologies that will be integrated in the model are given. Most of the information about these technologies is found in literature. However, some efficiencies and other values are calculated. In Subsection 2.2, the biomass availability and the energy demands of the test case are discussed. The information was mainly taken from Swiss government websites. Later on, during the thesis, more literature was used to make assumptions and support the calculations. This literature is referred to in the text. After all the required information is collected, it can be implemented in the model to fill the research gaps that are explained in Section 1. The information about biomass conversion technologies, contributes to the goal of the SWEET EDGE project to investigate possibilities of integrating biomass. The other information for the model will be used to create a recommender tool for the energy system of an urban neighbourhood.

Bauer et al. evaluated the available renewable energies that can be used in Switzerland on a project from the Bundesamt für Energie (BFE) [6]. The report describes all the available renewable energies that can be used in Switzerland. Data from the renewable biomass energy information of the report is very relevant for this thesis. Other technologies, like wind and solar energy in Switzerland, are not directly used but still interesting for the view on entire energy systems. The largest potential for biomass based electricity is the mobilization of manure and woody biomass. Currently, manure is rarely used to produce energy and woody biomass is mostly used to only produce heat. This should be changed to use the resources more, and more efficiently. Wind and PV power are expected to drop price in the future, but biomass technologies are expected to drop less. This is mostly due to the relatively high biomass feedstock costs. However, biomass can be not only used for electricity production like PV and wind, but also for heat and fuel production. In the report, cost estimations for biomass technologies are given for the present and the future. The part about waste incineration will not be used for this thesis, since the focus is on biomass.

The organisation ‘Joint Activity Scenarios and Modelling’ (JASM) wrote a report that contains information about biomass potentials and biomass conversion pathways [7]. There was only a total overview of biomass in entire Switzerland. For this thesis, more local biomass information needs to be gathered later. However, the paper provided useful insights about potentials and prices. There was an extensive overview of different biomass technologies for different resources. For some of these technologies, information about efficiency, costs and electricity use was provided. This information was extremely useful to create a complete overview. Also, the report contained multiple interesting citations. For example one of the citations is a poster about a testing platform for woody biomass conversion to synthetic natural gas (SNG) in Güssing, Austria [8]. A 1 MW_{SNG} demonstration plant displayed on the left of Figure 2 and an 8 MW_{th} gasification plant on the right. The efficiencies of the JASM report, are based on real life examples like the platform in Güssing. Another paper about a complete energy model from Switzerland is made by Marcucci et al. [9]. The model is unfortunately not publicly available, but the data can be used for comparison. The data for technologies is also taken from the JASM report. The difference with this thesis is that it will be publicly available and applied on an urban neighbourhood in different scenarios.

Figure 2: The SNG Technology Platform in Güssing [8].

Electricity and energy grids require a certain amount of flexibility. In the past, this was mostly during the steady energy production by fossil fuel plants and the decreasing demand during certain hours (e.g. during the night). In a grid with increasing renewable sources, another type of flexibility is required. Since renewable energy production can be highly intermittent, solutions with high flexibility are needed. This is the case for both short term (day and night) and long term (summer and winter). In 2015, the National Renewable Energy Labratory (USA) wrote a report on the changing grid demands and production [10]. At that time, the integration of solar energy in the grid created most of the challenges. One of the proposed solutions was Demand Side Management (DSM). This can be useful on short term. On the longer term, biomass can be an interesting additional factor that can change the energy production.

Another type of flexibility for energy grids, can be provided by energy storage. There are various options available and they all have advantages and disadvantages as explained by Shaqsi et al. [11]. In this thesis, the focus is on biomass energy. Energy storage is also possible with biomass techniques like power-to-gas. The main idea is to use hydrogen, that is produced by renewable sources, and make it react with carbon dioxide so it becomes (bio)methane. Usually during the production of methane from biomass, the carbon dioxide is emitted to the air. When there is hydrogen available, the carbon dioxide will react with the hydrogen instead of emitted. In this way, more methane can be produced from the biomass. The advantage of this is that the excess electricity from renewable energy production can be used for the production of green hydrogen, which can then be stored in methane. Methane can go in the gas grid if the quality requirements are met. So in fact, the electricity is stored in the gas grid. The technology collaboration program 'IEA Bioenergy', wrote a paper about the possibilities of flexibility from biomass technologies [12]. There is constant development on existing technologies like the methanation process described above. Adding the hydrogen was usually done with a fixed bed method. With a (relatively new) fluidized bed method [13], the same efficiency can be achieved with lower costs [14].

Biomass technologies that are already in use in Switzerland are for example wood fired heaters in houses and waste water treatment plants. However, there are big amounts of biomass that are not used yet. The Forschungsanstalt für Wald, Schnee und Landschaft (WSL), performed research on the biomass energy potentials in Switzerland [15]. The report contains information about how much available biomass is already used. These findings are used to identify interesting regions and recognize patterns. An example of a high potential biomass is animal manure. It is currently difficult to transport this type of biomass. The difficulties are partly due to rules and regulations but also because of transportation costs. This does not mean that manure should be forgotten. WSL published a white paper about the potentials of animal manure specifically [16] too. Next to potentials and different types of biomass, WSL provides information of the biomass per region [15]. On cantonal level in Switzerland there is information available on the amount and type of biomass. On smaller scale, like villages, there is only a total number of woody and non-woody biomass per year.

As described in the problem statement, a recommender tool needs to be developed. This will be done on city or canton scale. A similar tool was developed for a farm. Ter-Borch performed his master thesis on the topic of 'Swiss Future Farm' [5]. In this thesis, a model was partly developed and applied to a specific farm in Switzerland. This resulted in a suggestion of technologies to be installed for different cases. A Mixed Integer Linear Programming (MILP) model was used to optimize for the case of cost, emissions, or a mix. Additionally, a sensitivity analysis was performed. The model used in the thesis of Ter-Borch will be used as a base model for this thesis. Adaptions like the energy demands and the applicable technologies, need to be done. However, there are also similarities like the Swiss electricity grid. A similar adaption was done for the energy system of Danish islands by Chabchoub [17]. The focus of his thesis was the integration of wind energy.

2.1 Data Collection on Biomass Conversion Technologies

In this subsection, different biomass technologies will be discussed. Figure 3, contains all the relevant biomass conversion paths. These paths are discussed one by one based on the biomass inputs wood, animal manure, green waste and sewage sludge. One path will be added to the model as one unit. That means in the model that the input of a path is biomass and the output is biomethane, heat or electricity. Most of the information below is from the report about 'Biomass and waste potentials and conversion pathways for energy use in Switzerland' by JASM (Joint Activity Scenarios and Moddeling) and SCCER BIOSWEET (Biomass for Swiss Energy Future, Swiss Competence Center for Energy Research) [7]. For gaps in the JASM report, information from other research was used [6] [18] [19].

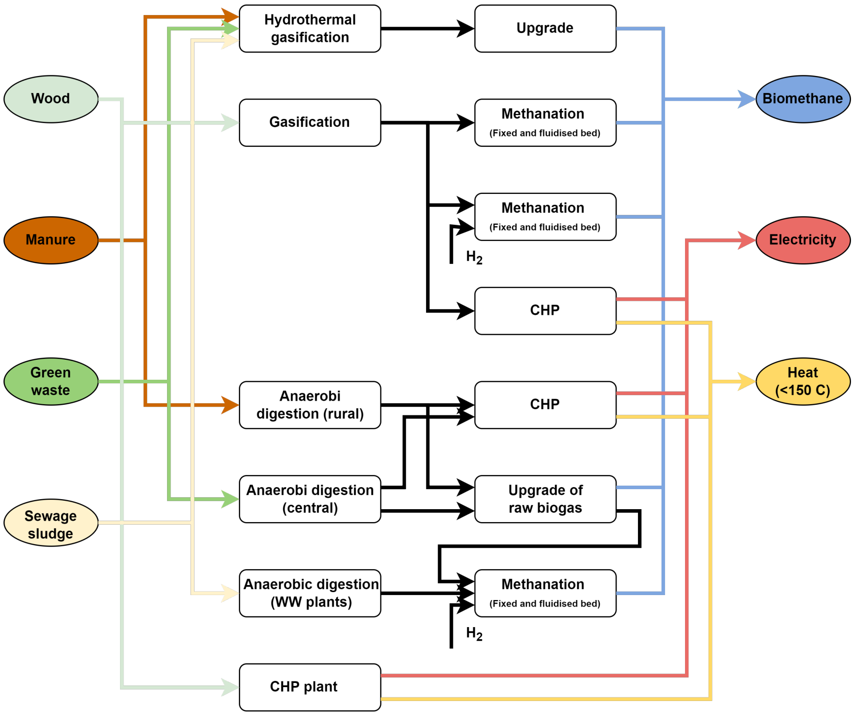

Figure 3: An overview of the Biomass Technologies to be used.

2.1.1 Wood

Gasification - Methanation 1 (WGM1)

A gasification unit can turn woody biomass into a syngas. The composition of the syngas is dependent on the temperature of the gasification process, but consists mainly of CO, CO_2 and H_2. After that, the syngas is upgraded by methanation. CO and CO_2 are converted to CH_4 with the reactions in Equation 1 and 2. For this process, hydrogen that is already in the syngas will be used. Important values of this path are given in Table 1. The methanation process uses a fixed bed, as can be seen in Figure 4. Since the process is Wood Gasification Methanation 1, the abbreviation is WGM1. This name will be used in the model too.

$$\mathrm{CO} + 3\mathrm{H_2} \rightleftharpoons \mathrm{CH_4} + \mathrm{H_2O} \tag{1}$$

$$\mathrm{CO_2} + 4\mathrm{H_2} \rightleftharpoons \mathrm{CH_4} + 2\mathrm{H_2O} \tag{2}$$

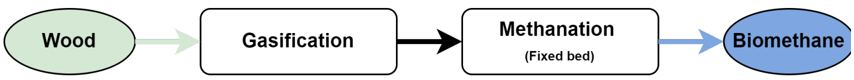

Figure 4: Schematic overview of WGM1.

Parameter	Value
Output	Biomethane
Inv. Cost (CHF/kW chem LHV)	3500
FOM (CHF/kW chem LHV)	40
Eff (LHV out/LHV in, %)	62.5
Elec. use (MWhel/MWh chem LHV)	0.094
Heat. prod (MWhth/MWh chem LHV)	0.09 (at 80°C)
Reference size (MW)	1

Table 1: Important Parameters for WGM1 [7].

Gasification - Methanation 2 (WGM2) This path is exactly the same as 'Gasification - Methanation 1', but instead of the fixed bed method, the fluidised bed method is used. The schematic of the path is given in Figure 5 and the important parameters in Table 2.

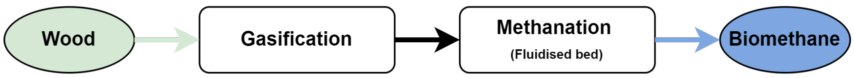

Figure 5: Schematic overview of WGM2.

Parameter	Value
Output	Biomethane
Inv. Cost(CHF/kW chem LHV)	2315
FOM (CHF/kW chem LHV)	40
Eff (LHV out/LHV in, %)	62.5
Elec. use (MWhel/MWh chem LHV)	0.094
Heat. prod (MWhth/MWh chem LHV)	0.09 (at 80 °C)
Reference size (MW)	1

Table 2: Important Parameters for WGM2 [7].

Gasification - Electrolysis - Methanation 1 (WGEM1)
This process is similar to 'WGM1', but now the CO_2 is not emitted to the air when it is separated from the methane. Additional hydrogen, that is produced with electrolysis, will react with the CO_2 to form more methane. Electrolysis will use electricity from renewable energy. In that way, it is possible to store renewable energy in the gas grid with a power-to-gas method. The process of adding the hydrogen is almost 84% efficient, but there are losses with producing the hydrogen too. Because the efficiencies are calculated based on the lower heating value of the biomass to the lower heating value of the biomethane, it is difficult to come up with one total efficiency. That is why the same efficiency as for WGM1 is used. When no hydrogen is added, for example in times that it is cloudy and not windy, the efficiency will be the same. When more hydrogen is added, the total yield of biomethane from the biomass will increase. However, there is a price for the hydrogen. The price for the process of adding the hydrogen is generally high. However, it is possible to integrate the process with the methanation process. Only half the costs of the hydrogen adding process need to be added to the original WGM1 costs [20]. The prices are given in Table 3. The schematic of the path can be seen in Figure 6.

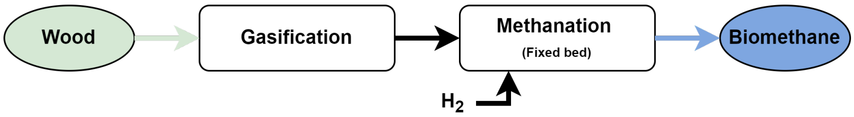

Figure 6: Schematic overview of WGEM1.

Parameter	Value
Output	Biomethane
Inv. Cost(CHF/kW chem LHV)	4008
FOM (CHF/kW chem LHV)	105
Eff (LHV out/LHV in, %)	62.5
Elec. use (MWhel/MWh chem LHV)	0.10
Heat. prod (MWhth/MWh chem LHV)	0.126 (at 80°C)
Reference size (MW)	1

Table 3: Important Parameters for WGEM1 [7].

Gasification - Electrolysis - Methanation 2 (WGEM2) This path is exactly the same as 'WGEM1'. As can be seen in Figure 7, the only difference is the use of the fluidised bed method instead of the fixed bed method. The prices are different and given in Table 4.

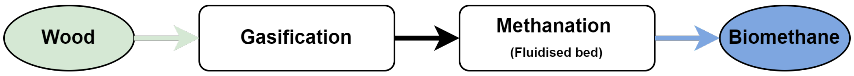

Figure 7: Schematic overview of WGEM2.

Parameter	Value
Output	Biomethane
Inv. Cost(CHF/kW chem LHV)	2706
FOM (CHF/kW chem LHV)	91
Eff (LHV out/LHV in, %)	62.5
Elec. use (MWhel/MWh chem LHV)	0.11
Heat. prod (MWhth/MWh chem LHV)	0.127 (at 80 °C)
Reference size (MW)	1

Table 4: Important Parameters for WGEM2 [7].

Gasification - Internal Combustion Engine (WGICE) The gasification process is the same as in the processes described above. However, instead of converging the syngas into biomethane, the syngas is burned in a internal combustion engine. The product is heat an electricity and the parameters can be seen in Figure 8 and Table 5.

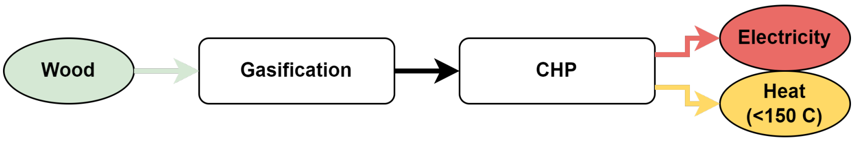

Figure 8: Schematic overview of WGICE.

Parameter	Value
Output	Electricity, Heat
LCOE (RP/kWhe)	12.25
Eff	Elec: 27.5, Therm: 36.25
Reference size (MW)	2.5

Table 5: Important Parameters for WGICE [6] [7].

Combined Heat and Power (WCHP) As can be seen in Figure 9, the wood is directly burned and the heat is used for a combined heat and power cycle. Important parameters are given in Table 6

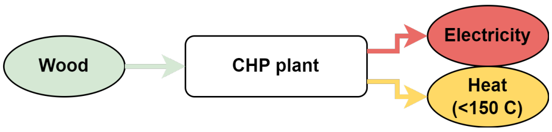

Figure 9: Schematic overview of WCHP.

Parameter	Value
Output	Electricity, Heat
LCOE (RP/kWhe)	16.2
Eff	Elec: 11.9, Therm: 53
Reference size (MW)	2.5

Table 6: Important Parameters for WCHP [6] [7].

2.1.2 Manure

Hydrothermal Gasification - Upgrading (MHYGUP)
Hydrothermal gasification converts wet biomass. High pressures are needed to achieve supercritical water conditions. Compared to the 'normal' gasification process describe before, this is advantageous for wet biomass since no drying process is required. This also means that more types of biomass can be used. To reach the biomethane consistency of 96% CH_4, an upgrading process is done. The parameters of the entire path are given in Table 7 and the schematic can be seen in Figure 10.

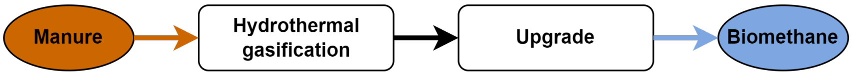

Figure 10: Schematic overview of MHYGU.

Parameter	Value
Output	Biomethane
Inv. Cost(CHF/kW chem LHV)	5788(avg)
FOM (CHF/kW chem LHV)	517
Eff (LHV out/LHV in, %)	65
Reference size (MW)	1

Table 7: Important Parameters for MHYGUP [7].

Anaerobic Digestion - Upgrading (MADUP)

Another process for wet biomass conversion is anaerobic digestion. The process breaks the biogenic carbon down and releases it as biogas (60% CH_4, 40% CO_2). This process takes place at anaerobic conditions with the aid of suitable microorganisms. The biogas will be separated by an upgrading unit which separates the CH_4 from the CO_2. The CH_4 will be of a high quality (¿ 96%), and the CO_2 will be emitted to the air. The parameters can be seen in Table 8 and the schematic of the path in Figure 11.

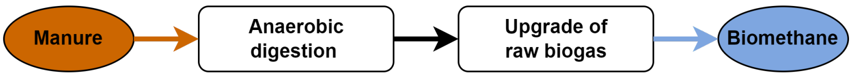

Figure 11: Schematic overview of MADUP.

