ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

MASTER THESIS

Energetic Environmental Economic Optimization of a Farm
Case study: *Swiss Future Farm*

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Abstract

The available wet biomass potential of the agricultural sector in Switzerland amounts to $26PJ$ per year in the form of manure[1]. Using this manure to produce renewable energy has the added benefit reduces direct methane emissions. Most of the available manure is localized in small scale farms. To devise an energy-efficient and cost-efficient strategy for small scale farms, the Farm Energy System (FES) is developed. The FES is written with Python to improve accessibility for future users[1]. The FES is a Mixed Integer Linear Programming (MILP) model made to fit an existing small-scale farm, i.e. the Swiss Future Farm (SFF). SFF is located in Aadorf (TG), Switzerland and hosts 139LSU. The existing farm heating system is connected to nearby housing apartments and relies on fossil energy only. The FES model includes 16 energy conversion and storage technologies, with a focus on the Solid Oxide Fuel Cell (SOFC) as a more efficient substitute to a small-scale Internal Combustion Engine (ICE). The solution set is explored via multi-objective optimization, minimizing both costs and emissions. The results show that installing an Anaerobic Digester producing $5m^3/h$ of biogas and a SOFC with deep gas cleaning, producing $16kW$ of electricity and heat can reduce emissions by more than half while keeping annual total costs below the current fossil-only scenario. The FES model is modified to represent an existing medium scale biogas installation for validation. A One At a Time (OAT) sensitivity analysis shows that economic parameters have the most impact on the model decisions. A Monte Carlo (MC) analysis of $2'500$ random parameter combinations shows that the SOFC and ICE are equivalent in terms of costs, when accounting for parameter uncertainty.

[1] The model is available on Github `https://github.com/terborch/SFF` and is open source, except for the academic or commercial licence required by the Gurobi solver

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[2] https://www.epfl.ch/labs/gem/about/lab/
[3] https://www.swissfuturefarm.ch/index.php/en_home.html
[4] https://waste2watts-project.net/
[5] https://www.epfl.ch/labs/ipese/
[6] Head of GEM and project professor
[7] Head of IPESE
[8] https://www.epfl.ch/research/domains/energy-center/
[9] https://www.zhaw.ch/en/university/
[10] https://www.rochatsolaire.ch/
[11] https://www.si-ren.ch/

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Nomenclature

List of abbreviations

Subscripts

a	animal
b	building
d	day
ext	exterior
h	hour
p	period
r	resource
u	unit

General

BES	Building Energy Systems
CAPEX	Capital expenses
CEPCI	Chemical Engineering Plant Cost Index
CHP	Cogenerated Heat and Power
ENVEX	Total annual emissions
EPA	American Environmental Protection Agency
FES	Farm Energy System
GEM	Group of Energy Materials
GHG	Green House Gas
GHI	Global Horizontal Irradiance
GWP	Global Warming Potential
HP	Heat Pump
IPCC	Intergovernmental Panel on Climate Change
IPESE	Industrial Process and Energy Systems Engineering
LCA	Life Cycle Assessment
LHV	Lower Heating Value
LP	Linear Programming
LSU	Live Stock Unit
MILP	Mixed Integer Linear Programming
MSE	Mean Squared Error
NLP	Non Linear Programming
OPEX	Operating annual expenses
RE	Renewable Energy
SFF	Swiss Future Farm
TOTEX	Total annual expenses
WBT	Wet Bulb Temperature

Superscripts

$+$	Flow entering a unit / grid / entity
$-$	Flow leaving a unit / grid / entity
buy	Buy a resource from the grid
fix	Fixed cost
LCA	Construction emissions
$maint$	Maintenance cost
$mult$	Cost multiplier
ref	Reference
$sell$	Sell a resource to the grid
$size$	Specific cost

Resources

BG	Biogas (Green)
Biomass	Biomass (Beige)
BM	Bio-methane (Green)
Diesel	Diesel (Black)
EL	Electricity (Blue)
NG	Natural Gas (Grey)
Q	Heat (Red)
Wood	Wood (Beige)

