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Biomass energy pathways in Switzerland

Relatore:
Prof. A. Lazzaretto

Correlatori:
Prof. F. Maréchal
Post-doc E. Peduzzi
PhD. S. Moret

Laureando:
Marco Nasato

Matricola:
1079264

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A Gloria e alla mia famiglia

Abstract

Through this thesis we tried to evaluate the impact of integrating biomass conversion technologies and biomass seasonal storage in the Swiss energy system. A model that describes the Swiss energy system has been developed and it is used to assess the most promising biomass conversion technologies. The best configurations of the system according to economic and environmental aspects are determined and discussed. These results represent a possible guide-line for decision makers to understand how the Swiss energy system can be erected and how biomass resources can be exploited in the absence of nuclear power production.

In Ch. 2 a classification of biomass resources and technologies is provided and the overall sustainable potential in Switzerland is calculated. Biomass feedstock is divided in five main categories: agricultural crops, woody biomass, we biomass, waste oil and fats and micro-algae. Biomass technologies are classified in terms of thermochemical conversion and biochemical conversion technologies. Then a classification in terms of combustion technologies, i.e. technologies that provide heat or electricity, and fuel generation technologies, i.e. that convert biomass in biofuels, is given. This classification permits to understand easily the results.

In Ch. 3 the model is presented. First the characteristics of the tools that have been used (OSMOSE and AMPL) are discussed, then the equations of the model, the parameters, the independent and dependent variables and all the constraints are listed. The model implemented by Stefano Moret [58] has been further developed to consider both economic and environmental aspects of biomass utilisation.

In Ch. 4 the optimisation problem is stated. It is defined as a Mixed integer linear programming (MILP) problem. A linear formulation where integer and non-integer variables are used to implement mathematically the superstructure of a system that will be optimised. The objective function, the additional constraints and the optimisation algorithm are defined. Then the methodology that is used to assess biomass energy pathways is explained.

In Ch. 5 different scenarios are defined. *Single-technology scenarios*, where all biomass is used only by one technology, are compared with *reference scenarios*, where the biomass can be used by more then one technology.

In Ch. 6 the results are discussed. A ranking of biomass technologies is provided considering the costs increase percentage of the scenarios over different values of the emission limit. Then the best configurations of the Swiss energy system according to economic and environmental aspects are shown highlighting the importance of biomass utilisation.

Sommario

Attraverso questa tesi si è cercato di valutare l'impatto dell'integrazione delle tecnologie e dello stoccaggio stagionale di biomassa nel sistema energetico svizzero. Un modello che descrive il sistema energetico svizzero è stato sviluppato ed utilizzato per valutare le tecnologie di conversione della biomassa più promettenti e la loro integrazione nel sistema. Le migliori configurazioni secondo aspetti economici e ambientali sono state determinate e discusse. Questi risultati rappresentano una possibile linea guida per coloro che dovranno decidere come realizzare il sistema energetico svizzero e come sfruttare le biomasse disponibili in assenza di produzione di energia da fonte nucleare.

Nel Cap. 2 viene fornita una classificazione delle risorse di biomassa e delle tecnologie e successivamente viene calcolato il potenziale sostenibile di biomassa in Svizzera. Le risorse di biomassa sono state divise in cinque categorie: colture energetiche, biomassa legnosa, biomassa umida, oli e grassi di scarto e microalghe. Le tecnologie di biomassa sono state invece divise in termini di processi di conversione: biochimici o termochimici. In seguito viene fornita anche una classificazione in termini di tecnologie di combustione, cioè tecnologie che forniscono calore o elettricità, e tecnologie di generazione di combustibili, vale a dire che convertirono la biomassa in biocombustibili. Questa classificazione permette di comprendere facilmente i risultati.

Nel Cap. 3 il modello realizzato viene presentato. Innanzitutto le caratteristiche degli strumenti che sono stati utilizzati (OSMOSE e AMPL) vengono discussi, poi sono elencate le equazioni del modello, i parametri, le variabili indipendenti e dipendenti e tutti i vincoli. Il modello implementato da Stefano Moret [58] è stato ulteriormente sviluppato per prendere in considerazione sia gli aspetti economici che ambientali dell'utilizzo della biomassa.

Nel Cap. 4 viene definito il problema di ottimizzazione. Quest'ultimo è classificabile come un problema di programmazione lineare intera (Mixed-integer linear programming o MILP in inglese). Una formulazione lineare nel quale vengono utilizzate variabili intere e non intere per descrivere matematicamente la superstruttura del sistema da ottimizzare. In questo capitolo viene definita la funzione obiettivo con i vincoli aggiuntivi al modello e l'algoritmo di ottimizzazione. Poi viene spiegata la metodologia utilizzata per valutare gli utilizzi energetici della biomassa.

Nel Cap 5 i diversi scenari sono stati definiti. Degli scenari difiniti come *single-tecnology scenarios*, cioè in cui tutta la biomassa viene utilizzata da una sola tecnologia, sono stati confrontati con degli scenari di riferimento, in cui la biomassa può essere utilizzata da più di una tecnologia.

Nel Cap. 6 i risultati ottenuti vengono discussi. Considerando la differenza di costo per diversi valori del limite di emissioni è stato possibile stilare una classifica delle tecnologie di conversione della biomassa. Infine vengono mostrate le migliori configurazioni ottenute del sistema energetico svizzero in base agli aspetti economici ed ambientali sottolineando l'importanza dell'utilizzo della biomassa.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Context

The world needs to improve strongly its efforts to tackle the challenges of climate change and security of energy supply. Since the first Conference of the Parties (COP) in 1995, greenhouse-gas (GHG) emissions increased steadily and in 2012 their atmospheric concentration was 435 parts per million carbon dioxide equivalent (ppm CO_2 eq). The International Panel on Climate Change has concluded that, in the absence of actions, climate change will have severe and irreversible impact across the world [35]. They estimated that to have a chance of limiting global warming to 2 ^oC the world can support a maximum carbon dioxide cumulative emission of 3 000 Gtons and an estimated 1970 Gtons had already been emitted before 2014 [36] . Greenhouse-gas emissions from the energy sector represent roughly 2/3 of all anthropogenic GHG emissions, therefore an effective action in the energy sector is essential.

A large share of energy related CO_2 emissions comes from a small amount of countries (Fig. 1.1).

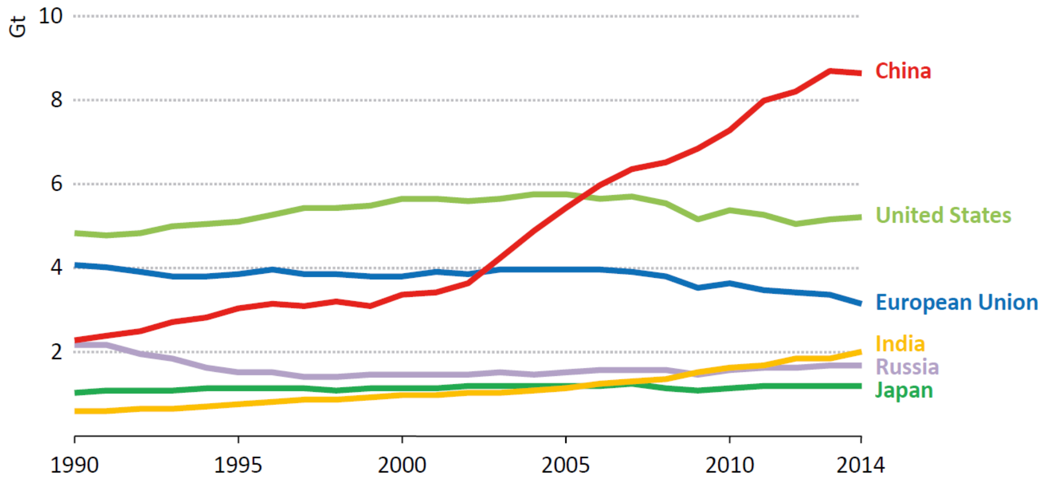


Figure 1.1: Energy-related CO_2 emissions for some countries (adapted from [35])

In 2012 China, the United States of America and India gave rise to half of global CO_2 emissions. European Union contributes to increase the total GHG emissions too, but since 1990 emissions in Europe declined by about a fifth [35]. Climate change is a global problem. To reduce the overall emissions and avoid the risk of dangerous changes each country will have to play its part.

In 2010 54 Mt CO_2 eq emissions have been produced in Switzerland. It is a small amount compared to the one of large countries such as China and United States of America (USA), but politicians have taken the decision to reduce by a fifth the GHG emissions by 2020. Furthermore after the accident at the Fukushima Daiichi nuclear power plant in March 2011 the government (Federal Council), followed by the parliament, decided not to allow the replacement of existing nuclear reactors and therefore to gradually phase out nuclear power while redefining the country's energy policy [34]. Nuclear power plants provide 40% of Switzerland's electricity generation, so the country has now the problem to identify the most viable ways to achieve GHG emission reduction with the least cost and at the minimum risk to its energy security.

Renewable resources, such as biomass, can have an important role in the Swiss energy system to reduce green house emissions and improve energy security. Plants contribute to decrease the concentration of CO_2 in the atmosphere by continuously producing biomass through photosynthesis. However, biomass is a scarce, non-homogeneous and low density material. Lignocellulosic biomass can be pretreated with torrefaction [53], pyrolysis, pelleting etc. and transformed into a higher volumetric and energy density material with improved transport and storage properties. Wet biomass, such as sewage sludge and manure, can be directly converted into biogas through digestion. The conversion into heat, electricity and fuels can therefore occur at a later time and in a different location from the harvesting. In 2010 biofuels and waste accounted for 9% of the total primary energy supply (TPES) while fossil fuels accounted for 53% [34]. Increasing the amount of biomass and of other renewables is therefore of prime importance if Switzerland really wants to reduce its GHG emissions without nuclear power plants.

To understand which could be the evolution of the Swiss energy sector from 2010 to 2050 the Swiss government commissioned a report to Prognos agency [55]. The report presents three scenarios considering different evolutions for efficiency in each sector, i.e. household, industry and services. Gironès et al. [30] developed an energy calculator (Swiss-Energyscope) [20] based on these scenarios to support decision-making at public level. The tool consists of an on-line energy calculator. The main users of the tool are expected not to be specialists of the energy domain. Thus it allows users to analyse different energy scenarios while introducing them to some of the key aspects of the energy sector [30]. In Fig. 1.2 it is possible to see how this calculator looks like. In the figure two different reference scenarios (2011 and 2035 medium) are compared in terms of final energy consumption. According to [55] in 2035 less energy demand is expected mainly because of the increase of efficiency in buildings, in fact waste heat is reduced strongly.

Optimisation and precisely Mixed integer linear programming (MILP) models are widely used for strategic energy planning of energy systems [38], [62]. Stefano Moret [58] developed a MILP formulation based on this calculator which, according to Gironès et al. [30], belongs to the "snapshot" category, i.e. it evaluates the energy system configuration and operation over a time span that is usually one year. This formulation models the entire energy system with a multi-period approach taking into account aspects related to seasonality and energy storage. The formulation permits to find the size, the load and the number of the energy technologies that minimise the total cost

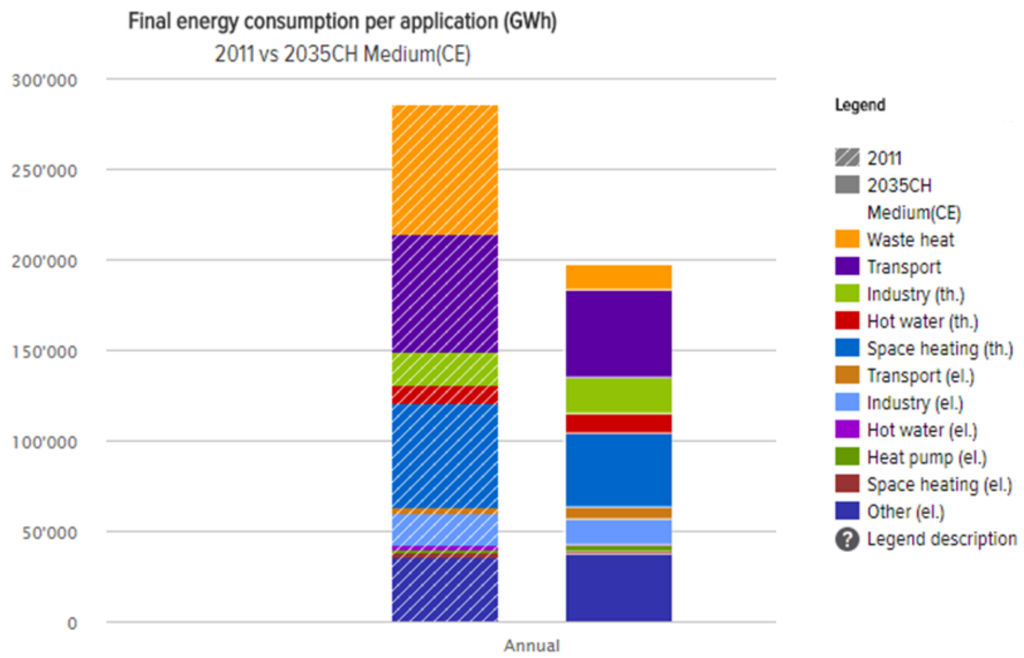


Figure 1.2: Swiss-Energyscope energy calculator

of the system with a low computational time [58]. These characteristics are considered very suitable to determine which is the best configuration of the Swiss energy system and to find out which are the best technologies for biomass utilisation in Switzerland. The model implemented by Stefano Moret [58] has been further developed by adding data about GHG emissions, energy technologies and resource availability. Then it has been adapted to assess different biomass energy pathways considering both the environmental impact and the cost of the system.

1.2 Objective

This study aims to evaluate the impact of integrating biomass conversion technologies and biomass seasonal storage in the Swiss energy system in the absence of nuclear power plants. Providing a classification of biomass resources and technologies is important to understand which are the possible biomass feedstocks and how they can be converted. The multi-period model of the Swiss energy system implemented by Stefano Moret [58] has been further developed integrating costs and environmental assessments. Different scenarios of biomass energy integration in the system are engendered and assessed. These represent different pathways for biomass utilisation, which are associated to different sets of technologies that can exploit biomass.

The main focus of this study is to assess the most promising biomass conversion technologies by making a ranking according to economic and environmental aspects and to define the best mix of biomass feedstocks and technologies which should be included in the system in the absence of nuclear power plants. First each biomass technology is tested without the possibility to integrate it with other biomass technologies. Then different integrated scenarios with different sets of biomass technologies are assessed and finally some results are proposed as possible configurations of the system for the future.

Chapter 2

Biomass Classification

To assess biomass energy pathways in Switzerland it is necessary to provide a classification of biomass feedstock, to determine how much biomass is available in the country and to specify which technologies can be used to convert it. In this chapter this classification is provided. First biomass feedstocks are classified according to the implementation in the model, then the biomass potential is given for different types of biomass. Finally a classification of biomass technologies is provided to understand which are the biomass conversion technologies that are considered in the model and how the conversion is developed.

2.1 Feedstocks

Many valid classifications of biomass feedstock are available in the literature. In 2009 Walther et al. [66] tried to assess biomass potential in Switzerland and in many other studies where the European potential is assessed are available. In 2010 Steubing et al. [59] made a classification of the sustainable biomass feedstock in Switzerland and divided biomass feedstock between technical and sustainable potential. The former is defined as the theoretical biomass available in Switzerland during one year that can effectively be supplied, the latter is a calculated amount in which economic, environmental, social and political constraints are considered. The sustainable potential is then divided into used potential and remaining biomass potential. This classification has been considered very suitable for this study since the biomass is not only classified but also divided between sustainable and unsustainable.

In this study a distinction between three main categories has been done to simplify the classification provided by Steubing et al. [59] and make it more suitable for modelling implementation: *Agricultural crops*, *Woody biomass* and *Wet biomass*. In Steubing et al. [59] the potential of some other possible feedstocks has not been considered. *Waste cooking oil and fats* can be used to produce biodiesel with transesterification reaction and *micro-algae* can be cultivated in facilities to produce biodiesel. These processes are not consolidated ones, but in the future they could be important for the energy transition in Switzerland. *Waste paper and cardboard* has been calculated by Steubing et al. [59] as the amount of not recycled waste paper in 2008 in Switzerland that has been totally incinerated with municipal solid waste (MSW) and it has been considered as biomass feedstock. In this study the amount of MSW that can be exploited in Switzerland has been calculated from the total value of waste that is produced per capta [14]. *Waste paper and cardboard* has been considered as a part of

MSW and not as biomass.

2.1.1 Agricultural crops

All crops that comes from meadowland, pastures and farmland are included in the Agricultural crops category. In view of this classification, the possible biomasses are divided as *Energy crops on farmland* , *Grass from extensive meadowland and mountain pasture land* and *Crops residues*, which are defined as the organic materials which are produced as the co-product of either harvesting or processing of agricultural crops [59].

2.1.2 Woody biomass

All the lignocellulosic biomass feedstock that has not been considered as agricultural crop is included in the woody biomass category. In woody biomass category *Forest energy wood*, *Industrial wood residues*, *Wood from landscape maintenance* and *Waste wood* are grouped.

All the wood that comes from the thinning operations or from harvested timber fractions that are not used by timber or the pulp and paper industry has been considered as *Forest energy wood. Industrial wood residues* are the residues of the wood processing industry. They can be used in the process to produce pulp and paper or to make wood chips and pellets. *Wood from landscape maintenance* includes woody biomass from maintenance of vegetation outside of forest areas as the one along the streets, railroad lines fields or rivers that has been estimated by Walther et al. [66] to be the 10% of Switzerland vegetation. Then *Waste wood* is classified by the *Swiss Air Pollution Control Act* [61] as two types of waste: waste wood and problematic waste wood. The former has been consider in this study as it can be used without many special requirements in the burning treatment, the latter has been neglected.

2.1.3 Wet biomass

All type of biomass which is usually collected with an humidity content between 60-80% has been considered in wet biomass category. Here is possible to distinguish between *Animal manure, Food industry waste, Biowaste* and *Sewage sludge*.

All excreta from livestock breeding are included in *Animal manure* . *Food energy wastes* is defined as a diverse mixture of organic substances produced during the food process, *Biowaste* as the organic waste from households or industry and *Sewage sludge* as the residual organic matter collected during waste water treatment.

2.1.4 Waste oils and fats

Waste oils and fats can be defined as the oils that have been used by restaurants, catering facilities and kitchens to cook food for human consumption. They are wastes as they are no longer fit for that purpose and are subsequently used as either feedstock for the production of biodiesel or as fuel for vehicles [12].

2.1.5 Micro-algae

Micro-algae are the most innovative feedstock for biodiesel production. In this process microalgae, i.e. small microorganisms that based their life on photosynthesis, are cultivated in water tanks and biodiesel can be obtained after the harvesting and the extraction of their lipid content. These micro-organisms are chosen because they can produce a large amount of lipids, that in some conditions can be the 70% of their mass by wet tonnes (wt), leading to a very high yield of oil per dried ton of algae biomass [6].

2.2 Biomass Potential

In Tab. 2.1 and Tab. 2.2 the input data used in the model for biomass potential are summarised.

2.2.1 Potential per each feedstock

Agricultural crops, Woody biomass and Wet biomass

Agricultural crops have no sustainable potential even if their technical potential is bigger then other ones. In Steubing et al. [59] the biomass sustainable potential from all energy crops is considered zero because of the strong constraints in biofuels production in Switzerland. Regarding *Energy crops on farmland* the *Swiss Federal Office of Energy* declared that, as Switzerland is a net food importing country, large-scale production of biofuels on arable land is not desirable while *Grass from extensive meadowland and mountain pasture land* are considered too expansive to harvest. *Crop residues* has a sustainable potential equal to zero, since the *Swiss Farmers Association* and the *Swiss Federal Office for Agriculture* do not consider this feedstock as a sustainable one because Switzerland already imports straw to satisfy its demand and most of the crops residues are used as animal fodder or as nutrients for the fields [59]. All the other biomass feedstocks have a sustainable potential. The ones with the highest value and therefore the most important for the biomass utilization in Switzerland are *Animal manure* and *Forest energy wood* .

Biomass	***Type***	***Technical Potential***	***Sustainable Potential***	***Total Sustainable Potential***
		tons (db)	*tons (db)*	*tons (db)*
Forest energy wood	***Woody biomass***	3 947 282	1 502 374	2 669 911
Wood from landscape maintenance		420 000	420 000	
Industrial wood residues		387 418	263 444	
Waste wood		640 000	484 093	
Sewage sludge	***Wet biomass***	346 947	346 947	2 338 454
Food industry waste		812 627	172 695	
Biowaste		500 322	400 667	
Animal Manure		2 836 290	1 418 145	
Energy crops	***Agricultural crops***	3 516 309	0	0
Grass from mountain pastures		3 000 975	0	
Crop residues		606 717	0	

Table 2.1: Biomass potential from [59]

Waste oil and fats

Regarding waste cooking oil potential unfortunately there is a lack of reliable statistics. In Ecofys [12] waste cooking oil potential has been estimated for EU-27 as 972 000 tonnes, according to BioDieNet [3] project this potential should be 3.55 million tonnes (8 liter per capita) and for Pelkmans [54] the European potential is 1% of the transport demand. Now it is possible to determine which could be the potential in Switzerland by scaling these data with Swiss population or transport demand (Tab. 2.2).

Reference	***Europe***	***Switzerland***	***Potential***
	tons	*tons*	*GWh*
Ecofys [12]	972000	15651	127
BioDieNet [3]	3550000	57163	465
Pelkmans [54]			641

Table 2.2: Estimated biodiesel potential from WCO

The value from Pelkmans [54] is calculated considering 65049 GWh of fuel transport demand in Switzerland [15] while other potentials have been calculated considering 816 900 as the amount of people in Switzerland [71] and 506 820 764 as the amount of people in Europe [70]. To determine the amount of bio-diesel producible from WCO data from Meng et al. [42] have been considered. Meng et al. [42] stated that it is possible to achieve roughly 89% of efficiency in the conversion of WCO into biodiesel which has a LHV of 32.9 MJ/kg. These results confirm that the amount of biodiesel from WCO is relatively low compared to other biomass feedstocks and even if an estimation is possible these values are really uncertain. As far as the author knows, no studies about waste cooking oil potential in Switzerland have been carried out therefore in this study this feedstock has not been considered, but future efforts should be done to assess the WCO potential and to comprehend whether it could be sustainable and important for biodiesel production in Switzerland.

Micro-algae

A different approach has been used to assess the amount of algae which can be exploited in Switzerland. The value of potential that has been reported in Tab. 2.3 is the total amount of biodiesel that can be produced by one reference plant. This value has been considered as the maximum amount of biodiesel producible in Switzerland because of the overall land that is needed for its construction. It has been evaluated by Davis et al. [9] as 7190 acre (roughly 29.1 km^2), which is the required land for a small city in Switzerland. Since it is difficult to find such an amount of land in a sunny place to grow micro-algae, only one of these plants has been considered feasible.

2.2.2 Overall potential

The total potential in dry basis (db) for each type of biomass (Tab. 2.1) has been used to calculate the amount of biomass feedstock in terms of energy.

In Tab. 2.3 the considered values of biomass potential in Switzerland are summarised. The values of the first two types of biomass feedstock derive from [59] while

Type	***Tot potential***	***Potential***	***LHV***	***Energy potential***
	tons (db)	*tons*	*GJ/t*	*GWh*
Woody biomass *(wb)*	2669911	5339822	8.3	**12279**
Wet biomass *(db)*	2338454	2338454	15	**9744**
Biodiesel from algae	[-]	31684	40	**352**

Table 2.3: Overall biomass potential

the considered value of *Biodiesel from algae* derives from [9] where two plant configurations to produce biodiesel from micro-algae are described.

Some simplifications have been done in the calculations of woody and wet biomass potential. The value of wet biomass potential has been calculated on dry basis by summing all biomass feedstock with a lower heating value (LHV) of $15MJ/kg$. This has been considered as a medium value over the different feedstocks in [59]. Woody biomass has been treated as wood at 50% of moisture content (mc) and a value of 19 MJ/kg for LHV_{db} has been used to calculated $LHV_{50\%}$ with the following formulation [18]:

$$LHV_{ref,mc} = LHV_{db} \cdot (1 - mc) - r \cdot mc \tag{2.1}$$

with: $r = 2.443MJ/kg$ (heat for water vaporisation).

50% has been considered as the reference moisture content because the biggest fraction in woody biomass (*Forest energy wood*) is usually harvested with this water content.

2.3 Conversion Technologies

Biomass is a resource that is directly linked to solar energy. Plants produce biomass continuously through the process of photosynthesis using carbon dioxide (CO_2) and water (H_2O) to grow. This is a renewable resource because plants are growing continuously and humans can exploit it in a sustainable way. Conversion technologies permit to transform this source in other forms of energy which have more energy density. Many classifications of conversion technologies are available, but usually a division in two mains categories is presented: *thermochemical conversion technologies* and *biochemical conversion technologies*. In biochemical conversion technologies biomass is converted into biofuels using chemicals treatments or microorganisms while thermochemical processing of biomass uses heat and catalysts to transform plants polymers into fuel chemicals or electric power [60].

A further division can be done for both categories. In biochemical conversion processes it is possible to distinguish between different kind of precesses to produce fuels from biomass:

- Ethanol production;
- Biodiesel production;
- Biogas production.

Among thermochemical conversion processes there are three categories that can be distinguished:

- Combustion;
- Gasification;
- Pyrolysis.

2.3.1 Ethanol production

Ethanol production technologies permit to produce ethanol from different kind of biomass resources trough biomass fermentation and ethanol distillation. A further division is useful to distinguish between different feedstocks. *First generation ethanol* specifies the ethanol that is produced from sugars, such as energy crops on farmland while *second generation ethanol* specifies the ethanol that is produced from lignocellulosic biomass such as woody biomass. The second one is considered more sustainable since it exploit a biomass that can not be used as food for humans. Since these two kind of feedstock have different chemical characteristics different processes are required too.

Ethanol (1^{st} generation)

As written above here ethanol is produced directly form sugars. The main natural materials that can be converted are agricultural crops such as sugarcane, sugar beet and sweet sorghum. These materials are rich of sugars that can be extracted by mechanical squeezing and fermented by yeast or bacteria [5]. Other agricultural crops such as corns, wheat and potatoes can be used in this kind of process adding a saccharification step. The starch contained inside crops is transformed into glucose trough enzymatic reactions catalysed by amylases. Then sugars are fermented to ethanol. This process is used in many countries, especially Brazil, to produce ethanol for transport, since a parentage can be added to gasoline in car engines without requiring any modifications. In Switzerland this feedstock has not been considered as sustainable (Sec. 2.2) therefore the conversion technologies that exploit crops to produce ethanol are not considered in this study.

Ethanol (2^{nd} generation)

Here wood, grasses or agricultural residues can be used to produce ethanol using their content of cellulose and hemicelluloses. The structure of lignocellulosic materials is very tough to biodegrade. The cellulose and hemicelluloses are tangled together and lignin forms a protection wall around them. Therefore three conversion processes are required: pretreatment, hydrolysis and fermentation. The pretreatment is used to remove lignin and to weaken biomass chemical structure, so cellulose and hemicelluloses become accessible for hydrolysis to produce sugars which can be fermented [5]. This process is more complex and expensive then the first one, but it is more sustainable.

In this study only one conversion technology which produces ethanol from woody biomass has been considered: Solvent based biomass deconstruction (SBBD). This process has been developed by Han et al. [31], that proposed a nonenzymatic sugar production strategy to convert simultaneously cellulose and hemicellulose into sugars using gamma-Valerolactone (GVL) as a solvent and diluted acid catalyst. They consider that this process could give an high yield of ethanol per ton of biomass and that it could be cost-effective for the future compared with other new biomass conversion technologies [32]. Making a complete description of this technology is out of the aim of this study. In Han et al. [31] and Han et al. [32] all information about process configuration, efficiency and costs are available and they have been used to make a simple model of this technology.

2.3.2 Biodiesel production

Biodiesel production processes are used to produce biodiesel from any material that contains fatty acids trough transesterification. Vegetable oils, animal fats, waste greases and edible oil processing wastes can be used, but different processes are needed to transform these feedstocks in the right reagent for transesterification reaction [5]. Like in ethanol production, in biodiesel production processes it is possible to distinguish between different categories that are based on different feesdstocks. In *first generation biodiesel* vegetable oils are extracted from plants and purified to be suitable for transesterification. In *second generation biodiesel* waste oil and animal fats can be used as feedstocks. The process becomes more complicated but the feedstock is more sustainable since it can not be used as food for humans or animals. *Third generation biodiesel* is the most innovative process. Here micro-algae are harvested to produce lipids that can be use as feedstock for transesterification. Micro-algae produce directly lipids converting carbon dioxide trough photosynthesis, so they are considered the best option concerning global warming.

Biodiesel (1^{st} generation)

In first generation biodiesel oil is extracted from plants such as rapeseed, sunflowers or palms by mechanical or chemical treatment and it is purified to remove the components that can be detrimental to subsequent steps. Then the transesterification reaction takes place. The main constituent of oils and fats are triglycerides, which are converted into fatty acid methyl esters (FAME), i.e. biodiesel, and glycerol ($C_3H_8O_3$) with an alcohol, usually methanol (CH_3OH):

$$Tryglicerides + CH_3OH \rightleftharpoons C_3H_8O_3 + Methyl\ esters$$

A catalysts is usually used to improve the transesterification reaction rate and yield. Then the product is purified to remove the excess methanol, catalysts and glycerol carried from transesterificatio process. Methanol is removed and recycled to the transesterification process.

Now biodiesel production from vegetable oil is a commercial process. In various countries biodiesel is added to fossil fuels for transport like ethanol, but this process has not been considered sustainable since it exploits energy crops which require arable land. Such conversion technologies have not been considered.

Biodiesel (2^{nd} generation)

In the second generation, waste cooking oil (WCO) or animal fats (AF) are used instead of vegetable oil to produce biodiesel. In this case it is not possible to develop the one-stage reaction because of the large amount of free fatty acids (FFA) in waste cooking oil. FFA crates many problems going through a one-stage process. More catalysts are needed, leading to higher costs, soap and water are formed and FFAs are not converted into fuel reducing the yield [5]. To obtain biodiesel it is necessary to treat the oil with a double-stage process. First the waste oil is inject in a reactor where an esterification reaction takes place. A large percentage of free fatty acids is converted in triglycerides with catalysts. Then it is possible to produce biodiesel through the common process.

As written in Sec. 2.2 studies about the potential of WCO and AF have not been carried out in Switzerland, so this feedstock has not been considered and neither associated conversion technologies.

Biodiesel (3^{rd} generation)

Producing biodiesel from algae has been touted as the most efficient way to make biodiesel. Some of the advantages are the rapid growth rates, a high lipid yield, much more then other feedstocks, and the absence of sulphur. Lipids can be extracted from algae producing biodiesel and residues can be used as feedstock for anaerobic digestion fulfilling the energy demand of the process. Anyway biodiesel production form algae is difficult and expensive and it requires also a huge amount of water. Many experiments and studies have been developed to assess the algae technology yield, cost and impact. In this study data from Delrue et al. [10] and Davis et al. [9] are considered.

Delrue et al. [10] assessed microalgae biodiesel technologies considering four evaluation criteria, i.e. net energy ratio, biodiesel production costs, greenhouse gases and water footprint, assuming that the production site is located in a sunny area in France (South-East). They considered different technologies to develop the process and determined the final results in three main different configurations, i.e. PBR, raceway and hybrid configuration, making a sensitivity analysis too. In the results they gave a range of the costs and emissions of the different configurations. They compared these biodiesel production costs with the ones in Davis et al. [9], which modelled a plant situated in USA, finding out that the costs in Davis et al. [9] are inside their range.

Since the plants studied by Delrue et al. [10] could be located in the south-east of France, it has been consider very suitable for Switzerland too and since costs given by Davis et al. [9] are inside the range defined by Delrue et al. [10], investment and maintenance costs in Davis et al. [9] have been used as reference. Two possibilities to produce biodiesel from micro-algae are considered. The first one via open pond (OP) and the second one via closed tubular photobioreactor (PBR) systems. Raw algal oil is subsequently upgraded to a green diesel blend stock via hydrotreating.

2.3.3 Biogas production

Biogas production is accomplished by anaerobic digestion from wet biomass. In this process the feedstock is transformed in biogas, i.e. a mixture of mainly CH_4 and CO_2, in anaerobic reactors. Inside the reactor four main reaction phases can be distinguished: hydrolysis, acidogenic phase, acetogenic phase and methanogenic phase. First strictly anaerobic bacteria accomplish the hydrolysis step. Polymers are broken down into monomers, long chain carbohydrates are transformed into short chain sugars, proteins into amino acids and fats into fatty acids and glycerin. Afterwards acidogenic bacteria degrade these products into short-chain acids, usually acetic acid, hydrogen and carbon dioxide and formed, but the main products are higher carbon number volatile fatty acids (VFAs) such as propionate, butyrate and alcohols. In the third phase fermentative intermediates (VFAs) are converted to methanogenic substrates as H_2, CO_2 acetic acids and unicarbon compounds by acetogenic bacteria. Methanogenic bacteria enter in symbiosis with acetogenic bacteria rapidly consuming the H_2 and forming CH_4, that is the desired product of the process. Only two genera, Methanosarcina and Methanothrix, in the Archea domain, can produce methane from acetic acid and they can grow only within a narrow range of environmental condition, consequently this phase could be a limiting step [67].

The described reactions are always present in an anaerobic digestion but they can be attained in different operation conditions which cause different yield and different time to obtain biogas. Based on the operating temperature inside the reactor, three main conditions can be defined:

- thermophilic (55-60°C);
- mesophilic (35-40°C);
- psychrophilic ($<$20°C)

These conditions influence the bacteria duplication time. Methanogens in particular, provide an high yield in mesophilic conditions, but others proliferate in thermophilic conditions. Further information are available in [67].

Anaerobic digestion is a commercial process and at the moment many plants are available in Switzerland, usually associated to farms. Animals are bred and their excreta are used in anaerobic digesters to produce biogas. In this model two different technologies are considered since biogas can be both burned in gas engines to produce electricity and heat or upgraded to methane.

Anaerobic digestion is usually associated to biogas combustion through combined heat and power (CHP) plants. In CHP, electricity is generated by burning fuel and then a heat recovery unit is used to capture heat from the combustion system's exhaust steam [67]. Data about costs and efficiency of this technology have been taken from various studies ([39], [16], [17]) and technical reports and a medium value has been calculated.

Another energy technology model has been created to consider the possibility to produce methane from anaerobic digestion. Methane can be injected in the Swiss natural gas network without problems and therefore it can be used in transport sector by NG cars or by other technologies. Many kind of processes are available to upgrade biogas in a NG equivalent fuel. Here anaerobic digestion is associated to pressure swing adsorption (PSA) since it has become one of the most widely used industrial gas separation technologies as result of its flexibility, relatively low capital cost and efficiency [51]. PSA processes are based on the ability of various adsorbent materials to selectively retain one or more components of a gas mixture under varying pressure conditions. Adsorbent materials are highly porous and separate gas components under high pressure according to molecular size. Biogas is mainly composed by CH_4 and CO_2. Carbon dioxide is allowed to enter into the matrix of the adsorbent material and it is retained while methane passes through interstitial spaces. The adsorbed component is then desorbed by reducing the pressure allowing the regeneration of the adsorbent material. Data about costs and efficiency of this technology have been taken from [51].