Parameter	Value
Output	Biomethane
Inv. Cost(CHF/kW chem LHV)	1053
FOM (CHF/kW chem LHV)	93.75
Eff (LHV out/LHV in, %)	30
Reference size (MW)	0.4

Table 8: Important Parameters for Anaerobic Digestion - Upgrading [7].

Anaerobic Digestion - Upgrading - Electrolysis - Methanation 1 (MADUP1)

The first part of MADUP1 is the same as the MADUP process, as can be seen in Figure 12. However, instead of being emitted to the air, the CO_2 goes through a methanation unit where it reacts with H_2 to CH_4. The CO_2 is not indicated in Figure 12, but is represented by the black arrow in between the upgrading unit and the methanation unit. The process of adding the hydrogen is the same as in WGEM1 and WGEM2. At this process, a fixed bed is used. The efficiency of the process is dependent on how much CO_2 reacts. Since that depends on the situation, it will be calculated in the model. The parameters are given in Table 9.

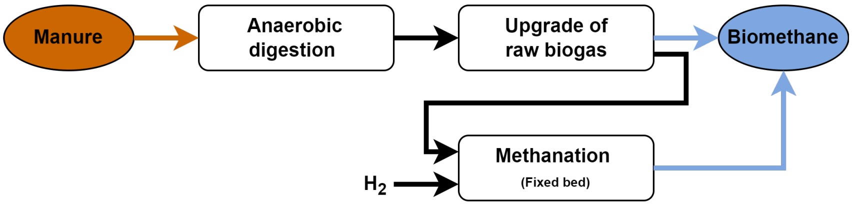

Figure 12: Schematic overview of MADUP1.

Parameter	Value
Output	Biomethane
Inv. Cost(CHF/kW chem LHV)	2068
FOM (CHF/kW chem LHV)	222.75
Eff (LHV out/LHV in, %)	30
Elec. use (MWhel/MWh chem LHV)	0.0135
Heat. prod (MWhth/MWh chem LHV)	0.073 (at > 280 °C)
Reference size (MW)	1-2

Table 9: Important Parameters for Anaerobic Digestion - Upgrading - Electrolysis - Methanation 1 (MADUP1) [7].

Anaerobic Digestion - Upgrading - Electrolysis - Methanation 2 (MADUP2)
This is almost the same as MADUP1, but a fluidised bed is used in this process instead of a fixed bed, as can be seen in figure 13. The other type of bed changes the prices, but the path has the same efficiencies. The important values are given in Table 10.

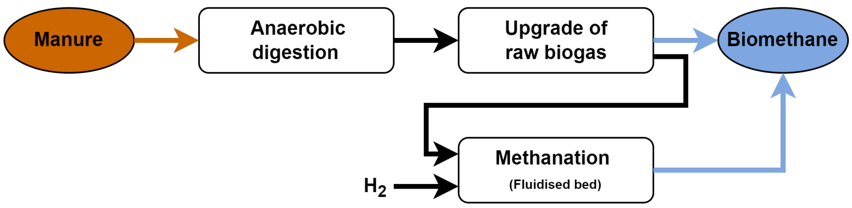

Figure 13: Schematic overview of MADUP2.

Parameter	Value
Output	Biomethane
Inv. Cost(CHF/kW chem LHV)	1834
FOM (CHF/kW chem LHV)	195.75
Eff (LHV out/LHV in, %)	30
Elec. use (MWhel/MWh chem LHV)	0.0205
Heat. prod (MWhth/MWh chem LHV)	0.072 (at > 280 °C)
Reference size (MW)	1-2

Table 10: Important Parameters for Anaerobic Digestion - Upgrading - Electrolysis - Methanation 2 (MADUP2) [7].

Anaerobic Digestion - Internal Combustion Engine (ICE) The anaerobic digestion step of this path is the same as for MADUP processes. However, the biogas is now immediately burned in an internal combustion engine. The output will be heat and electricity. This is schematically shown in Figure 14. The important parameters can be found in Table 11.

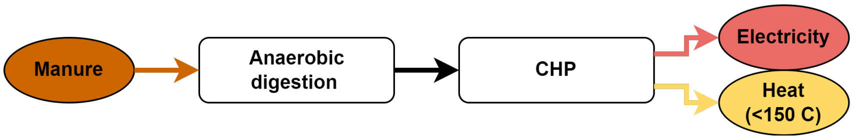

Figure 14: Schematic overview of MADICE.

Parameter	Value
Output	Biomethane
Inv. Cost(CHF/kW chem LHV)	1776
FOM (CHF/kW chem LHV)	147
Eff (LHV out/LHV in, %)	Elec: 13, Therm: 14.5
Reference size (MW)	5

Table 11: Important Parameters for Anaerobic Digestion - Internal Combustion Engine (MADICE) [7].

2.1.3 Green Waste

The paths are exactly the same as for manure. Only the 'Anaerobic Digestion - Internal Combustion Engine (ICE)' is not available for green waste. The difference between the manure processes and the green waste processes are due to the biomass input. Because of the different inputs, some of the efficiencies change. The prices and other values will stay the same. The table from the animal manure technology is given and the corresponding efficiency change.

- Hydrothermal Gasification - Upgrading (GHYDUP): Table 7, but the efficiency is 70%.
- Anaerobic Digestion - Upgrading (GADUP): Table 8, but the efficiency is 27.5%
- Anaerobic Digestion - Upgrading 1 (GADUP1): Table 9, but the efficiency is 27.5%
- Anaerobic Digestion - Upgrading 2 (GADUP2): Table 10, but the efficiency is 27.5%

2.1.4 Sewage Sludge

The paths are exactly the same as for manure. The method of displaying is the same as for the green waste processes.

- Hydrothermal Gasification - Upgrading (SHYDUP): Same as Table 7, but the efficiency is 60%
- Anaerobic Digestion - Upgrading (SADUP): Table 8.
- Anaerobic Digestion - Upgrading 1 (SADUP1): Table 9.

- Anaerobic Digestion - Upgrading 2 (SADUP2): Table 10.
- Anaerobic Digestion - Internal Combustion Engine (SADICE): Table 11.

2.2 Data Collection on Biomass Availability and Demands

In the introduction, it was mentioned that a model must be developed that can analyze different urban neighbourhoods. To get started with the model, the town of Martigny in Switzerland is used as the case. It is useful to start with a case to explore the model. Another advantage is that Martigny can be seen as an urban neighbourhood, and the existing model of a farm cannot. However, there was not enough data available for a thorough analysis. Even though there are rough biomass availability numbers, heat and electricity demands, it was not complete enough because of missing profiles and data [21] [22]. After discussions with researchers from WSL (Forschungsanstalt für Wald, Schnee und Landschaft), it was decided to take another area in account: the canton of Nidwalden. In this section, the biomass availability and the demands of Canton Nidwalden are discussed. All the different kinds of biomass will be taken into account and shortly analyzed. The energy demands of the canton are also discussed and some demand calculations are done to make sure the inputs of the model make sense. Nidwalden has around 43000 inhabitants, so the loads are comparable to a small city.

For the entire country of Switzerland, biomass potentials are investigated and mapped by WSL [15]. Ten types of biomass are distinguished: Manure, agricultural crop by-products, industrial organic waste, organic part of household garbage, green waste, sewage sludge, forest wood, industrial wood residues, waste wood and wood from landscape maintenance. The potentials per type of biomass are shown in Figure 15 for the entire country. Three types of potentials are given: theoretical potential, sustainable potential and additional sustainable potential. In Figure 16 it is explained how these types of potentials relate to each other. The theoretical potential is calculated with all the available data on biomass in Switzerland and refers to the maximum amount of nationally available biomass that could be used. The sustainable potential can be derived from this after deducting any ecological, economic, legal and political constraints. The additional or remaining potential is calculated by deducing the biomass already used for energy from the sustainable potential.

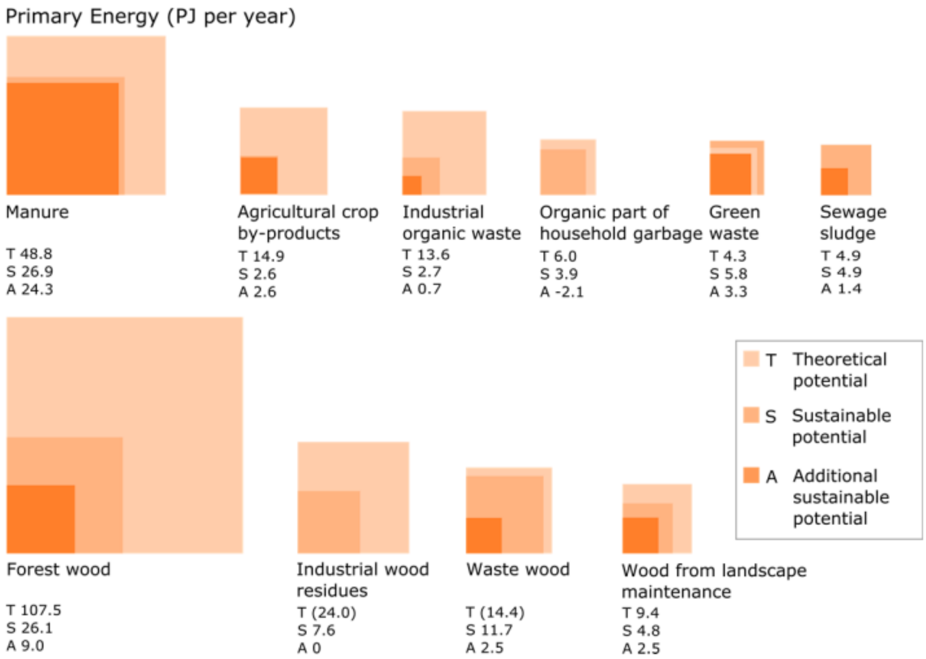

Figure 15: Energy potentials Switzerland [15].

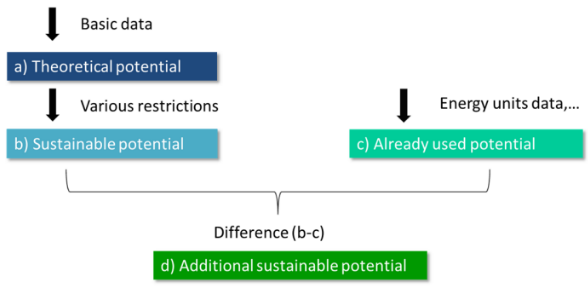

Figure 16: Levels of potentials [15].

The values from Figure 15 are geographically known in detail per canton. The division between the cantons can be seen in Figure 17. Nidwalden is the small canton in the middle of Switzerland with 1.4 PJ of primary energy. Note that this is the theoretical potential. The additional sustainable biomass potentials per biomass source are given below Figure 17. It can be seen that Nidwalden has a low theoretical potential compared to other cantons. It is interesting to look at this case because cities also have a low(er) potential compared to rural areas. Since the recommender tool will be developed for urban neighbourhoods, this is one of the most similar options of all the cantons.

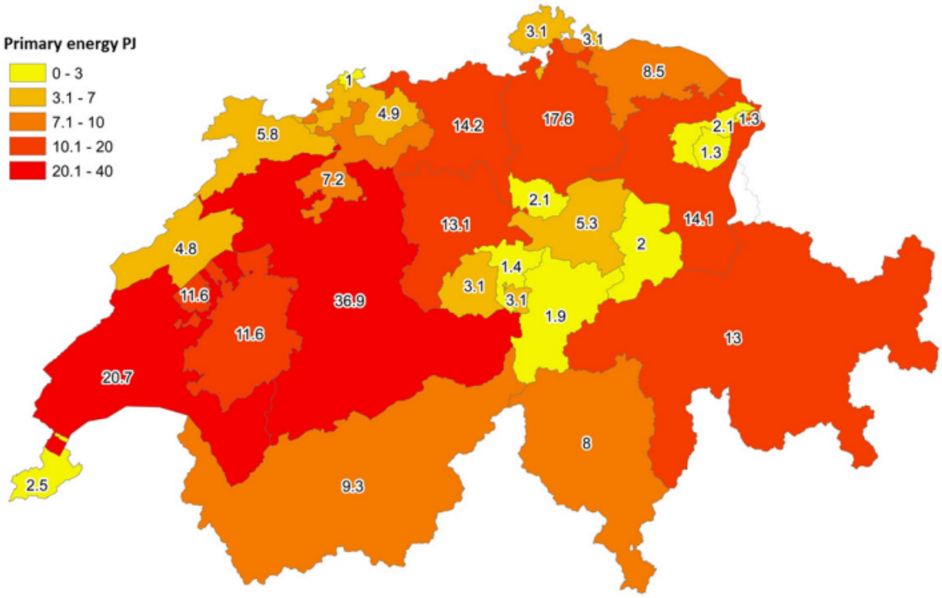

Figure 17: Energy potentials map Switzerland [15].

The available biomass is known on cantonal level. Additional sustainable potentials, are given in primary energy content in GJ per year [23] [15]. Since everything is calculated in kWh, MWh or GWh in the model, these yearly values are translated and given below:

- Green waste: 9.74 GWh
- Organic part of household 6.20 GWh
- Sewage sludge: 8.30 GWh
- Animal manure: 63.31 GWh
- Agricultural crop by-products: 0.0025 GWh
- Commercial and industrial organic waste: 3.19 GWh
- Wood: 89.22 GWh

The yearly demand of the canton of Nidwalden is given in detail in Figure 41 in Appendix A. Since that figure is in German, and not all the values are important, it was chosen to only display the overview here of the values that will be used. The short overview is given below in Table 12.

Type	**Value (GWh)**
Electricity	300
Gas	72
Heating	15

Table 12: A short overview of the demand inputs [6] [24].

For the gas, about 72 GWh is needed per year. It is assumed that this is a constant demand. To check if it is possible to produce that amount of biomethane with the available biomass, some quick calculations are done. In total there is approximately 90 GWh available in wood and 90 GWh in non-woody parts. For every biomass conversion technology there is a conversion efficiency, which is not 100%. When an average efficiency of 30% is assumed for the non-woody biomass and 60% for the woody biomass, it is possible to produce approximately 81 GWh of biomethane. So in total, it is possible to produce an amount of energy in the order of the gas demand.

The electricity load is 300 GWh per year according to Table 12. Since this is just one number, information from the Swiss network operator (Swissgrid) was requested. A very accurate file of electricity use in (Nidwalden, Obwalden and Uri) was provided. The file contained the amount of electricity used for every 15 minutes. Since the load was given for three cantons, a factor based on inhabitants was calculated to multiply with the data. To cross-reference the 300 GWh value from Table 12, the total sum of the electricity file was taken. The result was approximately 330 GWh per year, which matches the 300 GWh from the figure well enough. The electricity load is displayed in Figure 18.

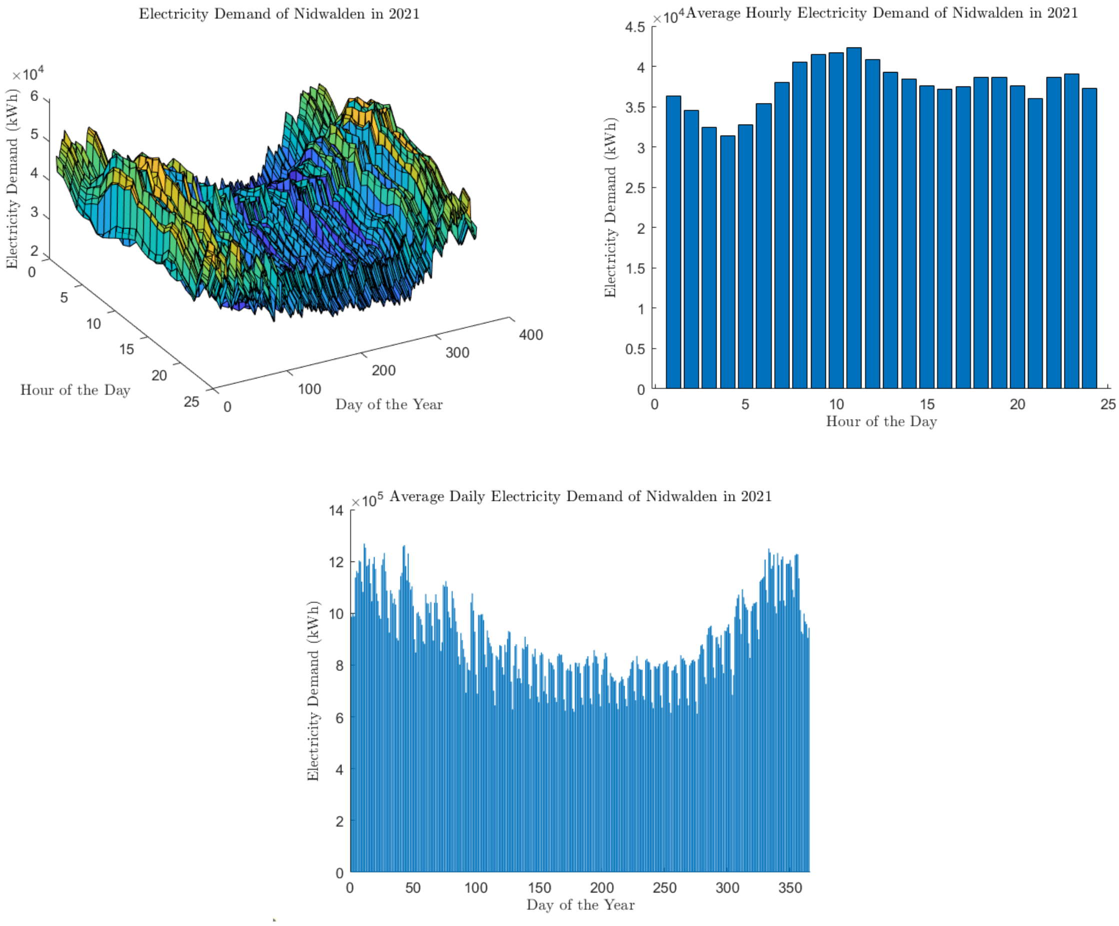

Figure 18: Several Plots of the Electricity Demand of Nidwalden [25].