Symbols

α	absorption coefficient

$\dot{E}$	Any energy flow
$\dot{m}$	Mass flow
$\dot{Q}$	Heat flow
η	Efficiency
ρ	Density
A	Area
C	Heat capacity
c	cost
COP	Coefficient of Performance
dt	Time step
f	"fraction" or coefficient
f_d	frequency of a typical day
I	solar Irradiance
m	mass
n	Lifetime
P	Profile
r^{sd}	Self discharge rate
S	Installed capacity
SOC	State of Charge
T	Temperature
t	Time or time function
U	Heat conductivity
x_{BG}	Biogas methane fraction
Z	"Is installed" or decision variable

Technologies

AD	Anaerobic Digestion
AHP	Air-Air Heat Pump
BAT	Battery
BS	Biogas Storage
BU	Biogas Upgrading
CGT	Compressed Gas Tank
EH	Electric Heater
GBOI	Gas Boiler
GCSOFC	Gas Cleaning unit for SOFC
GFS	Gas Fueling Station
GHP	Geothermal Heat Pump
GI	Grid Injection
ICE	Internal Combustion Engine
PV	Photovoltaic
SOFC	Solid Oxide Fuel Cell
WBOI	Wood Boiler

1 Introduction

Anthropogenic global warming has increased the global average temperature by $1.0°C$ compared to pre-industrial levels, according to the 2018 special report by the IPCC [2]. Global average temperature will likely reach $1.5°C$ within the next 10 to 30 years under the present trend [2]. The report highlights the necessity to keep global warming below $2.0°C$ and the consequences that would otherwise arise.

One consequence of near future global warming, highlighted in a recent study [3] is the upper physiological limit to heat. The authors explain that humans regulate their body temperature through sweating and that this ability depends on the surrounding temperature and humidity. When the Wet Bulb Temperature (WBT)[12] reaches $35°C$, sweating is no longer possible, leading to the individual's death. During the deadly heatwave of 2003 in Europe, the maximum WBT measured was $28°C$. The authors claim that, under the business as usual model of warming, the upper physiological limit of $WBT = 35°C$ will be regularly reached in parts of the Middle east and South East Asia, within the next 30 years.

Farms with cattle are widespread in Switzerland. Raising cattle and farming are generally considered as a Green House Gas (GHG) intensive activity [4]. Due to the use of fossil energy and methane emissions, with a Global Warming Potential (GWP) 28 to 36 times higher[13] than Carbon Dioxide (CO_2). Researchers [6] calculated that a tonne of pig manure, when left untreated, will emit up to $110kg - CO_2$ equivalent of GHG. Through an anaerobic process however, these emissions are mitigated and by producing renewable energy with the biogas, a net negative $-40kgCO_2$ per tonne pig manure can be reached.

The biomass potential of Swiss farms is $26PJ$ annual [1], or 2.4% of the national primary energy consumption [7]. 80% of the available of biomass is localized in small farms capable of producing $10kW$ of electricity or less, using an anaerobic process and a combustion engine. However, combustion engines are not efficient at such low scales, e.g. a state of the art micro-turbine of $10kW$ may reach 32% electric efficiency [8].

More efficient energy conversion technologies, storage solutions or alternative use of biogas has the potential to increase the Renewable Energy (RE) production and reduce emissions. A higher efficiency alternative to the combustion engine is the Solid Oxide Fuel Cell (SOFC) with up to 55% electric efficiency [9] when consuming biogas. An alternative use of biogas is as fuel for agricultural machinery.

The project partners and owners of the Swiss Future Farm (SFF), a small scale farm located in Aadorf (TG) Switzerland, wish to reduce their carbon footprint. The goal of this project is to find optimal energy pathways to reduce emissions at low costs, in the context of a small farm. For this, a global energetic, environmental and economic optimizations problem is formulated and solved under different conditions. This optimization model is referred to as the Farm Energy System (FES) and may help decisions regarding near future energy strategies. The FES is comprised of 16 energy conversion technologies referred to as units, that are sized and operated via optimization. The FES relies on commercialized or demonstrated technologies and their current performance to represent a solution that could be implemented in the near future. A schema of the FES is presented in Figure 1.

In the following sections, the default FES model is described in detail (Section 3) including the 85 equations and 200 model parameters. Choices regarding the modelling approach and model assumptions are explained. The SFF consumption and production potential is presented. The description of each of the 16 FES technologies is shown. The optimization process and methods are explained. Methods for sensitivity analysis are also presented. Finally, data regarding a medium scale biogas installation at a farm in Palézieux is shown for comparison.