Technologies	***Short name***	***Product***
Anaerobic digestion with CHP	AN_DIG_CHP	Electricity & Heat
Anaerobic digestion with upgrading	AN_DIG_UP	Methane

Table 2.4: Biogas production technologies

2.3.4 Combustion

Combustion is the most widely applied conversion method for biomass. The chemical energy of fuel is converted via combustion into heat which can be transformed by heat engines into mechanical or electrical energy [60]. Woody biomass constitute the primary class of biomass fuels, but energy crops and municipal solid waste (MSW) can be used too. In this model energy crops are not considered since their sustainable potential is zero and MSW has not been treated as biomass because of it can contain plastics and other materials created from fossil fuels.

Combustion is a complex phenomenon involving simultaneously heat and mass transfer with chemical reaction and fluid flow. Three components are needed to start the reaction: the fuel, the combustive agent, usually oxygen (O_2) and the ignition energy. Fully detailed model of the combustion process include drying, pyrolysis, gasification, flame combustion and char combustion, but here the simple reaction usually used to describe biomass combustion is reported in Eq. (2.2). Further information are available in [5] and [60].

$$C_xH_yO_z + aO_2 \rightarrow bCO_2 + cH_2O \tag{2.2}$$

Where $C_xH_yO_z$ can represent any kind of biomass feedstock using the right indexes for x, y and z. a, b and c define the number of moles per each molecule according to the composition of the biomass and to the amount of air.

Biomass combustion involves a wide range of technologies but the largest use is still in traditional cooking, heating and lighting applications, mostly in developing countries. More modern uses for power generation and CHP are equally deployed around the world. Given this huge amount of technologies combustion is the conversion process that is mostly represented in the model. Commercial technologies such as boilers for houses are considered, but there are also innovative technologies such as biomass integrated gasification combined cycles (BIGCCs) or Gasification associated with fuel cells. In Tab. 2.5 all these technologies are listed.

Technologies	***Short name***	***Product***
Decentralised wood boiler	DEC_BOIL_WOOD	Heat
Industrial wood boiler	IND_BOIL_WOOD	Heat
Industrial wood cogenerator	IND_COG_WOOD	El & H
Centralised wood boiler	DHN_BOIL_WOOD	Heat
Centralised dry wood boiler	DHN_BOIL_WOOD_DRY	H
Centralised wood cogenerator	DHN_COG_WOOD	El & H
Biomass integrated gasification combined cycle	BIGCC	El & H
Decentralised wood cogenerator	DEC_COG_WOOD	El & H
Decentralised wood gas burner	WGB	Heat
Externally fired micro-gas-turbine	MGT	El & H
Gasification- Fuel cell - Gas turbine	GAS_FC_GT	Electricity

Table 2.5: Biomass combustion technologies

Commercial technologies

The technologies that are above the intermediate line are considered commercial technologies. Decentralised wood boilers are the boilers that can be installed in houses to provide space heating and hot water. Industrial boilers and cogenerators provide process heating for industries while centralised boilers and cogenerators supply heat for district heating network (DHN). Industrial and centralised boilers and cogenerators have the same values of efficiencies and costs, since they are considered the same technologies. A small increase of efficiency can be achieved by using dry wood, which can be obtained by exploiting heat form DHN in dryers. Data to model these technologies have been taken either from [15] and [50].

Innovative technologies

The technologies under the intermediate line are considered innovative technologies. In BIGCC, biomass is first gasified and synthetic natural gas (SNG) is used as fuel for the combined cycle. In the model biomass is used as additional feedstock while natural gas is the main fuel. Data about costs and efficiencies have been taken from technical reports. Further information about this kind of technology can be found in [8].

Decentralised cogenerators are Stirling engines. These engines are based on a closed cycle where the working gas is alternately compressed in a cold cylinder volume and expanded in a hot cylinder volume. Heat is not supplied by the combustion of fuel inside the cylinder, but transferred from outside through a heat exchanger. Consequently the combustion system of biomass can be based on proven furnace technology [47]. Data have been taken from [15].

Decentralised wood gas burner is a system made by a gasifier and a burner. Woody biomass is filled from a storage tank into the first chamber of the wood gas burner to be gasified. In the second step produced gas is burned in a combustion chamber. Until now this technology has been only validated in the laboratory using realistic model compounds. Data about costs and efficiency have been taken from technical reports.

Externally fired micro-gas-turbine (EFGT) is a novel technology under development for small and medium scale power and heat supplies. Its configuration is similar to a normal gas turbine, but it has the thermodynamic advantage of the preheated air and the combustion gasses do not pass through the turbine. Here a recuperator is used. Both woody biomass and output gasses from the turbine are the input of the recuperator. Then exhaust gasses are used to heat up the outlet air after the compression with an heat exchanger. In comparison with directly fired gas turbine EFGT sets less stringent requirements with respect to composition and cleaning of the combustion gasses [37]. Data about this MGT are taken from technical reports too.

The last technology is the most innovative one and also the most expensive. It consists of a Solid Oxide Fuel Cell (SOFC) - gas turbine hybrid system associated to a woody biomass gasifier. This system has been modelled by Caliandro et al. [4] which determined the best configuration of the system with a multi-objective optimisation and revealed the importance of process integration. First the moisture content of the wood is decreased by an air dryer. Then a gasification step takes place producing syngas which is sent to the hot cleaning unit to remove the pollutant. The cleaned syngas is feed into the SOFC and the outlet stream can be exploited in a gas turbine to increase electricity production since it has a high exergy content [4]. A ranking cycle can exploit the heat from the heat exchanger network to increase the electricity production. All data have been taken from Caliandro et al. [4] considering the configuration with the best efficiency, which is related to the use of the ranking cycle.

2.3.5 Gasification

Gasification is a process that converts solid fuel to a gaseous fuel through partial oxidation. Gasification of coal was carried out in the 1800s for lighting, but the interest on biomass gasification is new and is driven by the use of energy sources that have a lower carbon footprint [5]. More precisely gasification is developed under reducing conditions with oxygen added in sub-stoichiometric amount compared with the amount needed for complete combustion (Eq. (2.2)). Gasification may be accomplished through the direct addition of oxygen, using exothermic oxidation reaction to provide the energy for gasification or through the addition of sensible heat in the absence of oxygen. Produced gas is a mixture of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4) and other low molecular weight hydrocarbons and nitrogen (N_2). In many configurations synthesis gas (syngas), a mixture of predominantly CO and H_2, is produced by removing CO_2 and it is used for heating, electricity generation or liquid fuel production [60].

The steps of by which biomass is converted are partially shared with combustion. Heating, drying, pyrolysis,, gas-solid reactions and gas-phase reactions can occur in rapid succession, but here a simple equation is reported to simplify the overall reaction (Eq. (2.3)).

$$C_xH_yO_z + aO_2 \rightarrow bCO_2 + cCO + dH_2O + eH_2 \tag{2.3}$$

Where indexes describe the number of moles according to biomass composition and amount of air like in combustion.

Many kind of gasification technologies are available and a classification is possible in terms of the manner in which energy is provided or according to the transport process inside the reactor. The former divides gasifiers in three categories: air-blown gasifiers, when air is used as oxidant, oxygen-blown gasifiers, when oxygen is used instead of air or indirectly heated gasifiers where heat is supplied through heat transfer surfaces or media. The latter distinguishes between fixed-bed reactors, bubbling fluidized bed (BFB) reactors, circulating fluidized bed (CFB) reactors and entrained-flow reactors. In each one the flow of feedstock through the reactor and mixing it with the oxidant or with heat carrier is accomplished in different ways. Further information can be found in [60].

In this study we consider two gasification technologies, but the second one is just an adaptation of the first one adding electrolysers. To make a model of the gasification technology without electrolysis data from [11], precisely *Gazobois project*, have been considered. This system can produce synthetic natural gas (SNG) from biomass through gasification and methanation steps. First the biomass is pretreated by drying and sizing, then dried biomass is gasified to produce syngas in a indirectly heated reactor with circulating fluidized bed. More precisely this is an indirectly-heated dual fluidized bed gasifier. Two chambers are used to develop the gasification. In the gasification chamber biomass is converted into syngas using steam. The char falls into the combustion chamber where it is burned in air heating the accompanying bed particles which circulate back in the other chamber. Then the syngas is cooled, cleaned and compressed to catalytically react in methanation reactor to produce a gas mixture of CO_2 and CH_4. Removing CO_2 is possible to obtain a SNG that matches the requirements for the injection into the gas network [11].

Gassner and Maréchal [27] highlighted the prospect of integrating an electrolyser in the gasification conversion system. They showed that electrolysis can be an efficient and economically interesting option for increasing the gas output of the process while storing electricity and producing fuel. In the model an electrolyser is associated to the indirectly-heated dual fluidized bed gasifier to exploit electricity in the national grid producing oxygen for combustion and hydrogen to increase gas yield in the methanation reactor. Data about this model have been taken from [27].

Technologies	***Short name***	***Product***
Indirect gasification	GASIF	SNG
Indirect gasification with electrolysis	PWTOGAS	SNG

Table 2.6: Gasification technologies

2.3.6 Pyrolysis

Pyrolysis is a process that is carried out in the absence of oxygen, at atmospheric pressure, and at a temperature range from 300^oC to 600^oC. Two possible ways of developing the process are possible. In the traditional slow pyrolysis charcoal is the main product obtained from woody biomass while with fast pyrolysis it is possible to obtain a dark-brown liquid fuel with half of the heating value of fossil fuel. Fast pyrolysis requires very high heating rates followed by rapid cooling and condensation of the vapours produced [60].

In this study only the fast pyrolysis process has been considered. Data have been taken from Shemfe et al. [57] which assessed the techno-economic performances of biofuel production from biomass fast pyrolysis. Two possible configurations are presented. In the first one the main product is bio-oil, which can be burned in oil boilers, in the second one bio-oil is upgraded to diesel in a hydroprocessing area containing hydrotreating and hydrocracking processes. Hydrogen required for hydroprocessing is generated in a hydrogen generation section [57].

Technologies	***Short name***	***Product***
Fast pyrolysis	FAST_PYR	Oil
Fast pyrolisis with upgrading	FAST_PYR_UP	Diesel

Table 2.7: Fast pyrolysis technologies

2.3.7 Other thermochemical technologies

Some technologies can not be classified perfectly inside the categories described in Sec. 2.3. Here different thermochemical processes are developed together in the system or one thermochemical process is developed in a slightly different way. This is the case of *hydrothermal gasification* where the gasification is developed into a pressurised water environment and *Fischer-Tropsch* where after a gasification step the product is converted into liquid fuel.

Hydrothermal gasification

Hydrothermal gasification (HTG) is a very innovative technology. Plants are now only available in a pilot-scale. The only input of the process is biomass slurry. It can be woody biomass with added water or wet biomass. Biomass is hydrolysed and gasified using catalysts and heat. The reaction written in Eq. (2.3) changes in :

$$C_xH_yO_z + aH_2O \rightarrow bCH_4 + cCO_2 + dH_2 \tag{2.4}$$

In this study catalytic hydrothermal gasification in supercritical environment is considered and the model developed by Gassner et al. [28] is used as a reference. The main input is wet biomass that is first hydrolysed. Then salts are removed to avoid the risk to plug the equipment and deactivate the catalyst. The product is gasified in a catalytic fixed bed and SNG is produced by water absorption and membrane for grid pressure gas separation. A small amount of electricity is also produced by a CHP plant. Further information about this technology are available in [60] and [28].

Biomass to liquids

Biomass to liquids (BtL) facility consists in a conversion process which converts biomass into fuels. Fischer-Tropsch (F-T) fuels are produced by a thermochemical conversion process of biomass. This conversion is generally carried out into four main steps: pretreatment; gasification, where biomass is transformed into a raw synthesis gas; gas conditioning, where the composition and the temperature is adjusted for the synthesis, and synthesis, in which clean gas is transformed into fuel through catalysts [52]. In the model data have been taken from Peduzzi [52]. Two possible process layouts are considered. The first one is a simple F-T process, where biomass is converted into diesel equivalent fuel, while in the second one electrolysers are added to improve the efficiency.

Technologies	***Short name***	***Product***
Fischer-Tropsch	FT	Diesel
Fischer-Tropsch with electrolysis	FT_EL	Diesel

Table 2.8: Fischer-Tropsch technologies

2.3.8 Fuel generation and combustion technologies

The classification provided above permits to divide all biomass technologies in several categories which define precisely the process that they use to transform biomass into fuels, heat or power. A simpler classification is used in this study to divide the technologies that have different kind of products. *Fuel generation technologies* can produce fuels for transport or combustion technologies while *combustion technologies* produce heat or power. This is a simple classification and it is used in Ch. 6 to explain the results.

Combustion technologies	***Fuel generation technologies***
Decentralised wood boiler	*Solvent based biomass deconstruction*
Industrial wood boiler	*Indirect gasification*
Industrial wood cogenerator	*Indirect gasification with electrolysis*
Centralised wood boiler	*Fast pyrolysis*
Centralised dry wood boiler	*Fast pyrolisis with upgrading*
Centralised wood cogenerator	*Fischer-Tropsch*
BIGCC	*Fischer-Tropsch with electrolysis*
Decentralised wood cogenerator	*Hydrothermal gasification*
Decentralised wood gas burner	*Anaerobic digestion with upgrading*
Externally fired micro-gas-turbine	*Open ponds*
Gasification- Fuel cell - Gas turbine	*Photo-bio reactors*
Anaerobic digestion with CHP	

Table 2.9: Combustion and fuel generation technologies

Chapter 3

Modelling

To study the future energy pathways for biomass technologies in Switzerland a mathematical model that describes the Swiss energy system has been realised. It is possible to give a definition of a mathematical model as follows: A model is a set of equations, such as equalities and inequalities, that defines the relationships between the variables of the system and that forces the variables to assume admissible values. Precisely in an energy model energy and mass balances are used to link thermodynamic variables [40].

It is challenging to create such a model starting from scratch because of the huge amount of data and relationships that have to be considered, but fortunately some models and tools are now available. Gironès et al. [30] provided a classification of different kind of models. "Evolution energy models", such as MARKAL [63], OSeMOSYS [33] and 2050 Pathways model [48], are defined as the ones in which the evolution of the national energy system is analysed over a time horizon, but the chronology is not taken into account. The time horizon is broken down into a series of periods, e.g. multiple years or only one year. Each period is then divided in time-slices to better simulate the energy demand variations, but they are not linked chronologically together. "Snapshot models" such as Energyplan[41] and HOMER [19] evaluate the energy system configuration and operation over a time span that is usually one year. In this case the chronologically aspect is taken into account by dividing the time span into chronological time-steps of 1 h or less. Moreover two approaches can be followed if we want to make a simulation tool: optimisation or simulation. The optimisation tool can find the best solution for a system considering a defined object and the simulation tools permit to create different scenarios.

Gironès et al. [30] developed a model that represents a combination of a snapshot model and simulation tool to make all people capable to understand the changes in the Swiss energy system and their effects. Moret et al. [44] implemented an on-line platform swiss-energyscope where all people can define their own scenario for Switzerland and understand the effects of their choice looking at the total cost ($MCHF/year$), at the environmental impact ($ktonsCO_2eq/year$) and at other indicators such as deposited waste and energy consumption.

Afterwards Stefano Moret [58] developed a muti-period Mixed-Integer-Linear-Programming (MILP) formulation based on this platform. The model is written in AMPL and it makes possible to optimise the system in terms of total annual cost, which is defined as the sum of annualised and maintenance cost of the technologies and operating cost of the resources. This formulation has been considered very suitable for this study because it permits to define the size, the operation load and the number of plants considering the possibility to store biomass in the meantime. The model has been implemented with OSMOSE, a platform developed by *Industrial process and energy system engineering* (IPESE) group and *Laboratoire d'Energétique Industrielle* (LENI) at École polytechnique fédérale de Lausanne (EPFL).

3.1 Modelling tools

In this study OSMOSE and AMPL have been used as tools to evaluate different biomass energy pathways.

AMPL is a modelling language for mathematical programming. The term mathematical programming is used to describe the minimisation or maximisation of an objective function of many variables, subject to constraints on the variables, while the modelling language is designed to express the modeller's form in a way that can serve as direct input to computer system. Then the translation to the algorithm's form is performed entirely by computer. AMPL language is an algebraic modelling language. It provides computer readable equivalents of algebraic notations such as $x_{i,j}$ or $j \in S$ that are familiar to anyone who has studied algebra or calculus [26]. In AMPL is possible to define mathematical relations between variables and parameters over "sets" allowing the description of large mathematical problems with a concise syntax.

OSMOSE is the main tool that has been used in this study. It is the acronym for Multi-Objective OptimiSation of integers Energy Systems (OptimiSation Multi-Objectifs de Systemes Energetiques integres in french) and it has been crated to allow to integrate different tools, such as flow-sheeting, process integration and costing tools to design and analyse integrated energy systems [49]. It has recently been translated from Matlab to Lua (LuaOSMOSE) by IPESE group and it will be further developed in the future.

3.1.1 OSMOSE motivations

The main goal of OSMOSE is to develop an engineering tool that make possible to [43]:

- Analyse existing energy systems in order to improve them:
  - couple flow-sheeting software with optimisers;
  - model the steady state and dynamic behaviour of a process;
  - identify bottlenecks of technologies
- Perform, design and synthesis of energy systems:
  - superstructure-free design;
  - superstructure-related design;
  - heat exchanger network synthesis

To achieve that goal OSMOSE has to handle different software, some of them could be flow-sheeting software as Aspen plus, Belsim Vali or Gproms and others can be an "optimisation" software as AMPL or GLPK. In this way OSMOSE becomes a key platform to perform calculations that are not possible to handle by using only one of them (Fig. 3.1).

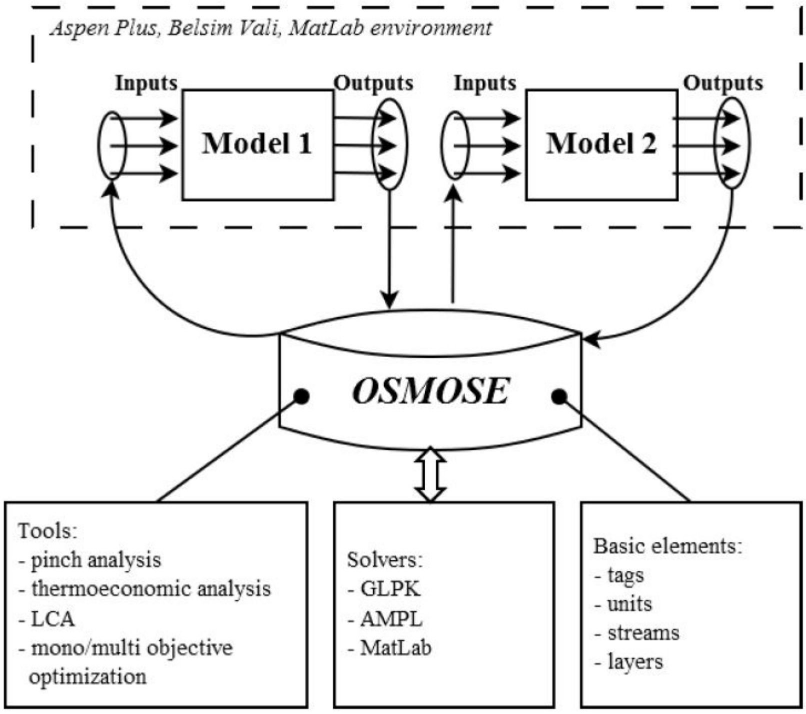


Figure 3.1: Organisation of osmose platform

3.1.2 OSMOSE architecture

OSMOSE is built following this architecture (Fig. 3.2):

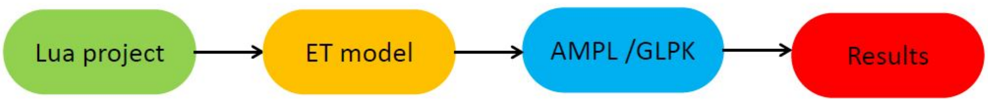


Figure 3.2: OSMOSE architecture (adapted from [49])

The information flux starts from a .lua file that is called usually *frontend* Here is possible to define the calculations that we want LUA to make and to load our energy technologies that contain all information about our problem, such as units, stream in units, tags and equations. The model is then solved. As the set of general equations is a part of LuaOsmose package OSMOSE generates only the input file for AMPL or GLPK and launch ampl.exe in order to find the optimal solution for our problem. Once AMPL find a solution it writes an output file in the result folder with all values of the problem variables that can be successively plotted.

As said all the calculations are organised in a main file called *frontend* where the problem is stated (Fig. 3.3).

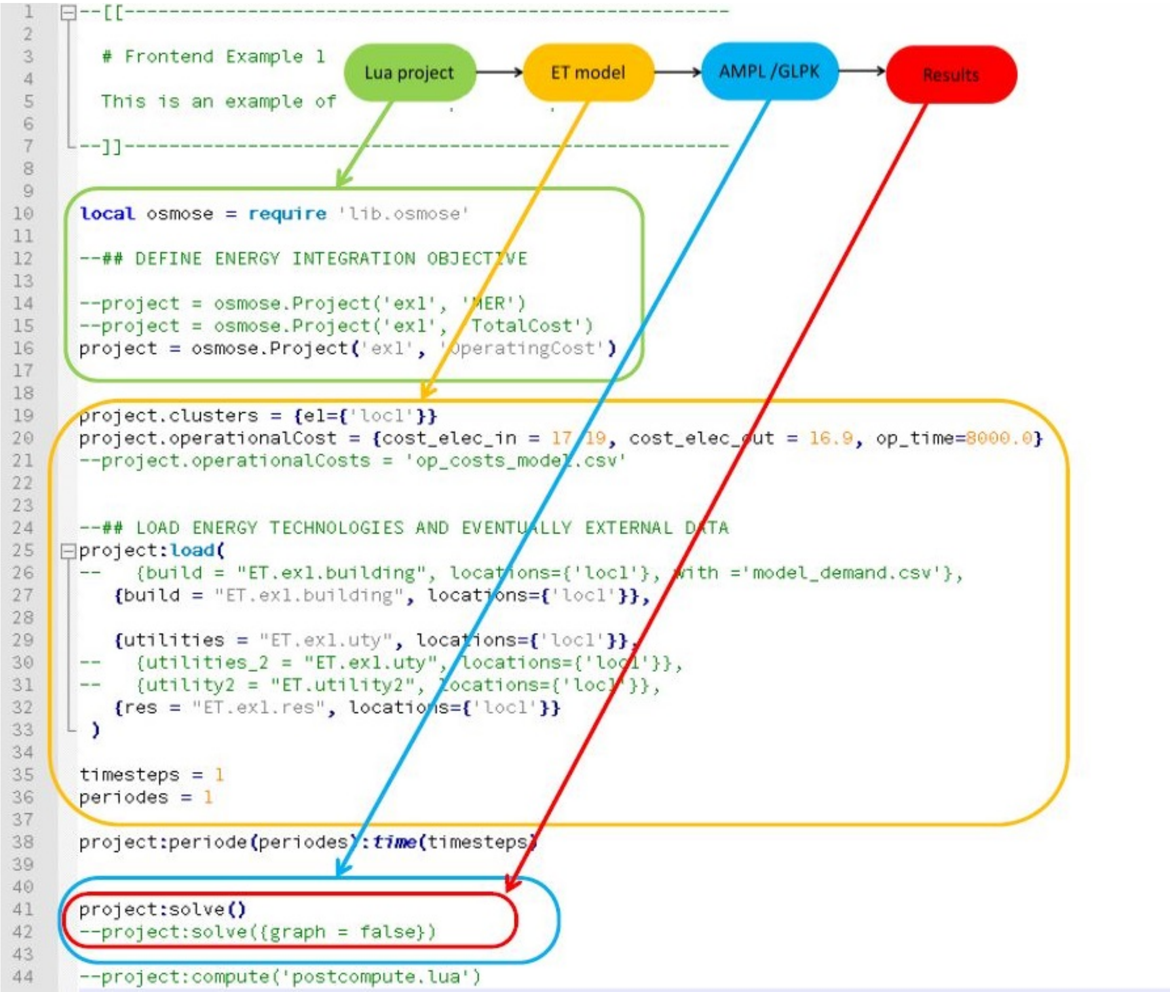


Figure 3.3: LuaOsmose frontend (adapted from [49])

In the first part of the frontend it is possible to define the objective function of our study, i.e. Total cost (costs optimisation), Impact (environmental optimisation), MER (maximum energy recovery), etc.. In the second part is possible to load our energy technologies, i.e. the technologies that we want to consider in our system. In the third part the model is solved and it can be post-computed with another .lua file.

The parameters used in the model are defined in the energy technologies that are implemented in a .lua files, in which it is necessary to declare different entries (Fig. 3.4) [49]:

- *Energy technology name*;
- *Input parameters*:
  The value of the parameters that are used in the model. They are treated as tags;
- *Output variables*:
  We could need to make some simple calculations to determine the value of the parameter that we need to use in the model. In this section is possible to make these calculations calling parameters from other energy technologies or connecting other software;

- *Layers*:
  The Layer is the environment in which the energy and mass balances are done. Each balance is made comparing the sum of inputs and outputs in terms of resources, mass or heat streams (see section 3.5.4). Therefore if we define the layer name as "electricity" we are saying that all streams in the E.T. model that belong to that layer are considered in the balance of electricity.

- *Additional equations and parameters*:
  In the definition of the energy technology is possible to add some equations and/or parameters that will be written in the input file read by AMPL;

- *Set of units*:
  Many units, such as technologies, services or resources can be defined in this part. An important distinction is made between processes, i.e units that have fixed size and utilities, i.e. units whose size and use has to be optimised;

- *Unit streams*:
  In this part the value of the parameters of the model are defined. All parameters are treated as streams and they are associated to a specified unit. Many kind of streams could be defined in this section, they can be of type mass, resource or heat and the first two have to be linked with a layer.

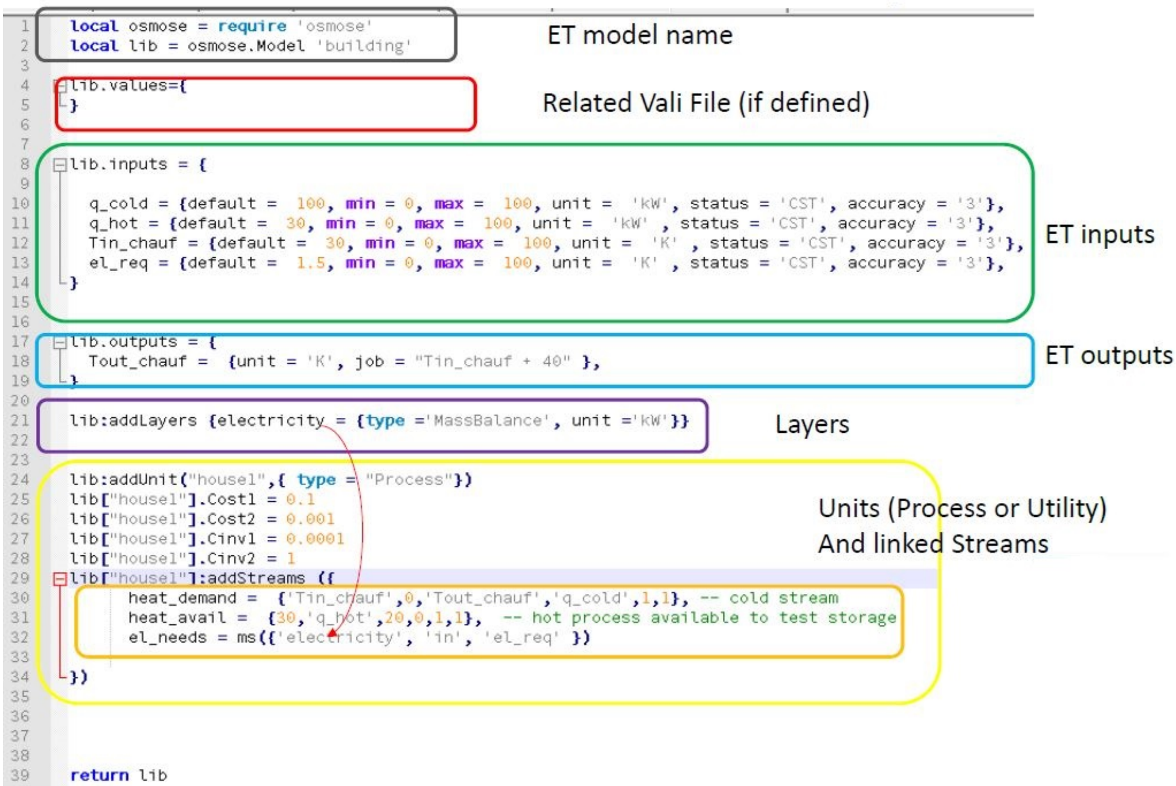


Figure 3.4: LuaOsmose Energy tecnology (adapted from [49])

This structure has been considered very suitable to develop the model. With LuaOSMOSE energy technologies the modelling of biomass and non-biomass technologies becomes simple and the definition of the MILP problem can take advantage of the default code. Then the model can be optimise directly by lunching ampl.exe and the results can be further elaborated in a post-computational section. In the future IPESE group can further develop this model. A more detailed modelling of energy technologies is possible by using flow-sheeting softwares like Belsim Vali or Aspen Plus and more time-steps can be considered.

3.2 Modelling framework

To implement a detailed model of the Swiss energy system would be for sure an appealing objective, but it will be too difficult to handle because of the huge amount of data that have to be collected. The model must be simple to require low computational time to be solved, but it must describe the system in a consistent way. Black-boxes models have been used to satisfy both requirements. Resources can supply energy in different forms, i.e. fossil fuels or biomass while energy technologies convert resources in more suitable forms of energy, i.e. fuels, electricity or heat to fulfil fixed energy demand with constant efficiency. In Fig. 3.5 the framework of the model is summarised.

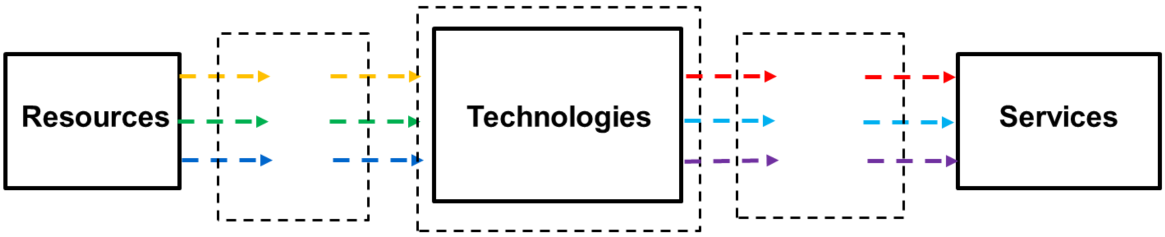


Figure 3.5: Modelling framework in OSMOSE

Arrows with different colours represent different forms of energy.

Resources, technologies and services are the *units* of this model. The services have a fixed profile during the year and technologies have to fulfil it. By fixing the amount of energy that is needed in different months is possible to determine the size of the technologies, their load per each month and the overall amount of resources that is needed. Then it is possible to determine these values according to the minimisation of one objective by optimising the system. According to OSMOSE definition (Sec. 3.1), energy technologies and resources are considered *utilities*, i.e. their size is undefined because it is an output of the optimisation, while demands are *processes*, so their profile over the year is fixed. Mass and energy balances are needed to describe the system and the technologies. With the constant map (Sec. 3.3.3) is possible to define the output of the technology as a percentage of the resource input:

$$E_{out,tech} = E_{in,tech} \cdot \eta_{in/out} \tag{3.1}$$

Where E_{out} can be different forms of energy output, i.e. heat, electricity and fuels, but in OSMOSE it is possible to define them also as other kind of outputs, such as transport service or mass streams. Different *layers* define different forms of energy.

The *layer balance* is used to equal the output of the resources with the input of the technologies and the output of the technologies with the input of the demands since there is not an energy conversion. The equivalent control volumes where these balances are made are highlighted with dashed lines:

$$\sum_{u \in Units} E_{in,units} = \sum_{u \in Units} E_{out,units} \quad \forall l \in Layers \tag{3.2}$$

In the following sections all the equations and variables that have been used to develop the model are further explained.

3.3 Assumptions

The model created by Stefano Moret [58] has been implemented and further developed to make it suitable for the aim of this study. This model can be considered as a MILP translation of the energyscope platform developed by Gironès et al. [30] where the key assumption is that the Swiss energy system is entirely rebuilt in the considered year. This assumption makes possible the comparison between the investment cost of 2011, that is considered as the reference year in Gironès et al. [30], with those for 2035 or 2050 without having to consider any installation or decommissioning pathway. Other assumptions are used to simply the implementation of the model and are discussed below.

3.3.1 Economic modelling

The objective of the economic modelling is to define the cost of different technologies in the most coherent way without making the model too difficult to solve. An accurate accurate economic modelling is difficult to develop. Many technologies exist only in a pilot scale and therefore reliable commercial and industrial data are difficult to find. Anyway in this study the methodology used to model costs of technologies is based on Turton et al. [64] and Ulrich and Vasudevan [65] and cost parameters are divided in two elements:

- CAPital EXpenditures (CAPEX), investment cost of the plant, it determines the financial cost;
- OPerational EXpenditures (OPEX): fixed and variable cost of operation, it determines the production cost

In the model they have been implemented as:

$$Cost_{tech} = Cost_{inv,an} + Cost_{maint} \tag{3.3}$$

The cost parameters used in this definition are the values of the investment (CAPEX) and maintenance costs per GW of one reference plant. $Cost_{inv,an}$ represents the annualised investment cost while $Cost_{maint}$ is the cost related to the maintenance. The costs of operation (OPEX) are usually divided in a fixed part associated to the maintenance and a variable part which is usually related mainly to the cost of the raw-materials. In this model the maintenance cost has been associated to the technology according to the size (Eq. (3.3)), while the cost of raw-materials, which is directly dependent to the production level, is associated to the use of the resources and it has been called operational cost ($Cost_{op}$):

$$Cost_{res} = Cost_{op} \tag{3.4}$$

In Eq. (3.3) the cost of the technology is given in $MCHF/GWy$. The annualised investment cost can be calculated by dividing $Cost_{inv}$ in MCHF by the capacity of the reference plant and by multiplying it by the annualisation factor (see Eq. (3.16) and Eq. (4.3)). $Cost_{maint}$ for each technology has been taken directly in $MCHF/GWy$ from different studies or calculated starting from the investment cost assuming that it is roughly 6% of $Cost_{inv}$ when not available.

Data about investment cost of energy technologies have been updated to the year 2015 by scaling them with Chemical plant cost indexes (CEPCI). They are dimensionless numbers employed to updating capital cost required to erect a chemical plant from a past date (B) to a later time (A), following changes in the value of money due to inflation and deflation [68].

$$Cost_{inv}\, at\, A = Cost_{inv}\, at\, B \cdot \frac{CEPCI\, at\, A}{CEPCI\, at\, B} \tag{3.5}$$

Data can be found in Tab. 3.1.