Unlike the gas demand, the heat demand is not assumed to be constant. The total amount is 15 GWh, as can be seen in Table 12. This is divided over January (25%), February (20%), March

(15%), April (5%), May (0%), June (0%), July (0%), August (0%), September (0%), October (5%), November (15%) and December (20%), which is shown in Figure 19. The total adds up to the 15 GWh from Table 12.

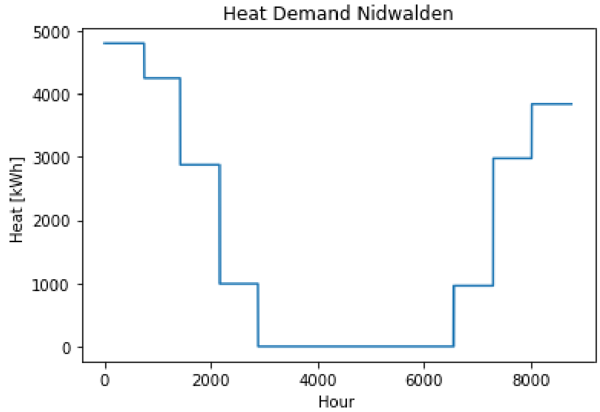

Figure 19: Heat Demand Nidwalden [24].

Simple calculations were done in MATLAB to check the maximum value that can be put in the model per path. The results are given in Figure 20.

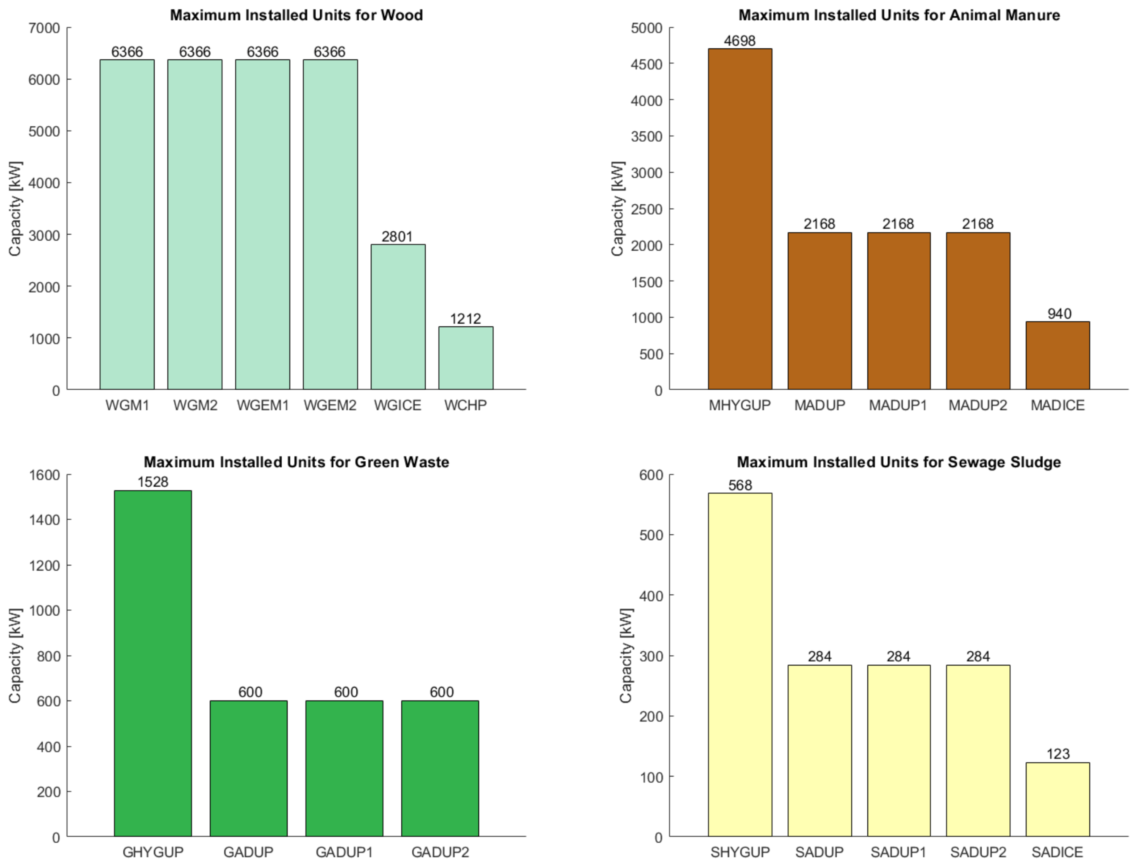

Figure 20: Maximum Installed Capacities.

3 Methodology

Research must be done on the previous model, as it should be fully understood before making any suggestions or changes to it. For background research, literature, other models and instructions are available. Information from the previous section needs to be added to the model. The way of adding units and changing the model will be explained in Appendix C. In this section, the way of testing the model will be explained first using different scenarios. After that, the model itself will be explained, the ways of optimization are explained and the method of the sensitivity analysis is discussed.

3.1 Scenarios for Biomass Conversion

Initially, the city of Martigny was used as the case study. There was not enough data available at the level of the municipality and more information was needed to come up with realistic scenarios. For this reason, it was decided to work on the canton of Nidwalden, one of the smallest cantons in the heart of Switzerland. The previous case (the city of Martigny) was still useful, as it made the model more familiar and some technologies were already introduced.

For the case of Nidwalden, there is more reliable information available. That is why the case is better for this thesis. With the calculations from Section 2.2, more information is known about the paths and the applications of them. The maximum sizes are calculated and can be introduced in the model. Then, different scenarios will be calculated with the model. Scenario A will be the current situation. In scenario B, the gas will be produced from biomass (biomethane). In scenario C, the biomass will be used to produced electricity and heat. For this, a city heating network needs to be available or something similar. Lastly, there is an optional scenario D, in which other renewable technologies will be introduced. The focus will be on the connection with biomass technologies. A distinction in scenarios is needed, because the energy balances in the model need to be manually changed. It is possible to make a scenario where all the technologies are involved. However, the different outputs and methods of calculating efficiencies make it impossible for the model to calculate the best option. Because of the different scenarios, all the units are checked and validated. Scenario A is a reference scenario, scenario B is to check the biomethane producing paths, scenario C is to check the heat and electricity producing paths and scenario D explores the possibilities of power-to-gas technologies. The text and figures per scenario are partly based on the calculations of Section 2.2. So the text and figures of this section are not results, but rather information based on calculations.

3.1.1 Scenario A

This is the current state scenario. The electricity is imported from the electricity grid and the gas demand is fulfilled by the gas grid. Additionally, the heating is assumed to be done with gas boilers. A gas boiler uses gas that is imported from the gas grid. In this scenario, the biomass resources are not used. In the legend in Figure 21, it can be seen that all the square boxes have to do with Nidwalden. So these are either demands from Nidwalden or inputs for Nidwalden. The rectangles with the rounded edges are technologies and the dashed arrows are imports. There is one normal error from the gas boiler to the heat demand. As the color suggests, this is the heat flow. The colored arrows from the biomass resources to ‘unused’ are WO, AM, GW and SS from top to bottom. The same methods for display are used for the other scenarios.

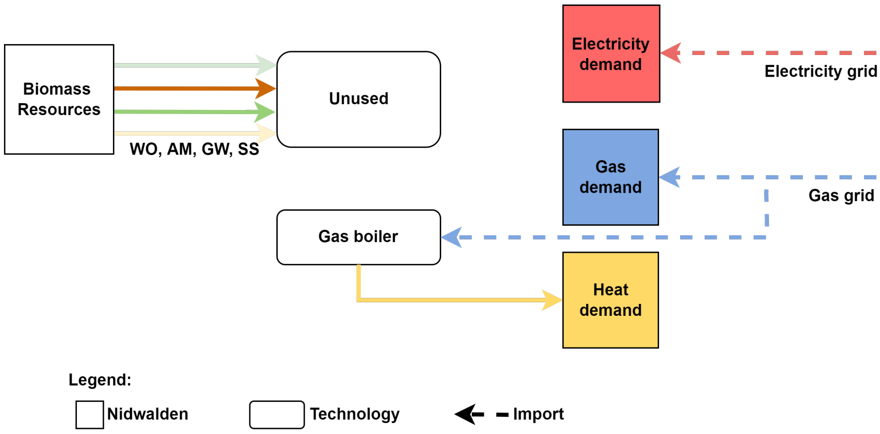

Figure 21: Schematic overview of Scenario A.

3.1.2 Scenario B

In this scenario, which can be seen in Figure 22, biomethane will be produced from biomass for the gas demand. Since the biomethane has a quality of $> 96\% CH_4$, it can be injected to the gas grid in Switzerland. It is assumed that this can be done with an efficiency of 100% for simplicity reasons. In reality, such an injection will have an efficiency of around 99% [5]. All four biomass resources can be used to produce biomethane. This could result in a high enough production to cover the gas load, and the required gas for the heat load.

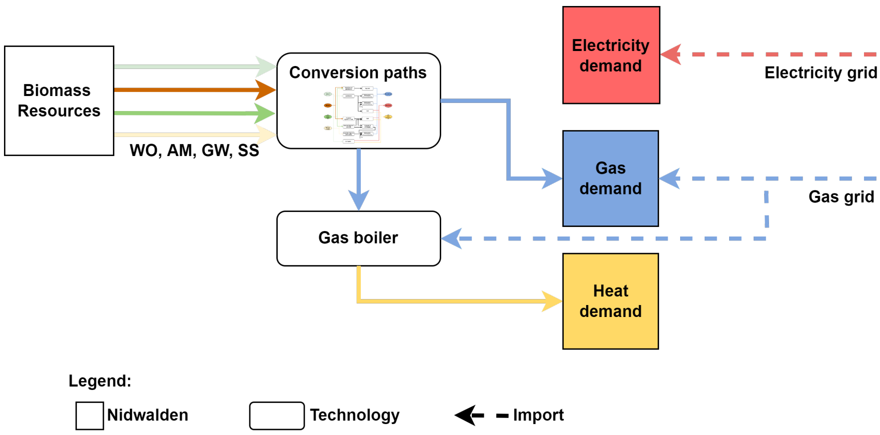

Figure 22: Schematic overview of Scenario B.

3.1.3 Scenario C

For Scenario C, which can be seen in Figure 23, the biomass resources are used to produce electricity and heat. Since the electricity demand is high, there is still electricity import from the grid. Since no biomethane is produced, all the gas is imported from the grid. In this scenario, green waste and sewage sludge are not used. Green waste is not used because there are no feasible technologies for electricity and heat production. For sewage sludge the reason of not using the source is that there is too little available for a reasonable amount of production.

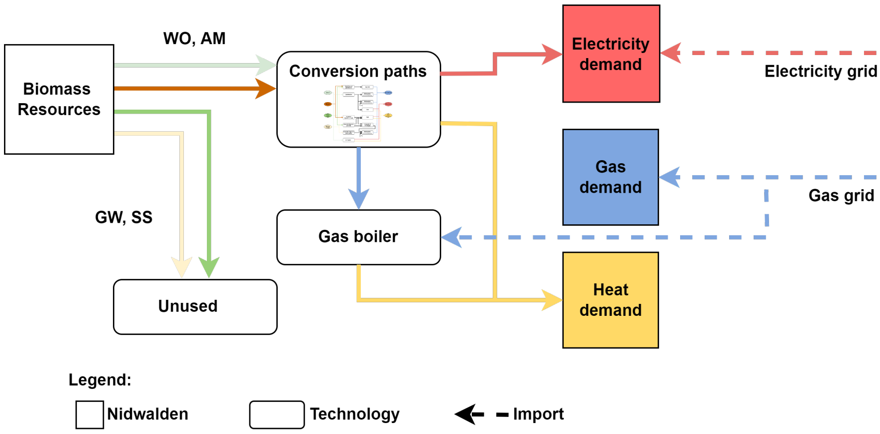

Figure 23: Schematic overview of Scenario C.

3.1.4 Scenario D

This scenario is similar to scenario B and the schematic overview is the same as Figure 22. The difference is that PV will be included in the model. With the excess electricity, hydrogen will be produced. In Switzerland, it is not allowed to produce hydrogen with 'regular' electricity. With this hydrogen, the possibilities of seasonal electricity storage (by using power-to-gas) will be explored for Nidwalden. The additions to the scenario are all part of the conversion paths and therefore do not affect the schematic.

From the conversion paths in Section 2.1, it is known how much CO_2 emitted compared to the produced amount of CH_4. The produced CH_4 is immediately used like in scenario B, and the CO_2 separated to react with H_2. This hydrogen is produced with an electrolyzer. Since the amount of produced CO_2 is known, it is possible to calculate the amount of required H_2. The reaction is given in Equation 3.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{3}$$

Parameter	**Value**
M_{CO_2}	44.01 g/mol
M_{H_2}	2.016 g/mol
M_{CH_4}	16.04 g/mol
LHV_{H_2}	33.3 kWh/kg
LHV_{CH_4}	13.9 kWh/kg
η_{el}	0.69
$\eta_{add_{H_2}}$	0.84

Table 13: Overview of the parameters for H_2 calculations [26] [7] [13] [17].

Since the amount of CH_4 is calculated by the model in kWh, it can be calculated how much kg CH_4 is produced. The ratio of CO_2 and CH_4 is known from the processes discussed in Section 2.1. So the amount of CO_2 production in kg can be calculated. With the help of Equation 3 and molar mass values from Table 13, the amount of kg H_2 can be calculated. The amount of electricity required for the electrolyzer, can be calculated with the LHV and the efficiencies from Table 13. This value is used to calculate how much PV needs to be installed. The day with the most irradiance is taken as a reference point, to avoid big hydrogen storage units. The electricity production by one 375 Wp PV-panel is shown in Figure 24. The day with the most electricity production is the 21^{st} of May with 3.16 kWh. The total required hydrogen per day divided by this value, is the amount of PV-panels that are required. The amount can be used to give an overview of of the total electricity production, thus the hydrogen production, thus the extra methane production.

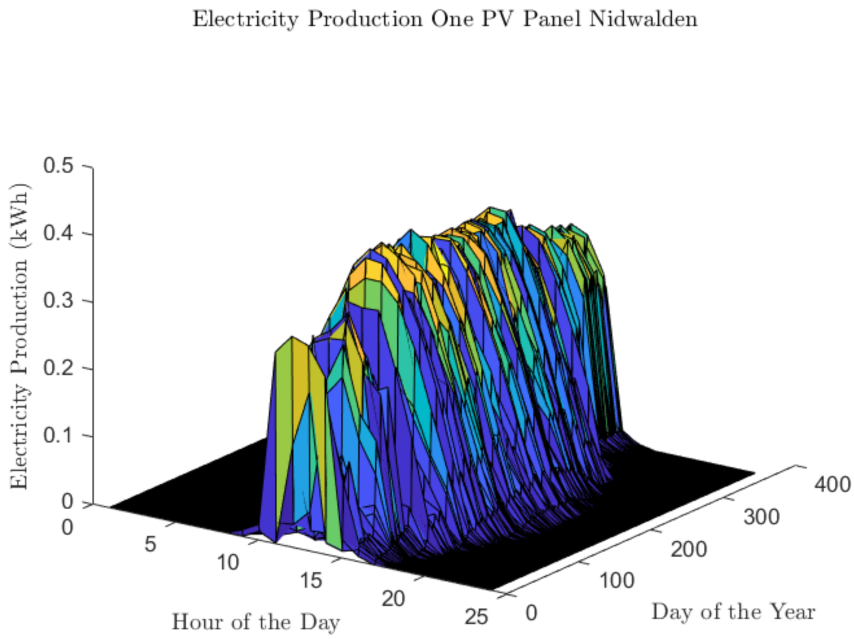

Figure 24: Production of One PV Panel.

3.2 General Model

As can be read before, the model is based on the Swiss Future Farm (SFF) model that was developed to analyze the energy system of a farm [5]. The model has been adapted to make it applicable to the case of Nidwalden. The technologies from Section 2.1 are added and the scenarios introduced like explained in Section 3.1.

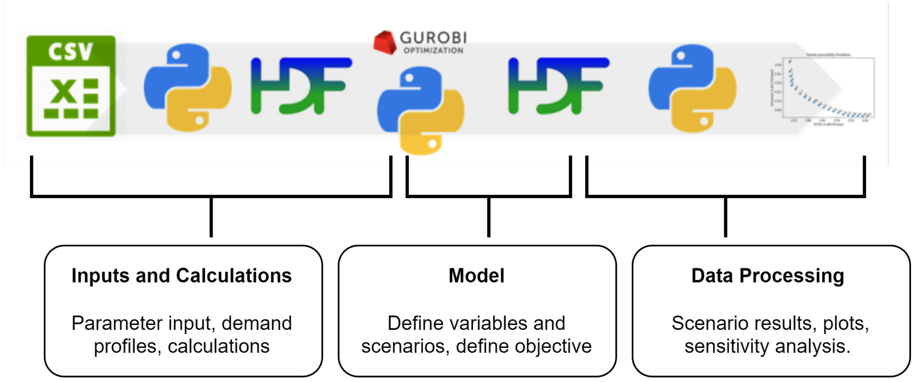

Figure 25: Schematic overview of the data flow in the model [5].