[12] The WBT is the temperature read by a thermometer when the surrounding air is 100% humid. For lower humidity levels the WBT can be calculated and will be below the air temperature.

[13] Over a 100 year time period, according to the American Environmental Protection Agency (EPA) [5]

Results for the FES are presented in section 4. Beginning with a brief summary of the most important results and the scenarios used. A scenario representing the current SFF energy system presented. Two different approaches are taken to explore optimal solutions for SFF, one focusing on costs, the other on both emissions and costs. The different optimal solutions are compared with the current scenario. Results for the sensitivity analysis, leading to two new scenarios are explored. A final scenario for SFF seeking to maximize RE production is shown. Optimal solutions for a modified FES model representing the medium scale farm at Palézieux are explored and compared with a current scenario. The effect of electricity feed-in tariffs on the competitivity of the SOFC is explored.

The discussion (section 5) opens with recommendations to the project partners of two optimal solutions, one minimizing emissions without increasing costs relative to the current scenario, another minimizing emissions as much as possible. The FES model limitations and possible improvements are listed and ideas for future research using the FES model is proposed.

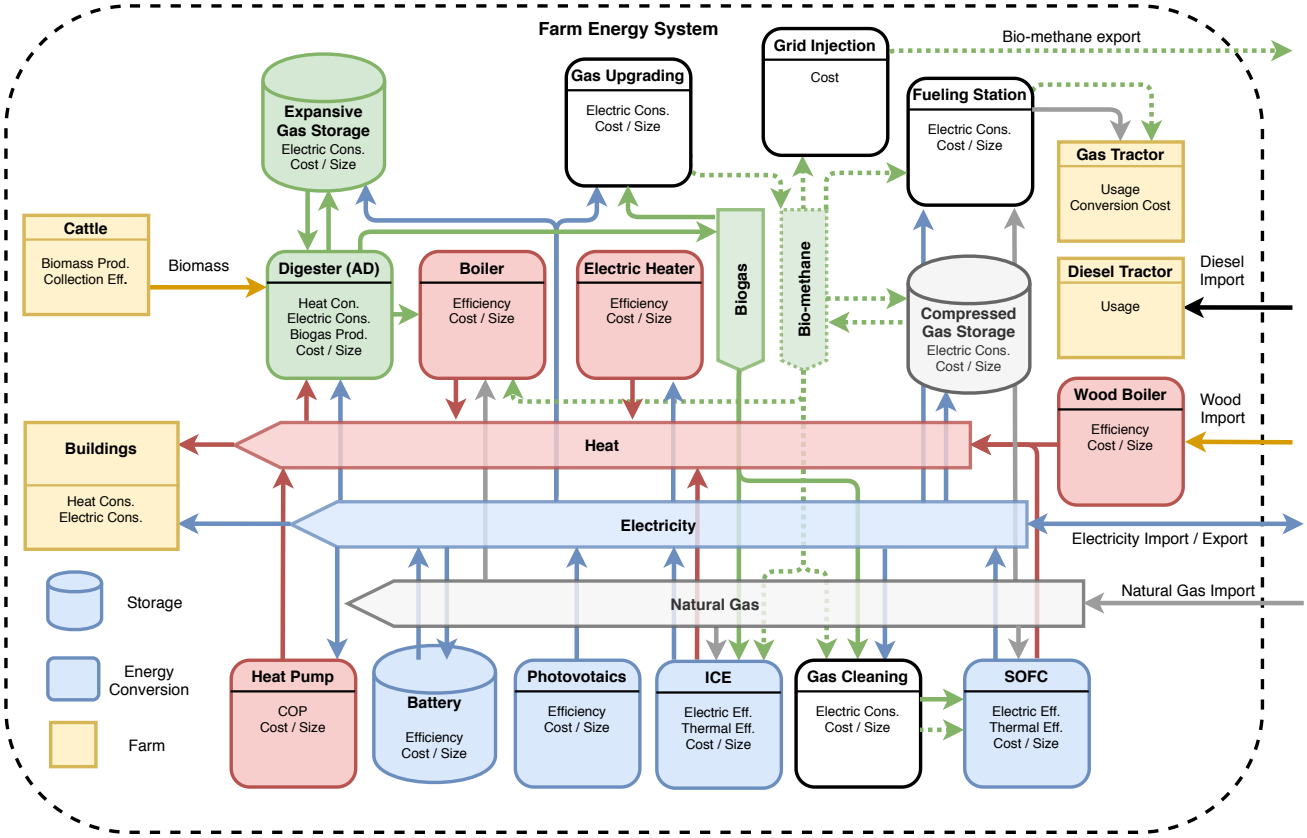


Figure 1 – Farm Energy System flow diagram. Round-edge boxes represent energy conversion technologies, cylinders are storage technologies and the sharp edge boxes represent the farm. Colours refer to a resource transported, stored or produced, red for heat, blue for electricity, grey for natural gas, green for biogas or biomethane and yellow for biomass. White represent utilities.

2 State of The Art

Fisher et al. [10] modelled in 1999 the use of fossil energy in the Swiss agricultural sector and evaluated the impact of different scenarios. They included fuel and lubricant for machinery as direct energy inputs and fertilizers, pesticides, fodder and Life Cycle Assessment (LCA) of machinery and buildings as indirect energy inputs. They compared the energy requirement of different products. Among crops, potatoes where most energy intensive at $20GJ/ha$, while dairy cows where the most energy intensive animals at $18GJ/LSU$. Crop energy consumption is mostly fuel for field work machinery and fertilizers, while animals require electricity and buildings. They projected that by 2003 the overall energy consumption of Swiss farms would be reduced due to policies promoting agriculture extensification, causing a reduction in the use of machinery. This study did not include the possibility to produce RE with biomass or solar.