Year	***Annual Index***
	(CEPCI)
2006	499.6
2007	525.4
2008	575.4
2009	521.9
2010	550.8
2011	585.7
2012	584.6
2013	567.3
2014	576.1
2015 (Jan)	573.1

Table 3.1: CEPCI indexes [21]

For biomass technologies cost data have been taken from various studies and they have been updated to the year 2035 considering a cost reduction coefficient ($c_{reduction}$)for each one. Its value is 1 for commercial technologies, 0.95 for technologies under development and 0.9 for idea-stage technologies (Eq. (3.6)).

$$Cost_{tech}\, at\, 2035 = Cost_{tech}\, at\, 2015 \cdot c_{reduction} \tag{3.6}$$

When necessary the investment cost of the technologies has been scaled with the installed capacity to find the cost on the reference size. A coefficient of 0.6 has been used to scale the investment cost [64], [65]:

$$C_{inv}\, at\, size\, A = C_{inv}\, at\, size\, B \cdot (\frac{ref_{size,A}}{ref_{size,B}})^{0.6} \tag{3.7}$$

Another simplification is related to the model of mobility sector. Usually the biggest part of the costs associated to the mobility are the fuel costs. In this model the cost associated to the technologies (cars, busses or trains) is zero, therefore only the cost of the resource can affect the choice of the technologies that are used.

3.3.2 Impact modelling

The minimisation of the overall environmental impact in terms of green house gasses (GHG) emissions is considered as the second objective of this study. The methodology to assess the environmental impact is based on Life Cycle Assessment (LCA), an international standardised tool (ISO 14040 and ISO 14044) for the integrated environmental assessment of products (goods and services). Upstream and downstream consequences of decisions must be taken into account to evaluate the impact of a product's life cycle from cradle to grate. In Life Cycle Impact Assessment (LCIA) phase of LCA emissions and resource data are translated into indicators that reflect environment pressures. One of these indicators ($IPCC2013 - GWP100a$) has been used to assess the global warming potential (GWP). All environmental data ($Emiss$) have been taken from ecoinvent v 3.2 [13] and have been further elaborated to obtain data on the required reference unit, i.e. $ktons_{CO_2eq}/GWy$ for technologies and $ktons_{CO_2eq}/GWh$ for resources. These values can be defined per unit of input or per unit of output of each technology according to the definition of the size (see Sec. 3.5.1).

Like the economic model, to develop an accurate model is difficult because of the large amount of steps that have to be considered in the plants lifetime, i.e. installation, operation, decommissioning, etc. In general GHG emissions related to plants can be expressed as the sum of the impact related to construction, operation, decommissioning and to combustion of resources, if present. In this model the impact related to the operation of the technologies, i.e. the emissions which are released by the plant during its operation excluding combustion, has been neglected since it is usually very low compared to the other parts. Emissions are then related to both resources and technologies. Emissions related to the technologies are mostly related to the construction and are calculated with Eq. (3.8):

$$Emiss_{const} = \frac{Emiss_{construction} + Emiss_{decommissioning}}{ref_{size} \cdot lifetime} \tag{3.8}$$

$Emiss_{const}$ in $ktons_{CO_2eq}/GWy$ have been calculated from data of global worming potential (GWP) related to construction and the decommissioning of the reference plant in [13] and by using the lifetime considered in the model. When not available, data about impact of one energy technology have been taken from similar technologies or from [29] and [45]. For example data for Fisher-Tropsch have been taken from gasification with SNG production technologies. To calculate the overall environmental impact of the system the emissions related to the use of resources are considered. In this case the operational emissions, i.e. the emissions which are released by the resource during its use excluding combustion, can be the most important part of the overall impact, e.g. harvesting and transportation of wood. Therefore the overall emissions related to the resources are defined as the emissions related to the combustion ($Emiss_{comb}$) and to the operation ($Emiss_{op}$) of resources.

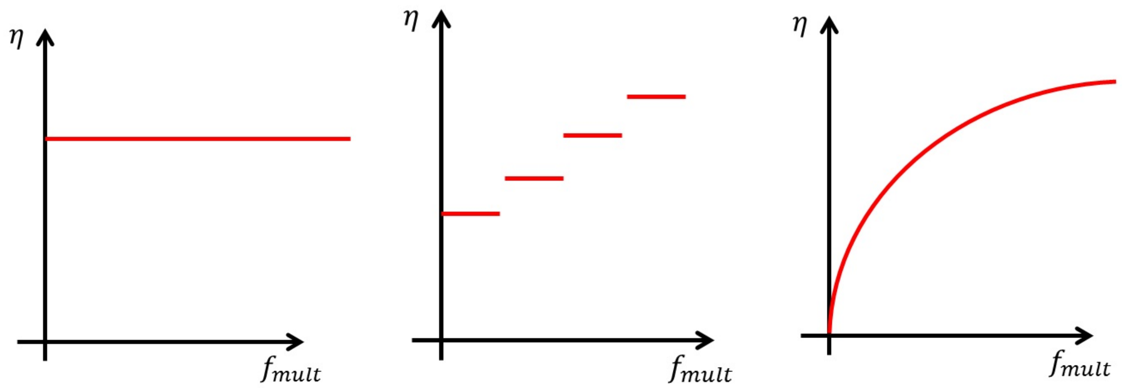
$$Emiss_{res} = Emiss_{op} + Emiss_{comb} \tag{3.9}$$

Emissions related to combustion can be calculated by separating all components of emissions of the technologies and keeping only the part related to combustion. Carbon capture and storage (CCS) technologies have less emissions related to combustion because they can capture CO_2. An efficiency of 95% has been used for CCS. Therefore in the model CCS technologies exploit an equivalent resource with emissions related to combustion which are only the 5% of the common fossil fuel.

The emissions related to the construction of transport technologies are considered zero because there is no way to control their value if the objective is the minimisation of the total cost of the system. By associating the emissions to the resources, the environmental impact related to the use of fuels in transport sector, which is usually the most important part, has been considered. Further explanation will be given in Section 3.5.3 .

3.3.3 Efficiency

The last important simplification is related to the efficiency of the technologies, which is considered constant. That means that the map of one technology does not vary with the load (f_{mult}). Sometimes this simplification can be used for chemical processes, but is a strong one if the range of variation is wide. However it is necessary for the implementation of the model to keep the problem easy and fast to solve. Different pathways to determine the efficiency are graphically summarised in Fig. 3.6.



(a) Constant map (b) Picewise map (c) Non-linear map

Figure 3.6: Different methods of describing efficiency map

A more correct approach could be the piecewise map approach. In this case it is possible to switch the value of the efficiency over different levels according to the load of the plant. This approach has the disadvantage to hugely increase the number of integer variables and to make the problem more complicated to solve. Furthermore this approach is difficult to implement in this model because the variable that represents the load of the technology (f_{mult}) does not describe the load of one plant, but the overall load of the plants of one kind of technology (see Section 3.5.1). Therefore it is possible to have different plants with full load and some plants with partial load. To deal with this, it is necessary to define as many technologies as the number of plants that can be available in Switzerland and this would increase hugely the number of variables. In this model we think to determine the exact number of plants that can supply the demand operating with full load in each time-step. In this way it is consistent to consider the efficiency as fixed.

3.4 Superstructure

Many possibilities are reasonable for the use of biomass. Woody biomass can be burned directly in boilers, or can be used as feedstock to produce biofuels such as biodiesel, ethanol or SNG in biorefineries. Wet biomass can be exploited in anaerobic digestion plants or to produce synthetic natural gas through catalytic hydrothermal gasification. These different pathways can be integrated in a superstructure, that can be optimised by writing a MILP problem. In Fig. 3.7 the superstructure of the model is represented with the following groups:

- *Services*:
  They represent the main services have to be supplied: heat, electricity and mobility. In this model a distinction has been made between two kind of mobilities: *Mobility freight*, i.e. the request of mobility for freight transport and *Mobility passenger*, i.e. the mobility demand associated to people. In addition the heat demand has been divided in two main parts: *Heat high temperature demand*, i.e. the request of process heating and *Space heating and hot water*, i.e. the heat request at low temperature;

- *Resources*:
  The resources are defined as: *Indigenous* which are available in the country and have limited availability and *Imported* which come from outside the country and can be limited or not. Algae are not considered in this framework, but they are used to produce biodiesel.

- *Technologies*:
  Conversion technologies are modelled as black-boxes which convert the resources into final energy services. In the Fig. 3.7 they are grouped in different sets, that gather the technologies that have the same output. Fuel generation technologies produce ethanol, biodiesel and SNG form biomass. They are considered fossil-fuel equivalents. Ethanol can substitute gasoline, biodiesel can substitute diesel and SNG can substitute natural gas (NG) without rising the GHG emissions.

The energy demand is not constant over time but it can vary highly over different months. In the model this variation has been considered by using data about monthly energy demand from [15] for the scenario "2035 Medium". In Energyscope calculator three possible scenarios of Swiss energy system are available for the year 2035. "2035 Low" with lower energy demand, "2035 High" with higher energy demand and "2035 Medium" with an intermediate value. These data are based on a report commissioned by Swiss government made by Prognos agency [55] which presents three energy scenarios for Switzerland: "BaU" (Business as usual), "PMF" (Political measures of the Federal Council) and "NEP" (New energy policies). These scenarios are possible evolutions of the Swiss energy sector from 2010 to 2050 and Gironès et al. [30] used them with macro-economic (population, economic growth) and behavioural parameters to determine the demand of their model.

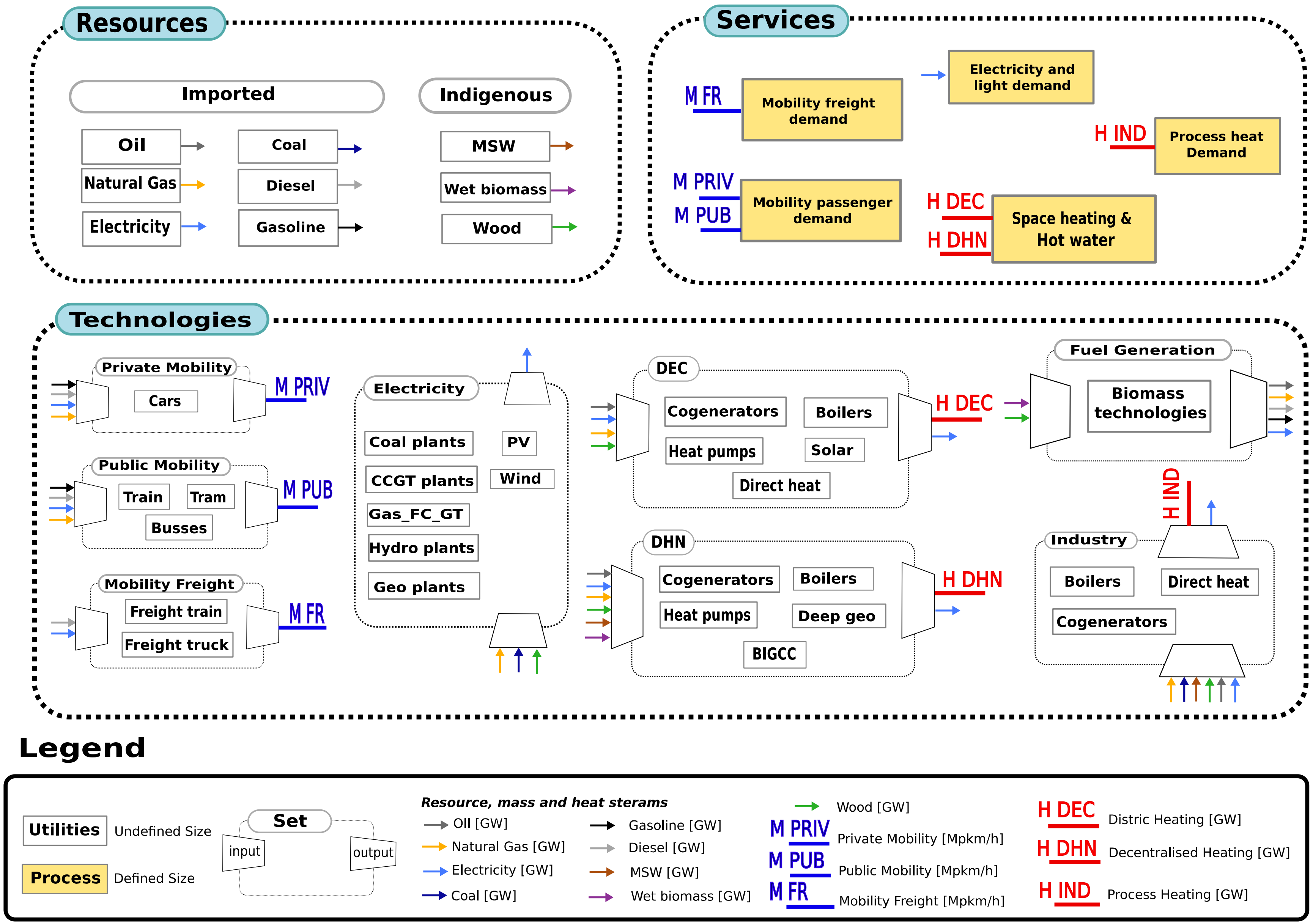


Figure 3.7: Swiss energy system model superstructure

3.4.1 Resources

Data about resources are shown in Tab. 3.2. Their meaning has been explained in Sec. 3.3. Imported resources are considered unlimited in this study while indigenous resources are considered limited. As reported in Ch. 2, data about biomass availability have been taken from Steubing et al. [59].

Resources	***Cost***	***LHV***	***GWP***		***Availability***
	c_{op}		em_{comb}	em_{op}	
	$MCHF/GWh$	MJ/kg	$ktons_{CO_2eq}/GWh$		GWh/y
Natural gas	0.058 [23]	47.76 [23]	0.20238	0.015499	unlimited
Gasoline	0.113 [15]	44.15	0.2647	0.06825	unlimited
Diesel	0.111 [15]	42.8	0.26567	0.03498	unlimited
Oil	0.086 [15]	42.74	0.26722	0.04442	unlimited
Coal	0.026 [15]	23.98 [13]	0.33595	0.08168	unlimited
MSW	0	12.35 [1]	0.15006		12809
Wet biomass	0	15 (db) [59]	0	0	9744
Wood	0.078 [15]	8.3 (wb) [18]	0.003667	0.008153	12279
Electricity	0.092 [15]	[-]	0.47294	0.105055	unlimited

Table 3.2: Data for resources

The amount of municipal solid waste (MSW) has been calculated using data from [14]. Here the future trend of MSW production in Switzerland is highlighted. 700 $kg/capta$ per year are considered as the future amount of MSW production with a 60% of it that can be recycled. In this model the number of people in Switzerland for the year 2035 has been taken from [15], "2035 Medium" scenario (8890000 people). All data about emissions have been taken from [13] and they have been further elaborated to determine the impact in terms of $ktons_{CO2eq}/GWh$. Equivalent resources (NG_ccs and Coal_ccs) with 5% of emissions related to combustion have been created to consider CCS technologies (see Sec. 3.3).

3.4.2 Conversion technologies

All data about conversion technologies are listed in appendix A. As this study wants to look at the future biomass energy pathways with an overall view, the energy technologies have been modelled in a simplified way. Units convert the main input (resource) in the main output (energy vector), such as electricity, heat or fuel (see Sec. 3.2). Efficiencies are key parameters for the definition of energy technologies.

3.4.3 Services

Services demand can be grouped in three main sectors: heat, electricity and transport. These are divided in several subsets that define the net demand for each month in each layer.

Demand	***Unit***	***Households***	***Services***	***Industry***	***Transportation***
Electricity	GWh/y	10848.11	15026.45	10443.52	
Lighting	GWh/y	425.14	3805.22	1263.78	
Heat high temperature	GWh/y			22609.93	
Heat for space heating	GWh/y	29489.24	17346.38	5819.94	
Heat for hot water	GWh/y	7537.81	3553.90	1471.49	
Mobility passenger	$Mpkm/y$				146049.29
Mobility freight	$Mpkm/y$				39966.67

Table 3.3: End uses demand

Since end uses demand for lighting and space heating is variable during the year, the coefficients li_{dem} and h_{dem} have been used to define the fraction between the demand per each month and the one in the overall year.

Month	li_{dem}	h_{dem}	t_{op}
	[-]	[-]	h
J	0.1035	0.1983	744
F	0.093	0.1654	672
M	0.0812	0.1421	744
A	0.0735	0.0319	720
M	0.0671	0	744
J	0.064	0	720
J	0.0671	0	744
A	0.0702	0	744
S	0.0782	0.0147	720
O	0.0899	0.0898	744
N	0.1046	0.1383	720
D	0.1077	0.2195	744

Table 3.4: Lighting and heating coefficients over different months [58]

The demand per each month is determined in GWh for energy or in $Mpkm$ for transport by using the following formulations. Each demand represents the amount that has to be supplied by the technologies per each layer and have been named $EndUses_{m,dem}$.

Electricity demand

$$El_{m,dem}(t) = \left(\frac{Tot_{el,dem}}{\sum_{t\in Time} t_{op}(t)} + \frac{Tot_{light,dem} \cdot li_{dem}(t)}{t_{op}(t)}\right) t_{op}(t), \quad \forall t \in Time \qquad (3.10)$$

This value represents the amount of electricity that has to be supplied by the system. In these formulations the variables $Tot_{el,dem}$ and $Tot_{light,dem}$ have been calculated as the sum of the energy demand per each sector with data from Tab. 3.3. t_{op} represents the operative time. In this model a "snapshot" future year is studied and 12 time-steps have been used, so t_{op} is the amount of hours per each month (Tab. 3.4). With this formulation is possible to define the equivalent value in GWh that represents the demand that has to be fulfilled by the energy technologies per each month.

Heat low temperature demand

The heat demand for space heating and for hot water has been grouped in one demand called *Heat low temperature demand* and calculated with a formula that is similar to $El_{m,dem}$:

$$Heat_{LOW,T,m,dem}(t) = (\frac{Tot_{HW,dem}}{\sum_{t \in Time} t_{op}(t)} + \frac{Tot_{SH,dem} \cdot h_{dem}(t)}{t_{op}(t)})t_{op}(t), \quad \forall t \in Time \quad (3.11)$$

This value is then divided into two components, $Heat_{DHN}$ and $Heat_{DEC}$. With this structure is possible to optimise the total amount of heat that is supplied by the district heating network (DHN) and by decentralised technologies (DEC), so their share among the overall heat low temperature is calculated by the solver. It is not possible to consider that all houses in Switzerland can be reached by the district heating. Nussbaumer and Thalmann [46] reported that only the 2% of the overall heat is supplied by DHN in Switzerland, but the statistics only cover large-scale plants. In Europe, particularly in northern countries, DHN is very important. It covers 10% of the total heat and 16% of the household annual heat demand and Nussbaumer and Thalmann [46] stated that it can provide economic advantages, flexibility and local environmental impact reduction. In the model it has been considered that only the 30% of $Heat_{LOW,T}$ can be supplied by DHN, but the minimum amount of DHN share is fixed at 10%.

In the model two different layers have been used to dived the heat that can be supplied by DHN and by decentralised heating. Two units have been created with a maximum demand that can be the 90% of $Heat_{LOW,T}$ for $Heat_{DEC}$ and 30% of $Heat_{LOW,T}$ for $Heat_{DHN}$ as written above. These units represent the energy demand for respectively decentralised and centralised technologies. Then both of them can supply the heat for $Heat_{LOW,T}$. In Fig. 3.8 this structure is summarised graphically.

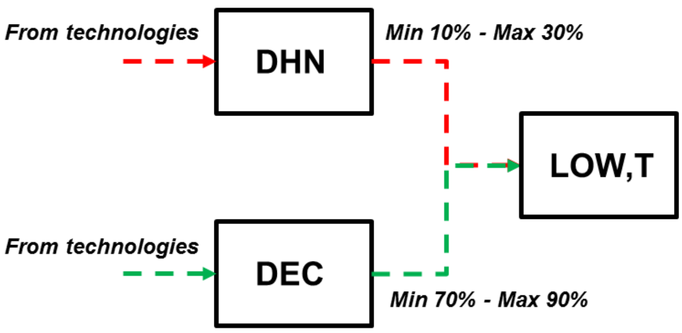


Figure 3.8: Decentralised heat and DHN heat units model

Others

For other demands a variation per each month is not considered, therefore a simple formulation is used to calculate the monthly demand:

$$Heat_{HIGH,T,m,dem}(t) = (\frac{Tot_{HHT,dem}}{\sum_{t \in Time} t_{op}(t)})t_{op}(t), \quad \forall t \in Time \quad (3.12)$$

$$Mob_{PASS,m,dem}(t) = (\frac{Tot_{MP,dem}}{\sum_{t \in Time} t_{op}(t)})t_{op}(t), \quad \forall t \in Time \tag{3.13}$$

$$Mob_{FREIGHT,m,dem}(t) = (\frac{Tot_{MF,dem}}{\sum_{t \in Time} t_{op}(t)})t_{op}(t), \quad \forall t \in Time \tag{3.14}$$

Only for transportation services a further division is made to account for the difference between private transport and public transport. Mobility passenger demand has been split into two parts, i.e. Mob_{public} and $Mob_{private}$ with a maximum share of 50% and a minimum of 30% for both. Like in Mob_{PASS}, a further division of $Mob_{FREIGHT}$ has been done done. Freight can be transported by trucks or by train with share going from 40% to 60%. The model implementation is similar to the one in Fig. 3.8.

3.5 Model Equations

In this section the equations used in the model are explained. A distinction between equations, mass balances and auxiliary equations has been made.

3.5.1 Variables

In Tab. 3.5 are declared the variables that are used in the model. They can have different indexes:

- *Units (u)*: They are the entities of the system. They can be energy technologies, resources, demands or storage technologies;
- *Layers (l)* : This definition is used in OSMOSE to define different forms of energy. Their meaning have been explained in Section 3.2. Each layer has a demand ($EndUses_{m,dem}$) that has to be fulfilled;
- *Time (t)*: It represents the operating time. In the model the time-step is one month.

Variables can be classified as independent and dependent variables. Dependent variables are linked to independent variables with equations. The optimiser has to define independent variables according to the minimisation of the objective function then dependent variables are calculated as a consequence. In this model the independent variables are $y_{use,t}$, f_{mult} and $Sto_{in/out}$. All other variables are linked directly or indirectly to them. However particular attention should be given to the variable f_{mult}, that represents the operational use of the technology per each month (period) and is linked directly with $y_{use,t}$ through Eq. (4.5). Even if they are linked, they are both independent variables, because, given the value of $y_{use,t}$, it is not possible to determine the value of f_{mult}, but only a range in which this can vary.

Variable	***Unit***	***Description***
$f_{size}(u)$	GW or $Mpkm/h$	Installed capacity of the unit
$f_{mult}(u,t)$	GW or $Mpkm/h$	Operation of the unit per each period
$y_{use}(u) \in \{0,1\}$	[-]	Investment decision for the unit
$y_{use,t}(u,t) \in \{0,1\}$	[-]	Use of the unit per each period
$C_{inv}(u)$	$MCHF$	Investment cost of the unit
$C_{maint}(u)$	$MCHF/y$	Maintenance cost of the unit
$C_{op}(u)$	$MCHF/y$	Operational cost of the unit
$Em_{const}(u)$	$ktons_{CO_2eq}/y$	Emissions related to construction
$Em_{res}(u)$	$ktons_{CO_2eq}/y$	Emissions related to resources
$f_{supp}(l,u,t)$	GW or $Mpkm/h$	Energy or service supplied by the unit
$f_{dem}(l,u,t)$	GW or $Mpkm/h$	Energy or service requested by the unit
$Sto_{level}(u,t)$	GWh	Level of the storage per each period
$Sto_{in}(l,u,t)$	GWh	Input of storage unit
$Sto_{out}(l,u,t)$	GWh	Output of storage unit
$\tau(u)$	[-]	Annualisation factor for investment cost

Table 3.5: List of variables

3.5.2 Parameters

All the parameters of the model are listed in Tab. 3.6.

Parameter	***Unit***	***Description***	***Value***
$EndUses_{m,dem}(l,t)$	GWh	Users demand per each layer	Tab. 3.3
$f_{min}(u)$	GW or $Mpkm/h$	Lower bound for unit size	Tab. A.1
$f_{max}(u)$	GW or $Mpkm/h$	Upper bound for unit size	Tab. A.1
$f_{max,perc}(u)$	$\%$	Maximum percentage of supply	Tab. A.1
$c_{inv}(u)$	$MCHF/GW$	Investment cost coefficient of the unit	Tab. A.1
$c_{O\&M}(u)$	$MCHF/GWy$	Maintenance cost coefficient of the unit	Tab. A.1
$c_{op}(u)$	$MCHF/GWh$	Operational cost coefficient of the unit	Tab. 3.2
$em_{const}(u)$	kt_{CO_2eq}/GWy	Emission coefficient of construction	Tab. A.1
$em_{comb}(u)$	$kt_{CO_2eq}/GWhy$	Emission coefficient of combustion	Tab. 3.2
$em_{op}(u)$	$kt_{CO_2eq}/GWhy$	Emission coefficient of operation	Tab. 3.2
$\eta(l,u)$	[-]	Input from or output to layers	Tab. A.2 - A.11
$c_p(u)$	[-]	Yearly capacity factor	Tab. A.1
$c_{p,t}(u,t)$	[-]	Monthly capacity factor	Tab. A.12
$\epsilon_{Sto}(l,u)$	[-]	Storage efficiency per different layers	Tab. A.13
Em_{max}	kt_{CO_2eq}/y	Limit of GHG emissions	
$t_{op}(t)$	h	Operational time	Tab. 3.4
i	[-]	Interest rate	0.03215
lt(u)	y	Life time of the unit	Tab. A.1
$c_{grid\&eff}$	MCHF/ y	Grid and efficiency cost	App. A

Table 3.6: List of parameters

3.5.3 Main equations

In this section are listed all equations that are considered fundamental for the model but are not energy or mass balances. These equations are mostly defined in the default OSMOSE code.

Technology size

In the model the variable f_{mult} defines how much a technology is used per each month as a fraction of the size. It could be considered as a capacity factor that describes the load of the technology during the reference year. Then the size of the technology is defined as the maximum level that f_{mult} reaches to supply the energy demand:

$$f_{mult}(u,t) \leq f_{size}(u), \quad \forall u \in Units, \forall t \in Time \tag{3.15}$$

Therefore the installed capacity (f_{size}) can be based on the input or on the output of technologies. This can change per each technology and it depends on the layer on which f_{mult} is defined (see appendix A).

In Eq. (3.15) the variable f_{size} is defined as a variable that is bigger than f_{mult}. This seams to give to f_{size} only a lower bound, but then the optimiser tends to give it a value that is as low as possible when the system is optimised in terms of cost, so f_{size} is usually the maximum value of f_{mult}.

Costs

As reported in Sec. 3.3 costs are divided in three main parts: investment, maintenance and operational costs. Investment and maintenance costs are linked to energy technologies and operational costs are linked to resources. Here all costs are declared.

- Investment cost:

$$C_{inv}(u) = c_{inv}(u) \cdot f_{size}(u), \quad \forall u \in Units \tag{3.16}$$

- Maintenance cost:

$$C_{maint}(u) = c_{O\&M}(u) \cdot f_{size}(u), \quad \forall u \in Units \tag{3.17}$$

- Operational cost:

$$C_{op}(u) = \sum_{t \in Time} c_{op}(u) \cdot f_{mult}(u,t) \cdot t_{op}(t), \quad \forall u \in Units \tag{3.18}$$

To determine the investment cost in the reference year an annualisation factor is used:

$$\tau(u) = \frac{i(i+1)^{lt(u)}}{(i+1)^{lt(u)} - 1}, \quad \forall u \in Units \tag{3.19}$$

In the model the cost associated to the construction of the electric grid and to improve the energy efficiency in buildings is considered too. This cost is fixed and it leads to a new component of the total cost:

$$C_{fix} = c_{grid\&eff} \tag{3.20}$$

The total cost of the system is calculated as a sum within all units considering the cost of resources and technologies:

$$C_{TOT} = C_{fix} + \sum_{u \in Tech} (\tau(u) C_{inv}(u) + C_{maint}(u)) + \sum_{u \in Res} C_{op}(u) \tag{3.21}$$

Impact

In this study we want to determine the best configuration of the system by optimising the model in terms of cost, but we want to take into account the impact that is related to that choice. In Gironès et al. [30] impact is related to the amount of waste that is produced by the system and to the GHG emissions. Here we considered only data about GHG emissions dividing them into two components as written in Section 3.3:

- Emissions related to construction:

$$Em_{const}(u) = em_{const}(u) \cdot f_{size}(u), \quad \forall u \in Units \tag{3.22}$$

- Emissions related to resources:

$$Em_{res}(u) = \sum_{t \in Time} (em_{comb}(u) + em_{op}(u)) \cdot f_{mult}(u,t) \cdot t_{op}(t), \quad \forall u \in Units \tag{3.23}$$

The overall environmental impact is calculated as the sum of these variables:

$$Em_{TOT} = \sum_{u \in Tech} Em_{const}(u) + \sum_{u \in Res} Em_{res}(u) \tag{3.24}$$

Since the cost of technologies is linked to f_{size} (see Eq. (3.16) and Eq. (3.17)), if the cost of the technology is zero, there is no way to control the value of f_{size}. Therefore for "mobility technologies" it is not useful to define the emissions related to construction, because f_{size} would be defined arbitrary by the optimiser without any relations with the real value of f_{mult} (see Sec. 3.3).

Units input and output

As said in Sec. 3.2 technologies have been modelled as black boxes and the efficiency is the key parameter. The main input (resource) can be converted in several forms of energy depending on the efficiency (see Eq. 3.1). Each output is then linked to a layer where the balances of the system are made. The energy supply and the energy demand per each unit are calculated as follows :

$$f_{supp}(l,u,t) = \eta_{out}(l,u) \cdot f_{mult}(u,t), \quad \forall u \in Units, \forall t \in Time, \forall l \in Layers \tag{3.25}$$

$$f_{dem}(l,u,t) = \eta_{in}(l,u) \cdot f_{mult}(u,t), \quad \forall u \in Units, \forall t \in Time, \forall l \in Layers \tag{3.26}$$

Their unit is GW, so Eq. 3.26 and Eq. 3.25 define the input and output power per each technology per each time. This output is considered fixed in the time-step (one month), so it is possible to calculate the total energy that one technology supplies in one month by multiplying f_{supp} with the operative time (t_{op}). A distinction between different layer is now important because each technology can produce different kind of output, e.g. electricity or heat, so it is necessary to distinguish between them and make sure that they are not processed in the same layer. The calculation of the size can be done on different kind of output, i.e. electric power for power plants or heat power for boiler. f_{mult} defines the output on the layer on which we want to fix the size, then efficiencies have to be stated according to this definition.

A further distinction has to be made for those technologies that have a defined profile of output during the year. $c_{p,t}$ represents the fraction of energy over the total year that can be released by the technology in one period. This is valid only for units such as solar systems, hydro plants, and wind turbines, that do not produce the same amount of energy over different months. In this case the output has been implemented as follows:

$$f_{supp}(l,u,t) = \eta_{out}(l,u) \cdot c_{p,t}(u,t) \cdot f_{mult}(u,t), \quad \forall u \in Units, \forall t \in Time, \forall l \in Layers \tag{3.27}$$

Storage

In this study we want to consider the possibility to use storage for biomass and other resources. The equation used to determine the level of the storage is given below:

$$Sto_{level}(u,t) = Sto_{level}(u,t-1) + \sum_{l|\epsilon_{sto}\neq 0} \left(Sto_{in}(l,u,t) \cdot \epsilon_{sto,in}(l,u) - Sto_{out}(l,u,t)/\epsilon_{sto,out}(l,u)\right) \quad \forall u \in Sto_{units}, \forall t \in Time \tag{3.28}$$

When ϵ_{sto} is equal to zero it is considered that there is not the possibility to store the resource.

3.5.4 Mass balance

Here is reported the equation used for the mass balance per each layer (see Eq. 3.2). As written in Sec. 3.4 heat demand has been divided only in low and high temperature. No heat cascade is used to make possible to use the waste heat from different technologies. In fact, considering such a big system, it is difficult to define the temperature of each stream supplied by technologies and it is even more difficult to account for the heat losses because data about distance between heat demand and supply are not considered.

$$\sum_{u\in Units} f_{supp}(l,u,t) \cdot t_{op}(t) + Sto_{out}(l,u,t) = \sum_{u\in Units} f_{dem}(l,u,t) \cdot t_{op}(t) + Sto_{in}(l,u,t) + EndUses_{m,dem}(l,t), \quad \forall l \in Layers, \forall t \in Time \tag{3.29}$$

3.5.5 Auxiliary equations

Here all equations that have a marginal importance compared to the previous ones are stated. Mainly these are the equations that have been added to the default OSMOSE code.

Capacity factor

The first equation is related to the definition of the yearly capacity factor. This parameter defines the fraction of operating hours in the overall year. Only in few cases it is equal to one, because usually a certain amount of time is necessary to provide the maintenance of plants during the year.

$$\sum_{t \in Time} (f_{mult}(u,t) \cdot t_{op}(t)) \leq f_{size}(u) \cdot c_p(u) \cdot \sum_{t \in Time} t_{op}(t), \quad \forall u \in Units \tag{3.30}$$

Electric losses

In the model the electric losses in the grid have been considered. The model is based on the assumption made by Gironès et al. [30] that the losses coefficient for grid transmission is 7%.

$$f_{mult}(el_{loss},t) = el_{loss} \cdot (\sum_{u \in Tech} f_{dem}(el,u,t) + \frac{EndUses_{m,dem}(el,t)}{t_{op}}) \qquad \forall u | \ \eta_{in}(el,u,t) \neq 0, \forall t \in Time \tag{3.31}$$

This equation is indexed with $\forall u | \eta_{in}(el,u,t) \neq 0$ because we want to consider in the sum only the units that request electricity as input. Therefore electric losses represent an additional demand due to electricity transmission through the national grid.

The electric loss coefficient is calculated as follows:

$$el_{loss} = \frac{7\%}{(1-7\%)} \tag{3.32}$$

Hydro dam equations

The level of the pumped hydro storage has been linked to the f_{mult} of new hydro dams that can be built.

$$Sto_{level}(sto_{pumphy},t) \leq c_{sto,pumphy} \cdot f_{mult}(Hydrodam_{new},t), \quad \forall t \in Time \tag{3.33}$$

The coefficient is defined as follows:

$$c_{sto,pumphy} = \frac{f_{max}(sto_{pumphy})}{f_{max}(Tot_{hydrodam}) - f_{min}(Tot_{hydrodam})} \tag{3.34}$$

A priority of use is given to the hydro dam too. Since in Switzerland many sites are available to exploit energy from dams and rivers, their usage is considered a wise choice. In the model the size of hydro dams is fixed to 8.1 GW, and a possibility to increase this capacity with 1 GW more is considered with new hydro dams as in [30].

Operation strategy

The operational strategy is implemented for the technologies that can supply decentralised heating. This is used to fix the ratio between the monthly output and the installed capacity per each technology and to ensure that a technology is not used as a base-load technology. Eq. (3.35) is indexed per all technologies except the decentralised solar, that can not be used in the same way.

$$(f_{mult}(u,t) + f_{mult}(solar_{dec},t)) \cdot t_{op}(t) \geq \frac{Heat_{LOW,T,m,dem}}{Tot_{LOW,T,dem}} \cdot \sum_{t \in Time} (f_{mult}(u,t) \cdot t_{op}(t)) \quad \forall u | l = Heat_{dec} \neq Dec_{solar}, \forall t \in Time \tag{3.35}$$

This equation forces the energy output of each technology to follow the the distribution of the energy demand of low temperature heat over the year. In this way we force the output of one technology during winter to be higher then the one during summer. Decentralised solar has an energy output that is completely different. It is higher during summer and it follows the solar irradiation distribution taken into account with the $c_{p,t}$.