The used model Mixed-Integer Linear Porgramming (MILP). Other options are Linear Programming (LP) and Non-Linear Programming (NLP). LP models are easy to solve and are therefore the fastest. The drawback is that the model can only be solved based on linear equations. NLP models can have a solution which is dependent on initial conditions. MILP models are often using linear constraints. However, they also allow binary and integer variables. Since the model is optimizing the installed technologies, the model has to choose the best option. Binary variable, that are also called decision variables, are used for this purpose. The MILP model also allows to calculate energy demand and supply for an entire year in a short time (a few minutes). This is done for a time step of an hour. Even though the data was available for every 15 minutes, it was decided to do it per hour. There is not much added value to execute for every 15 minutes and multiple other data files were based per hour. If it was decided to do this, the computing time would be higher. Another advantage of the MILP model over NLP is that the solution is deterministic.

The model is developed in Python, because it is a popular open-source language. Therefore, there is also a lot of information available on internet pages like stackoverflow or GitHub. The flow of the data through the model is illustrated in Figure 25. First, there is input data in the form of different csv-files. These files can be adapted and changed in the Notepad on every computer. A Python code is used to load the data in the Python file and do first calculations. These matrices, values and databases are stored in an hdf file (h5). Then, Python is used again to load the data from the hdf file to execute the optimization with Gurobi. The results are again stored in an hdf file. Lastly, the hdf file with the results can be loaded into Python to make graphs, tables and plots. To get more knowledge on Python, different tutorials from the course 'Programming in Engineering' were followed and the Python book 'Think Python' was used [27]. Additionally, Gurobi tutorials were followed on Youtube [28]. The tutorials and exercises made it easier to understand how the tool works. Especially with adding new technologies, the tutorials helped with the formulation of the constraints.

3.3 Model Development

As described in Section 3.2, this model is an adapted version of an existing model. To get a better idea of the code, a schematic overview of the different code files is given in Figure 26. The files are also explained in more detail in the Appendix Sections C.1 and C.2. The energy balance is explained in Section 3.3.1 .

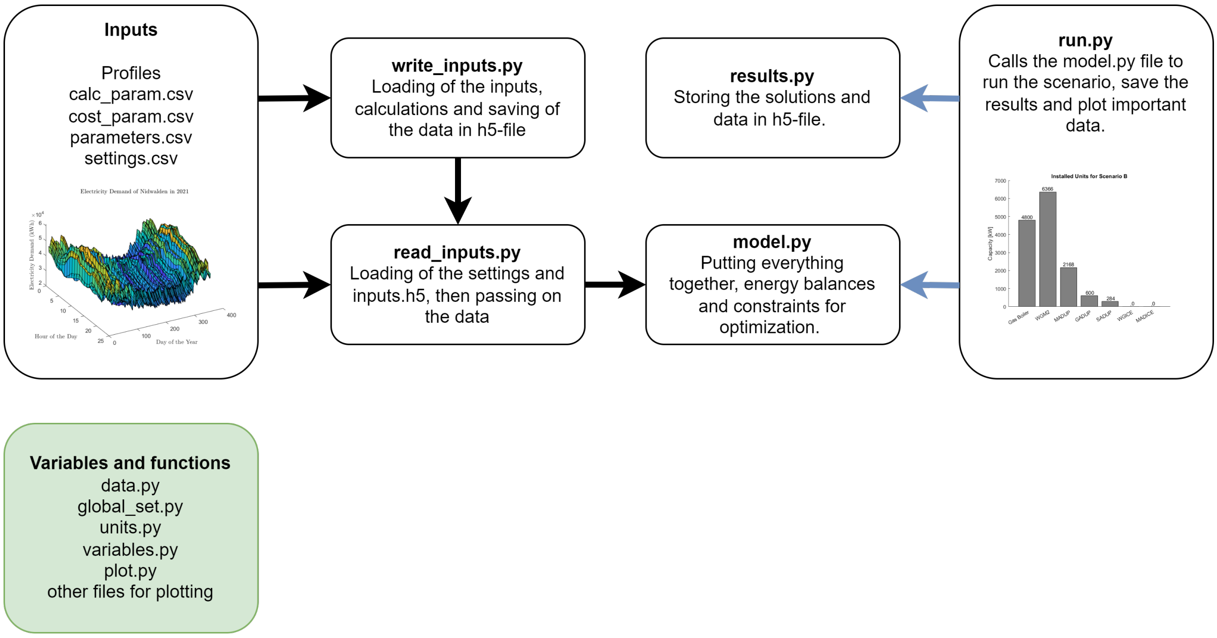

Figure 26: Schematic overview of the code files and their function.

To get the necessary information in the model, some assumptions were made. These assumptions mostly apply to the loads in the model. Assumptions on other topics are given in the corresponding sections. For the model, it is assumed that:

- biomass streams have a constant input. Yearly values were available, so these are just divided by 8760 to get the hourly value.
- the biomass input from the canton is free.
- almost all the available biomass will be used.
- the maximum installed unit is based on the amount of available biomass and the efficiency.
- the heat load is divided with percentages per month of the year. That means that winter months require more heating than summer months.
- the gas load is assumed to be constant.
- some loads are excluded from this report. For example the fuels for cars.

3.3.1 Energy Balance

Multiple resources were added to the model. First of all, the four different types of biomass biomass: wood, animal manure, green waste and sewage sludge. Also the three resources that will be imported or produced: electricity, heat and gas were added. These three resources have the same balance equations for every scenario, which are given in Equation 4, 5 and 6 for heat, electricity and gas respectively.

$$\sum_{u} \text{Heat}_{prod} = \text{Nid}^{Heat}_{cons} + \text{Unused}^{Heat}_{u} \tag{4}$$

$$\sum_u \text{Elec}_{prod} + \text{Grid}_{import} = \sum_u \text{Elec}_{cons} + \text{Grid}_{export} + \text{Nid}^{Elec}_{cons} + \text{Unused}^{Elec}_u \tag{5}$$

$$\sum_u \text{Gas}_{prod} + \text{Grid}_{import} - \text{Grid}_{export} - \text{Unused}^{Gas}_u = \sum_u \text{Gas}_{cons} + \text{Nid}^{Gas}_{cons} \tag{6}$$

In Figure 27, a visual representation of the energy balance of Equation 7 of scenario B is given. The weight scale is always in balance in the model.

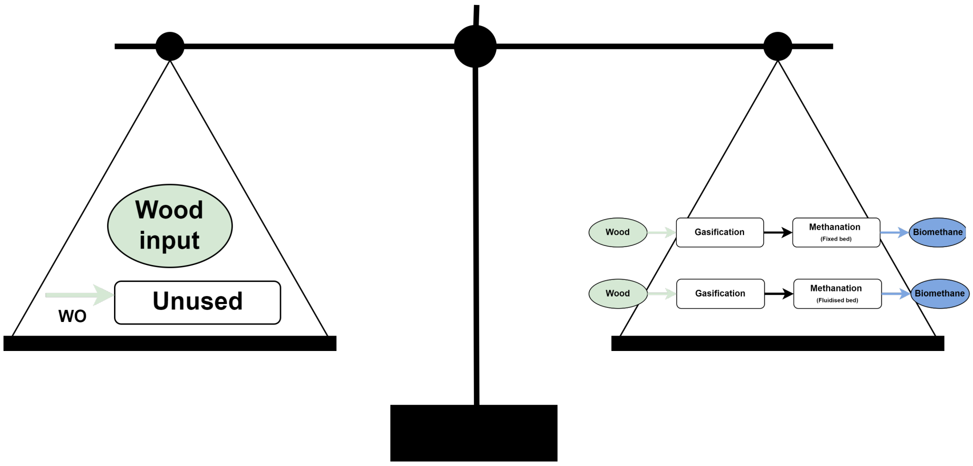

Figure 27: Schematic overview the scenario B balance of Equation 7.

For the different scenarios, the balances for the biomass resources change. The wood, animal manure, green waste and sewage sludge balances are given in Equation 7, 8, 9, 10 respectively for each scenario. In the model, this is written in a similar way to make it easier to switch scenario. In Section 3.1, it can be seen Figure 21, 22 and 23 match these balances.

Wood (WO)

$$\begin{aligned} \text{Nid}^{WO} + \text{Unused}^{WO} = & \\ & = 0 \quad \text{(Scenario A)} \\ & = \text{WGMO}_{cons} + \text{WGMT}_{cons} \quad \text{(Scenario B)} \\ & = \text{WCHP}_{cons} + \text{WGICE}_{cons} \quad \text{(Scenario C)} \\ & = \text{WGEMO}_{cons} + \text{WGEMT}_{cons} \quad \text{(Scenario D)} \end{aligned} \tag{7}$$

Animal Manure (AM)

$$\begin{aligned} \text{Nid}^{AM} + \text{Unused}^{AM} = & \\ & = 0 \quad \text{(Scenario A)} \\ & = \text{MHYGU}_{cons} + \text{MADUP}_{cons} \quad \text{(Scenario B)} \\ & = \text{MADICE}_{cons} \quad \text{(Scenario C)} \\ & = \text{MADUPO}_{cons} + \text{MADUPT}_{cons} \quad \text{(Scenario D)} \end{aligned} \tag{8}$$

Green Waste (GW)

$$
\begin{aligned}
\text{Nid}^{WO} + \text{Unused}^{WO} = & \\
&= 0 \quad \text{(Scenario A)} \\
&= \text{GHYGU}_{cons} + \text{GADUP}_{cons} \quad \text{(Scenario B)} \\
&= 0 \quad \text{(Scenario C)} \\
&= \text{GADUPO}_{cons} + \text{GADUPT}_{cons} \quad \text{(Scenario D)}
\end{aligned} \tag{9}
$$

Sewage Sludge (SS)

$$
\begin{aligned}
\text{Nid}^{SS} + \text{Unused}^{SS} = & \\
&= 0 \quad \text{(Scenario A)} \\
&= \text{SHYGU}_{cons} + \text{SADUP}_{cons} \quad \text{(Scenario B)} \\
&= \text{SADICE}_{cons} \quad \text{(Scenario C)} \\
&= \text{SADUPO}_{cons} + \text{SADUPT}_{cons} \quad \text{(Scenario D)}
\end{aligned} \tag{10}
$$

3.4 Optimization

The model is described and the inputs are known. The next important part is the actual optimization. The original model could optimize based on four different objectives [5].

- ENVEX: Total annual emissions.
- OPEX: Operating annual expenses.
- CAPEX: Capital expenses.
- TOTEX: Total annual expenses.

TOTEX is OPEX and CAPEX combined. In the model for this thesis, it was decided to exclude ENVEX optimization. There is not enough information available about the emissions of the biomass conversion paths and the installations. It would make no sense to use values from the previous model as they were mostly based on estimated CO_2 emission values per installed capacity.

The solver searches for the optimal solution based on running many different options an configurations. It will only return a result when there are no better combinations possible. The Gurobi MILP solver will fix the installed capacity of the specific technologies per scenario and decide what the operation graphs will look like. The modelling is done in Python, with different files interacting with each other. The optimization is done in Gurobi, which is a powerful optimization tool. The tool can optimize based on a certain objective, in this case TOTEX. Constraints are added where necessary, for example for the energy balances described in Section 3.3.1. Several tutorials about MILP models were followed for a better understanding [28]. The tutorials are available for free, but the software only with an academic license or with a temporary license.

The costs range from importing grid resources to installed capacity of installed technologies. Most of the information for the CAPEX is in the model in the form of CHF/kW. In the optimization, the solver calculates how much a technology would cost and how much is needed.

For the OPEX, a similar calculation is done, but now for the operating costs. In this objective, maintenance costs are put in the model in the form of a percentage of the CAPEX costs. In the case of the biomass conversion paths, these percentages had to be calculated with the available cost data. Next to the maintenance costs, other operating costs like the import of resources are taken into account.

To be able to compare the CAPEX and OPEX in a fair way for the TOTEX calculation, the CAPEX of each unit is taken into account as an annual cost. However, for these anual costs, the lifetime and an interest rate are taken into account. The lifetime from all the units are known, and the interest rate in Switzerland is taken as $i = 2.5\%$. For the CAPEX, the following constraints were added in the model:

$$CAPEX_u = 10^{-3} \cdot c_u^{mult} \left(c_u^{size} \cdot S_u + c_u^{fixe} \cdot Z_u \right) \tau_u \tag{11}$$

$$\tau_u = \frac{i(1+i)^{n_u}}{(1+i)^{n_u} - 1} \tag{12}$$

$$CAPEX = \sum_{u}^{\text{Units}} CAPEX_u \tag{13}$$

In Equation 11, the calculation of the CAPEX per unit is given. c_u^{mult} stands for the multiplication factor. In the Farm model this was used to transfer amounts of money from Euros (€) to Swiss Francs (CHF). In this model for Nidwalden, the multiplication factors are 1, because the price inputs of the conversion paths were already in CHF. Nevertheless, the factors will still be used for the sensitivity analysis. c_u^{size} stands for the specific cost per installed unit and S_u is the size of the unit. The second part in between the brackets is similar, but works if the installed unit has a set amount of costs. τ_u is the annualization factor and is calculated like in Equation 12, where n is the lifetime and i is the interest rate like mentioned before. To calculate the total CAPEX value, Equation 13 is used.

$$\text{OPEX} \; = 10^{-3} \sum_{r} \left(c_r^{\text{buy}} \cdot E_{grid}^{-r} - c_r^{\text{sell}} \cdot E_{grid}^{+r} \right) + \sum_{u} \left(c_u^{\text{maint}} \cdot \frac{CAPEX_u}{\tau_u} \right) \tag{14}$$

$$TOTEX = OPEX + CAPEX \tag{15}$$

In Equation 14, the OPEX is calculated. As can be seen, the formula consists out of a resources part and a maintenance part. In the first sum, the amount of a resource (E_{grid}^{-r}) is multiplied by the cost per kWh (c_r^{buy}). In the case of Nidwalden, the second part which calculates the selling is 0. The maintenance cost is calculated by multiplying the (non annualized CAPEX costs).

When both the CAPEX and OPEX are calculated and brought to the correct form, they can be added up to get the TOTEX output. This is displayed in Equation 15. All the calculations are multiplied by 10^{-3}, so the units are [MCHF/year]. The unit of Equation 12 is of course [-].

3.5 Sensitivity Analysis

A form of sensitivity analysis is often very important for MILP models, since there can be uncertainties in the input values. For some of the input values, there is quite a clear overview of what the costs and efficiencies are. For example if the technologies are developed and tested at PSI. However, some values are from literature. If it is not exactly known where the values are based on, the uncertainty becomes higher. The important values for the sensitivity analysis are given in Table 14. The values will be changed and the code will run with the different input value. This process will be done according to the 'One at a Time'-method. One parameter is changed and the rest will stay on the default. The good thing about this analysis is that the influence of one value can be isolated and studied. A drawback is that combinations of changed values are not taken into account, since only one value at a time is changed.

The sensitivity analysis is in the results folder with the name 'Sensitivity_Analysis'. The results are in the same order as the table. For example, the file called 'run_nbr_1', corresponds to the parameter 'Nid - WO - Minima'. The parameter is also displayed in the title. Since every parameters has two runs (minimum and maximum), there are 92 runs required. There are a few parameters that are not taken into account for the sensitivity analysis. For example, the input profiles like the electricity use or gas demand. Also the lifetime is not changed, since it is assumed to be the same for almost all installations. Additionally, those effects will be similar to adapting the multiplication factor. The percentages in the table can look random, but they all have a reasoning. For example, the gas price has a high uncertainty because of the current gas situation regarding the Russian-Ukrainian war. In that way, it is tried to also implement current events of the world in the model. Another example is the high uncertainty value for the WGICE and WCHP. These values are (partly) from different literature, so they have to be tested in a wider range. In Section 4, not all the results of the sensitivity analysis will be mentioned. Only the runs that had an interesting outcome are discussed. Interested readers can check all the outcomes in the results folder of the model.

Category	Parameter	Uncertainty	Minima	Maxima
Nid	WO (GWh)	20%	71.4	107.1
	AM (GWh)	20%	50.6	76.0
	GW (GWh)	20%	15.3	22.9
	SS (GWh)	20%	6.6	10.0
	Gas Load (GWh)	20%	57.6	86.4
	Heat Load (GWh)	20%	12	18
	Electricity Load (GWh)	20%	263.8	395.6
WGMO	Cost multiplication	30%	0.7	1.3
	Efficiency	10%	0.56	0.69
	Electricity cons (part of prod)	10%	0.085	0.10
WGMT	Cost multiplication	30%	0.7	1.3
	Efficiency	10%	0.56	0.69
	Electricity cons (part of prod)	10%	0.09	0.11
MHYGU	Cost multiplication	30%	0.7	1.3
	Efficiency	10%	0.59	0.72
MADUP	Cost multiplication	30%	0.7	1.3
	Efficiency	10%	0.27	0.33
Resources	Selling price electricity (CHF)	15%	0.010	0.14
	Purchase cost electricity (CHF)	15%	0.18	0.24
	Purchase cost gas (CHF)	50%	0.049	0.15
	Selling price gas (CHF)	50%	0.039	0.12
General	Annual interest rate	10%	0.028	0.022

Table 14: Parameters for Sensitivity Analysis (1).