Percentage of energy supply

Another equation has been implemented to fix the maximum amount of energy supply per each technology within a layer:

$$f_{mult}(u,t) \leq f_{max,perc}(u) \cdot \sum_{u \in Layer(l)} f_{mult}(u,t), \quad \forall u \in Units, \forall t \in Time \tag{3.36}$$

$f_{max,perc}$ makes a similar function of f_{max}, but it is more useful for layers that have a variable demand. DHN heating can go from 10% to 30% of the $Heat_{LOW,T,dem}$ while private mobility can have a share from 50% to 80% of the overall mobility passenger demand. If we use only f_{max} we can not vary the maximum amount with the share, therefore we can obtain some very improbable solutions, such as the electric cars as the only technology that can supply the private mobility demand or heat pumps for decentralised heating. A possible solution can be to fix the f_{max} in order to avoid these solutions, but Eq. 3.36 has been considered a simpler solution.

CCS technologies

Since the amount of technologies equipped with carbon capture and storage (CCS) that will be installed it is said to be very low for the year 2035 [22], an overall amount of 0.5 GW (one plant) has been consider possible for the system:

$$\sum_{u \in CCS\,tech} f_{size}(u) \leq 0.5 \tag{3.37}$$

Link between two technologies

Some additional equations have been used to follow the assumptions used by Gironès et al. [30] in their model. They are used to link f_{mult} of hybrid vehicles (CAR_HEV) with plug-in vehicles (CAR_PHEV) and diesel cars with gasoline cars:

$$f_{mult}(CAR\_HEV, t) = 0.429 \cdot f_{mult}(CAR\_PHEV, t), \quad \forall t \in Time \tag{3.38}$$

$$f_{mult}(CAR\_DIESEL, t) = 0.667 \cdot f_{mult}(CAR\_GASOLINE, t), \quad \forall t \in Time \tag{3.39}$$

Chapter 4

Optimisation

In this chapter the optimisation problem and the methodology to assess different biomass energy pathways are defined. Some additional equations and the objective function have been added to the model reported in Ch. 3 to optimise the system.

In general an optimisation problem can be stated as follows:

$$\begin{aligned} minimise \quad & f(x) \\ subject\,to: \quad & \\ & g_i(x) \leq 0, \; i = 1, ..., m \\ & h_i(x) = 0, \; i = 1, ..., p \end{aligned} \tag{4.1}$$

Where:
$g_i(x) \leq 0$ represents all inequality constraints,
$h_i(x) = 0$ represents all equality constraints.

In this model we are considering the possibility to store biomass and we are using binary variables to determine which is the best technology to exploit it. Using the storage the optimisation problem becomes a dynamic problem, i.e. the time-cycle is taken into account. The output variables that have been calculated in the first time step are used to calculate the value of the storage level in the second time step and so on. One year is the overall time of the simulation and at the end the value of the storage level must be the same of the beginning (see Sec. 3.5).

4.1 MILP definition

Our optimisation problem is a MILP problem. The problem is linear because all equations are linear and it is integer because integer (binary) variables are used to determine which technologies are chosen. In this case the optimisation problem can be written as [24]:

$$\begin{aligned} minimise \quad & f(x, y) = c^T x + d^T y \\ subject\,to: \quad & \\ & Ax + By \leq b \\ & x \geq 0, \; x \in X \subseteq \mathbb{R}^n \\ & y \in \{0, 1\}^q \end{aligned} \tag{4.2}$$

Where:
x is a vector of n continuous variables ,
y is a vector of q 0 - 1 variables ,
c, d are (n x 1) and (q x 1) vectors of parameters ,
A, B are matrices of appropriate dimension,
b is a vector of p inequalities.

4.1.1 Objective function

In this study a minimisation of the total cost of the system in $MCHF/y$ is considered as the objective:

$$\begin{aligned} minimise \quad f(x) = C_{TOT} = \\ C_{fix} + \sum_{u \in Tech} (\tau(u) C_{inv}(u) + C_{maint}(u)) + \sum_{u \in Res} C_{op}(u) \end{aligned} \quad (4.3)$$

4.1.2 Additional constraints

Other equations are used in addition to the ones in the model to achieve the optimisation of the system.

Impact limit

The total impact in terms of GHG emissions in the system has been limited to see the trade off between costs and emissions:

$$Em_{TOT} = \sum_{u \in Tech} Em_{const}(u) + \sum_{u \in Res} Em_{res}(u) \leq Em_{max} \quad (4.4)$$

By varying the parameter Em_{max} it is possible to to determine different configurations of the system that minimise the cost remaining under different maximum values of environmental emissions in $ktons_{CO_2eq}/y$. This leads to the possibility to develop a constrained optimisation and to assess the trade-off between costs and environmental impact (see. Sec. 4.3).

Multiplication factor

$$f_{min}(u) \cdot y_{use,t}(u,t) \leq f_{mult}(u,t) \leq f_{max}(u) \cdot y_{use,t}(u,t), \quad \forall u \in Units, \forall t \in Time \quad (4.5)$$

This equation links two independent variables: $y_{use,t}$ and f_{mult}. Even though the variable f_{mult} is linked with $y_{use,t}$ it is considered an independent variable because it is not possible to define directly its value from Eq. (4.5). This equation is useful only to bring to zero the value of f_{mult} if $y_{use,t}$ is equal to zero and to define a boundary if $y_{use,t}$ is equal to one. Per each unit the optimiser have to choose the value of $y_{use,t}$ and f_{mult} which minimise the total cost of the system remaining under a certain value of impact.

Units Use

Another variable is introduced to define clearly if the unit (technology or resource) is used or not:

$$y_{use,t}(u,t) \leq y_{use}(u), \quad \forall u \in Units, \forall t \in Time \tag{4.6}$$

While $y_{use,t}$ represents the use per each period y_{use} defines the use during the year. If all values of $y_{use,t}$ over time are zero y_{use} can be zero too.

4.2 Optimisation algorithm

The optimisation problem has been written with OSMOSE (see Sec. 3.1.2), a software that can connect different tools. In this study it has been used with AMPL to write the optimisation problem that is solved successively by IBM ILOG CPLEX Optimisation Studio, usually referred simply as CPLEX. This solver uses *branch and bound* associated to *simplex method* to solve MILP problems.

Simplex method is usually used to find the optimal solution of multivariables problems. The idea is that a system of liner inequalities defines a plytope (Fig. 4.1) as a feasible region. The simplex method is an algorithm with which we examine corner points starting from a vertex and moving along the edges of the polytope until we reach the best solution [69].

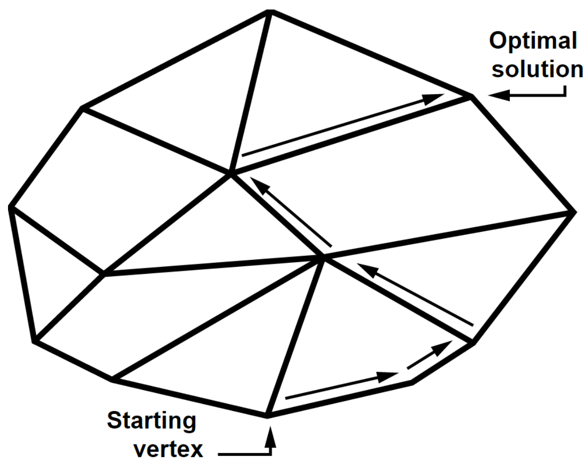


Figure 4.1: Polytope representation (adapted from [69])

To handle the equations of the LP problem the coefficients are expressed in a tabular form called *simplex tableau*:

$$\begin{bmatrix} 1 & -c^T & 0 \\ 0 & A & b \end{bmatrix}$$

Vectors and matrices are defined according to the MILP definition in Sec. 4.1. When the tableau is completed the algorithm starts to calculate the solutions over different vertex of the polytope to find the best solution. Further information can be found in [25].

In simplex algorithm integer variables are not taken into account. To deal with integer variables *branch and bound* algorithm is used. Here basically the problem is divided in many sub-problems (branches) where the integer variable y_i has the value zero in the first and one in the second sub-problem. Each time a *relaxed* problem is solved generating a tree of solutions that can be seen in Fig. 4.2 (further information in [25]).

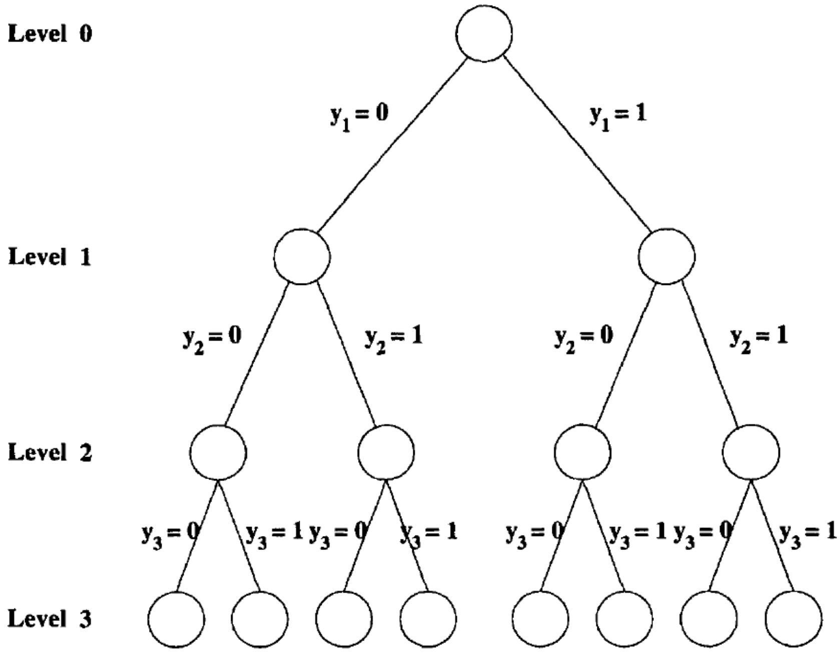


Figure 4.2: Binary tree representation (adapted from [24])

4.3 Methodology

Given the optimisation problem defined in Sec. 4.1 and the model defined in Ch. 3 it is necessary to define a strategy to assess alternative pathways. In this study a scenario analysis has been developed. The methodology has been summarised graphically in Fig. 4.3.

The MILP problem is optimised in terms of cost and the trade-off between economic and environmental aspects has been assessed by varying the value of Em_{max} in Eq. (4.4). The maximum amount of GHG emissions is varied in the range $50000 - 11000\, ktons_{CO2eq}/y$ and one series of configurations is obtained per each scenario. By plotting C_{TOT} and Em_{TOT} of each configuration we obtain a curve, which expresses the trade-off between cost and environmental impact. This methodology is called *constrained optimisation* and permits to find the best configurations of the system considering two objectives without requiring as much time as a multi-objective optimisation. Furthermore with constrained optimisation it is possible to determine the value of the lowest impact that is achievable by the system as the value where the MILP problem becomes infeasible.

In a multi-objective optimisation high computational time is required to run the algorithm to find the best solutions according to both objectives. A constrained optimisation is more like a parametric analysis. Here only one constraint, i.e. the maximum

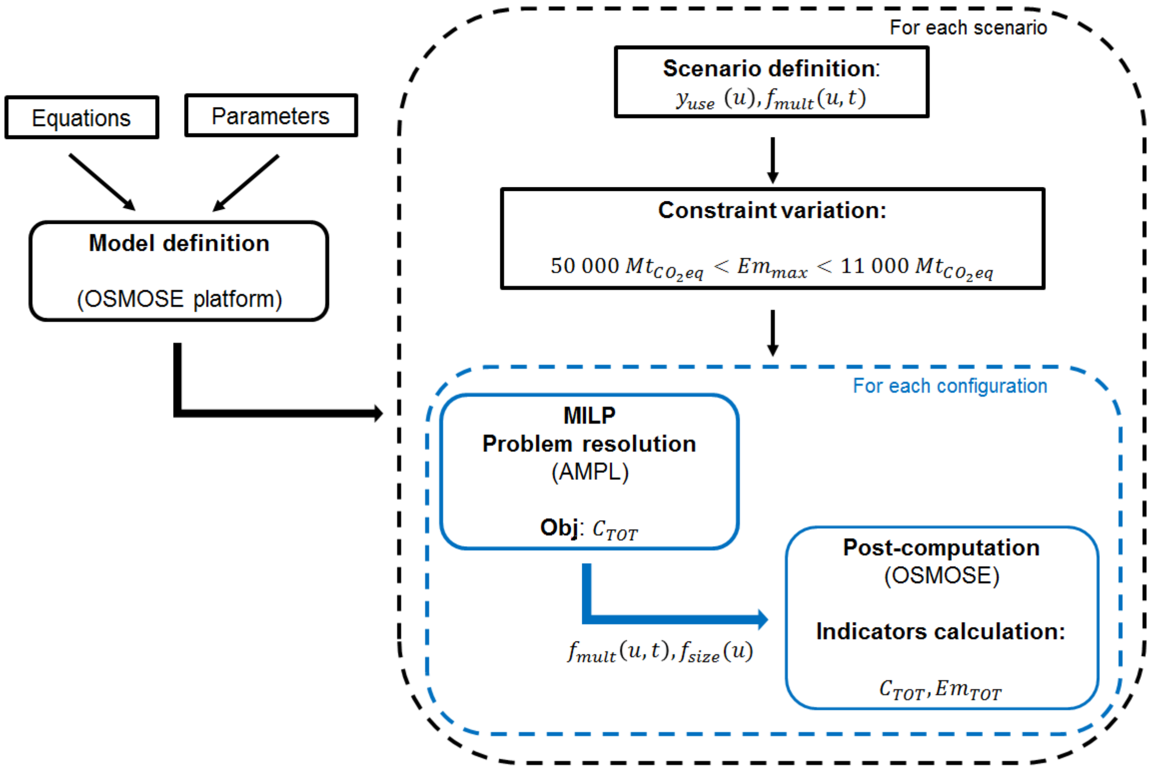


Figure 4.3: Methodology framework

value of GHG emissions, is modified to see the trade-off between two objectives. The decision maker can choose the best configuration according to his requirements.

To assess which are the most promising biomass conversion technologies and therefore to rank the possible pathways for biomass utilisation, two kinds of scenarios has been defined: *single technology scenarios* and *reference scenarios*. In *single technology scenarios* the biomass feedstock is forced to be used by only one technology and only one kind of biomass feedstock is available, i.e. woody biomass, wet biomass or algae. Each of these scenarios is called like the name of the technology which exploits the biomass feedstock. These scenarios have been compared with some *reference scenarios* where one biomass feedstock is forced to be used, but the optimiser is allowed to choose which are the best technologies to exploit it.

To compare the results of these different pathways, where only one technology is available, and make the ranking, the total cost in reference scenarios has been used to calculate the percentage of cost increase of different *single-technology scenarios*. The best pathways are the ones with the lowest cost increase percentage. This makes possible to compare the biomass technologies that exploit the same feedstock on the same basis and to find out which are the most promising ones.

This formulation has been used to calculate the percentage of cost increase:

$$\Delta C\% = \frac{C_{TOT\, single\, tech\, scenario} - C_{TOT\, ref\, scenario}}{C_{TOT\, ref\, scenario}} \cdot 100 \tag{4.7}$$

These calculations are made per each value of Em_{max} determining a vector of cost increase percentage per each scenario. The dimension of the vector is equal to the number of Em_{max} that has been fixed to find the different configurations. An example of the calculation is reported in Tab. 4.1. Data are taken from real results, i.e. scenarios WOOD_100% and GAS_FC_GT (see Ch. 5). Where results are not available that means that the limit is not achievable by the system.

Em_{max}	$C_{TOT_{sing\,tech,scen}}$	$C_{TOT_{ref,scen}}$	$\Delta C\%$
$ktons_{CO_2eq}/y$	$MCHF/y$	$MCHF/y$	%
50000	17868	16646	7.3
45000	17868	16646	7.3
40000	17868	16682	7.1
35000	17907	16751	6.9
32000	17941	16829	6.6
30000	17983	16895	6.4
28000	18113	16955	6.8
26000	18282	17027	7.4
24000	18463	17197	7.4
22000	18646	17416	7.1
20000	18993	17727	7.1
18000	19763	18441	7.2
16000	21749	19927	9.1
15000	23963	21082	13.7
14000	[-]	23429	[-]
13000	[-]	[-]	[-]
12000	[-]	[-]	[-]
11000	[-]	[-]	[-]

Table 4.1: Example of $\Delta C\%$ calculation

To find the best mix of biomass feedstocks and technologies to include in the Swiss energy system in the absence of nuclear power plant production, another scenario, called *free scenario*, has been assessed. In this scenario all possible biomass feedstocks are available and the optimiser can choose the best configuration according to the constraints. Here the *constrained optimisation* is used to determine the total cost and the total environmental impact of the system. The trend of the solutions permits to find the best trade-off between the two objectives and to determine the best configuration of the system in terms of size and load of technologies to exploit biomass and other resources in the absence of nuclear power plants.

Chapter 5

Scenarios

As written in the introduction there are many possibilities to use biomass technologies. Lignocellulosic biomass can be pretreated with torrefaction, pyrolysis or pelleting and transformed into a higher volumetric and energy density material with improved transport and storage properties. Wet biomass, such as sewage sludge and manure, can be directly converted into biogas through digestion. The conversion into heat, electricity and fuels can also occur at a later time and in a different location from the harvesting.

In this model a scenario analysis has been developed to assess different biomass energy pathways. In this chapter the scenarios have been defined and classified as *reference scenarios* or *single technology scenarios*. The results of different scenarios are presented giving the values of costs, environmental impacts and sizes of the chosen technologies.

5.1 Scenarios definition

Different scenarios have been defined with a function in OSMOSE, which permits to add these equations to the model:

$$y_{use}(u) = 0; \tag{5.1}$$

$$y_{use}(u) = 1; \tag{5.2}$$

$$f_{mult}(biomass_{feedstock}, t) = biomass_{potential} \, , \forall t \in Time \tag{5.3}$$

With Eq. (5.1) the use of the unit is avoided, while, when Eq. (5.2) is added, the unit can be used by the system. By disabling and enabling the use of some technologies that can exploit biomass it is possible to control the use of biomass in the system, while with Eq. (5.3) the use of all biomass that is available is forced in each period. In each scenario storage technologies are activated.

5.2 Reference scenarios

Three *reference scenarios* (WOOD_100%, WETBIOM_100% and ALGAE_100%) are used to compare the results of *single-technology scenarios* (see Sec. 4.3).

The curves that represent the reference scenarios of this study are shown in Fig. 5.1:

- NO_BIOM:
  Biomass feedstock is not used.
- WOOD_100%:
  Only woody biomass feedstock can be used in the system, no wet biomass or algae.
- WETBIOM_100%:
  Only wet biomass feedstock is available in the system.
- ALGAE_100%:
  Micro-algae are the available biomass feedstock.

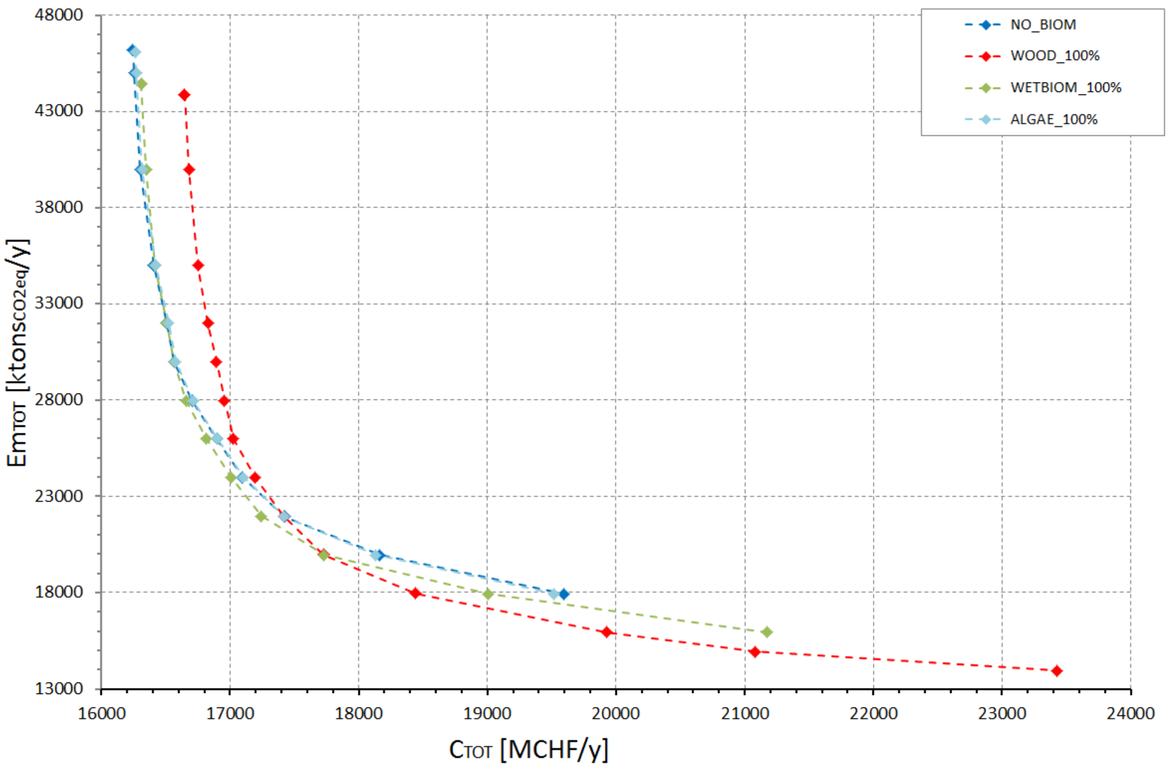


Figure 5.1: Reference scenarios

5.2.1 No biomass scenario

This scenario permits to understand the effect on the system if the decision makers do not consider the use of biomass technologies as a wise option, so it is used as a reference for other scenarios. Here the following equations have been added to avoid the use of biomass resources and technologies:

$$y_{use}(u) = 0\,, \forall u \in Biomass\,technologies\,and\,resources, \qquad (5.4)$$

By optimising the system with the highest value of GHG emission limit it is possible to reach the best condition in terms of cost, but also the worst in terms of emissions. The lowest value of achievable impact in NO_BIOM scenario is equal to the one in ALGAE_100% scenario but the cost is higher.

Now it is useful to understand which are the energy technologies chosen by the optimiser over different values of GHG emission limit when the biomass is not used (NO_BIOM). Other scenarios will have roughly the same behaviour, i.e. the same technologies chosen, when decreasing the GHG limit, but they can reach lower values of impact or cheaper conditions of cost because biomass is exploited.

	Conf. n.1	*Conf. n.2*	*Conf. n.3*	*Conf. n.4*
Em_{max} $[ktons_{CO_2eq}/y]$	***50000***	***30000***	***24000***	***18000***
Decentralised gas boiler	9.16	9.16	1.38	0.46
Thermal heat pump	6.11	6.11	5.07	3.13
Centralised gas boiler	1.07	0.75	1.39	0.80
Deep geothermal plant	0.08	0.08	0.29	1.04
Centralised heat pump	0.55	0.71	2.04	3.25
hydro dam plants	8.16	8.15	8.20	8.20
hydro river plants	3.80	3.80	3.80	4.50
Waste boiler for industry	1.33	1.33	1.33	1.33
Wind turbines		4.50	4.50	4.50
Coal plants	3.02			
Coal boiler for industry	1.54	0.72		
Coal plants with CCS		0.50	0.50	
Centralised gas cogenerator		0.16	0.59	
Gas cogenerator for industry			1.38	1.09
Gas boiler for industry			0.27	1.30
Decentralised heat pumps			6.23	8.19
Decentralised solar				1.85
CCGT with CCS				0.50
Photovoltaic pannels				15.34
Direct electricity for industry				1.38

Table 5.1: f_{size} [GW] of technologies over different impact limits (NO_BIOMASS scenario)

The technologies that are chosen in all scenarios are presented in the first part of Tab. 5.1 . Hydro plants are always chosen because, as written in Section 3.5.5, a minimum amount of 8.1 GW for dams and 3.8 GW for river plants has been fixed. Other technologies are mainly ones that exploit natural gas (NG) or MSW. This result is easily understandable if we consider the cost of the resources. MSW has a c_{op} that has been fixed to zero and among fossil fuels NG is more expensive than coal. Therefore in Configuration n.1 the optimisation is driven mainly by the operational costs (c_{op}). Hydro plants represent the most important component in the investment cost while maintenance costs are roughly one other of magnitude less then investment costs. In Configuration n.2 the electricity produced by coal plants is substituted by the electricity that comes from CCS plants, gas cogenerators and wind turbines. This allows to the system to decrease the use of coal and to reduce drastically the impact. A further reduction can be achieved by substituting coal boilers with less emitting gas boilers and by using more efficient technologies to supply heat such as decentralised heat pumps (Configuration n.3). When the impact reaches the feasible limit (Configuration n.4) it is not sufficient to avoid the use of coal, but it is necessary also to invest on renewable energy. Decentralised solar collectors and photovoltaic panels have to provide respectively heat and electricity for the system and heat can be supplied by electrical resistances.

5.2.2 Woody biomass scenario

This scenario has higher costs than other scenarios when the impact limit is higher, but it can achieve the lowest values of emissions released. Here these equations have been activated:

$$y_{use}(u) = 0\,, \forall u \in Wet\,biomass\,technologies\,and\,resources, \tag{5.5}$$

$$y_{use}(u) = 0\,, \forall u \in Micro - algae\,technologies, \tag{5.6}$$

$$f_{mult}(Woody\,biomass, t) = \frac{12279\,GWh}{8760\,h/y},\ \forall t \tag{5.7}$$

With the last equation is possible to fix the amount of wood in GWh that is used per hour in Switzerland. For this scenario the curve starts from the highest value of cost because the use of all woody biomass is more expensive than other feedstocks. This is easily understandable if we think about the biomass cost. The cost of wet biomass is fixed to zero while biodiesel production from algae is very low compared to the wood availability in Switzerland. In woody biomass scenario the curve starts from higher values of costs than *NO Biomass* scenario. This result is still related to the operational cost of the resources. When the impact limit is higher centralised wood boilers substitute centralised gas boilers, reducing the impact and increasing the overall operational cost since $c_{op}(Wood) > c_{op}(NG)$. In Tab. 5.2 all biomass technologies that have been chosen over different impact values are reported.

When the limit is higher (Configuration n.1) centralised boilers exploit all the available biomass and storage of wet wood is used to store wood during summer, when heat demand is lower, to use it during winter, when the demand is higher. Only combustion technologies are used in the system until the impact limit reaches the value of 15 000 $ktons_{CO2eq}/y$, then fuel generation technologies are used to produce fuel for transport (Fast pyrolysis with oil upgrading) and for gas boilers or cars (Gasification with electrolysis).

	Conf. n.1	*Conf. n.2*	*Conf. n.3*	*Conf. n.4*
$Em_{max}[ktons_{CO_2eq}/y]$	***50000***	***30000***	***18000***	***14000***
Centralised wood boiler	3.28	1.57		
Centralised dry wood boiler		0.53	1.63	0.23
Dryer		0.24	0.62	0.07
BIGCC		0.20	0.84	0.26
Industrial wood boiler		0.50	1.24	1.38
Fast pyrolysis with upgrading				0.52
Indirect gasification with electrolysis				0.46
Storage wet wood	5927.34	2727.19	2377.62	2483.35
Storage dry wood		796.88	3071.19	282.25

Table 5.2: f_{size} [GW] and Sto_{level} [GWh] of woody biomass technologies (WOOD_100% scenario)

5.2.3 Wet biomass scenario

This scenario has intermediate results in terms of costs and impact. Here these equations have been activated:

$$y_{use}(u) = 0\,, \forall u \in Woody\,biomass\,technologies\,and\,resources, \tag{5.8}$$

$$y_{use}(u) = 0\,, \forall u \in Micro - algae\,technologies, \tag{5.9}$$

$$f_{mult}(Wet\,biomass, t) = \frac{9744\,GWh}{8760\,h/y},\ \forall t \tag{5.10}$$

The amount of wet biomass that has to be used is fixed by the optimiser can choose which technologies should exploit it. Wet biomass cost is fixed to zero, therefore the cost is lower than WOOD_100% scenario. The lowest value of impact that is achieved is higher than the one in woody biomass scenario. It is due to the fact that wet biomass potential is roughly 20% less than woody biomass one. In Tab. 5.3 the technologies that have been chosen are reported.

	Conf. n.1	*Conf. n.2*	*Conf. n.3*	*Conf. n.4*
$Em_{max}[ktons_{CO_2eq}/y]$	***50 000***	***32 000***	***22 000***	***16 000***
Anaerobic digestion with CHP	0.32	0.32	0.32	0.06
Anaerobic digestion with upgrading				
Hydrothermal gasification				1.11

Table 5.3: f_{size} [GW] of wet biomass technologies (WETBIOM_100% scenario)

Here anaerobic digestion with CHP is the technology that is chosen over all different configurations. Hydrothermal gasification is the most expensive technology over wet biomass technologies and it is chosen only when the impact limit reaches its lowest values.

5.2.4 Micro-algae scenario

In this scenario these equations have been activated:

$$y_{use}(u) = 0\,, \forall u \in Woody\,and\,wet\,biomass\,technologies\,and\,resources, \qquad (5.11)$$

$$\sum f_{mult}(u,t) = \frac{352\,GWh}{8760\,h/y}, \forall u \in Micro-algae\,technologies, \forall t \qquad (5.12)$$

Therefore here the overall amount of biodiesel that micro-algae technologies have to produces have been fixed. In this scenario the results are very similar to NO_BIOM, because, as written before, the amount of biodiesel that can be produced from micro-algae is very low compared to other feedstocks. A small improvement in terms of costs can be achieved compared to NO_BIOM when the GHG emission limit is lower. Here only OPs are chosen to produce biodiesel since their cost is less than PBRs and the impact in terms of $ktons_{CO_2eq}/GW$ is the same.

5.3 Single technology scenarios

In the following sections *single-technology scenarios* have been divided in subcategories which gather together the biomass technologies that exploit the same kind of biomass.

5.3.1 Woody biomass technologies

Here the results of *single technology scenarios* for woody biomass are reported. All these scenarios are compared to a red curve (WOOD_100%) where all woody biomass technologies is used. To facilitate the visualisation of the curves many diagrams have been created combining technologies with the same output according to the classification made in Sec. 2.3.8. Each scenario has been created adding Eq. (5.1) for each biomass technology and resource except the one that we want to assess in the scenario. In woody biomass scenario all woody biomass is used (Eq. (5.3)) and only the technology that we want to assess can exploit it (Eq. (5.2)).

Fuel generation technologies

All technologies that exploit woody biomass feedstock with a size going form 200 to 300 MW and whose main output is a biofuel are grouped in Fig. 5.2.

The name of the scenarios are related to the technologies that exploit biomass feedstock:

- FT: Fisher-Tropsch;
- FT_el: Fisher-Tropsch with electrolysis;
- SBBD_eth: Solvent based biomass deconstruction.

The curve that represents SBBD scenario is a dominant solution, so this option proved to be the best choice among large size fuel generation plants. It is interesting to notice the behaviour of the other two curves. The use of FT without electrolysis proved

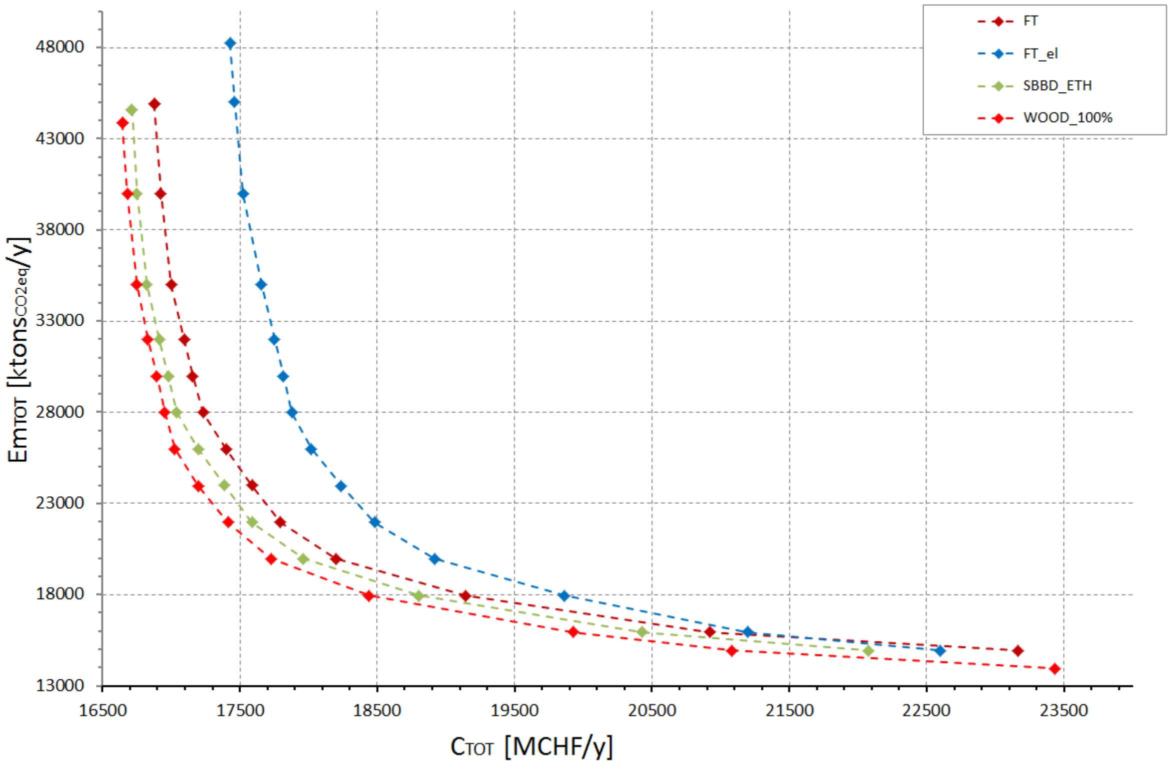


Figure 5.2: Woody biomass: Fuel generation technologies scenarios (Large plants)

to be the best choice when the system is optimised with higher values of impact limit. The costs of FT with electrolysis are always in the range 17500-18500 MCHF while the use of FT is in the range 16500-17500 MCHF. Mainly this is due to the different cost of the technologies. Furthermore FT with electrolysis scenario has a higher impact than others when the most affecting objective is the minimisation of the total cost. This is due to the fact that in these conditions the optimiser tends to produce the electricity with cheap and emitting technologies such as coal plants. If we force the use of FT with electrolysis we are increasing the electricity demand too, increasing the emissions of the system. A different situation is present when the system is optimised with a low impact limit. In this case the use of FT with electrolysis is better than FT because now the electricity is produced mainly by renewables or by less emitting technologies such as CCGT with CCS.

Results for fuel generation technologies with size going from 10 to 20 MW are shown in Fig. 5.3:

- FAST_PYR: Fast pyrolysis;
- FAST_PYR_UP: Fast pyrolysis with oil upgrading;
- PW_TO_GAS: Indirect gasification with electrolysis;
- GASIF: Indirect gasification.

All these technologies except one have roughly the same behaviour among different impact limits. Small differences are due to the specific cost of each technology. The forced use of gasification with electrolysis causes an increase of SNG that has to be

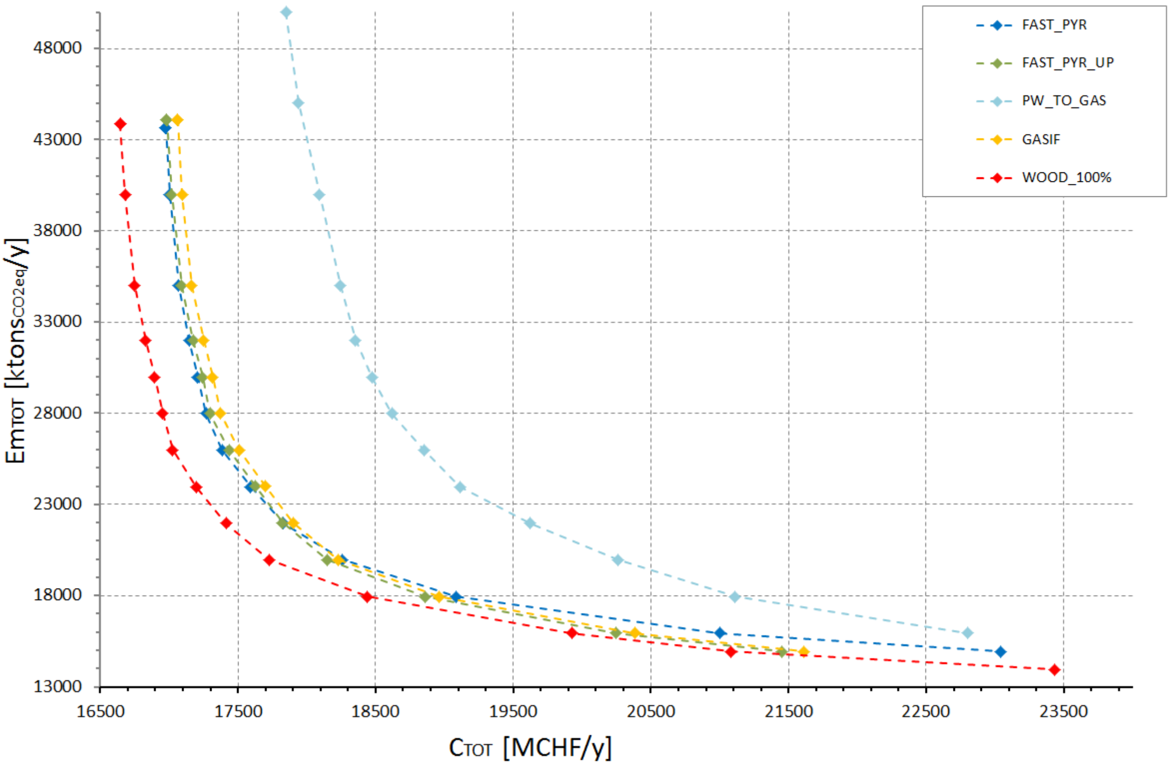


Figure 5.3: Woody biomass: Fuel generation technologies scenarios (Intermediate size)

exploited mainly by boilers or cogenerators, reducing the use of cheaper resources, especially coal. In any case a high value of impact is reached because of the electricity demand that is supplied by coal plants. Then the difference between other scenarios decreases with the impact limit, for the same reason of FT with electrolysis.

Decentralised heating technologies

- WGB: Wood gas burner;
- MGT: Externally fired micro-gas turbine;
- DEC_BOIL_WOOD: Decentralised wood boiler;
- DEC_COG_WOOD: Decentralised wood cogenerator.

In Fig. 5.4 there is still one technology that is much more expansive then others (MGT) because of his specific cost. Then a clear difference is visible between cogenerators and boilers. Scenarios with technologies that supply electricity can achieve lower values of impact and have lower values of impact when the limit is higher. The reason of that is liked to how is produced the electricity in the system and how it is used. At higher impact limit the electricity produced by cogenerators substitutes the one produced by coal plants, while at lower values of impact additional electricity is useful to the system to provide energy for heat pumps and direct heat.

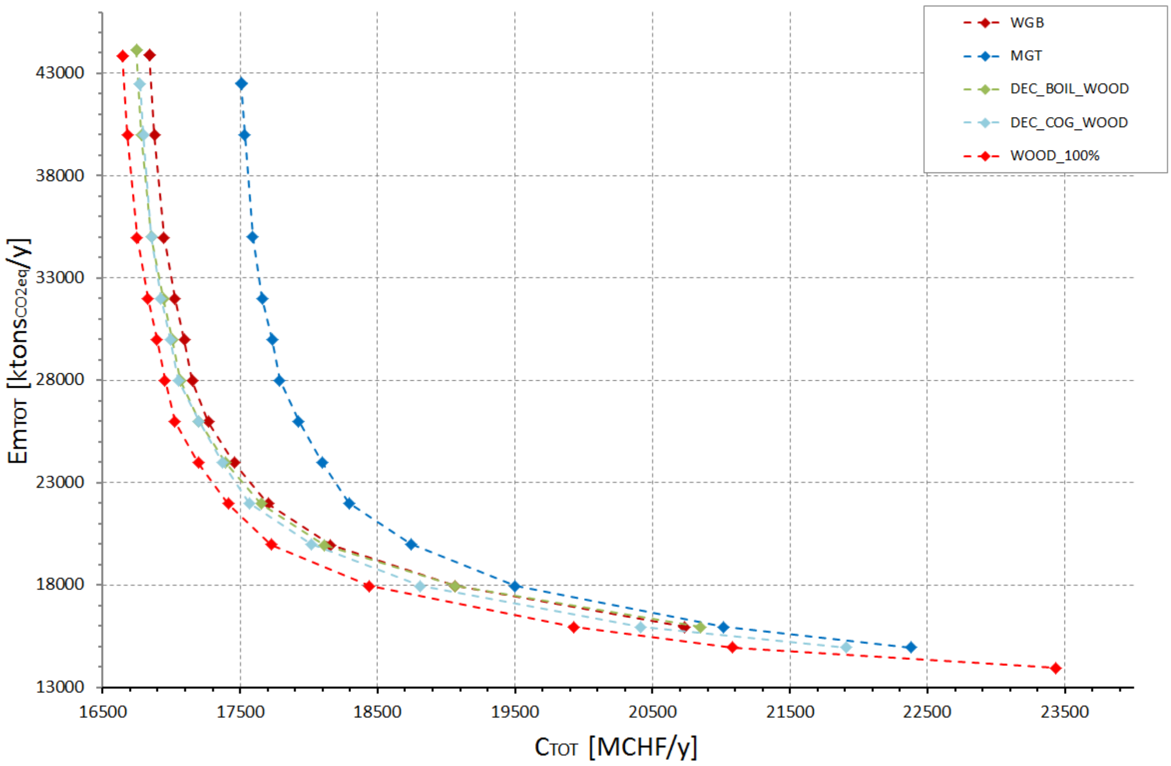


Figure 5.4: Woody biomass: Decentralised heating technologies scenarios

Centralised heating technologies

All centralised technologies are the ones that produce heat for district heating networks. Their reference size goes from 1 to 20 MW.

- DHN_BOIL_WOOD: Centralised wood boiler;
- DHN_COG_WOOD: Centralised wood cogenerator;
- DHN_BOIL_WOOD_DRY: Centralised dry wood boiler.

The use of all wood that is available in centralised wood boilers demonstrated to be the best choice in terms of cost. All other options have a higher cost, especially the cogeneration, but it is more convenient for lower values of impact limit. Centralised wood boiler and centralised dry wood boiler technologies have the same costs, but different results are due to the fact that dryers have to be used to produce dry wood from wet wood, increasing the costs.

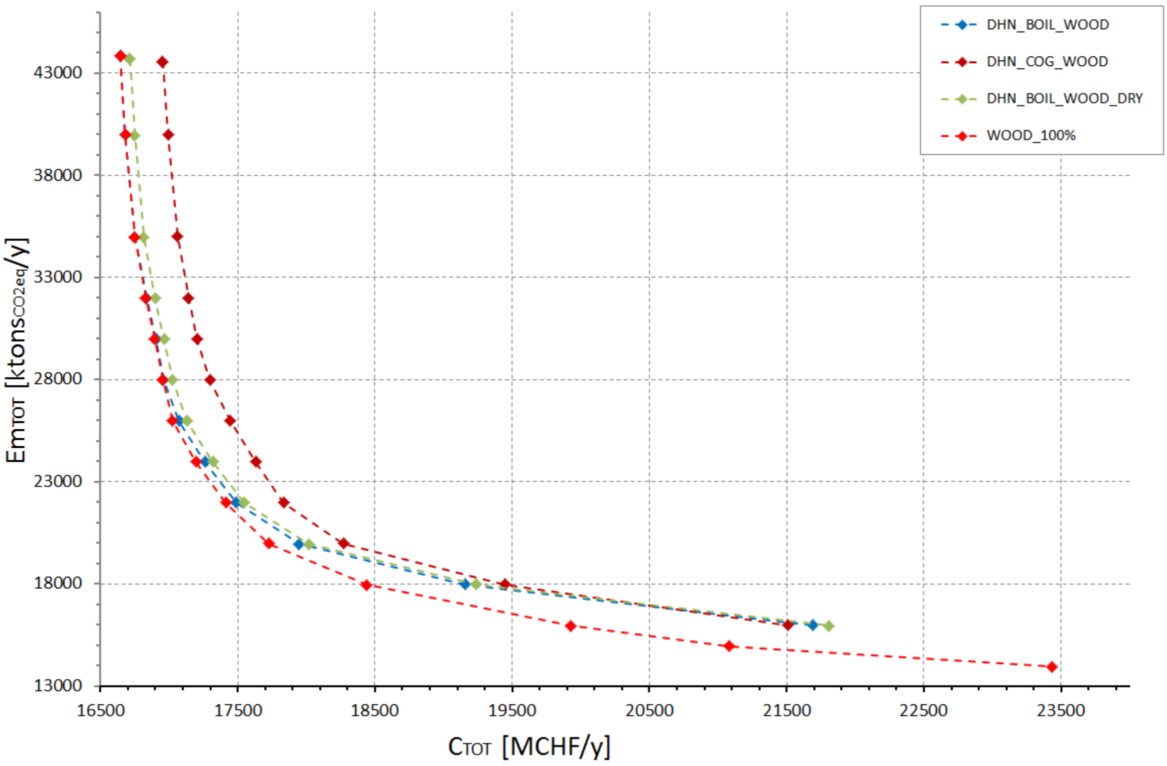


Figure 5.5: Woody biomass: Centralised heating technologies scenarios

Industry and electricity

- IND_BOIL_WOOD: Centralised wood boiler for industries;
- IND_COG_WOOD: Centralised wood cogenerator for industries;
- BIGCC: Biomass integrated gasification combined cycle;
- GAS_FC_GT: Gasification with fuel cell and gas-turbine.

Results for technologies that can supply high temperature heat and electricity are shown in Fig. 5.6. Boilers and cogenerators for industries are the same technologies used for DHN, but different results are due to the fact that they are associated to different layers.

Among technologies for industries, the use of wood in boilers proved to be always the best choice. Usually we have an improvement in terms of cost increase for cogenerators compared to boilers when the impact limit is reduced and therefore the curves cross one another. Here the crosses are not visible because of the efficiency of cogenerators. If we consider to use all available wood into cogenerators we have less amount of process heating than with boilers, that means that we have to supply the demand with other technologies that would not be chosen by the optimiser because too expensive. Furthermore when the impact limit is higher the scenario with boilers is slightly better in terms of impact then the one with boilers because in the latter the system tends to use more industrial coal boilers to supply heat since cogenerators have less heat efficiency.

Technologies that provide mainly electricity proved to be the best choice in terms of impact when the limit is higher. They tend to substitute the electricity produced

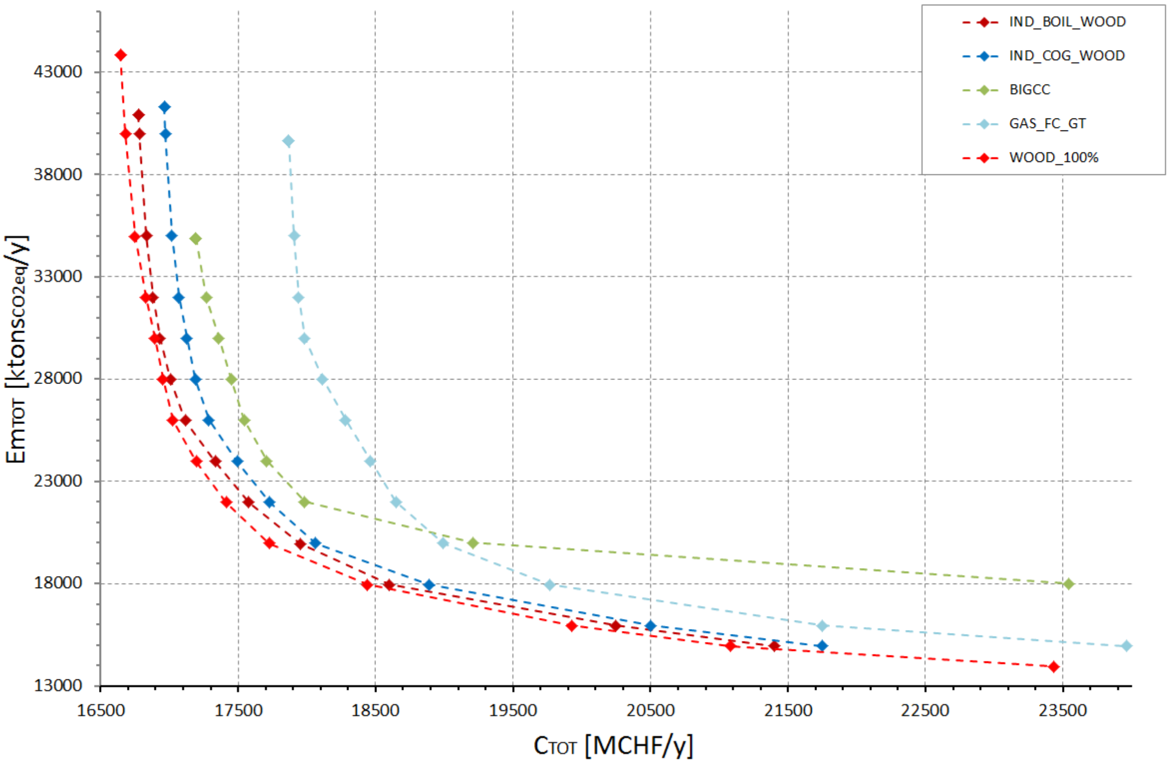


Figure 5.6: Woody biomass: Process heating and electricity production technologies

by coal plants and therefore to reduce the overall emissions of the system without forcing the impact limit. Among these, Biomass integrated gasification combined cycle (BIGCC) scenario is quite near to the reference scenario at the beginning, but when the impact limit is reduced the increase of cost becomes quite high. This behaviour is due to the NG requirement of this technology. To reduce the emissions of the system to its lowest values the use of NG should be limited, therefore if we fix the use of BIGCC his NG requirement becomes fixed and it is not possible to reduce the emissions like in other scenarios.

Storage

Two storage technologies have been implemented in this study:

- *Storage of dry wood*: They are facilities where dry wood can be stored after being dried by driers;
- *Storage of wet wood*: They are facilities where wet wood can be stored after being harvested.

In NO_STO_WOOD scenario both of them have been disabled to see if they are used by the system, in which conditions they are used and how much they decrease the cost. In Fig. 5.7 it is clear how the storage is always used by the system and its absence causes always an increase of cost, especially decreasing the impact limit.

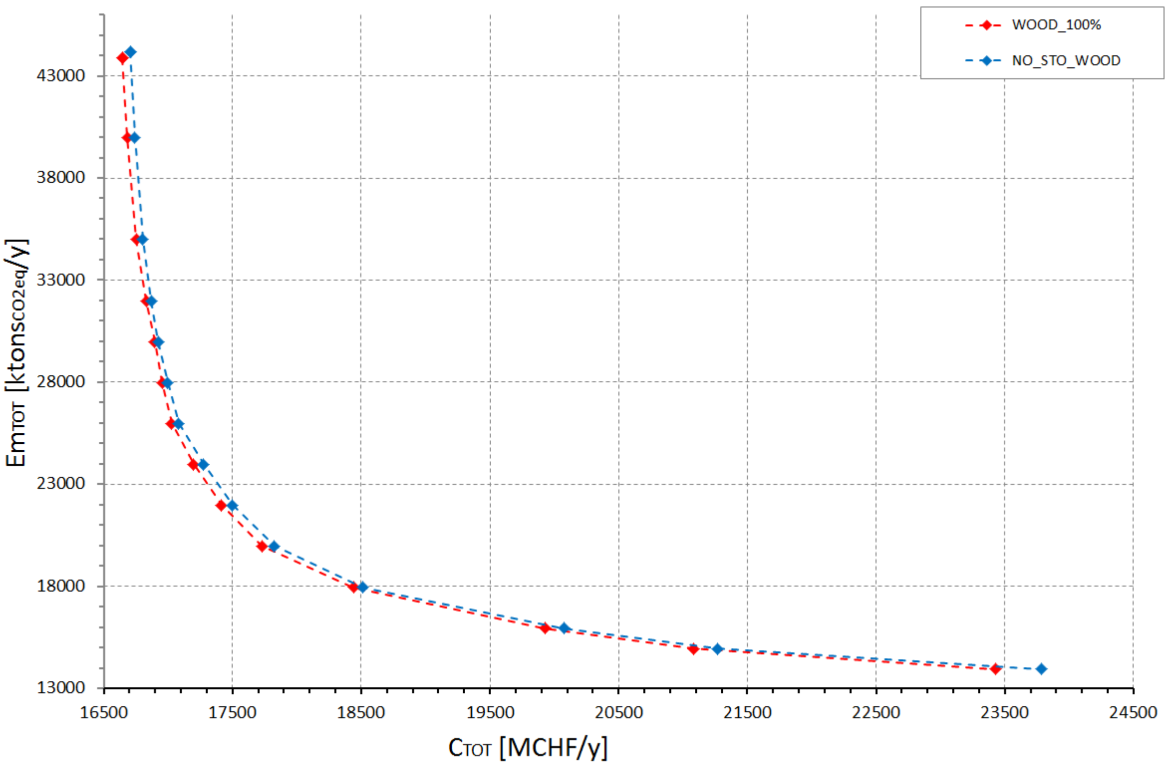


Figure 5.7: Woody biomass: Storage technologies

5.3.2 Wet biomass technologies

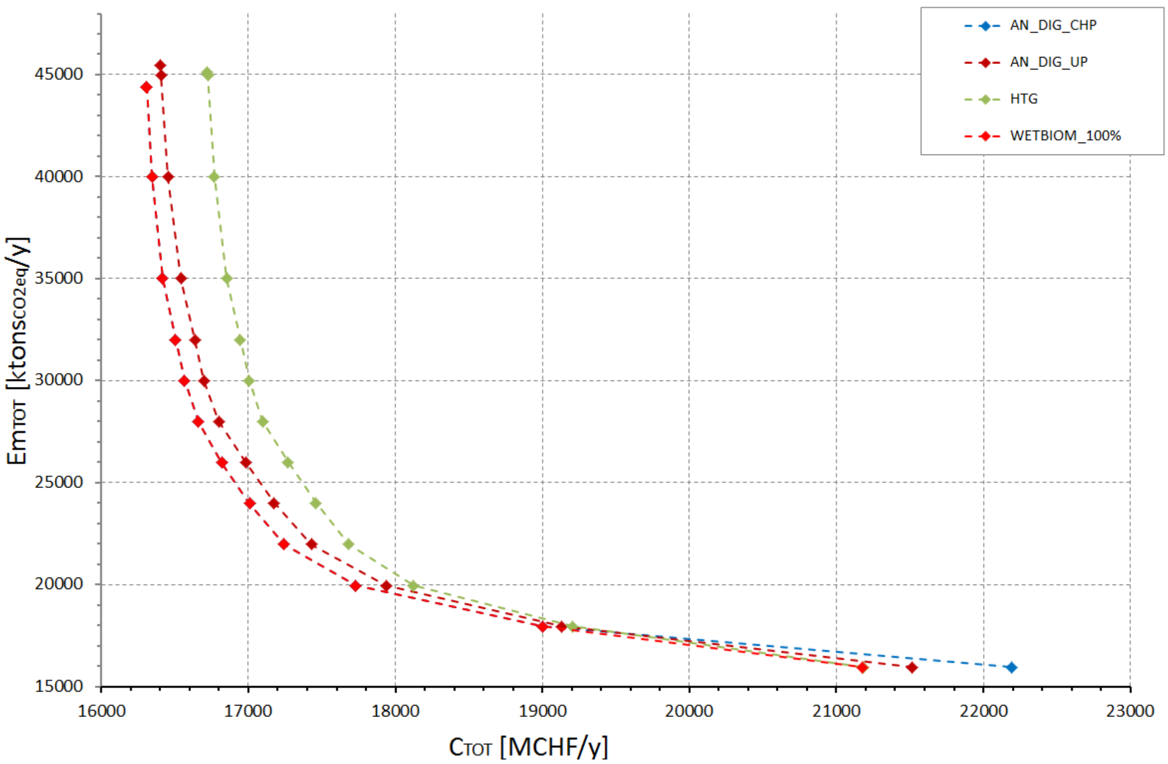


Figure 5.8: Wet biomass technologies

- AN_DIG_CHP: Anaerobic digestion with combined heat and power (CHP) plant;
- AN_DIG_UP: Anaerobic digestion with biogas upgrading;
- HTG: Hydrothermal gasification;

Like in woody biomass utilisation, there is a curve that can not be seen because it is just under the reference one, that means that in the first configurations of WET-BIOM_100% scenario anaerobic digestion with CHP is the only technology which exploits wet biomass. Anaerobic digestion with CHP proved to be the best choice for wet biomass utilisation until low values of impact limit ($\approx 18000\, ktons_{CO_2eq}/y$) while technologies that produce fuel are more expensive, especially HTG, but their use causes less cost increase under this value of impact.

5.3.3 Micro-algae technologies

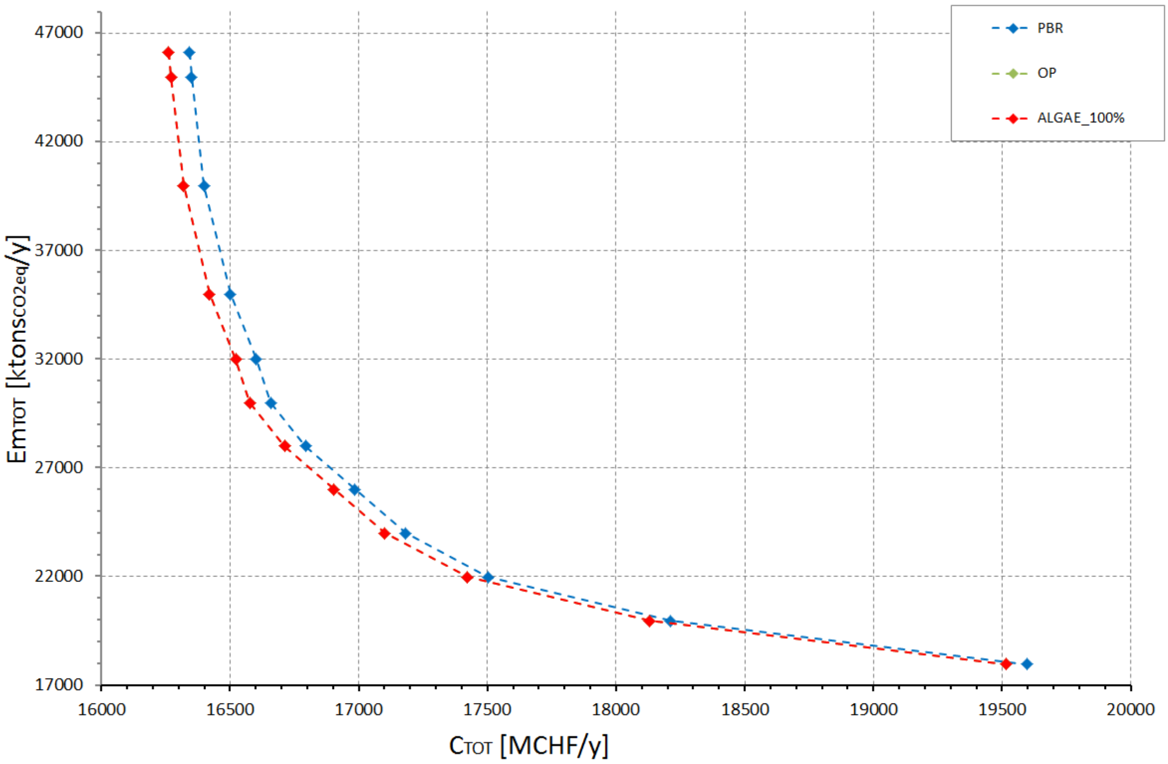


Figure 5.9: Microalgae technologies

- OP: Open ponds;
- PBR: Photo-bio reactors.

Within micro-algae technologies the production of biodiesel from open ponds (OP) represents always a better solution in terms of cost and emission then photo-bio reactors (PBR). This is due to the fact that PBR are extremely more expansive and the emission coefficient is assumed equal to OP. The main reason to shift from open ponds to photo-bio reactors is the extremely lower amount of water that is lost in the latter, but this factor has not been considered in this study.

5.4 Free scenario

In previous sections a comparison between different pathways, where only one biomass technology is used in the system, has been shown. We found out that both impact and cost of technologies are important to assess different pathways, but we did not determine how to use biomass feedtocks together because in reference scenarios and in single technology scenarios only one type of biomass has to be exploited. A scenario called *free scenario* or free_100% has been created to show how to exploit biomass feedstocks together. Here woody biomass and wet biomass have to be used (Eq. (5.3) activated) but the optimiser can choose how to exploit them. The results in terms of cost and environmental impact are discussed in the following chapter giving three solutions as possible configurations for the Swiss energy system in the year 2035.

Chapter 6

Results

In this chapter all scenarios defined in Ch. 5 are assessed with the methodology explained in Sec. 4.3. Different pathways are ranked in terms of cost increase percentage to understand which are the most promising biomass conversion technologies (Sec. 6.1). Then three configurations of *free scenario* are determined and discussed. The first one represents the configuration with the lowest cost of the system considering to exploit all the available biomass. With the second one it is possible to achieve the lowest impact of the system while the third one represents the best trade-off between cost and environmental impact which we found in this study (Sec. 6.2). Finally the results are analysed trying to assess the potentiality of combustion and fuel generation technologies and to understand how the results can change if we modify the available technologies and the amount of biomass that is used (Sec. 6.3).

6.1 Ranking

Ranking different technologies pathways is an aim of this study. From Fig. 6.1 to 6.6 cost increase percentage for each *single technology scenario* are shown over different values of impact limit. With these data is possible to understand when the use of the technologies is desirable and how much the use of one is better then another. The ranking can change over different values of impact limit, therefore the results are shown for three values of Em_{max}. The first is the maximum value of impact limit used in the model (50 000 $ktons_{CO_2eq}/y$). To understand which are the results when the impact does not affect the optimisation. The second value (26 000 $ktons_{CO_2eq}/y$) is an intermediate value and makes possible to understand the trend of the solutions. The third value (16 000 $ktons_{CO_2eq}/y$) is a limit that is achieved by practically all technologies and makes possible the comparison of the results when the impact is the most affecting objective. Only BIGCC can not achieve this value of impact, so its data are taken from the achievable limit (18 000 $ktons_{CO_2eq}/y$).

6.1.1 Woody biomass technologies

Woody biomass can be exploited by 19 different technologies. In Fig. 6.1 it is possible to visualise easily the difference between the *single-technology scenarios* shown in the previous section.

Centralised wood boilers proved to be the best choice to use woody biomass, followed by ethanol production with SBBD. In the first ten positions mainly combustion

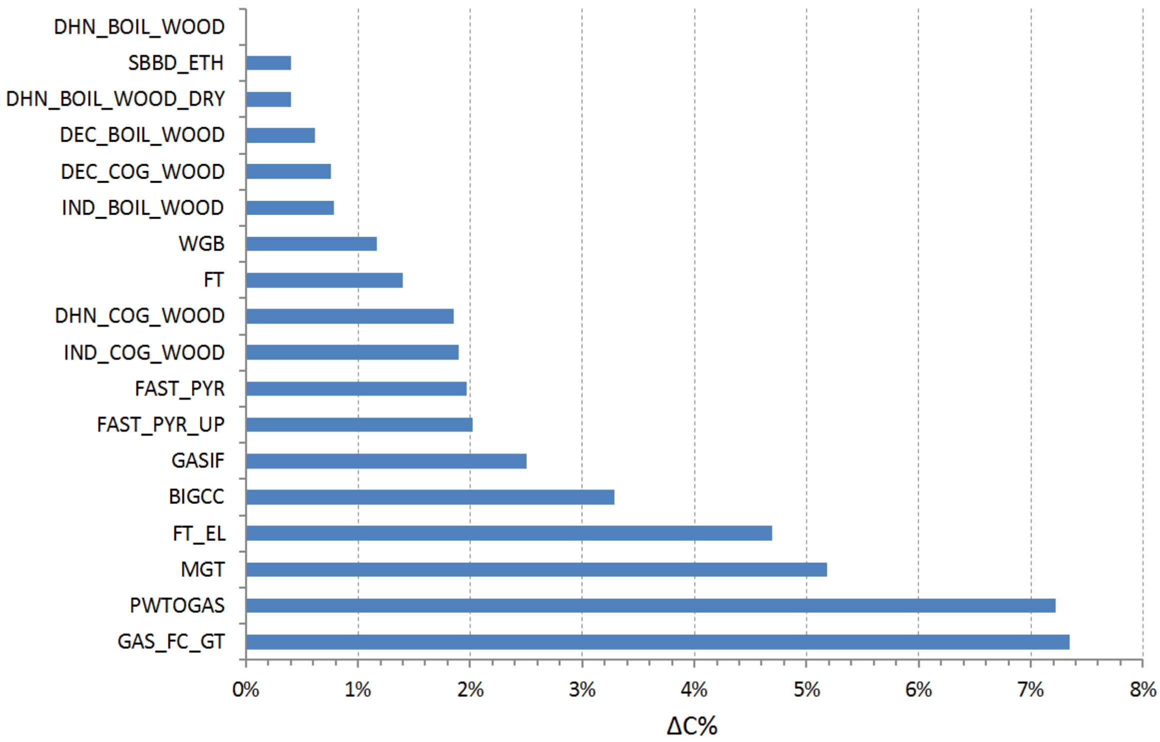


Figure 6.1: Woody biomass technologies: Ranking for impact limit of 50000 $ktons_{CO_2eq}/y$

and large fuel generation technologies are ranked. Combustion technologies are usually cheaper then fuel generation technologies, especially centralised boilers (see Tab. A.1) and large size fuel generation technologies, like SBBD, can take advantage of economic scale to reduce the costs.

For intermediate values of impact limit $\Delta C\%$ increases for all technologies but the ranking does not change too much. This means that for these values of impact the best solution for wood exploitation is to use many combustion technologies together, not only one of them. In Fig. 6.2 still combustion technologies are in the first part of the ranking, the only changes are the substitution of centralised wood cogenerator with fast pyrolysis and the lower position of large size fuel generation plants.

When the impact limit is reduced to its lower values the ranking starts to change. In Fig. 6.3 five combustion technologies and five fuel generation technologies are ranked in the first ten positions. This trend shows how fuel generation technologies become more important for woody biomass exploitation when the limit decreases. Fast pyrolysis with oil upgrading and gasification of wood become the best ways to produce fuels from biomass while the use of centralised boilers can increase the cost of the system of roughly 10% more then the reference one. Even if BIGCC is associated to an impact of 18 000 $ktons_{CO_2eq}/y$, so it can take advantage of the lower value of the reference cost, the use of all available wood by them is the worst choice.