Category	Parameter	Uncertainty	Minima	Maxima
WGICE	Cost multiplication	50%	0.5	1.5
	Electrical Efficiency	30%	0.19	0.34
	Thermal Efficiency	30%	0.25	0.47
WCHP	Cost multiplication	50%	0.5	1.5
	Electrical Efficiency	30%	0.083	0.15
	Thermal Efficiency	30%	0.37	0.69
MADICE	Cost multiplication	30%	0.7	1.3
	Electrical Efficiency	30%	0.12	0.14
	Thermal Efficiency	30%	0.13	0.16
SADICE	Cost multiplication	30%	0.7	1.3
	Electrical Efficiency	30%	0.12	0.14
	Thermal Efficiency	30%	0.13	0.16

Table 15: Parameters for Sensitivity Analysis (2).

4 Results and Discussion

The results are given and interpreted in the discussion section per scenario. Afterwards, an overview of the evaluated scenarios is given. At the end, in Section 4.7, there is a general discussion. As mentioned, the results are given per scenario, so the results of scenario A, B, C and D will be given in Section 4.1, 4.2, 4.3 and 4.4 respectively.

4.1 Scenario A: Current Situation

In this scenario, no biomass resources are used. The energy supply is similar to the current situation in Nidwalden, both electricity and gas are imported. To satisfy the heat load, a gas boiler is installed as can be seen in Figure 28. The heat load is not the same throughout the year. The 15 GWh per year needs to be produced, but this is divided over the months with percentages. The winter months have a high percentage and the summer months have 0%. In the two coldest winter months an installed capacity of 4800 kW is required.

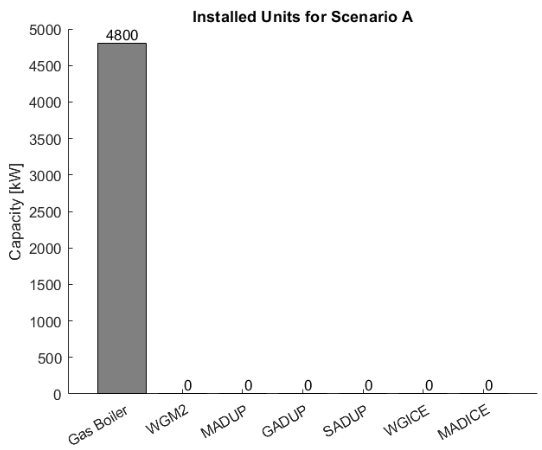

Figure 28: The installed capacity for Scenario A.

In Figure 29 the import of electricity from the grid is visualized in the left figure. The imported electricity matches the demand exactly. In the right figure, the gas import is displayed. There is a constant gas demand of more than 8 MW. On top of that, the required gas for the gas boiler is added. The gas boiler has a very high efficiency, so the right figure has the same shape the heat production. The figures of the gas boiler use and the heat production specifically can be seen in Appendix B.

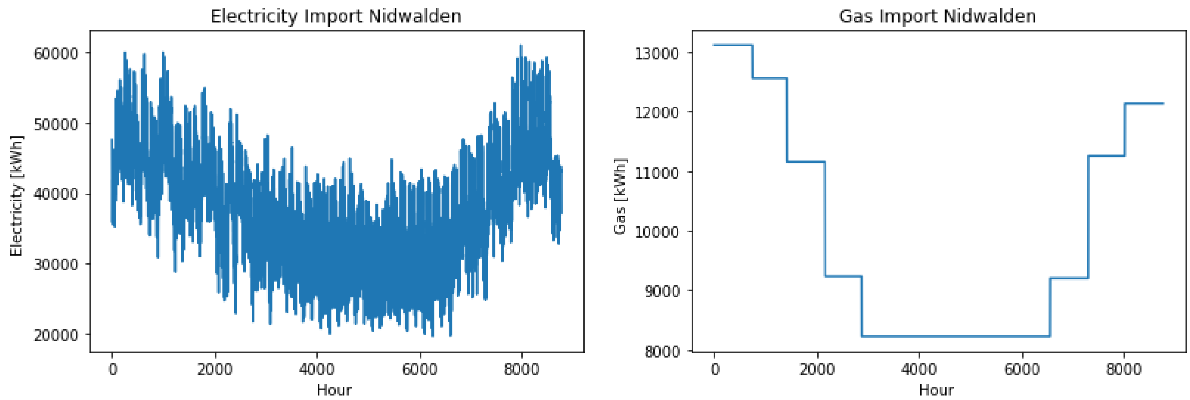

Figure 29: Results of Scenario A.

The costs of scenario A are given in Table 16.

Type	**Value**	Price (MCHF)
Electricity Import	330 GWh	69.5
Gas	87 GWh	8.5
Gas Boiler CAPEX	4800 kW	0.87
Gas Boiler OPEX	4800 kW	0.044

Table 16: The costs of Scenario A.

Scenario A Discussion

In this scenario, everything is grid imported and the biomass is not used. The heat is covered by gas boilers. The installed units of gas boilers do not use the same amount of gas all year around. The heat demand in the winter time is higher than the summer time. From May till September, the heat demand is zero. In the months of October till April, the total heat load is divided over the months with a percentage. The convenience of this scenario, is that the energy is only imported when needed. There is no case of overproduction, or other storage related challenges that have to be taken into account. However it will still be a challenge on a national level, it is not taken into account for this thesis. The costs of the electricity import are the highest. One of the reasons of the higher costs, is the electricity price per kWh being approximately twice as high as the gas price per kWh. Another reason is that the total electricity load almost 4 times as high as the total gas load. It must be mentioned that the gas boiler CAPEX costs are for the entire lifetime of the units, and the OPEX costs are yearly. The technologies that have 0 kW installed capacity in Figure 28, are installed in the other scenarios.

4.2 Scenario B: Biomethane Production

In this scenario, the biomass resources are used to produce biomethane. In Figure 30, it can be seen that GADUP, MADUP, SADUP and WGM2 are the installed units for biomass conversion. Since there is only a small heat production by biomass technologies, there is still an installed capacity of 4800 kW for gas boilers. The required gas is mainly provided by the installed units and for a small part by the grid import.

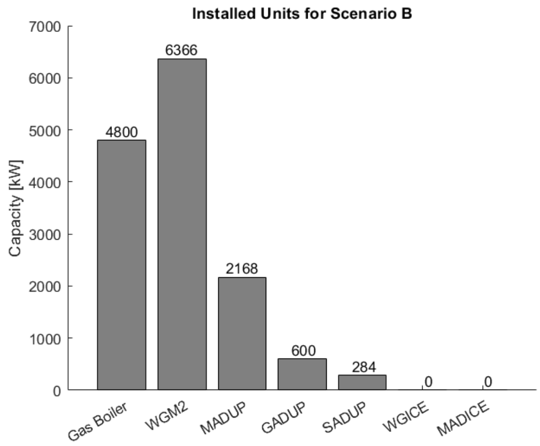

Figure 30: The installed capacity for Scenario B.

From Figure 31 can be seen that the left side is similar to the one from Scenario A. However, the gas import on the right side differs a lot. The gas import is significantly less, which can also be seen in the costs in Table 17. The gas production of the biomass conversion technologies is on full capacity in winter, but not all are during summer. These changes can be seen in Figure 43 in Appendix B.

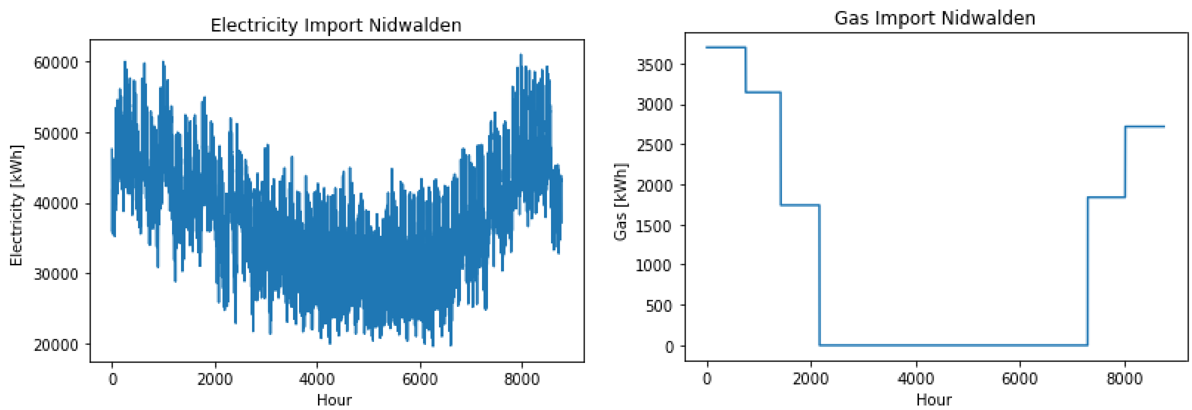

Figure 31: Results of Scenario B.

Type	**Value**	Price (MCHF)
Electricity Import	330 GWh	69.5
Gas Import	9.5 GWh	0.93
Gas Boiler CAPEX	4800 kW	0.87
Gas Boiler OPEX	4800 kW	0.044
WGM2 CAPEX	6366 kW	14.7
WGM2 OPEX	6366 kW	0.25
MADUP CAPEX	2168 kW	2.28
MADUP OPEX	2168 kW	0.20
GADUP CAPEX	600 kW	0.63
GADUP OPEX	600 kW	0.056
SADUP CAPEX	284 kW	0.30
SADUP OPEX	284 kW	0.027

Table 17: The costs of Scenario B.

Scenario B Discussion

The installed technologies provide a large part of the gas production for the canton. However, still some import from the grid is needed. That makes it clear again that all the available biomass in Nidwalden, is by far not enough to power the entire canton. Later in Section 4.5, it is given what percentage of the total load is covered by the biomass technologies. It can be seen that the division of the different biomass sources is as expected. The wood has more installed capacity than manure, green waste and sewage sludge. The technologies that are suggested by the model are the expected installed technologies. The technology that is the cheapest, also when taking into account the efficiency, is installed. The gas boiler capacity is the same as in scenario A, which is true. The costs of installing the biomass units are approximately 18 MCHF. In 3 years this can be earned back when taking into account the gas import costs in scenario A. Of course, this is not completely realistic, since the transport costs of biomass also need to be taken into account. However, it can still make an impact in making the gas support more renewable and reliable.

4.3 Scenario C: Electricity and Heat Production

In this scenario, the biomass conversion technologies will produce heat and electricity. That means that the gas is completely imported from the grid. The installed technologies are MADICE and WGICE.

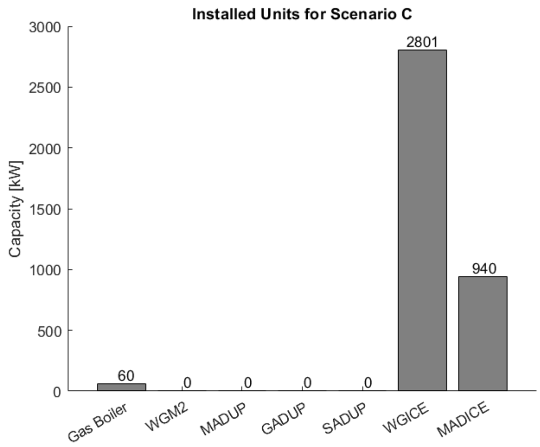

Figure 32: The installed capacity for Scenario C.

The electricity import on the left of Figure 33 looks the same as for other scenarios. However, the entire import per year is reduced by more than 30 GWh. This is approximately 10% of the total electricity load. Only a very small amount of gas boilers is needed, so the gas consumption and heat production of the gas boilers are almost 0. The MADICE heat and electricity production is a constant 1050kW and 940kW, respectively, and for WGICE the constant production is 3690kW and 2800kW respectively. Most of the year, that is enough for the heat production. In the coldest month, 60 kW of gas boilers needs to be installed. Since this negligible, the costs are taken to be 0. This, and other cost values, can be seen in Table 18. Because of the constant electricity production of the WGICE and MADICE (see Appendix B), there is also a constant heat production. However, the heat is not always needed throughout the year. This results in an amount of unused heat, as can be seen in Figure 34.

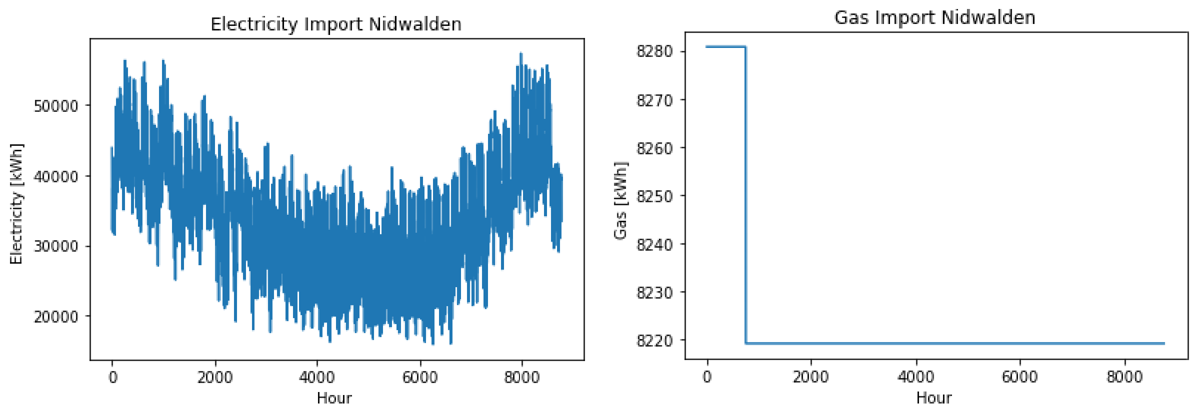

Figure 33: Results of Scenario C.

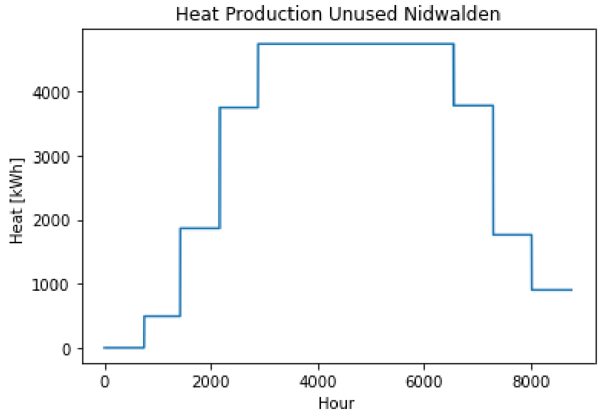

Figure 34: Unused Heat in Scenario C.

Type	**Value**	Price (MCHF)
Electricity Import	297 GWh	62.6
Gas	72 GWh	7.0
Gas Boiler CAPEX	60 kW	0.0
Gas Boiler OPEX	60 kW	0.0
WGICE CAPEX	2801 kW	2.4
WGICE OPEX	2801 kW	0.059
MADICE CAPEX	940 kW	1.7
MADICE OPEX	940 kW	0.14

Table 18: The costs of Scenario C.

Scenario C Discussion

It can be seen that only two out of four biomass sources have an installed unit. For green waste, nothing is installed because there are no suitable green waste conversion technologies for the production of heat and electricity, as was already mentioned in Section 3. For sewage sludge, the minimum installed capacity was not reached due to the available amount of biomass.

Even though the heat is not always needed, the two installed units, constantly produce heat throughout the year. That results in unused heat, which can also be seen in Figure 34. The model has no good solution for this, since the biomass stream is constant and the electricity is still needed. In scenario B, this problem was not visible, because part of the biomethane is used constantly throughout the year. The model is not (yet) able to come up with a solution for this problem. Note that this is only a problem for the heat, since electricity is always used throughout the year as well. It needs to be checked whether the technology can adapt the heat production. For example, produce more electricity and no (or less) heat. Another option is to find users that need heat throughout the year. The investment costs are under 5 MCHF. These costs can be earned back within a year because of lower electricity and gas import costs.

4.4 Scenario D: Power-to-Gas

Scenario D is similar to scenario B, but different in biomethane production. The electricity consumption is almost the same as the left hand side of Figure 31. In this scenario, there is less installed capacity required from gas boilers because of the extra heat production of these paths. The final installed units are displayed in Figure 35.

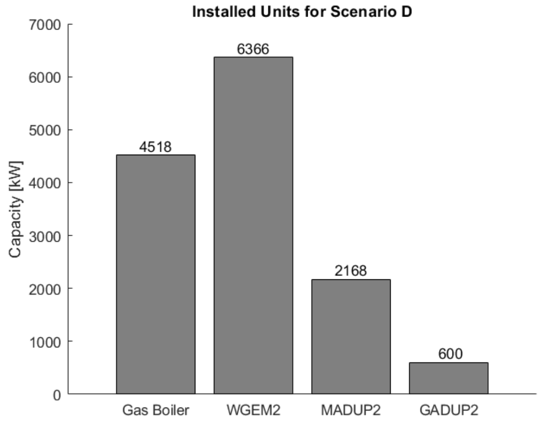

Figure 35: The installed capacity for Scenario D.

The total amount of electricity needed for enough hydrogen production to react with all the CO_2 is approximately 59 GWh per year, so 162 MWh per day. One PV panel produces 3.16 kWh on the best day, which means that 51270 panels are needed [29] [30]. That is a total PV size of 19.2 MWp and an electrolyzer size of 6.8 MW. The costs related to all the units and resources are given in Table 19.

With the known hydrogen production, the methane production can be calculated like explained in Section 3.1. In scenario B, it could be seen that the technologies did not provide enough methane for the winter months. With the extra methane production throughout the year and especially in summer, no more net import is required. On the left side of Figure 36, the methane import without extra methanation is given, and on the right side the methane import with extra methanation is given. During the summer months, more methane is produced than needed. This is displayed like a negative import. The winter month deficit is compensated by the summer month surplus. On the left side of Figure 36, 9.5 GWh of extra gas import was needed and on the right side there is a surplus of 1.7 GWh.