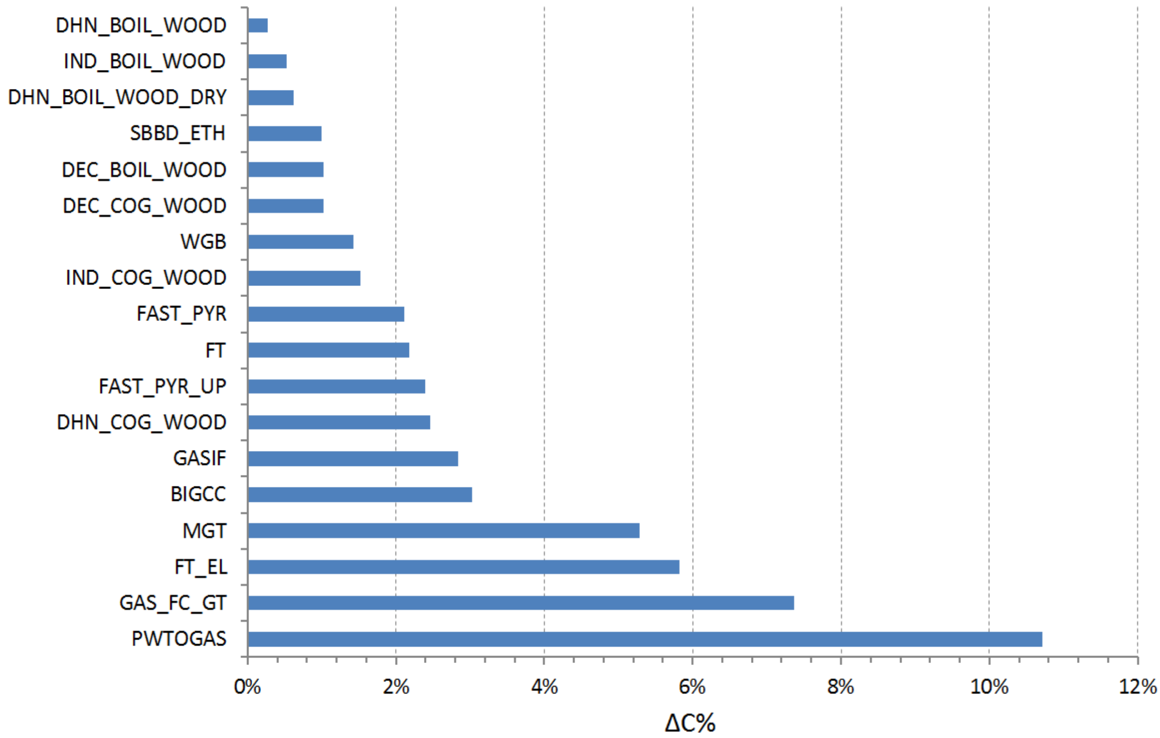


Figure 6.2: Woody biomass technologies: Ranking for impact limit of 26000 $ktons_{CO_2eq}/y$

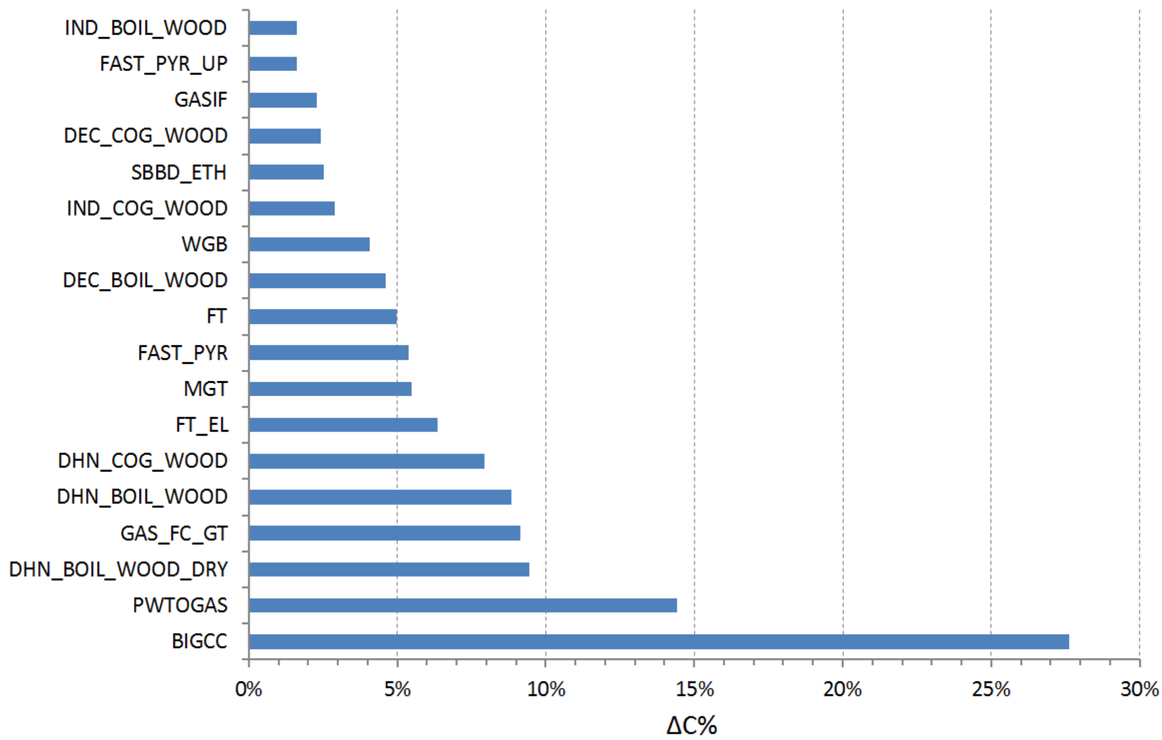


Figure 6.3: Woody biomass technologies: Ranking for impact limit of 16000 $ktons_{CO_2eq}/y$

6.1.2 Wet biomass technologies

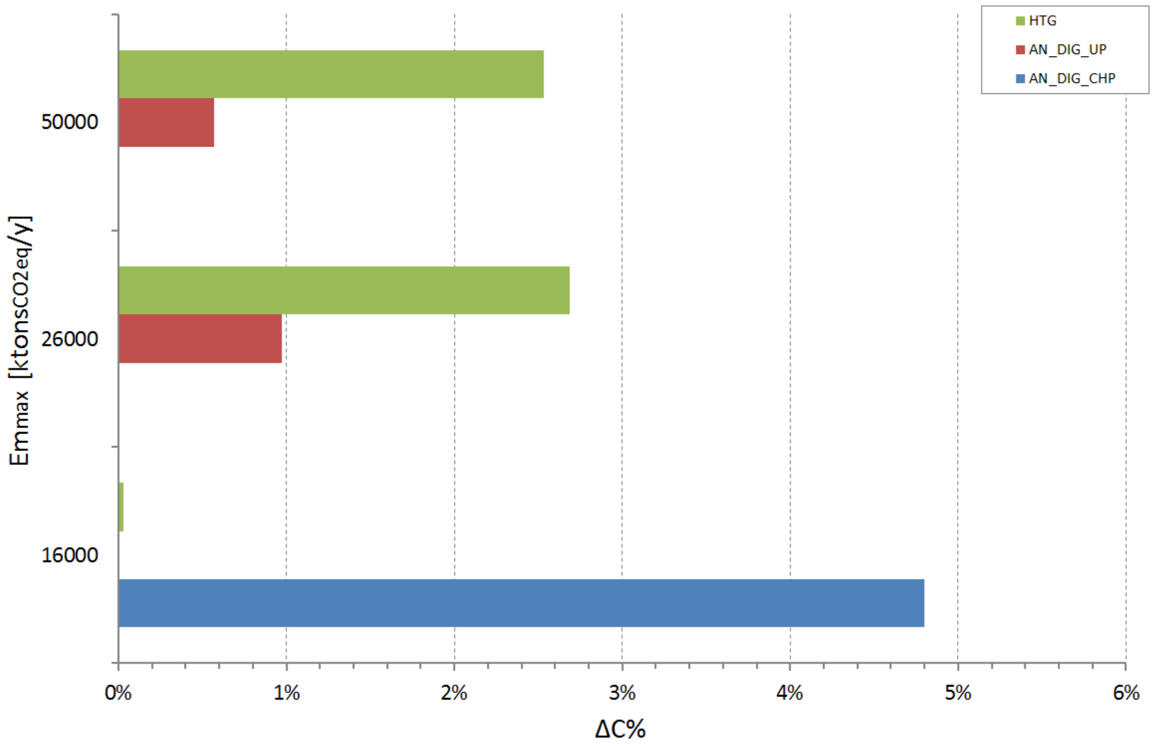


Figure 6.4: Cost increase for wet biomass over different values of impact limit

In this case only three technologies can exploit the biomass, so only one diagram is shown to understand the ranking and the effects of the use of one technology or another.

The same trend found for woody biomass is obtained for wet biomass in Fig. 6.4. The production of heat and electricity through anaerobic digestion and biogs combustion proved to be the option that increases less the cost of the system. Fuel production is the best option when the impact limit decreases. At 16 000 $ktons_{CO2eq}/y$ the most promising option to generate fuel is the anaerobic digestion with biogas upgrading, but if we look at Fig. 5.8 it is clear how hydrothermal gasification becomes the best option for lower values of impact.

6.1.3 Storage and Micro-algae technologies

As written in section 5.3.3 the production of biodiesel by open ponds demonstrated to be a dominant solution among algae technologies, therefore there is no meaning to make a ranking. Fig. 5.9 is only necessary to see which is the cost increase of we do not follow this pathway. Another diagram is shown to see the effects on the system if we avoid the used of wood storage.

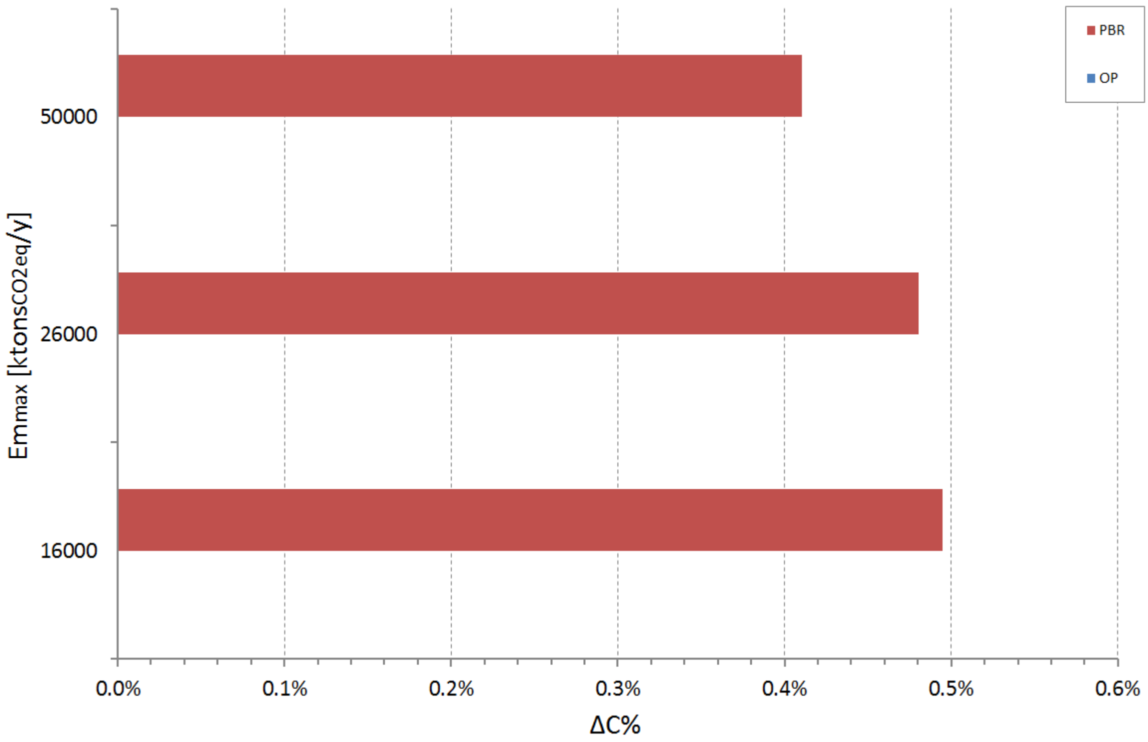


Figure 6.5: Cost increase for micro-algae technologies

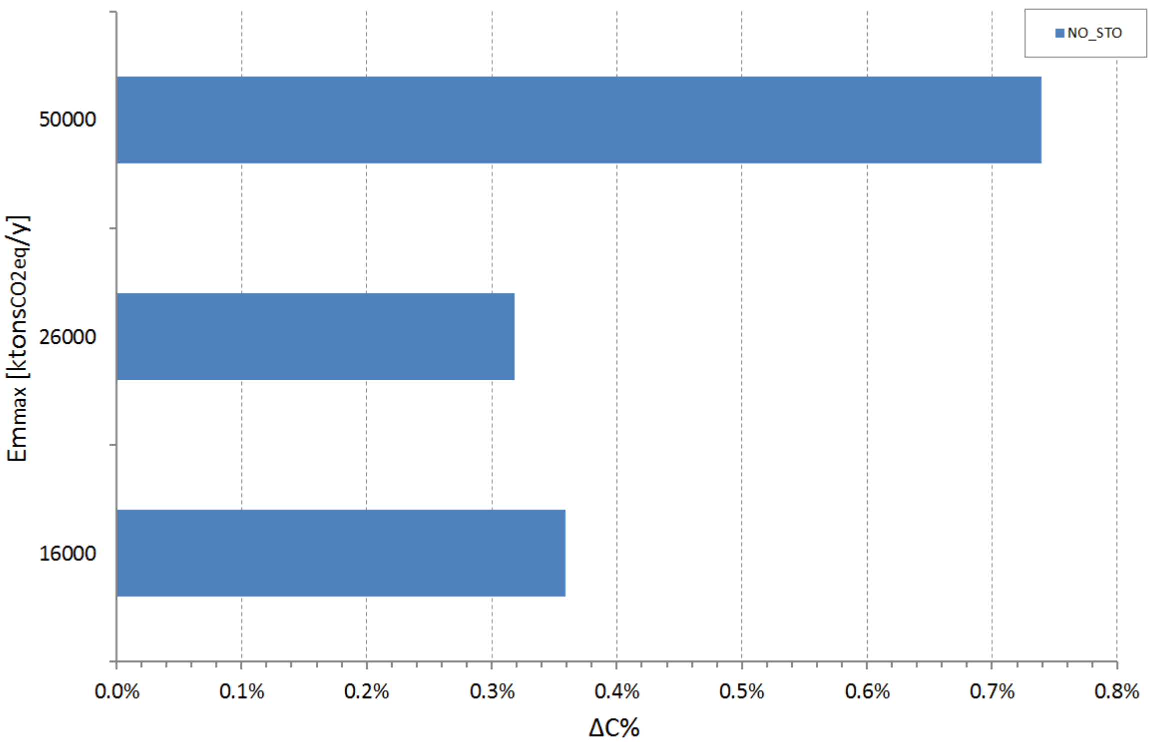


Figure 6.6: Cost increase for no storage option

6.1.4 Overall technologies comparison

Technology name	$\Delta C\%$	
	50000 $ktons_{CO_2eq}/y$	16000 $ktons_{CO_2eq}/y$
Woody Biomass		
Fast pyrolysis with oil uprading	2.0%	1.6%
Fast pyrolysis	2.0%	5.4%
Solvent based biomass deconstruction	0.4%	2.5%
Indirect gasification	2.5%	2.3%
Indirect gasification with electrolysis	7.2%	14.4%
Fisher Tropsch	1.4%	5.0%
Fischer Tropsch with electrolysis	4.7%	6.4%
BIGCC	3.3%	27.6%
Gasifier - SOFC - GT	7.3%	9.1%
Industrial wood cogenerator	1.9%	2.9%
Industrial wood boiler	0.8%	1.6%
Centralised wood cogenerator	1.8%	8.0%
Centralised wood boiler	0.0%	8.9%
Centralised dry wood boiler	0.4%	9.4%
Wood gas burner	1.2%	4.1%
Decentralised wood boiler	0.6%	4.6%
Decentralised wood cogenerator	0.8%	2.4%
Externally fired micro gas turbine	5.2%	5.5%
Wet biomass		
Hydrothermal gasification	2.5%	0.0%
Anaerobic digestion with CHP	0.0%	4.8%
Anaerobic digestion with upgrading	0.6%	0.0%
Micro-algae		
Photo-bio reactors	0.5%	0.4%
Open ponds	0.0%	0.0%

Table 6.1: Cost increase percentage for two different values of impact

In Tab. 6.1 the results shown in the previous sections are summarised trying to show which are the most promising biomass conversion technologies and for which value of impact limit. Different colors have been used to underline the results:

- Woody biomass:
  - 50 000 ktons: green for technologies that have a cost increase percentage less then 1% and light green for increase less than 2%;
  - 16 000 ktons: green for technologies that have a cost increase percentage less 2% than and light green for increase of 4%;

- Wet biomass:
  Green for technologies that have less cost increase percentage than 1%;

- Micro-algae:
  Green for the technology that has less percentage of cost increase;

The difference between the two values of impact for woody biomass is due to the overall increase of the costs when the system is optimised with lower values of impact. Fuel generation technologies seem to be the best choice when the system has a lower values of impact limit, while mainly combustion technologies should be used when the limit is higher.

6.2 Free scenario analysis

In Sec. 6.1.4 the most promising pathways have been assessed considering the cost increase percentage. Combustion technologies proved to be the best choice to exploit biomass when the impact limit is higher while fuel generation technologies are useful to reduce impact to its lowest value. With this methodology we assessed which are the most promising biomass conversion technologies, but we did not determine how to use them together in the system because in reference scenarios only one type of biomass has to be exploited. By analysing *free scenario* we want to show how to exploit biomass feedstocks together and furthermore we want to see how the configuration can change if we vary impact in terms of GHG emissions. Usually genetic algorithms are used to find Pareto curves and to assess the trade-off between two objectives. Here a constrained optimisation has been used to answer this question.

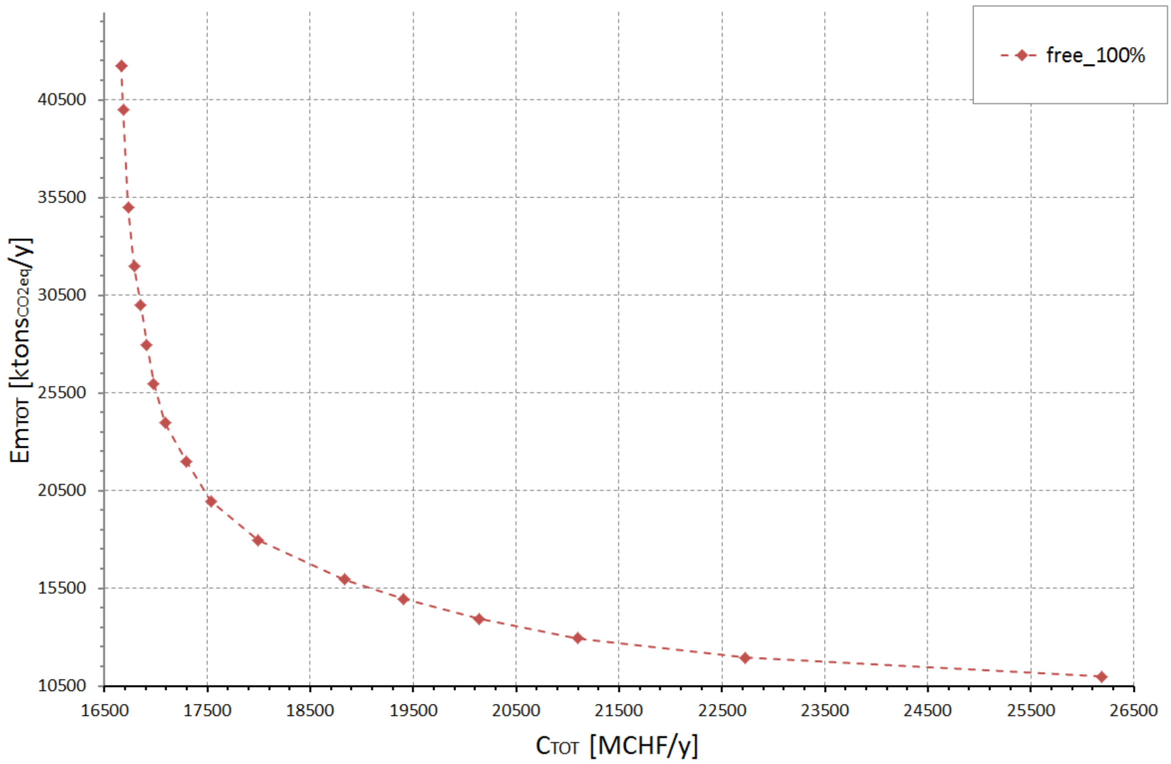


Figure 6.7: Objectives results (scenario free_100%)

The results of the objectives are reported in Fig. 6.7. Like in single technology scenarios when the impact is decreased through the constraint (4.4) we can obtain a "Pareto-like" curve that represents the trade off between costs and impact. C_{TOT} increases reducing E_{max} because we need to exploit resources with more efficient and therefore expensive technologies. For high impact limits it is possible to decrease the emissions in the system practically without increasing costs. It is possible to decrease the emissions around 20 000 $ktons_{CO_2eq}/y$ with an increase of cost of less then 1000 of $MCHF/y$. When E_{TOT} is around 20 000 $ktons_{CO_2eq}/y$ the derivative dEm_{TOT}/dC_{TOT} starts to decrease rapidly. To reduce emissions, it necessary to largely increase costs. In the end we need to spend roughly 3500 $MCHF/y$ to reduce impact of 1000 $ktons_{CO_2eq}/y$. The best configurations are considered the ones that permit to reduce impact without largely increase the costs. These conditions can be found in the range $24000 < Em_{TOT} < 18000\, ktons_{CO_2eq}/y$.

Now it is interesting to show which are the technologies that are chosen by the optimiser. Each configuration can be used as a reference for the decision makers to understand how the Swiss energy system can be realised if we want to achieve the minimisation of costs obtaining a certain GHG emission reduction.

6.2.1 Minimum cost

Here it is reported the first configuration of the scenario free_100% ($C_{TOT} = 16664\, MCHF/y$, $Em_{TOT} = 42263\, ktons_{CO_2eq}/y$). When E_{max} has a value that is higher then 45 000 $ktons_{CO_2eq}/y$ the model is optimised practically in terms of cost. The only constraint that increases the costs is the use of all available biomass in the system. Reporting the configuration in this case it is possible to understand how the system should be structured if we want to achieve the lowest cost.

In Tab. 6.2 the sizes of technologies in this configuration are reported while in Tab. 6.3 all resource consumption is shown.

Technologies	f_{size}
	GW
Decentralised gas boilers	7.89
Thermal heat pumps	5.26
Centralised wood boilers	3.26
Centralised heat pumps	0.28
Anaerobic digestion with CHP	0.32
Coal plants	2.72
Hydro dam plants	8.16
Hydro river plants	3.80
Industrial coal boilers	1.54
Industrial waste boilers	1.33

Table 6.2: Size of technologies (cost minimisation, free_100% scenario)

Resources	$\sum f_{mult}$
	GWh/y
Natural gas	59335.05
MSW	12809.00
Gasoline	6178.62
Coal	52506.94
Wood	12279.37
Diesel	8194.77
Wet biomass	9743.56

Table 6.3: Resource consumption (cost minimisation, free_100% scenario)

Here the configuration is very similar to the first one in *NO biomass* scenario. Deep geothermal plants are substituted by centralised wood boilers which exploit woody biomass while all wet biomass is used in anaerobic digesters to produce heat and power. This configuration provides the lowest cost of the system because the technologies exploit mainly coal and NG which have a low operational cost (c_{op}). MSW has a c_{op} equal to zero, so even if it is fixed only the maximum amount, it is practically always all used.

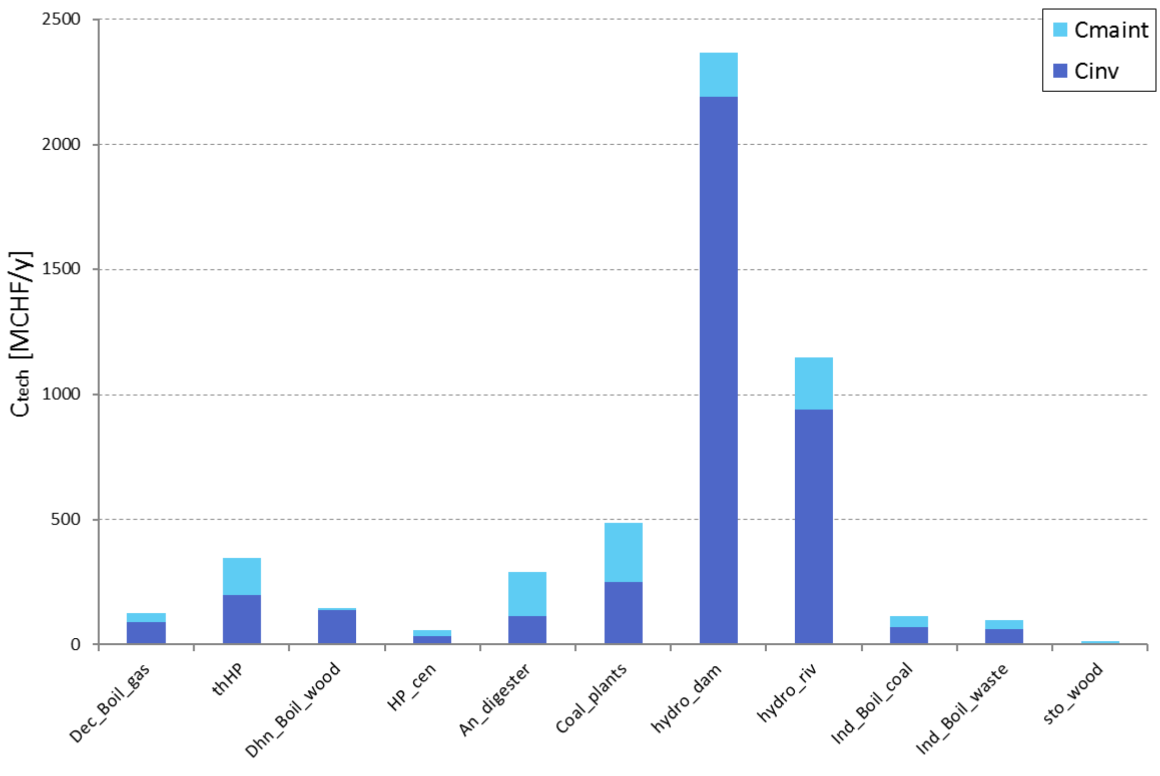


Figure 6.8: Technologies costs (cost minimisation, scenario free_100%)

Hydro dams and hydro river plants costs are the most important ones among energy technologies (Fig. 6.8), only anaerobic digesters with CHP can reach 500 $MCHF/y$ while the sum of costs of hydro plants is roughly 3500 $MCHF/y$. C_{fix} is the cost associated to the construction of the electric grid and to the efficiency improvement in buildings. It is equal to 4099 $MCHF/y$ while C_{TOT} is 16664 $MCHF/y$, so it is clear that the most important part of the total cost is related to the resources.

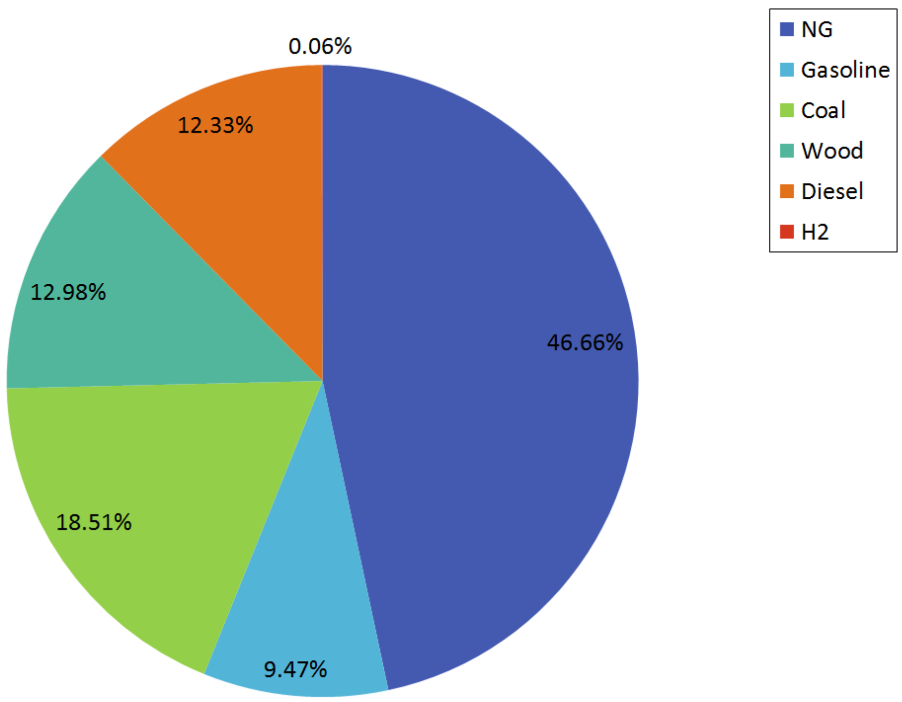


Figure 6.9: Resource costs (cost minimisation, scenario free_100%) $\sum C_{op} = 7376\,MCHF/y$

NG is the resource that is mostly used (Tab. 6.3) and therefore roughly 50% of the resource cost is related to it. Coal is less expensive, so even if its amount is similar to NG its cost is only 20% of the total (Fig. 6.9). Other resources (Wood, Diesel and Gasoline) represent the 30% of the total amount and H_2 is negligible. It is used in FC cars but it is a low amount since they can supply only the 1% of total mobility passenger demand.

All available biomass is used by centralised wood boilers and anaerobic digestion that proved to be the cheapest way to exploit biomass in the pathways comparison. In the model it is possible to define the load of technologies during different months considering a reference hour per each month. In Fig. 6.10 the load of biomass technologies is reported. f_{mult} for energy technologies has been translated in GWh to define the amount of energy that biomass technologies have to supply per each month.

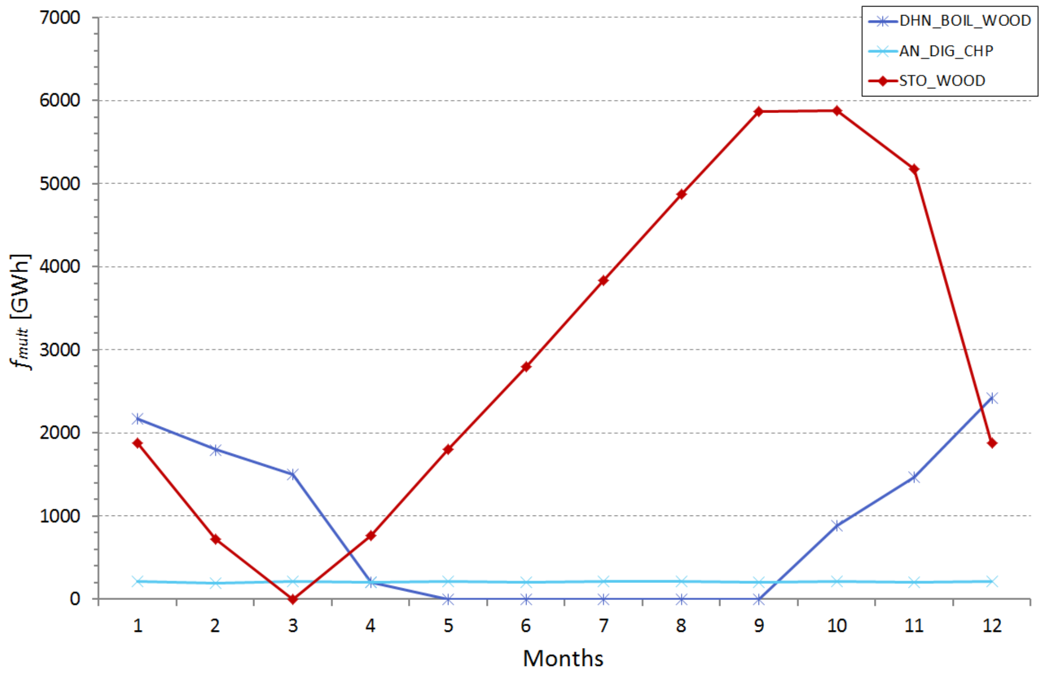


Figure 6.10: f_{mult} for biomass technologies (cost minimisation, scenario free_100%)

Here it is clear how woody biomass is used during the year. During winter, when heat demand is high, woody biomass is burned in centralised boilers, while during summer is stored since heat demand decreases. That permits to make available more wood during winter and therefore to increase the share of heat supply from wood among technologies that can provide heat. Anaerobic digestion is used to produce electricity and heat. Its output is roughly 200 GWh of heat in DHN per month and 50 GWh of electricity. Wet biomass can not be stored, so all available biomass is used directly each month.

6.2.2 Minimum impact

With this configuration is possible to achieve the lowest value of impact in terms of GHG emissions in the system but costs increase of half respect to the first configuration ($C_{TOT} = 26187\, MCHF/y$, $Em_{TOT} = 10981\, ktons_{CO_2eq}/y$). Here E_{max} is fixed at 11000 $ktons_{CO_2eq}/y$ and if we try to reduce it more, the optimisation problem becomes infeasible. That means that 10 981 $ktons_{CO_2eq}/y$ is roughly the minimum amount of GHG emissions that the system can produce if we want to supply the demand.

Technologies	f_{size}
	GW
SOFCs	0.71
Decentralised solar	20
Decentralised heat pumps	10.69
Thermal heat pumps	2.77
Centralised dry wood boilers	0.16
Deep geothermal plants	0.35
Centralised heat pumps	1.19
CCGT with CCS	0.50
Hydro dam	8.20
Hydro river	4.50
Photovoltaic panels	25
Wind turbines	4.50
Industrial waste boiler	1.20
Industrial wood boiler	0.82
Industrial direct heat	2.58
Fast pyrolysis with upgrading	0.82
Gasification and electrolysis	0.38
Hydrothermal gasification	1.26
Open ponds	0.04
Dryers	0.03

Table 6.4: Size of technologies (impact minimisation, free_100% scenario)

In this configuration the number of technologies increases (Tab. 6.4). All kind of renewable technologies are chosen. PV, Hydro, wind turbines and geothermal plants can provide electricity and heat while efficient technologies such as SOFCs and heat pumps are used in DEC heating and in DHN. Other technologies are mainly biomass technologies. Combustion technologies such as centralised dry wood boilers and industrial wood boilers are used to supply heat respectively to DHN and industries. Especially industrial boilers proved to be a good choice to exploit biomass in "single-technologies" scenarios even if E_{max} is low. When the limit is lower the best fuel generation technologies (Fast pyrolysis and HTG) are used in the system with Gasification and electrolysis while open ponds are used to produce diesel from algae.

This system can achieve the lowest value of impact because it can substitute a large amount of resources with biomass and renewables. The resources that are needed are exploited by efficient technologies reducing the overall impact. Natural gas is still the resource that is mostly used. Coal is completely substituted while MSW is reduced from the first scenario even if its cost is equal to zero.

The cost of technologies is mostly related to PV, Hydro plants and solar collectors(Fig. 6.11), but SOFCs and HPs are important too. Investment cost is still the most important part among technologies cost. It consists of 14 008 $MCHF/y$ while maintenance cost is 1/3 of it. To reduce the overall impact it is necessary to exploit as less resources as possible, so the cost related to resources decreases. All resources have roughly the same amount of use over different configurations except NG that is strongly reduced. NG is still the resource that is mostly used by the system and its

Resources	$\sum f_{mult}$
	GWh/y
Natural gas	16439.79
MSW	7123.24
Gasoline	6178.62
Wood	12279.37
Diesel	5734.49
Wet biomass	9743.56

Table 6.5: Resource consumption (impact minimisation, free_100% scenario)

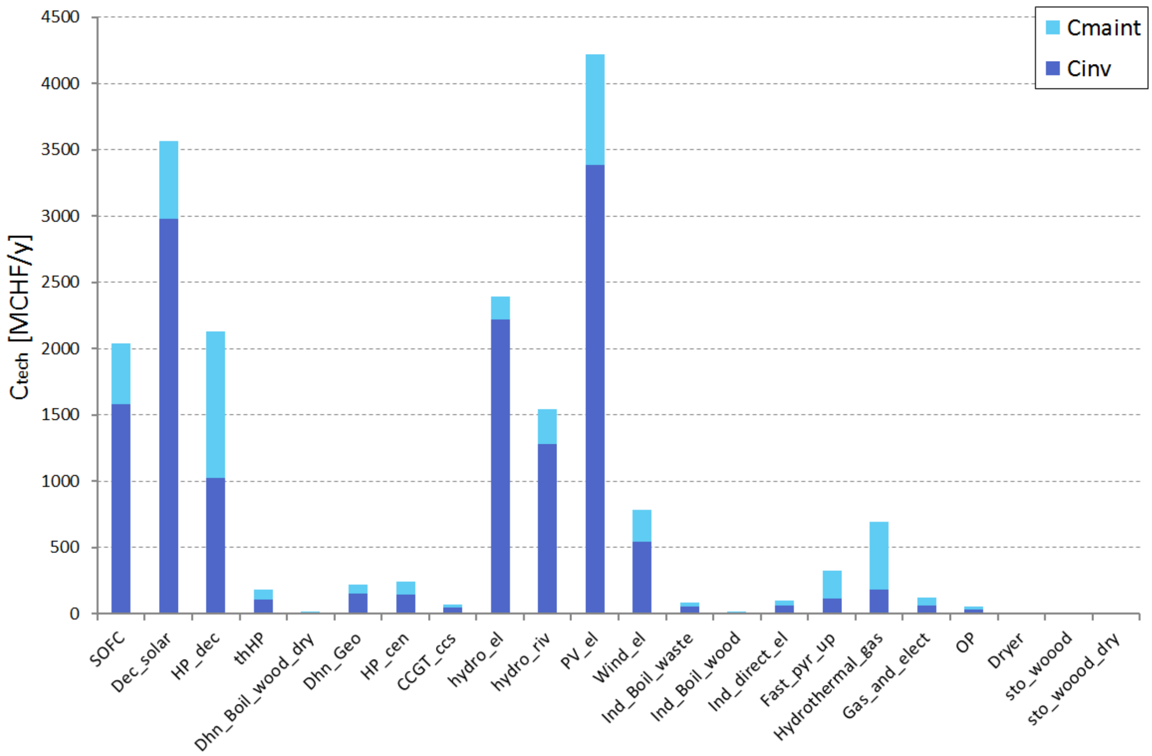


Figure 6.11: Technologies costs (last cofiguration scenario free_100%)

cost equal the one of woody biomass (Fig. 6.13).

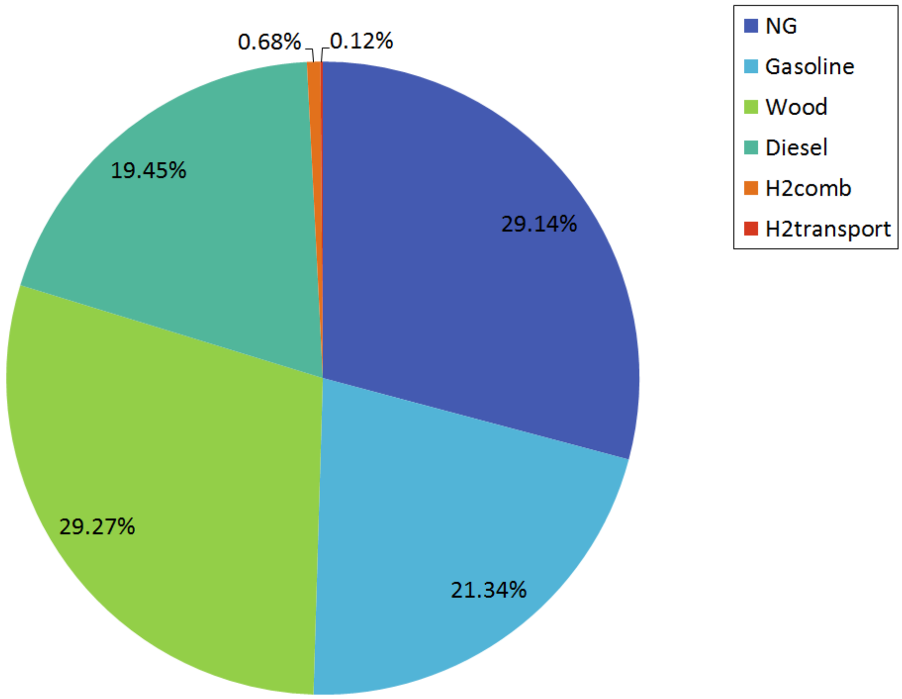
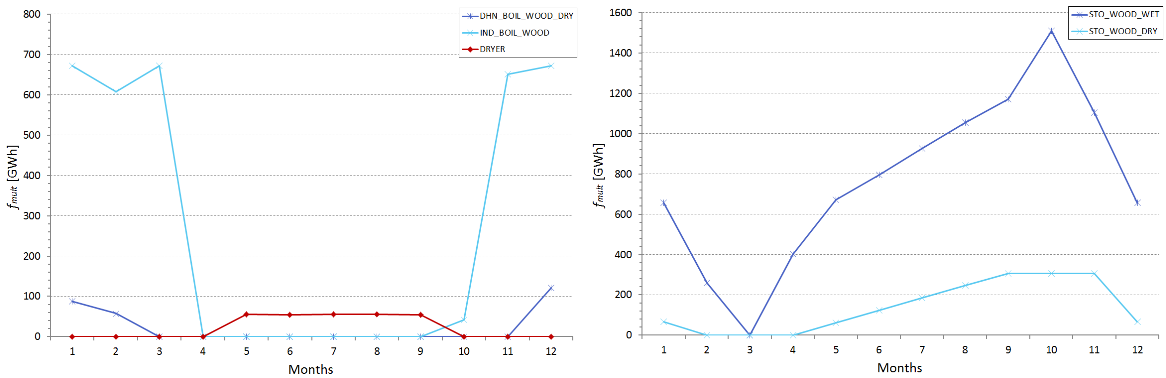


Figure 6.12: Resource costs (impact minimisation, scenario free_100%) $\sum C_{op} = 3272\, MCHF/y$

In this configuration biomass is used in several technologies. Combustion technologies are used mainly to supply heat during winter season. This is straightforward for DHN technologies because during winter the demand increases and it is important to use wood to supply heat for space heating, but it is less obvious for process heating which remains constant during the overall year. Now renewables are the main sources of the system and they produce a large amount of electricity which is used by electric heat pumps during winter and by direct heaters in process heating during summer. Industrial wood boilers are used during winter to substitute the heat supplied by direct heaters. Storage of dry wood is used to store dry wood produced by dryers during summer. Then dry wood is used during winter when heat demand increases. Storage of wet wood is still important to manage the biomass resources.

Fuel generation technologies are used to supply SGN and diesel for combustion and transport technologies (Fig. 6.14). Hydrothermal gasification (HTG) exploits all wet biomass to produce SNG, allowing the system to use the same amount of NG cars reducing the overall impact. Open ponds produce diesel from micro-algae and Fast pyrolysis for trucks. Since transport demand is constant over the year fuel generation technologies output remains quite constant. A small fluctuation is visible for technologies that exploit wood. Since wood is important to produce heat during winter fast pyrolysis and gasification and electrolysis (PWTOGAS) have higher load during summer than during winter season. SOFCs are not fuel generation technologies, but H_2 is produced by wood and NG, so their use is linked to other biomass technologies. Their load follows the demand in decentralised heating as fixed by Eq. (3.35).



(a) Combustion (b) Storage

Figure 6.13: f_{mult} for biomass combustion technologies (impact minimisation, scenario free_100%)

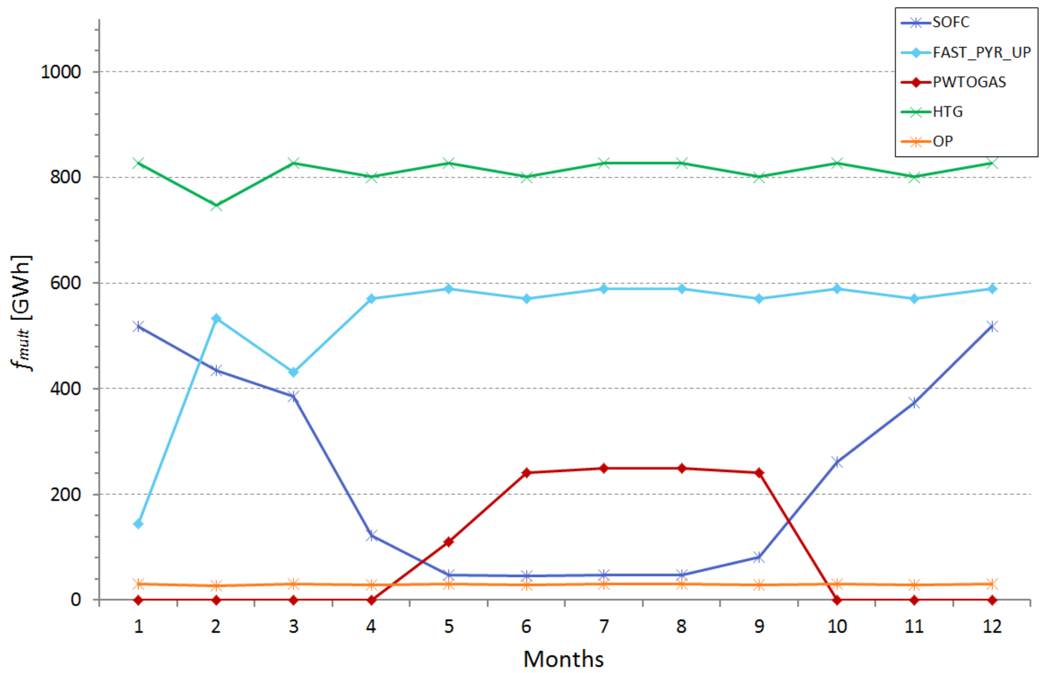


Figure 6.14: f_{mult} for biomass fuel generation technologies and SOFC (impact minimisation, scenario free_100%)

6.2.3 Best trade-off

The goal of the constrained optimisation is to find the best trade-off solutions between the two competing objectives. All these solutions are feasible and optimal under certain constraints and the decision maker can decide which is the best according to his priorities. One can prioritise costs without accounting for impact or can prioritise impact because thinking that it is really necessary to reduce GHG emissions to their feasible values. Here we think that it is possible to accept small increases in costs to reduce GHG emissions as low as possible. It is therefore important to consider the derivative

dEm_{TOT}/dC_{TOT} and define the best solutions as the ones in which this value is higher. All the fist part of the curve has good solutions, but since we want to decrease GHG emissions as low as possible the interval between 24 000 and 18 000 $ktons_{CO_2eq}/y$ is considered as the best trade-off. Four solutions are within this interval. But here the one with $C_{TOT} = 17297\,MCHF/y$ and $Em_{TOT} = 21966\,ktons_{CO_2eq}/y$ is shown. After this configuration the system needs to use FCs, open ponds, solar collectors and to increase the use of more efficient technologies such as HPs increasing the costs.

Technologies	f_{size}
	GW
Decentralised gas boilers	3.17
Decentralised heat pumps	3.95
Thermal heat pumps	4.75
Centralised dry wood boilers	1.38
Centralised wood boilers	0.31
Deep geothermal plants	0.30
Centralised heat pumps	1.72
Anaerobic digestion with CHP	0.32
BIGCC	1.10
Coal plants with CCS	0.50
Hydro dam plants	8.15
Hydro river plants	3.80
Wind turbines	4.50
Industrial waste boilers	1.33
Industrial wood boilers	0.80
Industrial gas cogenerators	0.81
Dryers	0.19

Table 6.6: Size of technologies (best configuration, free_100% scenario)

This configuration is an intermediate one also in terms of chosen technologies (Tab. 6.6). All technologies in the configuration with minimum costs are chosen except the ones that exploit coal, which is used in coal plants with carbon capture and storage (CCS) to reduce the impact related to the resource. The amount of renewable is increased with wind turbines and HPs reduce the installed power of decentralised boilers. Woody biomass is used in combustion technologies that can provide low cost such as centralised boilers or power plants (BIGCC) while wet biomass is exploited in anaerobic digesters with CHP.

The overall cost of technologies is still mostly related to hydro plants, but here wind turbines and HPs become important.

Natural gas is roughly six times bigger than other resources in terms of GWh. This resource consumption is very similar to the one in the first configuration (Tab. 6.3), but the amount of coal is strongly reduced. As a consequence the cost of resources is mostly related to natural gas (Fig. 6.16). The overall operational cost is similar to the investment cost of technologies.

In this configuration only combustion technologies are used. Dry wood is produced by dryers during summer and stored to be burned in centralised boilers during winter (Fig. 6.17).

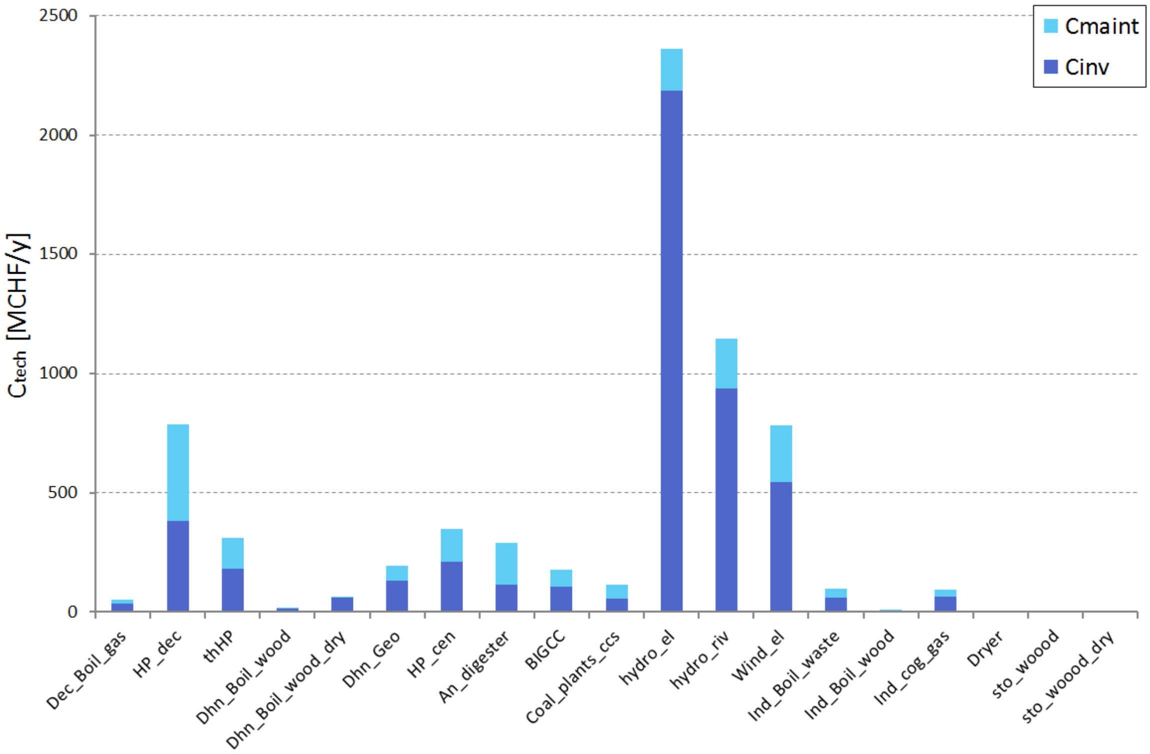


Figure 6.15: Technologies costs (best configuration, scenario free_100%)

Resources	$\sum f_{mult}$
	GWh/y
Natural gas	61695.49
MSW	12809.00
Gasoline	6178.62
Wood	12279.37
Diesel	8194.77
Coal	7811.00
Wet biomass	9743.56

Table 6.7: Resource consumption (best configuration, free_100% scenario)

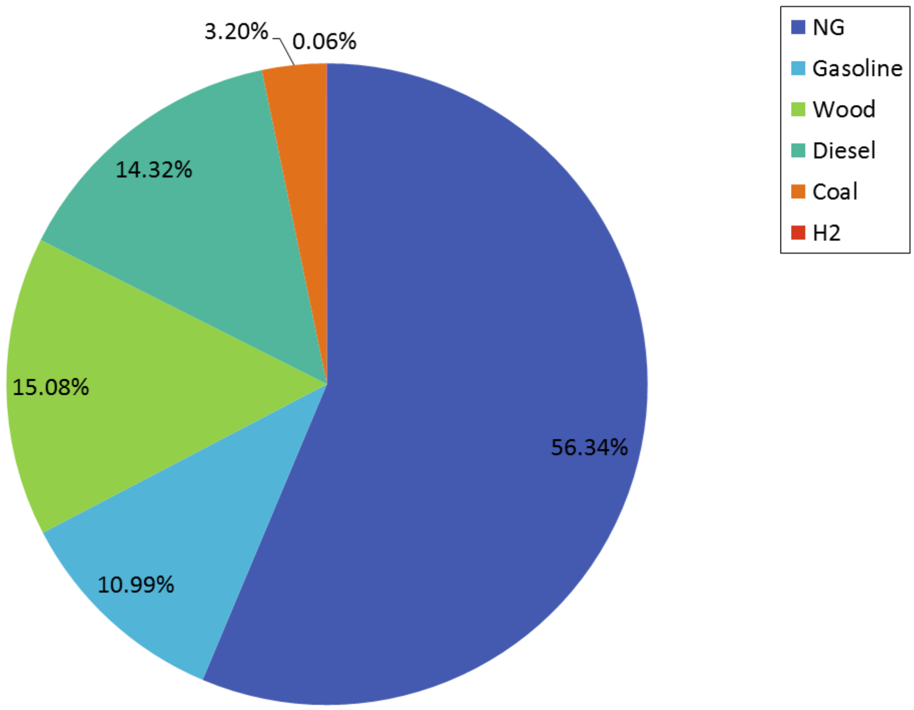
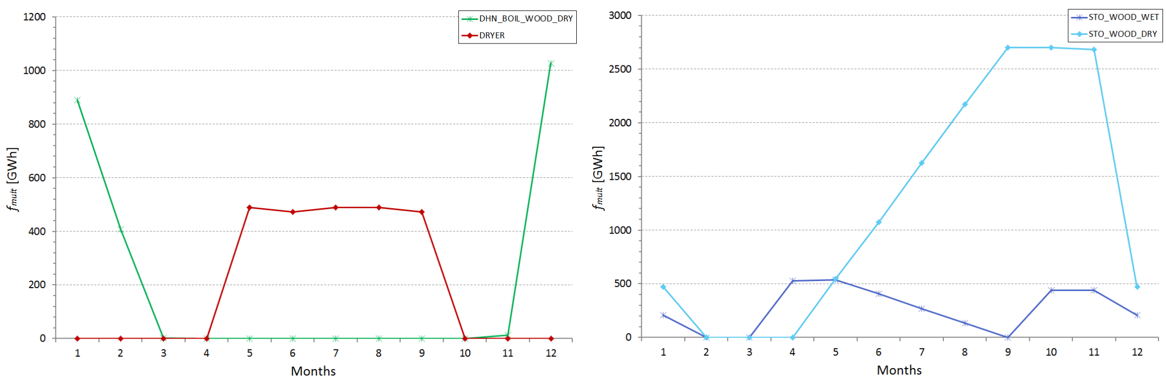


Figure 6.16: Resource costs (best configuration, scenario free_100%) $\sum C_{op} = 6331\, MCHF/y$)



(a) Combustion of dry wood (b) Storage

Figure 6.17: f_{mult} of biomass dry wood and storage technologies (best configuration, scenario free_100%)

Other woody biomass technologies are used in the same way since they mainly supply heat for houses (Fig. 6.18). Only industrial boilers maintain a high load during summer since process heating demand is constant during the overall year. All wet biomass is exploited in anaerobic digesters with practically the same load during the year.

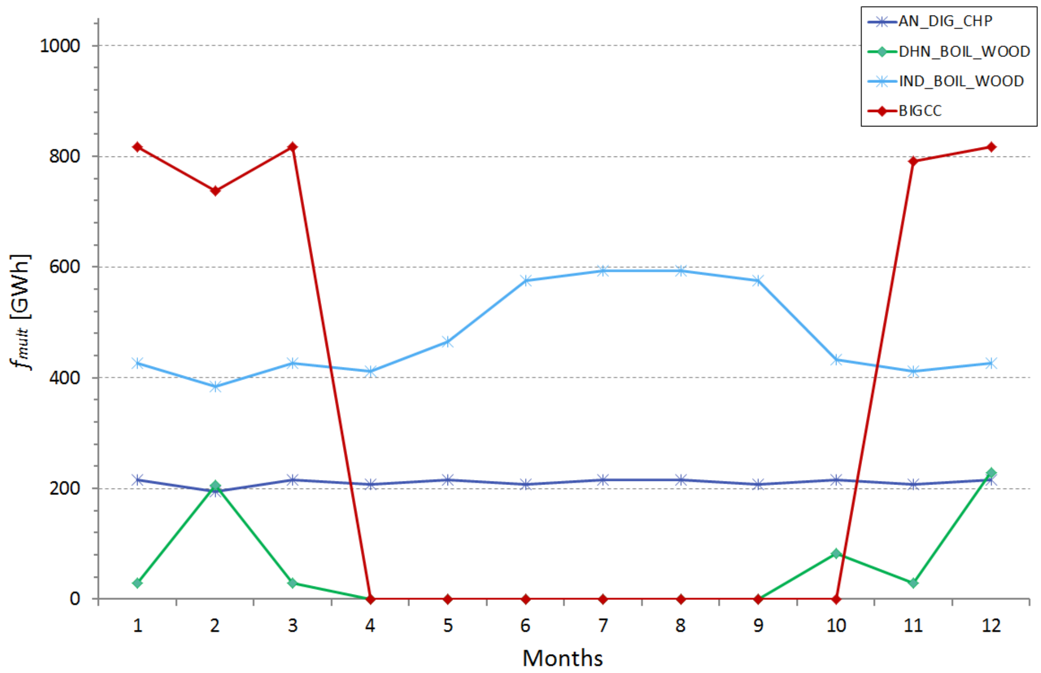


Figure 6.18: f_{mult} for biomass technologies (best configuration, scenario free_100%)

6.3 Results analysis

6.3.1 Fuel generation and combustion technologies

Creating the scenarios reported in Ch. 5 we tried to assess different biomass energy pathways where in each scenario all biomass is only used in one technology. This permits to determine which are the most promising biomass conversion technologies. In Sec. 6.1 these pathways are ranked and in Sec. 6.1.4 they are summarised. We found out that combustion technologies seem to be the best way to exploit biomass when the impact limit is higher. Their cost increase percentage is usually lower then fuel generation technologies and this is due to their lower investment and maintenance cost coefficient (c_{inv} and $c_{O\&M}$). When the impact limit decreases the optimiser tries to decrease the use of the resources because the impact associated to them is usually higher then the one associated to the construction of technologies. In this situation it is important also to exploit the resources with the most efficient technologies. Fuel generation technologies, which substitute fossil fuels with biofuels, seem to reduce emissions in a higher way. To prove that, in Fig. 6.19 two different scenarios have been compared. In the first one (No_fuel_gen) the use of fuel generation technologies has been avoided with Eq. (5.1) while in the second one (free_100%) they can be chosen by the optimiser. In each scenario biomass have to be exploited (Eq. (5.3)).

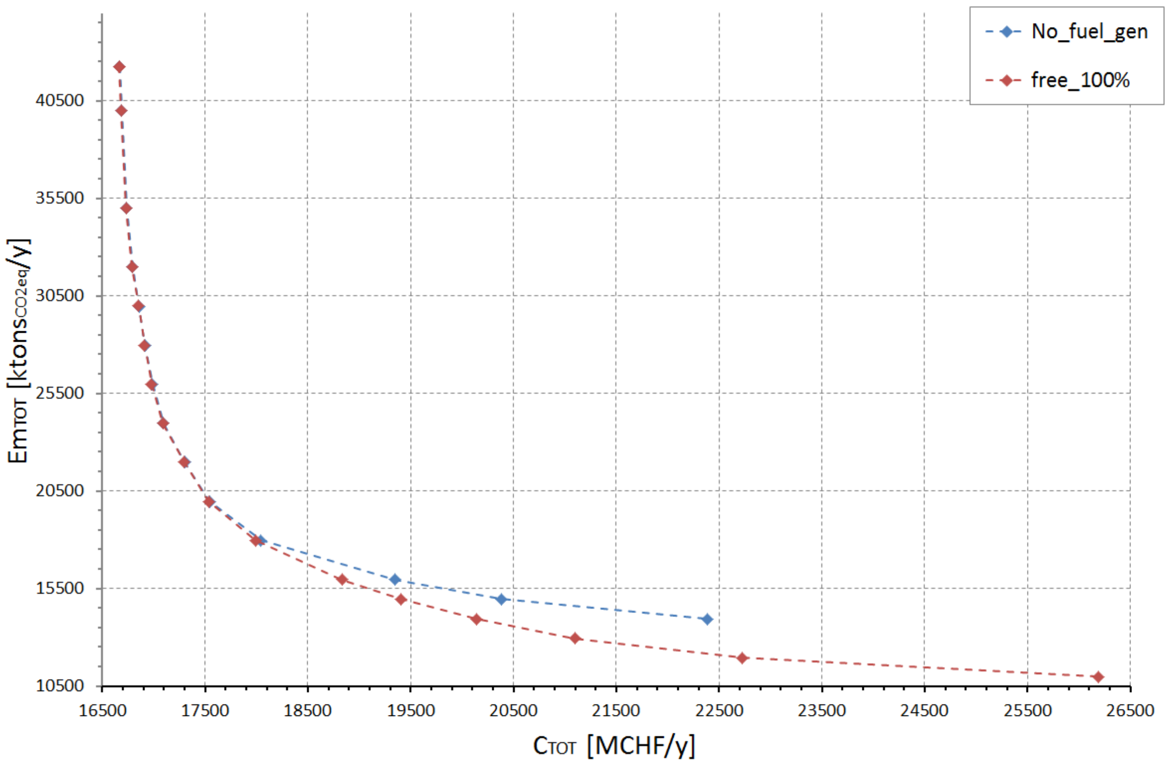


Figure 6.19: Fuel generation vs Combustion technologies

Here it is clear how fuel generation technologies become important to reduce the cost of the system when Em_{max} reaches 16 000 $ktons_{CO_2eq}/y$. Furthermore without fuel generation technologies the system can achieve only the value of 14 000 $ktons_{CO_2eq}/y$ while with them it is possible to reach roughly 11 000 $ktons_{CO_2eq}/y$.

In Fig. 6.20 values of cumulative emissions for free_100% scenario are plotted. Each configuration is related to one impact limit, therefore this figure represents the emission sources per each configuration. The overall emissions of the system are calculated as the sum of the emissions due to the resources and to the technologies. Emissions related to technologies are always negligible when the limit is higher than 16 000 $ktons_{CO_2eq}/y$. Natural gas (NG) and coal are the resources that are mostly used in the first configurations, therefore operational costs represent the largest part of total cost. After this value their quantity decreases because biofuels, renewables and more efficient technologies are used. Coal is used mainly when Em_{max} is higher because its cost (c_{op}) is the lowest one, but it is the first resource that the optimiser tries to substitute reducing the impact limit because of its high emission coefficients (em_{comb}, em_{op}). Natural gas is quite stable until 22 000 $ktons_{CO_2eq}/y$. The system tries first to substitute coal with natural gas because the latter provides lower emissions, but then also NG has to be substituted.

Emissions related to the other resources remain quite constant over different values of impact limit. The use of gasoline and diesel is related to transport sector whose technologies remain quite constant over different values of impact (Tab. 6.8).

The cost related to the technologies in transport sector has been fixed to zero (see Sec. 3.3). Therefore technologies that are chosen with higher impact limit are the ones that provide lower fuel consumption, but to have a low fuel consumption is the goal of

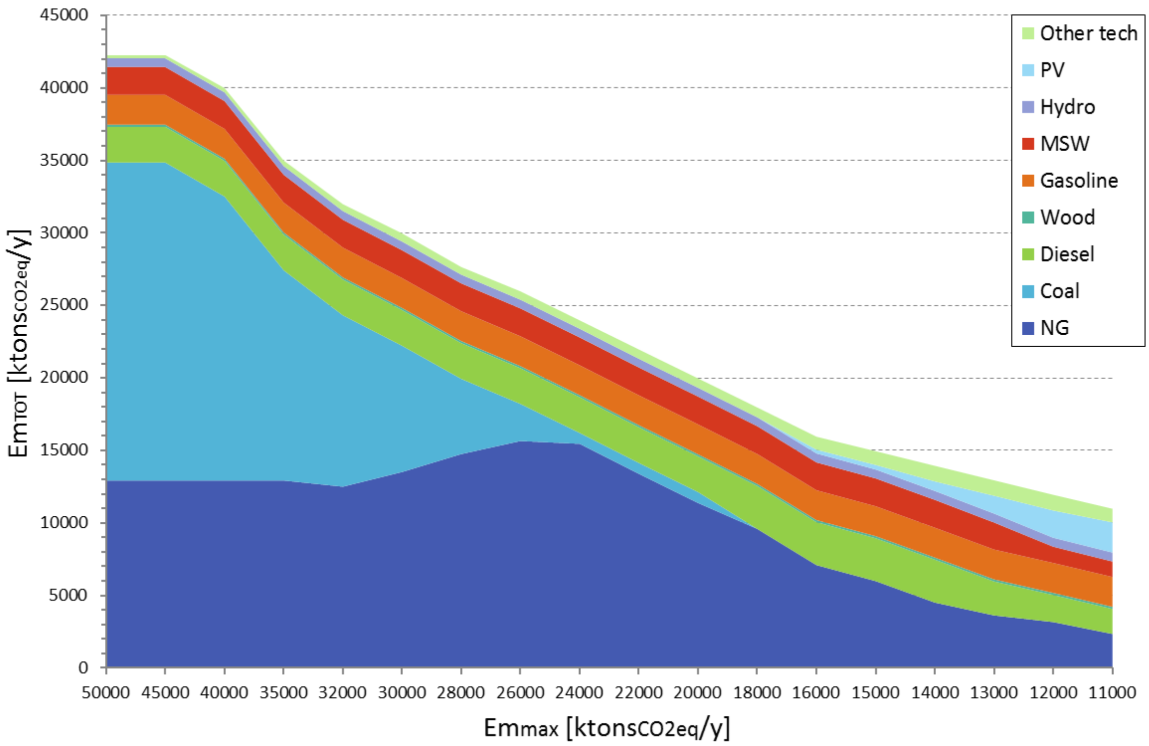


Figure 6.20: Cumulative E_{TOT} over different impact limit (free_100% scenario)

	Conf. n.1	*Conf. n.2*
Em_{max} $[ktons_{CO_2eq}/y]$	***50000***	***11000***
BEV car	1.67	1.67
FC car	0.08	0.08
HEV & PHEV car	3.57	3.57
NG car	3.01	3.01
NG bus	1.25	
Hybrid diesel bus		1.25
Public train	5.84	5.84
Tram & Trolley	1.25	1.25
Freight train	2.74	2.74
Freight truck	1.82	1.82

Table 6.8: f_{size} [Mpkm/h] for different transport technologies (free_100% scenario)

the optimisation when the impact limit is lower too. Hybrid diesel busses substitute NG busses because they can fulfil the demand consuming less fuel, but, apart from that, the same technologies are chosen over different values of impact. Gasoline and diesel consumption becomes quite constant while MSW potential is low amount, so there is no way to decrease the use of resources except reducing natural gas. When Em_{max} reaches 14 000 $ktons_{CO_2eq}/y$ all energy technologies that exploit natural gas are practically substituted, but there is still a NG demand for NG cars. Substituting them with diesel or gasoline cars would increase the emissions, so fuel generation technologies have to exploit biomass to produce NG for cars and diesel for trucks. In some configurations NG is also used to produce hydrogen for Solid-Oxide-Fuel-Cells (SOFCs) or it is burned in thermal heat pumps (ThHP) with high efficiency.

In Tab. 6.9 fuel generation technologies that are chosen in the scenario free_100% are reported.

	Conf. n.1	*Conf. n.2*	*Conf. n.3*
Em_{max} [$ktons_{CO_2eq}/y$]	***18000***	***14000***	***11000***
SOFC	0.02	0.40	0.70
Open ponds	0.04	0.04	0.04
Hydrothermal gasification		1.26	1.26
Gasification with electrolysis			0.38
Fast pyrolysis with upgrading			0.82

Table 6.9: f_{size} [GW] for different fuel generation technologies (free_100% scenario)

SOFCs do not generate fuels, but they are included in Tab. 6.9 because we need to produce it from NG and wood through a fuel generation process to generate the hydrogen for them. Fuel generation technologies start to be used in the system when Em_{max} reaches 18 000 $ktons_{CO_2eq}/y$. SOFCs are used for cogeneration in decentralised heating and open ponds produce biodiesel from algae. These technologies have an high investment and maintenance cost but they have a high efficiency. Especially SOFCs have a high electrical efficiency which leads to low resource consumption while open ponds produce biodiesel without requiring any fossil fuel and considering only one plant it is possible to produce biodiesel with:

$$C_{Open\,ponds} = \tau C_{inv} + C_{maint} = 29.33 + 27.69 = 57.02\, MCHF/y \tag{6.1}$$

Wet biomass is used to produce SNG. It has not any emissions associated, therefore fuel generation technologies can substitute fossil NG reducing the emissions. When the limit is lower than 14 000 $ktons_{CO_2eq}/y$ woody biomass starts to be used in fast pyrolysis to produce diesel for transport. Gasification with electrolysis can take advantage of the large amount of electricity that is produced in the system by photovoltaic panels (PV) and hydro dams to produce SNG. In these configuration combustion technologies are still used to substitute heat produced by coal and NG boilers.

6.3.2 Readiness level

In the previous scenarios we considered that all technologies that have been implemented will be available in the year 2035. This expectation for the reference year is reasonable and it is supported by the studies that assessed the energy technologies. In spite of that, in this section we want to understand how the configuration can change if only commercial technologies are available in the system. In this way we can obtain some configurations that will be for sure feasible in the reference year. Now the definition of the *technology readiness level* (TRL) becomes important to understand which are the commercial and non-commercial technologies. TRL is are a method of estimating technology maturity. In [7] nine levels are defined to express the technologies maturity. Here a simplified approach is used by dividing the whole range in three levels:

- Level 1, Idea - stage ($1 < \text{TRL} < 3$):
  The technology has not even been validated in the lab. Only experimental proof of concepts has been done;

- Level 2, Development stage ($4 < \text{TRL} < 7$):
  The technology has been validated in the lab, in a relevant environment or in a system prototype demonstration;

- Level 3, Commercial stage ($8 < \text{TRL} < 9$):
  The technology has been proved in operational environment.

Data about RL are available in Tab. A.1.

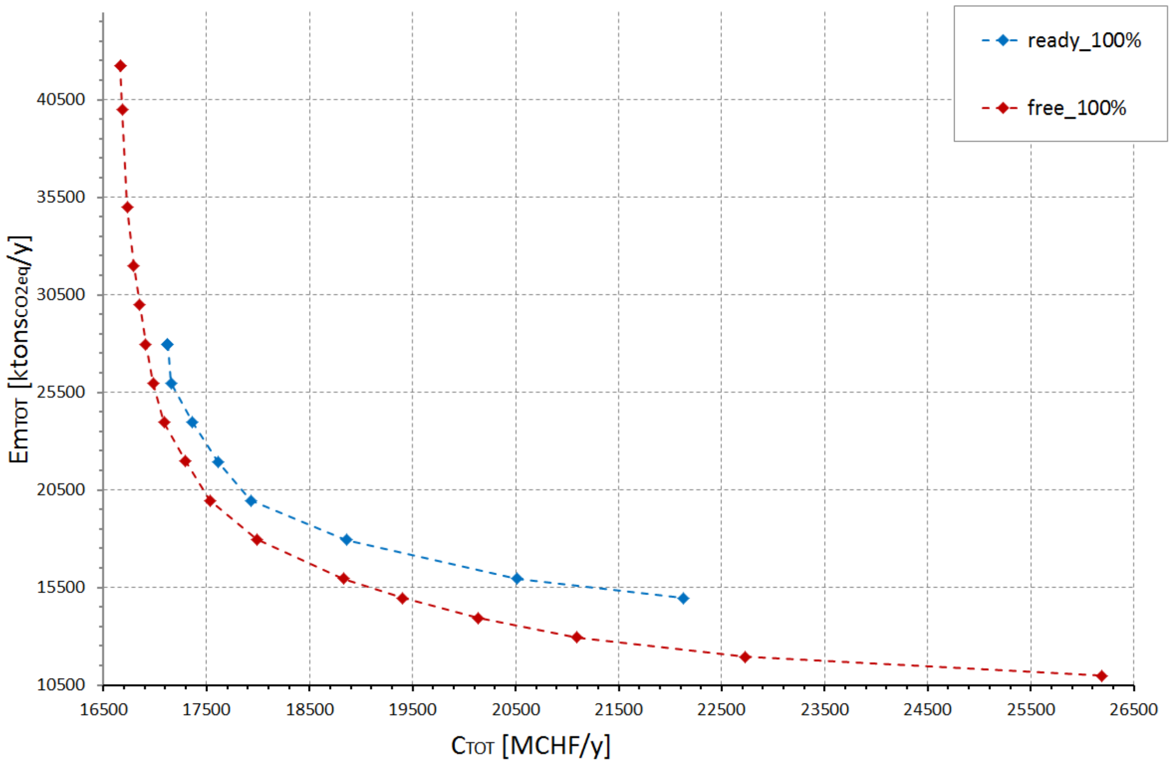


Figure 6.21: Only commercial technologies (ready_100% scenario)

	Conf. n.1	*Conf. n.2*
Em_{max} $[ktons_{CO_2eq}/y]$	***28 000***	***15 000***
Decentralised gas boiler	14.95	1.04
Centralised wood boiler	1.13	
Centralised dry wood boiler	0.59	0.20
Centralised heat pump	0.01	3.56
Anaerobic digestion with CHP	0.32	0.32
hydro dam plants	8.11	8.20
hydro river plants	3.80	4.50
Wind turbines	4.50	4.50
Wood boiler for industry	1.33	1.03
Waste boiler for industry	0.94	1.20
Gas cogenerator for industry	0.96	0.92
Dryer	0.12	0.02
Decentralised wood boiler		2.04
Decentralised solar		8.72
Decentralised heat pump		8.31
Deep geothermal plants		1.04
Photovoltaic panels		22.71
Direct electricity for industries		2.58

Table 6.10: Chosen technologies (ready_100% scenario)

Fig. 6.21 represents the comparison between two scenarios. The first one (free_100%) has been previously explained and in the other one (ready_100%) only commercial technologies (RL=3) are available. The use of all technologies that has a readiness level lower than 3 has been avoided via Eq. (5.1). The results are easily understandable if we consider Fig. 6.20. Since all the technologies that exploit coal are considered technologies under development because they are both supercritical and IGCC plants, they can not be used in the system and all scenarios where coal is used are not feasible. As a result the curve (ready_100%) starts from lower values of impact than free_100% (28000 $ktons_{CO_2eq}/y$). Furthermore fuel generation technologies are not available, therefore the curve can reach only 15000 $ktons_{CO_2eq}/y$. As found in previous scenarios different configurations show an increase of renewables and biomass technologies (Tab. 6.10). Particularly decentralised boilers seem to be a good choice to substitute non-commercial technologies in decentralised heating reducing the use of natural gas in gas boilers.