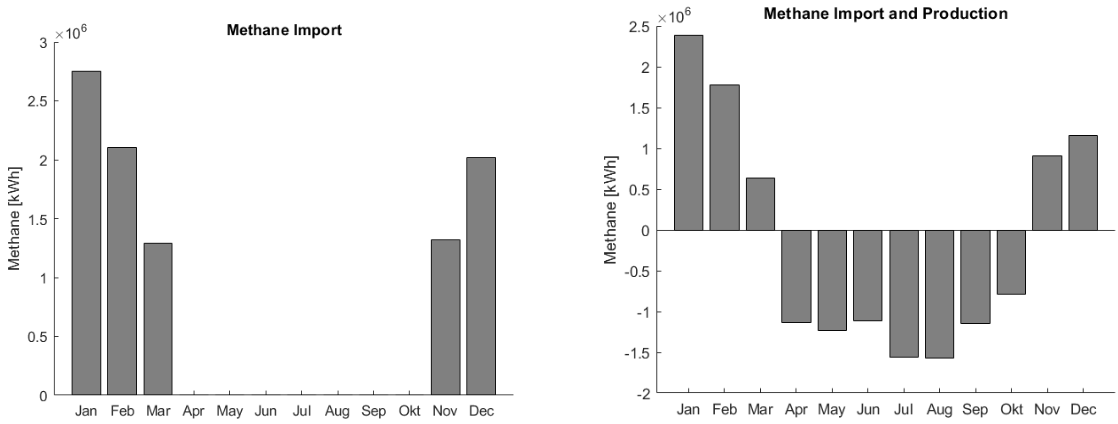

Figure 36: Results of Scenario D.

Type	**Value**	Price (MCHF)
Electricity Import	330 GWh	69.5
Gas Export	1.7 GWh	0.13
Gas Boiler CAPEX	4518 kW	0.82
Gas Boiler OPEX	4518 kW	0.041
WGEM2 CAPEX	6366 kW	17.2
WGEM2 OPEX	6366 kW	0.45
MADUP2 CAPEX	2168 kW	3.98
MADUP2 OPEX	2168 kW	0.42
GADUP2 CAPEX	600 kW	1.1
GADUP2 OPEX	600 kW	0.12
PV CAPEX	19.2 MWp	14.2
PV OPEX	19.2 MWp	0.18
Electrolyzer CAPEX	6.8 MW	15.6
Electrolyzer OPEX	6.8 MW	0.31

Table 19: The costs of Scenario D [29] [30].

Scenario D Discussion

Most of the results are very similar to the results of scenario B. The difference is that gas is exported instead of imported. The difference in costs that is caused by that, is 1.06 MCHF. That can cover the OPEX costs of the electrolyzer and PV with still having 0.57 MCHF left over. The units both last 20 years, so 11.4 MCHF can be saved. That is not enough compared to the CAPEX costs of 29.8 MCHF. However, the PV is used in an elegant way, where there is no unused peak electricity. The electrolyzer being based on the best solar day, is causing the unit to be large. This is unnecessary if the electricity can be stored for a short period of time. Additionally, it would be valuable to look at using part of the electricity load for the electricity use. At the moment, only around 50000 PV panels are installed. If the roof space of all the buildings in Nidwalden is added up, this would be around 350000 PV panels [31]. Since there are no overproduction problems in the Swiss electricity grid yet, it is a good option to replace part of the electricity import with the use of PV panels. The high peaks in summer can then be used by electrolyzers for hydrogen production. If this hydrogen (and the CO_2) can be stored for a short period, this can save in the size of electrolyzer unit.

4.5 Overview of all Scenarios

In Figure 37, an overview of the installed units per biomass source is shown. For completeness, the gas boiler is also added. It is interesting to know how much of the heat is covered by the installed biomass conversion technologies. That is included in Figure 38. It can be seen that for scenario B, more than the gas load can be covered. For scenario C, around 10% of the electricity is covered, and approximately 3 times the heat load.

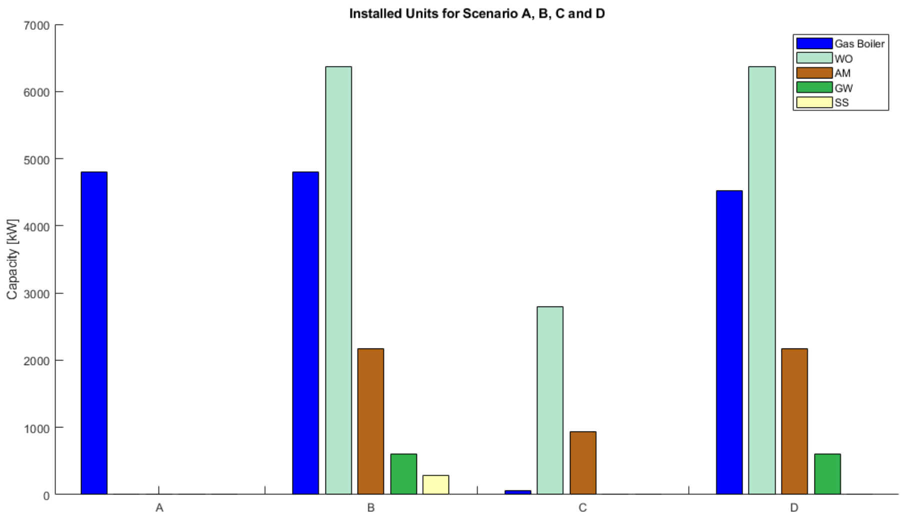

Figure 37: Overview of the Installed Capacities for the Different Scenarios.

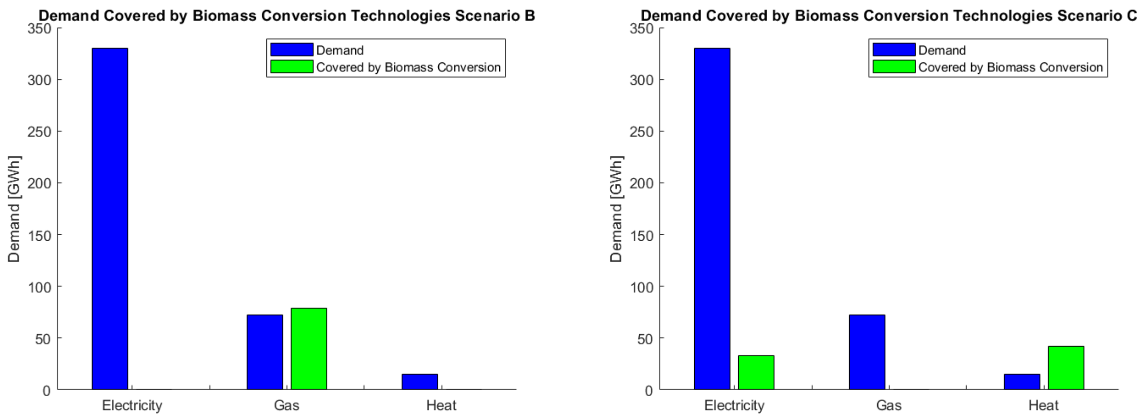

Figure 38: Demand Covered by Biomass Conversion Technologies.

Discussion

The biomass conversion paths can only cover a part of the total load. However, they still can provide a significant part of the energy demand. The costs are not unproportionally high, even though it is not a complete overview of the costs. In addition to adding costs for the biomass supply (transport), it is good to come up with scenario or case that can combine scenario B, C and D. The main challenge for that is to find proper constraints for in the model. Another option is to run separate scenarios, analyze the results and pick the technologies manually. The final run with all the manual inputs, will not be an optimization run in that case, but more an overview. Additionally, it is not necessary to have a constant biomass input. For example, (dried) wood can be stored well. It would be interesting to investigate the options of flexible biomass energy use, maybe in combination with solar energy.

4.6 Sensitivity Analysis

The default setting for the sensitivity analysis is Scenario B. This scenario has the most installed units and is therefore the most logical option to check for irregularities. Some units can only be checked in another scenario, for example WGICE. That is why the division is made in Table 14 for scenario B and Table 15 for scenario C. The results will be given in the same order that is given in the table. The results of the sensitivity analysis are discussed immediately in this section. Some parts of the code were changed due to problems that were found during the sensitivity analysis. An example is given in Appendix A.2. The results that are given in this thesis, are produced with the code that already contains the improvements.

For the category 'Nid' of Table 14, most parameters did exactly what was expected. For the minimum value, the biomass consumption was less which resulted in less installed capacity for that technology. For the maximum value, the installed capacity mostly stayed the same because of the built in safety option. In the file 'settings.txt', the minimum and maximum installed capacity of all the technologies are given. The maximum capacity was calculated and given in Section 2.2. The unit that was installed in the base case was still the best option, so it would be the one installed again. However, due to the relatively small change in biomass availability, there would not be another unit installed. For the gas and electricity load, the import would just increase or decrease with the minima and maxima. However, the heat load gave some concerning results. The gas boiler installed unit did not change. And with some further investigations, the gas boiler consumption and heat did not change either. Then another thing was found, the heat load in general was not working correctly. The total was not 15 GWh and it became clear that the monthly division was not good. The input.h5 file was not saved properly, and one of the calculations was wrong. The mistakes were fixed and the model was run again. This resulted in different installed units. The results described earlier in this section, are already the updated results.

In Table 14, the technologies for scenario B are shown. However, not all of them are shown in the table. GHYGU and SHYGU have similar values as MHYGU and the same holds for GADUP, SADUP and MADUP. All the technologies follow normal behaviour for efficiency and cost multiplication changes. Technologies interchange in a logical way when variables are adapted. The only strange thing was the electricity consumption of the technologies. It seemed not to affect the system at all, also when the extremes were made more extreme. There was a small problem in the 'units.py' file that caused the problem, but this was easily fixed. Again, the displayed results in this section are already based on the updated version. In general, it was found that the model was more sensitive to changes in efficiency. The focus of this model is on the biomass (technologies), so it is more important that the biomass is used with a good efficiency since there is not so much biomass available in the first place. Of course, the price is also important, but extra money is less of a problem than 'wasting' biomass.

For the resources, all the runs were as expected. The prices changed, but there was not a lot of influence on the technologies, since they are also dependent on the availability. The selling prices did not have any influence, which makes sense. The selling of resources was not included in this model. Since the Russian-Ukrainian war, the gas prices have been rising. That is why the uncertainty was increased. The influence of the gas prices on the model are as expected, and no sensitivity was found.

The annual interest rate has very little influence on the result. This is not weird, since optimizations were done based on the TOTEX. The interest rate has the most influence on the ratio between OPEX and CAPEX. For most technologies, these are in line with each other and therefore do not give strange results.

The sensitivity analysis for the values of Table 15 did not give any weird results. Since there were very little options for electricity and heat producing technologies, not much changed. It was interesting to see that also the technologies with a higher uncertainty had very little influence on the final result. That was mostly due to the difference between WGICE and WCHP. A noticeable result was that the thermal efficiency had no influence on the composition of the installed units. This is also expected because everything is based on the electrical efficiency. For example, the costs are per electrical unit installed.

4.7 General Discussion

So far, there has only been a discussion part in Section 4 about the results and how good they are. Here, all the other topics from the report are taken into account. It is checked whether the assumptions and results are accurate. This is focused on the technology information and the model limitations. Later on, in Section 5, there are conclusions and recommendations.

The provided overview of biomass conversion technologies is not complete. There are more options to transform biomass to energy or an energy carrier. The technologies introduced in the report were found to be the most applicable in cases in Switzerland. This has partly been based on conversations with experts [20], but more research should be done to check why other technologies are less applicable. Another option would be to add everything to the model and let the model decide what is the best technology. After all, the model will probably be used by the people who advised these technologies.

Another important note about the technologies, is that the sources and citations for the technologies are not all the same. Some of the technologies are developed or used at PSI. That means that a lot of information was available about those technologies, for example the heat and electricity production details. For technologies from other sources, less extensive information was available and it was more difficult to check if the values made sense. Additionally, for some technologies it was assumed that combination of units of technologies was possible, which basically resulted in a lower investment cost. These assumptions were made based on an interview with an expert [20]. However, it is never physically proved that this is actually the case.

Different biomass availability and the demand load information was used throughout the thesis. First, the Martigny case was studied. It was decided to move to another case, because of the lack of information and the amount of required assumptions. For example, there was only information available for woody and non-woody biomasses. There were also only yearly values available for electricity and heat load, and no data on gas load. The switch to the case of the canton of Nidwalden, provided more information. However, still some assumptions had to be made as can be seen in Section 3. The assumptions for the model and loads were mostly done because of a lack of data. It would have been better to get more precise data on availability and price of biomass, as well as getting daily or hourly information for the heat and gas load. In addition to that, it would also be better to include the other energy loads (for example for transport), to get a more complete overview of the energy system.

The designed scenarios work good to optimize for output specific technologies. It was chosen to formulate the scenarios like this, because otherwise the technologies cannot be compared properly. For example, it would have been necessary to say that a minimum amount of biomethane needed to be produced or that a certain amount of heat is needed. That would result in under- or over-constraints in the model. However, it would have been possible to select an optimal combination of both scenarios and combine those in a model. Then the model is not an optimization model anymore, but just a demand and production calculator.

It was known that there is a heat network for the 15 GWh per year in Nidwalden. However, there was no information available about the network and how it is powered. Therefore it was assumed that the heating network could be used for Scenario C, but that gas boilers were used for the other scenarios. This not the same as in real life, but a good alternative since there was no data available. It would be better to request the real life data, or otherwise similar heating network data. However, for this thesis it was not a severe problem to approach it this way. It was still proved that the model works and using gas boilers is also not unrealistic.

It is possible to change the case and scenario quite easily per case. This is also explained in Appendix C. One of the goals from the introduction was also to create an open-source recommender tool. Most of the parts of the model are publicly available, like Python and Excel. However, the Gurobi optimizer is not fully public. With an academic account, Gurobi can be downloaded without any problems. Without an academic account, it is possible to download the trial version. Unfortunately, this version is only available for 30 days. So the model is semi-publicly available. To change this, another optimizer has to be used. That could be interesting to implement for a future research, but for this thesis a semi-publicly model is sufficient.

Not all of the other technologies that were provided by the previous model were used [5]. This is mostly due to the fact, that the cases were different. In the case of a more complete energy system model in the future, all things from the models have to be combined. There are also similar models available that use for example wind energy [17]. The other technologies are given in Appendix A.1. A gap in the available models, is a proper energy storage and export system.

Another improvement would be the addition of emission values to the model. This needs to be done on multiple levels, like the biomass level, the transport, the technologies, the use, etc. The extra information that is provided by these emission values, can be used by the model. At the moment, optimization is only done on CAPEX, OPEX and TOTEX objectives. With the inclusion of emissions, optimization with an ENVEX objective is also possible. That would open up new opportunities for analysis as well. As shown in the previous research, a Pareto analysis can be performed [5]. That would make it possible to combine different objectives, for example with ENVEX/TOTEX Pareto graphs. This can yield results for minimum emission and minimum cost configurations.

5 Conclusions

An optimizer tool for energy systems of urban neighbourhoods in Switzerland was developed. This was part of a Swiss project, called SWEET EDGE. The tool was developed in Python with a Gurobi optimizer, based on an existing model for a farm. In order to develop a model for a neighbourhood, boundary conditions such as demands, technologies, energy balances and scales had to be changed. Different scenarios were introduced to compare the biomass technologies, and a sensitivity analysis was performed to check irregularities in the model. The model can be adapted and used for other cases, but it is important to think about differences when the scale changes. This model is specifically developed for a Swiss energy system in the scale of 40000 inhabitants.

Previous studies showed that there is a great potential in using biomass for energy production in Switzerland. Twenty different biomass conversion technologies, for the conversion of wood, manure, green waste and sewage sludge, were selected and investigated in depth. The energy system of the canton of Nidwalden was chosen as a case study to analyze and study the possibilities of implementing the technologies. Demand loads that needed to be (partly) covered by the biomass conversion technologies, were electricity (330 GWh/year), gas (72 GWh/year) and district heating (15 GWh/year). The available wood, manure, green waste and sewage sludge, were 89, 63, 19 and 8 GWh per year respectively in the canton.

Four different scenarios were included in the model to check the different biomass technologies. The scenarios are:

- Scenario A: The current situation in which gas and electricity are imported and the heating is done with gas boilers.
- Scenario B: Biomass conversion technologies produce biomethane. The biomethane is used for both the gas demand as the heat demand (gas boilers).
- Scenario C: Biomass conversion technologies produce electricity and heat.
- Scenario D: Similar to scenario B, but including power-to-gas solutions. The CO_2 from the biogas reacts with green hydrogen and produces extra biomethane. In scenario B, this CO_2 was emitted to the air.

The model is a MILP solver that can optimize based on ENVEX, OPEX and TOTEX objectives. ENVEX optimization is also possible for this model, but only when more emission data is available. A sensitivity analysis is important for MILP solvers, since input values have an uncertainty. For the sensitivity analysis, the model was run 92 times to check the influence of all the important parameters. No curious sensitivity was found, but multiple problems were solved because of findings from the sensitivity analysis. Examples are, the heat load, the electricity consumption and the gas boiler.