6.3.3 Biomass use

In previous scenarios the overall amount of biomass that has to be used in the system has been fixed. All sustainable biomass potential has been considered as the amount of biomass that has to be exploited. Here a scenario *free*, i.e. where the overall amount of biomass has not been fixed (without Eq. (5.3)), has been assessed to understand if to exploit biomass partially could be more interesting.

In Fig. 6.22 the curve *free* starts from higher values of impact since the use of biomass is not mandatory. Biomass is substituted by coal or NG which are less expen-

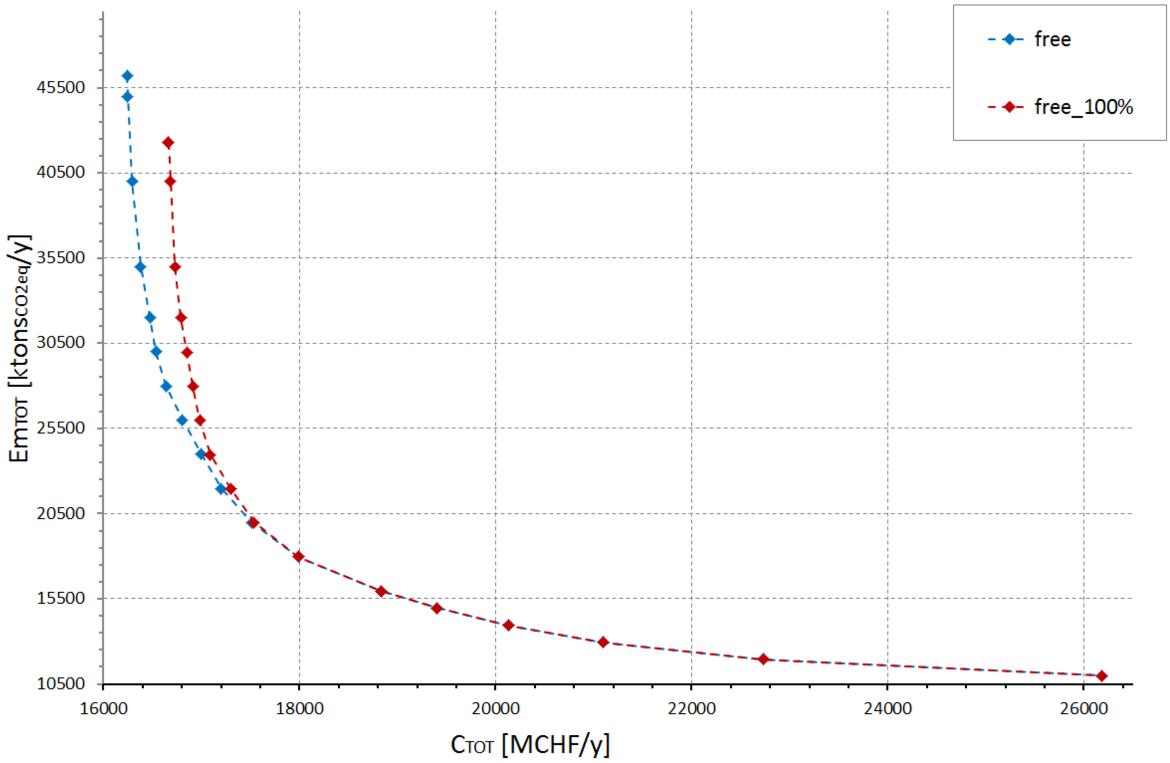


Figure 6.22: Partial use of biomass (free scenario)

sive.

The amount of biomass increases with impact reduction and when the limit reaches 18 000 $ktons_{CO_2eq}/y$ the system uses all available woody biomass. Until 24 000 $ktons_{CO_2eq}/y$ only the 0.74% of the total amount of woody biomass is used to produce hydrogen for transport. Then, between 24 000 and 18 000 $ktons_{CO_2eq}/y$, this amount increases until the maximum value. Wet biomass increases from the first configuration until the limit reaches 28 000 $ktons_{CO_2eq}/y$, where its value stops at 91% of the total amount. When E_{max} reaches 20 000 $ktons_{CO_2eq}/y$ the amount of wet biomass equals the availability (Fig. 6.23).

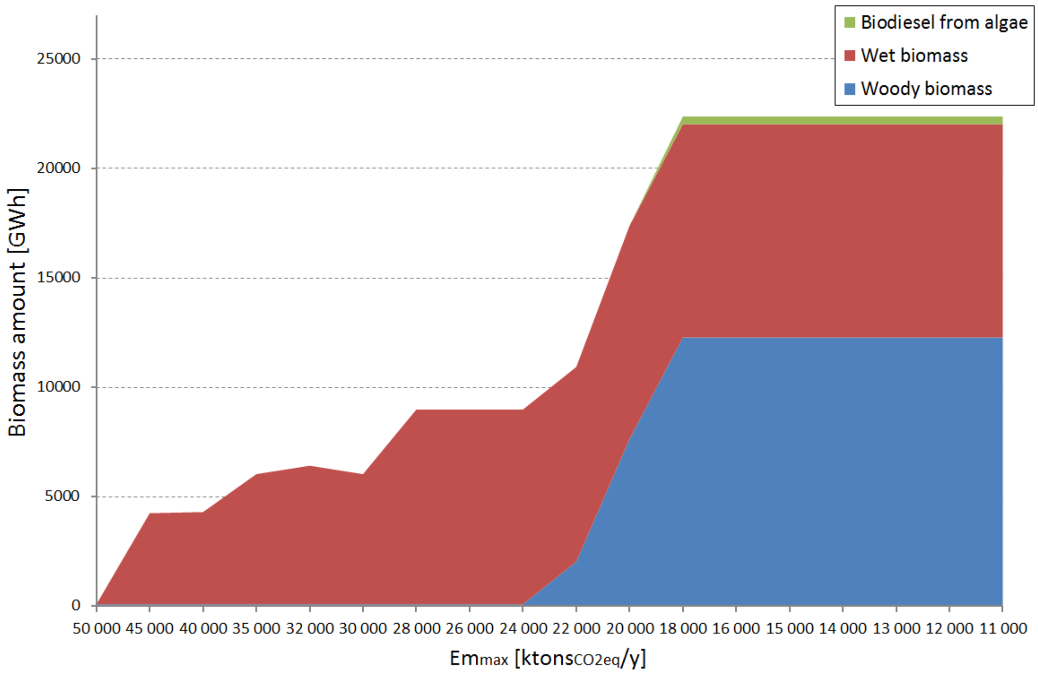


Figure 6.23: Amount of biomass (free scenario)

Chapter 7

Conclusions

Through this thesis we tried to evaluate the impact of integrating biomass technologies in the Swiss energy system including storage. A model that describes the Swiss energy system has been developed and it is used to assess the most promising biomass conversion technologies. The best configurations of the system according to economic and environmental aspects are determined and discussed. These results represent a possible guide-line for decision makers to understand how the Swiss energy system can be erected and how biomass resources can be exploited in the absence of nuclear power production.

In Ch. 2 a classification of biomass resources and technologies is provided and the overall sustainable potential in Switzerland is calculated. Biomass technologies are divided between combustion technologies, i.e. they provide electricity or heat by burning biomass, and fuel generation technologies, i.e. they convert biomass into biofuels. In Ch. 3 the model is reported. First the characteristics of the tools are discussed, then the equations of the model are listed. In Ch. 4 the optimisation problem and the methodology are stated. The optimisation problem is defined as a MILP problem, where integer and non-integer variables are used to optimise the system. In Ch. 5 different scenarios are defined. *Single-technology scenarios*, where all biomass is used only by one technology, are compared with *reference scenarios*, where the biomass can be used by more then one technology. In Ch. 6 the results are determined with a *constrained optimisation* and then they are analysed. A ranking of biomass technologies is provided considering the costs increase percentage of the scenarios over different values of the emission limit. Then the best configurations of the Swiss energy system according to economic and environmental aspects are shown highlighting the importance of biomass utilisation.

For *single-technology scenarios* the results show a variation of the increase of cost percentage compared to reference scenarios varying the limit of the impact in terms of GHG emissions. In general, common commercial technologies, such as combustion technologies, proved to be the best way to exploit biomass when the limit is higher ($50000 < Em_{TOT} < 16000\, ktons_{CO_{2}eq}/y$) especially if they have a big size, i.e centralised and industrial combustion technologies. Large fuel generation plants are also interesting because they can take advantage of the economic scale. When the limit is reduced under $\approx 16000\, ktons_{CO_{2}eq}/y$ also medium size fuel generation technologies starts to become interesting. Fast pyrolysis with oil upgrading proved to be one of the best choices to exploit woody biomass when the impact limit is reduced, but also gasification with SNG production and SBBD. Among combustion technologies industrial boilers are the best choice to exploit wood when the impact limit is lower. To exploit wet biomass the production of heat and power after anaerobic digestion proved to be cheaper than other options, but, when the impact limit is at its lowest value, hydrothermal gasification becomes the best option because of its high conversion efficiency. Open ponds demonstrated to be the best option to produce biodiesel from algae, but further investigations should be done to evaluate the impact of losses of water. The best configurations ($24000 < Em_{TOT} < 18000\, ktons_{CO_{2eq}}/y$) combine these biomass technologies and they change according to the value of the GHG emission limit. When the limit is higher only the cheapest technologies are chosen, for intermediate values a combination of combustion technologies can supply the demand and with the lowest limit some other fuel generation technologies, such as gasification with electrolysis can take advantage of the configuration and become interesting.

Configurations where only commercial technologies are available proved to be more expensive than reference ones while partial use of all sustainable potential of biomass demonstrated to be an interesting option. Among the best configurations partial use of woody biomass permits to reach the required limit of GHG emissions with lower costs. Particularly, in the best configuration presented in Sec. 6.2.3, by using only 16% of the total woody biomass and 91% of the wet biomass it is possible to achieve the same GHG emissions with a cost reduction of roughly 100 MCHF/y.

As written above, these results want to be a possible guide-line for decision makers to understand how the Swiss energy system can be realised and how biomass resource can be exploited in the absence of nuclear power plants. In the next future these configurations can be further tested with a real multi-objective optimisation, assessing the trade-off between costs and impacts and determining the best configurations of the system according to both objectives. More energy technologies can be implemented and previous models can be further developed.

In the long terms it will be possible to switch from black-box models into flow-sheeting models and to include the possibility to set up the heat cascade using pinch analysis and process energy integration to optimise the system. Clearly it will increase the computational time, but also the accuracy of the model. Then it is possible to add the spatial characteristics of the problem by dividing the geographical area into a number of individual networks that interact with each other (clusters). Moreover, accounting for uncertainties is important in long term energy planning. Data about costs and demand can be different than the considered ones. With this analysis it will be possible to determine which are the most affecting parameters and which are the best configurations of the system if demands and costs change.

Appendices

Appendix A

Data

This appendix reports all data about technologies and resources. In Tab. A.1 all data that have been used as an input for technology models are reported. These values have been taken either from Energyscope calculator [20], from ecoinvent v 3.2 [13] database and from other various studies. Before the first intermediate line, all technologies that are available in the current Energyscope calculator are reported. Data have been further elaborated to obtain the values in the required unit. Costs data in [15] are the average for the year 2012, therefore they have been scaled with CEPCI at a later time. The maximum load (f_{max}) of CCS technologies is reduced from the one in the calculator according to [22]. Then in centralised technologies, i.e. the ones that produce heat for DHN, an additional cost is implemented to account for the costs related to the connection to the DHN. A fixed cost of 866 MCHF/GW with depreciation time of 60 y has been used. By using the formulation in Eq. (3.19) and annualising the investment cost it is possible to determine the value of the additional cost. C_{fix} has been used to account for the costs related to the construction of the grid and the efficiency improvement in buildings. A fixed cost of 1720.71 MCHF/y is used for the efficiency improvement and 68100 MCHF with depreciation time of 80 y has been used for the grid. All other information about the operation of these technologies are available in [15].

After these technologies, all mobility technologies are listed. The model is simplified because costs and emission data are not used (see. Sec. 3.3) but $f_{max,perc}$ is defined according to [15] and [2] to obtain consistent results. Then two storage technologies are reported. Pumped hydro is associated to hydro dam plants, so its cost is linked with hydro dams. Storage of wood costs have been taken from Rentizelas et al. [56], these values are lower then the ones of other technologies because their unit is $MCHF/GWhy$.

Biomass technologies are listed in the end of the table. Their costs data have been calculated according to Sec. 3.3 by using reduction coefficients. Particularly data of the dryer have been taken from [29], emission data of algae technologies have been taken from [13] considering the ones from chemical plants, while emissions of gasification plus electrolysis or fuel cell has been calculated by adding emissions related to all components to the gasifier (GASIF).

In Tab. A.2 the values of $\eta_{in/out}(l,u)$ per each resource and per each layer are reported. The output of the resource "ELECTRICITY" refers to the layer electricity while GASOLINE refers to the layer gasoline, where the value of η is one. f_{mult} is defined in that layer where η is one , so the value of f_{supp} of that layer is equal to the value of f_{mult} (see. Eq. (3.25)). NG, wood and electricity are required to produce H_2 for transport. The model has to take into account the conversion costs from these resources to hydrogen, so a cost of $c_{op} = 0.031\, MCHF/GWh$ has been considered. Then to produce H_2 for cogenerators only NG and wood are required. Here a cost of $c_{op} = 0.035\, MCHF/GWh$ has been used to account for the conversion.

From Tab. A.3 to Tab. A.11 the same structure has been used. In each table are listed the technologies whose f_{mult} is defined in the layer stated in the caption. Particularly in Tab. A.3 the input and the output for demands are defined. $Heat_{DEC}$ and $Heat_{DHN}$ are the demands in the respective layer and they represent the input for $Heat_{LOW,T}$ which is fixed in the model. Their output is limited with f_{min} and f_{max} defined in Sec. 3.4.

In Tab. A.12 all data about $c_{p,t}$ has been reported per each operative time, the output profile of these technologies is fixed by Eq. (3.27), while in Tab. A.13 the efficiency of storage technologies has been reported. The efficiency of wood storage is not equal to one according to [56].

Table A.1: Technologies data

$Units\, u \in Technologies$	ref_{size}	c_{inv}	c_{maint}	f_{min}	f_{max}	$f_{max,perc}$	lt	c_p	em_{const}	RL
	GW or GWh/y	$\frac{MCHF}{GW}$	$\frac{MCHF}{GWy}$	GW or $Mpkm$	GW or $Mpkm$	%	y	[-]	$\frac{ktons_{CO_2eq}}{GWy}$	[-]
CCGT	0.5	913.87	24.76	0.5	10	100	25	0.85	15.71	3
CCGT_CCS	0.5	1537.39	44.14	0.5	0.5	100	25	0.85	15.71	2
COAL_S	0.5	2126.97	61.37	0.5	10	100	40	0.87	8.29	2
COAL_US	0.5	1988.73	67.83	0.5	10	100	40	0.87	8.29	2
COAL_AUS	0.5	2400.00	67.83	0.5	10	100	40	0.89	8.29	2
COAL_IGCC	0.5	1986.46	82.90	0.5	10	100	40	0.86	8.29	2
COAL_S_CCS	0.5	3403.15	86.13	0.5	0.5	100	40	0.87	8.29	2
COAL_US_CCS	0.5	3181.98	95.20	0.5	0.5	100	40	0.87	8.29	2
COAL_AUS_CCS	0.5	3840.00	95.20	0.5	0.5	100	40	0.89	8.29	2
COAL_IGCC_CCS	0.5	2383.75	109.82	0.5	0.5	100	40	0.86	8.29	2
PV	0.001	2214.44	32.14	0	25	100	25	1	83.26	3
WIND	0.001	1692.54	51.08	0	4.5	100	20	1	31.41	3
HYDRO_DAM	0.100	5686.53	20.76	8.1	8.2	100	40	1	64.15	3
HYDRO_RIVER	0.010	5300.00	53.00	3.8	4.5	100	40	1	20.22	3
GEOTHERMAL	0.010	11164.48	390.76	0	0.7	100	20	0.85	1246.45	3
IND_COGEN_GAS	0.020	1307.81	33.62	0	20	100	25	0.90	19.64	3
IND_COGEN_WASTE	0.020	3127.34	175.58	0	20	100	25	0.80	14.70	3
IND_BOILER_GAS	0.001	58.20	1.16	0	20	100	17	0.95	3.08	3
IND_BOILER_OIL	0.001	58.20	1.16	0	20	100	17	0.95	1.20	3
IND_BOILER_COAL	0.001	574.04	27.13	0	20	100	17	0.90	3.20	3
IND_BOILER_WASTE	0.001	574.04	27.13	0	20	100	17	0.90	21.62	3
IND_DIRECT_ELEC	0.001	283.73	13.68	0	20	100	15	0.95	0.10	3
DHN_HP_ELEC	0.001	1464.73	75.92	0	20	70	25	0.95	6.60	3

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$Units\, u \in Technologies$	ref_{size}	c_{inv}	c_{maint}	f_{min}	f_{max}	$f_{max,perc}$	lt	c_p	em_{const}	RL
	GW or GWh/y	$\frac{MCHF}{GW}$	$\frac{MCHF}{GWy}$	GW or $Mpkm$	GW or $Mpkm$	%	y	[-]	$\frac{ktons_{CO_2eq}}{GWy}$	[-]
DHN_COGEN_GAS	0.020	1307.81	33.62	0	20	100	25	0.95	19.64	3
DHN_COGEN_WASTE	0.020	3127.34	175.58	0	20	100	25	0.95	14.70	3
DHN_BOILER_GAS	0.001	58.20	1.16	0	20	100	17	0.95	3.08	3
DHN_BOILER_OIL	0.001	58.20	1.16	0	20	100	17	0.95	1.20	3
DHN_DEEP_GEO	0.010	5684.28	198.95	0	20	30	20	0.85	634.62	3
DEC_HP_ELEC	0.001	1486.21	99.34	0	20	70	23	0.95	7.17	3
DEC_THHP_GAS	0.001	532.35	26.62	0	20	40	20	0.95	20.97	2
DEC_COGEN_GAS	0.001	2349.41	110.18	0	20	100	20	0.95	36.68	2
DEC_COGEN_OIL	0.001	1960.08	87.35	0	20	100	20	0.95	37.73	2
DEC_ADVCOGEN_GAS	0.001	31206.62	624.69	0	20	15	20	0.95	95.54	2
DEC_ADVCOGEN_H2	0.001	31206.62	624.69	0	20	5	20	0.95	95.54	2
DEC_BOILER_GAS	0.001	142.20	4.27	0	20	100	17	0.95	3.08	3
DEC_BOILER_OIL	0.001	142.20	4.27	0	20	100	17	0.95	3.08	3
DEC_SOLAR	0.001	2089.93	28.21	0	20	40	20	1	15.30	3
DEC_DIRECT_ELEC	0.001	239.72	8.08	0	20	20	15	0.95	0.10	3
TRAMWAY_TROLLEY	[-]	0	0	0	16.7	15	[-]	[-]	0	3
BUS_COACH_DIESEL	[-]	0	0	0	16.7	30	[-]	[-]	0	3
BUS_COACH_HYDIESEL	[-]	0	0	0	16.7	30	[-]	[-]	0	3
BUS_COACH_CNG_STOICH	[-]	0	0	0	16.7	30	[-]	[-]	0	3
BUS_COACH_FC_HYBRIDH2	[-]	0	0	0	16.7	1	[-]	[-]	0	2
TRAIN_PUB	[-]	0	0	0	16.7	70	[-]	[-]	0	3
CAR_GASOLINE	[-]	0	0	0	16.7	100	[-]	[-]	0	3
CAR_DIESEL	[-]	0	0	0	16.7	100	[-]	[-]	0	3
CAR_NG	[-]	0	0	0	16.7	1	[-]	[-]	0	3

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$Units\, u \in Technologies$	ref_{size}	c_{inv}	c_{maint}	f_{min}	f_{max}	$f_{max,perc}$	lt	c_p	em_{const}	RL
	GW or GWh/y	$\frac{MCHF}{GW}$	$\frac{MCHF}{GWy}$	GW or $Mpkm$	GW or $Mpkm$	%	y	[-]	$\frac{ktons_{CO_2eq}}{GWy}$	[-]
CAR_HEV	[-]	0	0	0	16.7	30	[-]	[-]	0	3
CAR_PHEV	[-]	0	0	0	16.7	30	[-]	[-]	0	3
CAR_BEV	[-]	0	0	0	16.7	20	[-]	[-]	0	3
CAR_FUEL_CELL	[-]	0	0	0	16.7	1	[-]	[-]	0	2
TRAIN_FREIGHT	[-]	0	0	0.92	3.2	100	[-]	[-]	0	3
TRUCK	[-]	0	0	0.92	3.2	100	[-]	[-]	0	3
PUMPED_HYDRO	[-]	0	0	0	2400	[-]	[-]	[-]	0	3
STO_WOOD_WET	30	0.02030	0.00081	0	10000	[-]	25	[-]	0	3
STO_WOOD_DRY	60	0.01728	0.00069	0	10000	[-]	25	[-]	0	3
BIGCC	0.200	961.80	59.38	0.2	10	100	20	0.74	17.79	2
DEC_MGT	0.001	3008.43	181.01	0	20	100	15	0.91	3.68	1
DEC_WGB	0.001	634.40	10.15	0	20	100	50	0.23	2.25	1
HTG	0.005	1919.95	383.99	0	20	100	15	0.88	2.68	2
AN_DIG_CHP	0.005	5620.59	540.46	0	20	100	25	0.91	29.61	3
AN_DIG_UP	0.005	2303.90	138.23	0	20	100	20	0.91	9.61	2
FAST_PYR_UP	0.010	2180.05	248.56	0	20	100	20	0.91	0.62	2
SBBD	0.020	7255.12	827.21	0.02	20	100	20	0.91	29.01	1
GASIF	0.020	22636.10	1366.54	0	20	100	20	0.80	25.32	2
GAS_EL	0.020	2481.52	148.89	0	20	100	20	0.80	28.18	1
GAS_SOFC_GT	0.010	5752.42	345.15	0	20	100	15	0.91	26.94	1
F_T	0.200	1391.59	83.50	0.2	20	100	25	0.91	1.84	2
F_T_el	0.200	4805.05	288.30	0.2	20	100	25	0.91	1.84	2
FAST_PYR	0.010	850.22	51.01	0	20	100	20	0.91	2.30	2

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$Units\, u \in Technologies$	ref_{size}	c_{inv}	c_{maint}	f_{min}	f_{max}	$f_{max,perc}$	lt	c_p	em_{const}	RL
	GW or GWh/y	$\frac{MCHF}{GW}$	$\frac{MCHF}{GWy}$	GW or $Mpkm$	GW or $Mpkm$	%	y	[-]	$\frac{ktons_{CO_2eq}}{GWy}$	[-]
PBR_ALGAE	0.040	25689.34	1541.36	0.04	20	100	20	0.92	199.90	2
OP_ALGAE	0.040	10120.04	607.20	0.04	20	100	20	0.92	199.90	2
DRYER	0.001	337.72	16.89	0	20	100	50	1	0.73	3
DHN_WOOD_BOILER_DRY	0.020	103.30	2.07	0	20	100	17	0.95	5.04	3
DHN_COGEN_WOOD	0.020	1822.58	82.88	0	20	100	25	0.95	0.65	3
DHN_BOILER_WOOD	0.020	103.30	2.07	0	20	100	17	0.95	5.04	3
IND_COGEN_WOOD	0.020	1822.58	82.88	0	20	100	25	0.80	0.65	3
IND_BOILER_WOOD	0.001	103.30	2.07	0	20	100	17	0.95	5.04	3
DEC_COGEN_WOOD	0.001	1201.53	41.25	0	20	100	20	0.95	20.12	2
DEC_BOILER_WOOD	0.001	543.20	19.01	0	20	100	17	0.95	6.62	3

Table A.1: Technologies data

$Units\, u \in Resources$	Layers											
	Electricity	Gasoline	Diesel	Oil	NG	Wet wood	Coal	MSW	$H_{2,trans}$	$H_{2,cog}$	Wet biom	Dry wood
ELECTRICITY	1	0	0	0	0	0	0	0	0	0	0	0
GASOLINE	0	1	0	0	0	0	0	0	0	0	0	0
DIESEL	0	0	1	0	0	0	0	0	0	0	0	0
OIL	0	0	0	1	0	0	0	0	0	0	0	0
NG	0	0	0	0	1	0	0	0	0	0	0	0
WOOD_WET	0	0	0	0	0	1	0	0	0	0	0	0
COAL	0	0	0	0	0	0	1	0	0	0	0	0
URANIUM	0	0	0	0	0	0	0	0	0	0	0	0
WASTE	0	0	0	0	0	0	0	1	0	0	0	0
H2_TRANS	-0.470	0	0	0	-0.417	-0.694	0	0	1	0	0	0
H2_COGEN	0	0	0	0	-0.625	-1.042	0	0	0	1	0	0
WET_BIOM	0	0	0	0	0	0	0	0	0	0	1	0
WOOD_DRY	0	0	0	0	0	0	0	0	0	0	0	1

Table A.2: $\eta_{in/out}(l, u)$ per each resource unit

Units	*Layers*								
	$Heat_{DEC}$	$Heat_{DHN}$	$Heat_{LOW,T}$	Mob_{priv}	Mob_{pub}	Mob_{pass}	$Mob_{freight,rail}$	$Mob_{freight,truck}$	$Mob_{freight}$
HEAT_DEC	-1	0	1	0	0	0	0	0	0
HEAT_DHN	0	-1	1	0	0	0	0	0	0
MOB_PRIV	0	0	0	-1	0	1	0	0	0
MOB_PUB	0	0	0	0	-1	1	0	0	0
MOB_FREIGHT_RAIL	0	0	0	0	0	0	-1	0	1
MOB_FRIGHT_TRUCK	0	0	0	0	0	0	0	-1	1

Table A.3: $\eta_{in/out}(l, u)$ per each demand unit

$Units\, u \in MobTechnologies$	*Layers*									
	Electricity	Gasoline	Diesel	Oil	NG	$H_{2,trans}$	Mob_{pub}	Mob_{priv}	$Mob_{freight,rail}$	$Mob_{freight,road}$
TRAMWAY_TROLLEY	-0.165	0	0	0	0	0	1	0	0	0
BUS_COACH_DIESEL	0	0	-0.265	0	0	0	1	0	0	0
BUS_COACH_HYDIESEL	0	0	-0.183	0	0	0	1	0	0	0
BUS_COACH_CNG_STOICH	0	0	0	0	-0.306	0	1	0	0	0
BUS_COACH_FC_HYBRIDH2	0	0	0	0	0	-0.225	1	0	0	0
TRAIN_PUB	-0.092	0	0	0	0	0	1	0	0	0
CAR_GASOLINE	0	-0.430	0	0	0	0	0	1	0	0
CAR_DIESEL	0	0	-0.387	0	0	0	0	1	0	0
CAR_NG	0	0	0	0	-0.483	0	0	1	0	0
CAR_HEV	0	-0.247	0	0	0	0	0	1	0	0
CAR_PHEV	-0.045	-0.176	0	0	0	0	0	1	0	0
CAR_BEV	-0.107	0	0	0	0	0	0	1	0	0
CAR_FUEL_CELL	0	0	0	0	0	-0.179	0	1	0	0
TRAIN_FREIGHT	-0.068	0	0	0	0	0	0	0	1	0
TRUCK	0	0	-0.513	0	0	0	0	0	0	1

Table A.4: $\eta_{in/out}(l,u)$ per each unit within mobility technologies

Units u ∈ Technologies	*Layers*									
	Electricity	Gasoline	Diesel	Oil	NG	Wet wood	MSW	Wet biom	Dry woody	$Heat_{DHN}$
DHN_HP_ELEC	-0.250	0	0	0	0	0	0	0	0	1
DHN_COGEN_GAS	1.250	0	0	0	-2.500	0	0	0	0	1
DHN_COGEN_WOOD	0.340	0	0	0	0	-1.887	0	0	0	1
DHN_COGEN_WASTE	0.444	0	0	0	0	0	-2.222	0	0	1
DHN_BOILER_GAS	0	0	0	0	-1.087	0	0	0	0	1
DHN_BOILER_WOOD	0	0	0	0	0	-1.163	0	0	0	1
DHN_BOILER_OIL	0	0	0	-1.087	0	0	0	0	0	1
DHN_DEEP_GEO	0.509	0	0	0	0	0	0	0	0	1
BIGCC	0.906	0	0	0	-1.375	-0.625	0	0	0	1
AN_DIG_CHP	0.889	0	0	0	0	0	0	-3.852	0	1
SBBD	0.151	5.441	0	0	0	-12.945	0	0	0	1
GASIF	0.346	0	0	0	8.132	-10.989	0	0	0	1
DRYER	-0.074	0	0	0	0	-4.294	0	0	4.808	-1
DHN_BOILER_WOOD_DRY	0	0	0	0	0	0	0	0	-1.149	1

Table A.5: $\eta_{in/out}(l, u)$ per each unit within DHN (centralised) technologies

$Units\, u \in Technologies$	$Layers$		
	Electricity	NG	Coal
CCGT	1	-1.587	0
CCGT_CCS	1	-1.754	0
COAL_S	1	0	-2.174
COAL_US	1	0	-2.000
COAL_AUS	1	0	-1.923
COAL_IGCC	1	0	-1.852
COAL_S_CCS	1	0	-2.174
COAL_US_CCS	1	0	-2.326
COAL_AUS_CCS	1	0	-2.222
COAL_IGCC_CCS	1	0	-2.083
PV	1	0	0
WIND	1	0	0
HYDRO_DAM	1	0	0
HYDRO_RIVER	1	0	0
GEOTHERMAL	1	0	0

Table A.6: $\eta_{in/out}(l, u)$ per each unit within electricity technologies

$Units\, u \in Technologies$	$Layers$						
	Electricity	Oil	NG	Wet wood	Coal	MSW	$Heat_{High,T}$
IND_COGEN_GAS	1.250	0	-2.500	0	0	0	1
IND_COGEN_WOOD	0.340	0	0	-1.887	0	0	1
IND_COGEN_WASTE	0.444	0	0	0	0	-2.222	1
IND_BOILER_GAS	0	0	-1.087	0	0	0	1
IND_BOILER_WOOD	0	0	0	-1.163	0	0	1
IND_BOILER_OIL	0	-1.087	0	0	0	0	1
IND_BOILER_COAL	0	0	0	0	-1.220	0	1
IND_BOILER_WASTE	0	0	0	0	0	-1.220	1
IND_DIRECT_ELEC	-1	0	0	0	0	0	1

Table A.7: $\eta_{in/out}(l, u)$ per each unit within industrial technologies

Units u ∈ Technologies	*Layers*						
	Electricity	Oil	NG	Wet wood	$H_{2,cog}$	Dry wood	$Heat_{DEC}$
DEC_HP_ELEC	-0.250	0	0	0	0	0	1
DEC_THHP_GAS	0	0	-0.667	0	0	0	1
DEC_COGEN_GAS	0.957	0	-2.174	0	0	0	1
DEC_COGEN_OIL	0.907	-2.326	0	0	0	0	1
DEC_COGEN_WOOD	0.343	0	0	-1.493	0	0	1
DEC_ADVCOGEN_GAS	2.636	0	-4.545	0	0	0	1
DEC_ADVCOGEN_H2	2.636	0	0	0	-4.545	0	1
DEC_BOILER_GAS	0	0	-0.980	0	0	0	1
DEC_BOILER_WOOD	0	0	0	-1.176	0	0	1
DEC_BOILER_OIL	0	-1	0	0	0	0	1
DEC_SOLAR	0	0	0	0	0	0	1
DEC_DIRECT_ELEC	-1	0	0	0	0	0	1
DEC_MGT	0.270	0	0	-1.331	0	0	1
DEC_WGB	0	0	0	0	0	-1.18	1

Table A.8: $\eta_{in/out}(l,u)$ per each unit within decentralised technologies

Units u ∈ Technologies	*Layers*				
	Electricity	Diesel	Oil	NG	Wet wood
FAST_PYR_UP	0	0.626	0	-0.032	-1
GAS_EL	-1.445	0	0	1.700	-1
GAS_SOFC_GT	0.710	0	0	0	-1
F_T	-0.016	0.434	0	0	-1
F_T_EL	-0.542	0.842	0	0	-1
FAST_PYR	0.014	0	0.668	0	-1

Table A.9: $\eta_{in/out}(l,u)$ per each unit within woody biomass technologies

Units u ∈ Technologies	*Layers*		
	Electricity	NG	Wet biom
HTG	0.074	0.514	-1
AN_DIG_UP	0	0.364	-1

Table A.10: $\eta_{in/out}(l,u)$ per each unit within wet biomass technologies

Units u ∈ Technologies	*Layers*
	Diesel
PBR_ALGAE	1
OP_ALGAE	1

Table A.11: $\eta_{in/out}(l,u)$ per each unit within algae technologies

Units	*Operative time* (t_{op})											
	J	F	M	A	M	J	J	A	S	O	N	D
PV	0.044	0.079	0.107	0.138	0.151	0.165	0.178	0.169	0.138	0.089	0.055	0.044
WIND	0.353	0.303	0.306	0.198	0.191	0.152	0.162	0.147	0.176	0.303	0.341	0.368
HYDRO_DAM	0.279	0.291	0.200	0.164	0.206	0.223	0.227	0.233	0.324	0.251	0.295	0.244
HYDRO_RIVER	0.363	0.274	0.288	0.433	0.556	0.760	0.802	0.753	0.644	0.487	0.321	0.385
DEC_SOLAR	0.065	0.091	0.120	0.123	0.141	0.152	0.161	0.149	0.135	0.101	0.068	0.055

Table A.12: $c_{p,t}$ data for renewable technologies

Units	*Layers*					
	In	Out	In	Out	In	Out
	Electricity		Wet wood		Dry wood	
PUMPED_HYDRO	1	1				
STO_WOOD_WET			1	0.995		
STO_WOOD_DRY					1	0.995

Table A.13: ϵ_{sto} per each storage technology

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