The most interesting results are the installed units per scenario. For scenario A, the only installed unit is 4800 kW of gas boilers. Import prices add up to 78 MCHF for both electricity and gas. For scenario B, the same amount of gas boilers is needed as for scenario A. In addition to this, the following biomass to biomethane technologies were installed: WGM2 6366 kW, MADUP 2168 kW, GADUP 600 kW and SADUP 264 kW. Because of these technologies, less gas needed to be imported which is saving approximately 7.5 MCHF per year. With the saved costs, the installment costs will be earned back in three years. In scenario C, only 60 kW of gas boilers are needed because of the heat production of WGICE (2801 kW_{el}) and MADICE (940 kW_{el}). Approximately 8.5 MCHF is saved per year on electricity and gas. The installment costs for scenario C are lower than for scenario B, and the investment costs can be earned back in one year. In scenario D, only 4518 kW of gas boilers were needed. The biomass to biomethane technologies are WGEM2 6366 kW, MADUP2 2168 kW and GADUP2 600 kW. Additionally, 19.2 MWp of PV panels and a 6.8 MW electrolyzer are needed. All the electricity production of the PV panels is used for the electrolyzer that produces hydrogen to make extra methane. With gas grid storage, the methane deficit during winter is compensated by the surplus production during summer.

In conclusion, a model of the local energy system of Nidwalden was developed and the operation was evaluated. Extensive information about the demand load and biomass availability is needed as input. Information about biomass conversion technologies was gathered they were successfully integrated in the model. The model chooses the most cost effective composition of installed units based on efficiency, complexity and costs. The tool can be used for other local energy systems in Switzerland in the same order of magnitude as Nidwalden. For local energy systems of another order of magnitude, not only changes in demand and biomass, but also changes in technology values are necessary.

5.1 Recommendations

It is recommended to find and include more data about the grid to get a more accurate idea of the costs of import and export. It is possible to include fluctuating prices and emissions for the grids. The grid share of renewable energy fluctuates due to the intermittency of renewable energy sources. For example, during a day with a lot of water flow and sun, the Swiss grid will have less emissions per kWh than on dark days with little water flow. The extra data should also take into account the grids from surrounding countries, since they often work together.

Add the technologies for biomethane export and storage to the model. There are cases where there is more biomass available than the energy demand. It would be interesting to look how this (over)production can be used for storage or export. Similarly, this is interesting for cases where there is too much electricity and heat consumption.

In this thesis, the optimizer tool is used for the case of a town and a canton, instead of a farm and an island in previous research [5] [17]. To make sure the model can be used for any energy system, like described in the SWEET EDGE objective, switches should be added. Switches in Python can automatically change the parameters of technologies to the value of the corresponding order of magnitude. Currently the model is only applicable to one case at a time.

The tool can be more complete with the inclusion of topics like transportation. This is a part of the energy balance that is currently not taken into account, since the focus was on biomass conversion technologies. However, transportation is being more and more integrated with the rest of the energy system. Most vehicles are still powered by benzine or diesel, but the transition to electrical and gas powered vehicles already started. More accurate data on transportation use and consumption is required to include this. Additionally, more combined demand data can provide more clarity for the entire energy system. For example, a more clear division in the heat and gas load.

In combination with an LCA, a similar model can provide more information for sustainability. Combining an optimized energy system with the outcomes of an LCA for the neighbourhood should result in conclusions for the most sustainable configurations. These kind of tools and analysis, will become more important the closer we get to the climate goals of 2030 and 2050 [32]. There will also be newly invented technologies in the future that can help significantly with the change to a sustainable future. It is important to keep the model up to date with these new and promising technologies. In every sector, major changes are needed to meet the goals. In good collaboration, and by investing where necessary, this can actually be achieved [33].

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Appendices

A Appendix A: Values & Calculations

In this appendix, the outcome values of calculations are shown. The calculations are explained in the text and the Figures of this appendix are referred. In Appendix A.1 and A.2, some code specific information is given.

Paths_WO	**Max_installed_WO**
{'Max_WGM1' }	6365.6
{'Max_WGM2' }	6365.6
{'Max_WGEM1'}	6365.6
{'Max_WGEM2'}	6365.6
{'Max_WGICE'}	2800.9
{'Max_WCHP' }	1212

Paths_AM	**Max_installed_AM**
{'Max_MHYGUP'}	4697.6
{'Max_MADUP' }	2168.1
{'Max_MADUP1'}	2168.1
{'Max_MADUP2'}	2168.1
{'Max_MADICE'}	939.53

Paths_GW	**Max_installed_GW**
{'Max_GHYGUP'}	1527.9
{'Max_GADUP' }	600.23
{'Max_GADUP1'}	600.23
{'Max_GADUP2'}	600.23

Paths_SS	**Max_installed_SS**
{'Max_SHYGUP'}	568.17
{'Max_SADUP' }	284.08
{'Max_SADUP1'}	284.08
{'Max_SADUP2'}	284.08
{'Max_SADICE'}	123.1

Figure 39: Maximum Installed Capacities.

Names	Values
"Maintenance_WGM1"	0.011429
"Maintenance_WGM2"	0.017279
"Maintenance_WGEM1"	0.026198
"Maintenance_WGEM2"	0.033629
"Maintenance_WGICE"	0.02
"Maintenance_WCHP"	0.02
"Maintenance_MHYGU"	0.089323
"Maintenance_MADUP"	0.089031
"Maintenance_MADUP1"	0.10771
"Maintenance_MADUP2"	0.10673
"Maintenance_MADICE"	0.08277
"Maintenance_GHYGU"	0.089323
"Maintenance_GADUP"	0.089031
"Maintenance_GADUP1"	0.10771
"Maintenance_GADUP2"	0.10673
"Maintenance_SHYGU"	0.089323
"Maintenance_SADUP"	0.089031
"Maintenance_SADUP1"	0.10771
"Maintenance_SADUP2"	0.10673
"Maintenance_SADICE"	0.08277

Figure 40: The percentage of the total investment cost that is spent on maintenance.

Kanton Nidwalden	Haushalte	Industrie	Dienstleistungen	Verkehr	Statist. Differenz inkl. Landwirtsch.	Total	Anteil	Total pro Kopf
	GWh	GWh	GWh	GWh	GWh	GWh	%	MWh pro Einw.
Erdölprodukte	171	45	46	354	5	621	54.1%	15.0
- davon Erdölbrennstoffe (Heizöl, Schweröl)	171	45	46		5	267	23.2%	6.5
- davon Benzin und Diesel				354		354	30.9%	8.6
- davon Flugtreibstoffe								
Elektrizität	108	97	71	16	8	300	26.1%	7.3
- davon erneuerbar, Produktion CH	28	25	18	4	2	77	6.7%	1.9
- davon erneuerbar, Produktion Ausland	6	6	4	1	0	17	1.5%	0.4
- davon nicht-erneuerbar, Produktion CH	38	34	25	6	3	105	9.2%	2.5
- davon nicht-erneuerbar, Produktion Ausland	36	33	24	5	3	100	8.8%	2.4
Gas	3	38	25	2	4	72	6.3%	1.7
Kohle	0	2				2	0.2%	0.0
Energieholz	53	37	8		2	99	8.6%	2.4
Fernwärme	5	6	4			15	1.3%	0.4
Industrieabfälle		4				4	0.4%	0.1
Übrige erneuerbare Energien	27	2	3	1	0	34	3.0%	0.8
Total	**366**	**232**	**157**	**373**	**19**	**1'147**	**100%**	**27.8**
Total exkl. Flugtreibstoffe	366	232	157	373	19	1'147	100%	27.8
Total erneuerbar	118	78	37	6	5	244	21%	5.9
Total nicht erneuerbar	248	154	120	367	14	903	79%	21.9
Total nicht erneuerbar exkl. Flugtreibstoffe	248	154	120	367	14	903	79%	21.9

Figure 41: Total Overview of the Energy Demand in Nidwalden [24]

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In Figure 41, it can be seen that a high share of the total energy demand is fossil dependant on fossil fuels. Out of the total amount of energy use which is 1147GWh, 621GWh is 'Erdölprodukte'. Those are all fossil fuels and used in different categories in the canton: households, industry, services and mobility. The focus of this thesis is not to replace these fuels, but rather to implement the biomass technologies. From simple calculations it follows that the available biomass is by far not enough to cover the load of the fossil fuels. It would be very nice if the fossil fuels can be replaced by the biomass produced energy, but that is not realistic. So the focus of this thesis is to implement the biomass technologies in the other categories:

- Elektrizität/electricity: In the figure, it can be seen that the canton of Nidwalden uses around 300GWh electricity per year. Since this is just one number, information from Swissgrid (the Swiss network operator) was requested. A very accurate file of electricity use in (Nidwalden, Obwalden and Uri) was provided. The file contained the amount of electricity used for every 15 minutes. Since this was the load for three cantons, a factor based on inhabitants was calculated to multiply with the data. To check if the numbers were making sense, the total sum of the file was taken. This was indeed resulting in approximately 300GWh per year.
- Gas/gas: The gas load is 72GWh per year. Since it might be possible to produce biomethane (gas) of a high enough quality, this is an interesting parameter.
- Kohle/coal: It is unknown where the coal is used for. Also it is such a small amount that this is not taken into account.
- Energieholz/wood for heating: In Switzerland, there are still a lot of old houses that only have wood fired cooking and heating facilities. In canton Nidwalden this type of heating is about 100GWh of energy per year. Because this is not included in the biomass potentials, this category is not taken into account either.
- Fernwärme/city heating: The city heating network in Nidwalden is using 15GWh per year. Since the facilities are already present, this can be an interesting parameter for the heat producing technologies. Currently this heat is provided by conventional industry. Since no information is available about the heat production, it is assumed for now that this is a (partial) heating demand.
- Industrieabfälle/industrial waste: This energy use is 4GWh per year. Since this is little in the total picture and because waste is not the main focus here, this part is left out.
- Übrige erneuerbare Energien/ other renewable energies: This category is mainly containing PV panels. The total amount is 34GWh per year and is not taken into account in this case, since it is not desirable to replace renewable energy technologies.

A.1 Other Technologies

In the model for the Swiss Future Farm [5] and Danish Islands [17], other technologies were included. In this thesis, the focus is on integrating the biomass possibilities, but a future user can also use the technologies from previous research. Efficiencies and other important values can be found in the thesis of Nils Ter-Borch [5] or can be seen in the model. The energy conversion units are: gas boiler, wood boiler, air-air heat pump, geothermal heat pump, electric heater, solid oxide fuel cell (SOFC), internal combustion engine, anaerobic digester, photovoltaic panels, battery, compressed gas tank, biogas storage, gas cleaning for SOFC, biogas upgrading, gas fueling station, grid injection and wind turbines. It is important to check the reference size. For example, in the previous model the units were used for a farm, which is a different scale than a canton. Therefore, not all parts of the model can be used for the case of Nidwalden. It is possible to eliminate a technology by putting the 'maximum installed capacity' to zero in the settings file.

A.2 Testing

While running the code and focusing on the OPEX, it became clear that the way the FOM costs in the model were not correct. The inputs in the model should be in the form of a percentage of the CAPEX costs. Therefore the percentages are calculated with the information from Section 2.1 and displayed in Table 20.

Path	**Maintenance Share**
WGM1	0.011429
WGM2	0.017279
WGEM1	0.026198
WGEM2	0.033629
WGICE	0.02
WCHP	0.02
MHYGU	0.089323
MADUP	0.089031
MADUP1	0.10771
MADUP2	0.10673
MADICE	0.08277
GHYGU	0.089323
GADUP	0.089031
GADUP1	0.10771
GADUP2	0.10673
SHYGU	0.089323
SADUP	0.089031
SADUP1	0.10771
SADUP2	0.10673
SADICE	0.08277

Table 20: The percentage of the total investment cost that is spent on maintenance.

B Appendix B: Figures

All important figures are given in the thesis itself. For some of the results, the figures below were not necessary in the corresponding section. To improve readability, the figures are included in this appendix for the reader who wants to see more complete results per scenario.

Scenario A

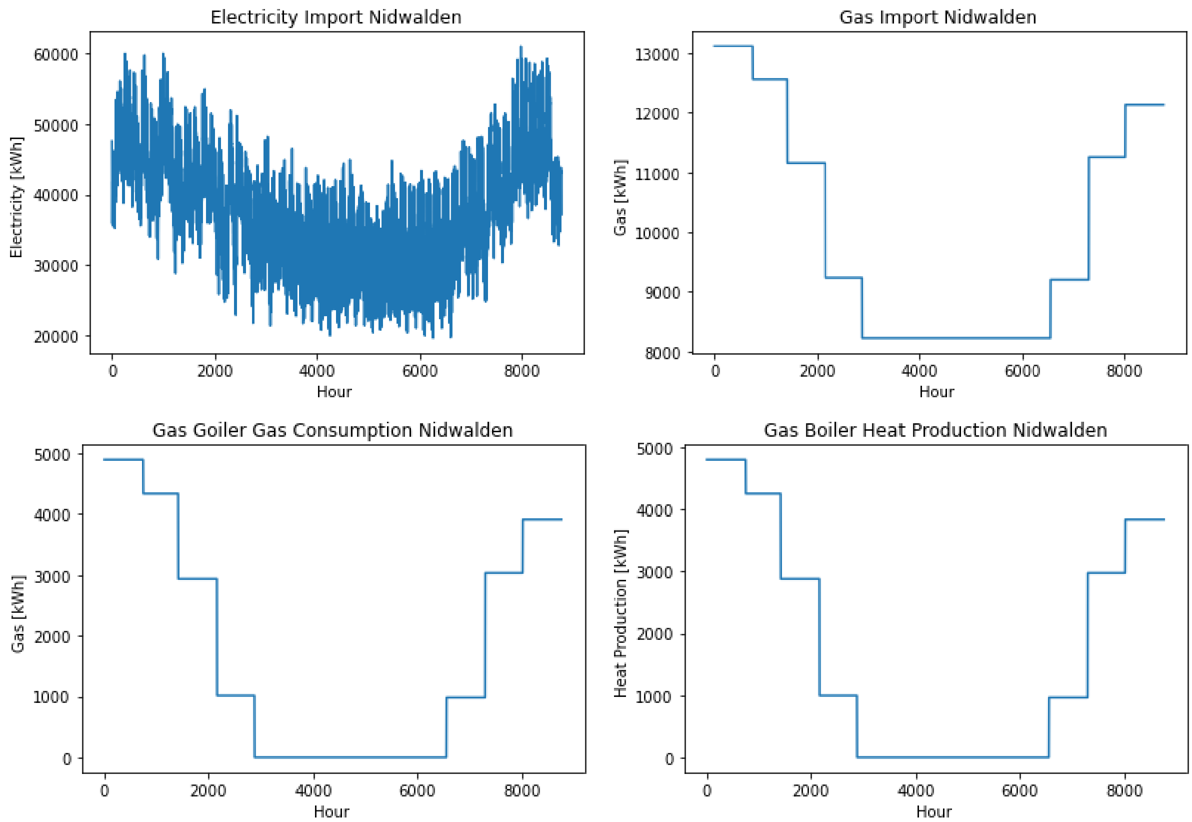

Figure 42: Results of Scenario A.

Scenario B

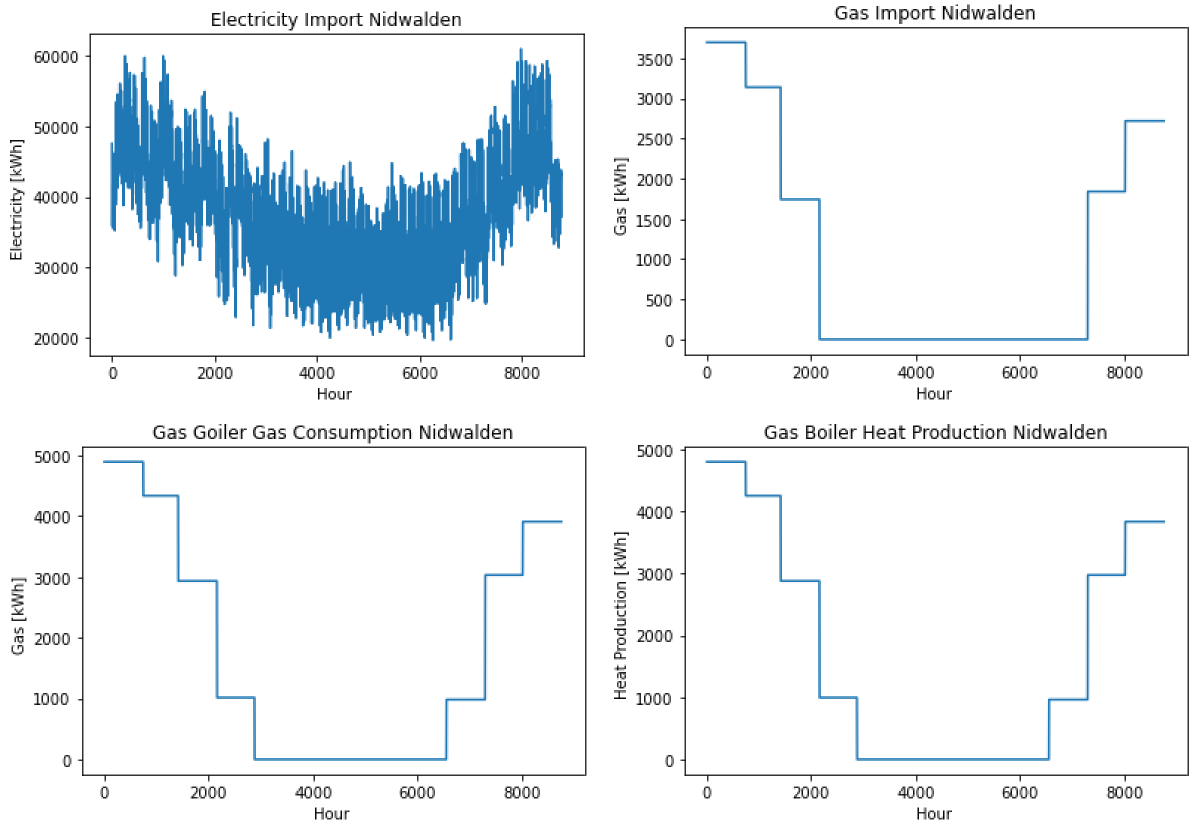

Figure 43: Results of Scenario B.

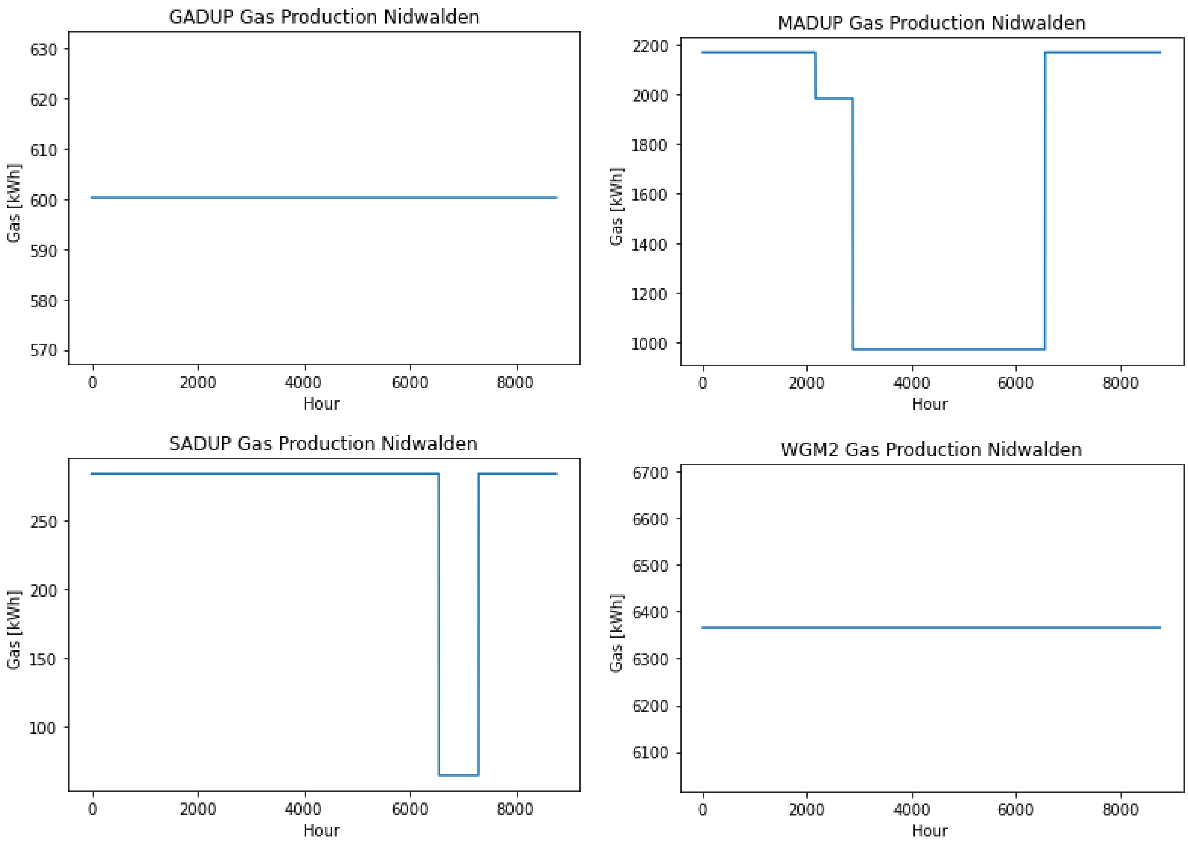

Figure 44: Results of Scenario B (2).

Scenario C

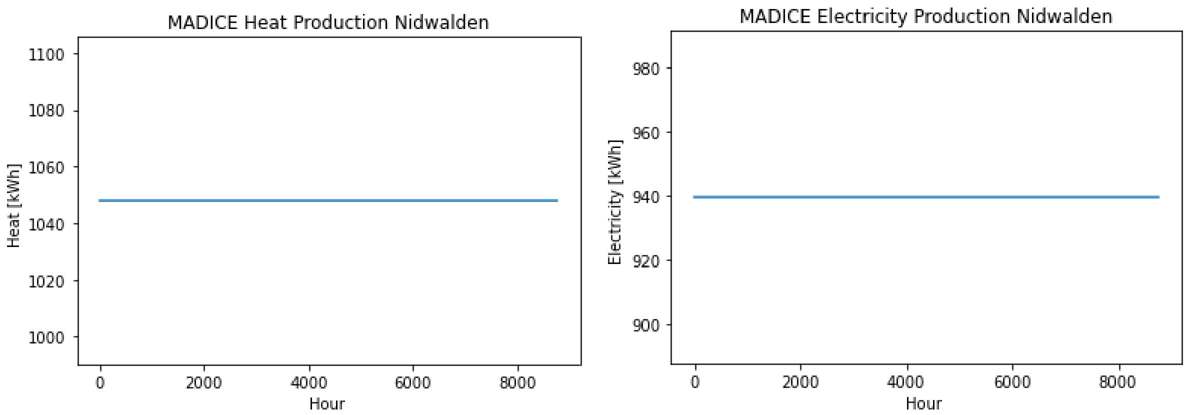

Figure 45: Results of Scenario C MADICE.

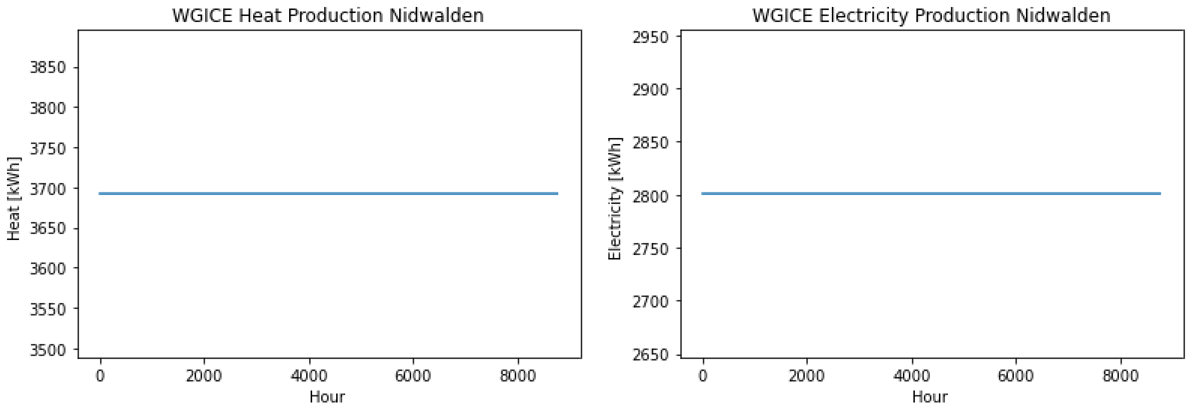

Figure 46: Results of Scenario C WGICE.

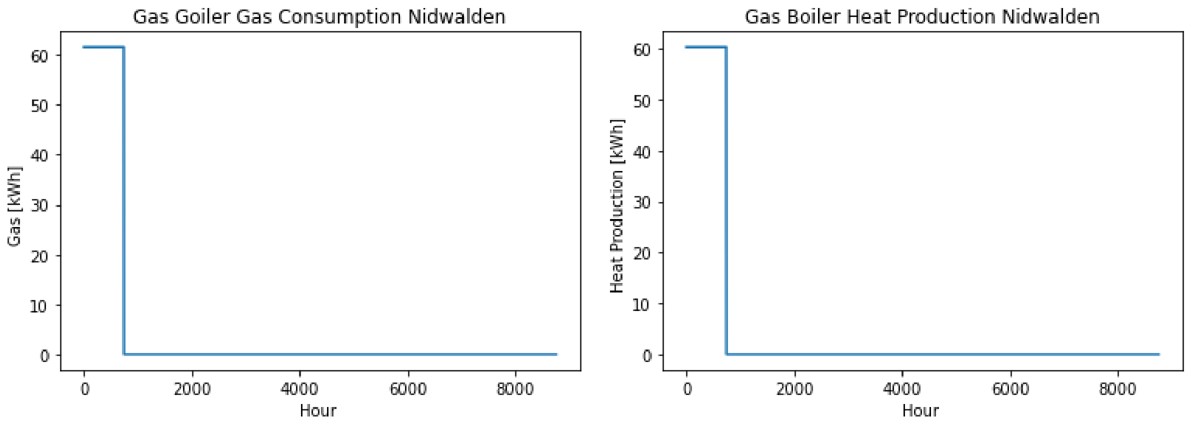

Figure 47: Results of Scenario C Gas Boiler.

C Appendix C: Code Tutorial

This Appendix contains the necessary information to use the code. The code is available on Github: https://github.com/lucfandijk/thesiscode.

C.1 Input Files

cost_param
In this file, the following inputs are given:

- Kind of technology: the abbreviation of a technology is given and a description.
- Cost multiplier: For some technologies or processes it is necessary to multiply European costs with a certain factor to get to a reasonable Swiss cost.
- Cost per size: the costs are mostly given in kCHF/kW since most literature provides the costs like that. Sometimes, the costs per unit are given in kCHF.
- LCA: emission estimations are given in tCO_2/kW. This is only a default thing for the constructions of the plants.
- Lifetime: the estimated lifetime of a plant in years. Usually this is around 20 years. This can be used to calculate total production in a lifetime.
- Maintenance: this is a percentage of the total cost which is spent on maintenance. This is often already included in the total price.
- Minimum size: the technologies/plants usually have a minimum size.
- Reference size: the size where all the values are based on.

parameters
In this file, any values that are needed for the energy calculations are included. Examples are:

- Efficiency: every possible form of efficiency can be included. For example chemical, thermal or electrical efficiency.
- Electricity consumption: this is often not included in the efficiency and therefore introduced seperately.
- Heat consumption: idem as electricity. Also heat production is possible for a process. Often the temperature at which the heat is produces is known too.
- COP: the coefficient of performance, for example used for heat pumps.
- Heat and electricity load: the demands of the area are included here. For example in GWh/year. The same counts for the gas demand.
- Available biomass: different kind of available biomass are included, also in GWh/year.
- Profiles: different kind of profiles are called here in the form of a csv-file. These are for example irradiance or electricity load.

settings

- General model values: Parameters like the solver time and the max/min variable size are included here. Also the date and starting and ending periods are defined.
- Clusters: The data can be sorted in amount of clusters to save computing time.
- Capacity: the minimum and maximum installed capacity of all the different technologies are listed in kW.

C.2 Python Files

The different python files are shortly described here. The description of the interaction between them is made as clear as possible and is based on the GitHub webpage from Nils Ter-Borch [34].

global-set.py
The module declares global sets of Units, and what each unit consumes, produces or stores as well as Resources and which are exchanged with the grids. This module has no local dependencies.

data.py
The module declares a number of data handling related functions used in all other modules to read parameter values from input files, read weather data, modify input files or pass data from one format to another. Generally this module contains functions that are use full for multiple modules. This module has no local dependencies.

clustering.py
The module is used to cluster weather parameters using a k-means algorithm and write the resulting cluster-mediod index to the clusters.h5 file.

write-inputs.py
The module handles the pre-calculation. It transforms weather data according to the selected clustering, calculate the electric load profile, the biomass energy and emissions potentials and fueling profile, saving all time dependent inputs to inputs.h5 and signle values to calc-param.csv.

read-inputs.py
The module will read the settings, parameters and profiles from settings.csv, parameters.csv, cost-param.csv, calc-param.csv and inputs.h5 and pass them on for the model description.

model.py
The module calls all functions necessary to describe and solve the FES model. It receives the inputs from read-inputs.csv and global-set.py. It initializes the MILP model called m. It calls on variables.py to initialize the model variables. It fixes unit size bounds according to settings.csv. It calls on units.py to model each unit. It describes the energy balance. It describes the objective functions. It describe basic scenarios for multi objective solving and a function run that when called will solve the optimization problem.

variables.py
The module declares all the unit related variables according to the sets from global-set.py.

units.py
The module describes one by one each unit, each in its own function.

run.py
The module is used to solve the FES model once or multiple times, using default or custom

settings regarding inputs, objectives, and outputs. Its run function will solve the model once along a given objective and store the solution results into a new folder. Its pareto function will solve the model n times between two objectives, store each intermediary solution in single folder along with the relevant graphs.

results.py
The model is called by run.py to store the model solution to a results.h5 file. Data in results.h5 can be read to three pandas dataframes called 'Single' for 0D single value results, 'Daily' for 2D daiy-hour format results and 'Annual' for 1D hourly results (only the SOC of storage units). The module also contains functions related to automatic folder creation for results. The results.py model is called by run.py to plot graphs of all kind. Alternatively graphs of inputs may be directly generated by this module.

Various Analysis Files
To analyze the results from the results.h5 file, several python files were made. To get specific results, I recommend to create your own analysis files. The files I used are: own_plots.py, own_plots2.py, own_plots3.py, scenario_A.py, scenario_B.py, scenario_B_sensitivity.py, scenario_C.py and scenario_D.py. The first thing that is done in these files is loading the results.h5 file that is needed. Then the specific data or arrays are taken and they are plotted or saved. These results are either plotted or exported to be plotted in another environment. A few times, data was saved in a txt or csv file to be plotted in MATLAB.

C.3 Running the Code

For this thesis, Spyder (Python 3.9) and Anaconda were used to program. The code can also be run in any Python environment, but it is possible that some changes are required. The following steps need to be taken in order to install Anaconda:

- Install Anaconda via https://www.anaconda.com/products/distribution
- Check if everything is installed properly by opening the Anaconda Prompt.
- Get an academic (or temporary) Gurobi license and download it. The steps are explained on the Gurobi website.
- Open the Anaconda Prompt and type 'conda config –add channels http://conda.anaconda.org/gurobi', then 'conda install gurobi'.
- Open Spyder or another Python environment and type 'import gurobipy as gp'. It is now also possible to open the files from 'Nidwaldan.zip' from the Github page.

Once the files are opened and explored, it is possible to run the code. This can simply be done by going to 'run.py' and pressing run (F5). This will cause the code to optimize with TOTEX. It is also possible to run with another optimization by just typing 'run('opex')' or 'run('envex')' in the console.

When input information is changed, it is sometimes necessary to make a new input.h5 file. This can be done by running the write_arrays.py file and then writing write_arrays(path) in the console. An error can occur if the path is unknown or incorrect. This can be fixed by selecting the correct path or running read_inputs.py once. You can type 'path' in the console to check if the path is now correct.

C.4 Adapting the Code

One of the most important changes that will be done to the model are the imputs. These can easily be changed in the txt/csv files in the inputs folder. Sometimes it is necessary to run the write_arrays file like described above, but often not. If a new scenario is similar to Nidwalden, the loads can be easily adapted. Look at the data in the profiles and inputs and check what is different. It is also possible to change the profile input, but this might require changes in the write/read_inputs file.

Another important change can be the addition of a unit. This is well described on the Github page of Nils [5]. A screenshot of this page is displayed below in Figure 48.

Example: Adding a unit to the model

Adding a a technology to the model should not take more than $10min$ once the user has gathered cost and performance parameters and decided on a mathematical description. For this example we will add a simple thermal solar panel unit with an efficiency only.

1. Chose an abbreviation, e.g. TS
2. Add the efficiency to `parameters.csv` and the related costs to `cost_param.csv`
3. Add the unit to the tuple *Units* in `global_set.py`
4. Add the unit and the resource it consumes and produces to the dictionaries *U_cons* and *U_prod*, execute `global_set.py` and check that *U_res* contains the right information for TS. Use the existing PV for comparison.
5. Create a new function in `units.py` called *ts* and describe the unit using the Gurobi python (The online Gurobi documentation is available at url{https://www.gurobi.com/documentation/9.0/`. I highly recommend using it extensively and trying a few of their examples.) and the new variables that where automatically generated by changing `global_set.py`. Since the TS is similar to the PV, simply copy the *pv* function and change the relevant information. Use the pandas series *P* to access the unit parameters you entered into the .csv files.
6. In `model.py`, call the function you just wrote with *units.ts(...)* inside of the *model_units* function.
7. Execute the `model.py` module to check for errors.
8. Make sure the unit is part of the right energy balance, in this case it produces heat only and will be automatically added to the right constraint if it is part of the *Heat* subset in the *U_prod* set. And keep in mind all other technologies produce and consume in kW-resource.
9. Execute a single run in the `run.py` module with 'envex' as the objective. If the TS does not appear in the results, try constraining its size to any reasonable value inside of the `settings.csv` file to force it to be installed.

Figure 48: Step by step plan to add a new unit to the model [5].

Switching scenario is not difficult. However, a few steps need to be taken. In the global_set.py file, changes are required in Units, U_prod and U_cons. It is only needed to comment the things from other scenarios and put the necessary values not in comments. It is indicated in the code, which values belong to which scenario. Additionally it is of course possible to create a new scenario. It is convenient to look at the existing scenarios to create a new scenario. Secondly, changes are required in the model.py file. First of all, in the function model_units, the units of the other scenarios need to be in comments. Just like the values mentioned before, it is indicated in the code which units belong to which scenario. Lastly, it is also important to change the WO, AM, GW and SS balances. This works again with comments. Now the code is ready to run for the new scenario. Errors that have to do with this topic are easy to trace and solve.