Dirk Lauinger developed a MILP based decision tool for single family housing energy systems [11], during his master thesis. He used non clustered yearly weather parameters and a weekly electric consumption profile, with a focus the SOFC. He concluded that this technology was not yet economically viable without feed-in tariffs schemes. He noted that the low carbon intensity of the Swiss grid means the deployment of SOFC is not improved by a direct carbon tax. This study focusses on building energy systems and does include the biogas production system or gas cleaning of biogas for SOFC. This model may also benefit from clustering weather parameters to reduce computational time.

Samuel Majerus developed a MILP based optimization model [12] for small scale farms producing biogas and cogenerating heat and electricity during his master thesis and for subsequent publications [13]. The study evaluates the profitability of the SOFC as a Cogenerated Heat and Power (CHP) for small scale biogas installations, compared to the classical Internal Combustion Engine (ICE). The result is that the SOFC is not competitive with its current cost and lifetime. The study shows that the SOFC has to cost 13′000 CHF/kW with a lifetime of 12 years to be profitable, while the AD as to remain at or below 6′000 CHF/kW regardless of the CHP. This model is the closes to the FES, although upgrading biogas to biomethane and using it to fuel vehicles, do grid injection or long term storage is not included.

Harchaoui et al. [14] modeled the global energy balance of farms in France. They used an total approach, including all energy inputs and output of an average farm in their model. They found that current farms are energy deficient, because self fuelling was progressively replaced by imported fossil fuels for powering machinery and facilities or producing fertilizers. The largest negative contribution to the energy balance is fodder imports. They argue that producing energy from biomass is important and will benefit the energy balance, but reaching energy neutrality requires additional changes such as suppressing fodder imports and minimizing soil tillage to reduce field work. They note the importance to achieve energy neutrality in terms of food security related to fossil imports. They argue that reaching a net energy positive balance would be extremely challenging. Their study, while complete is very general and does not focus on a specific farm, moreover biogas as machinery fuel is not explored.

Paul Stadler developed a MILP for Building Energy Systems (BES) during his doctoral thesis at IPESE [15], describing energy conversion, storage and solar based production technologies for single family houses, apartment blocks and housing districts in Switzerland. His BES is complete with dynamic operation of units, a heat cascade to describe for the heating system integration and a market cost evaluation of each technology. The BES uses weather clustering with 8 typical days and a one hour time-step. Many of the used parameters like heat consumption, inhabitant related consumption and the building thermal parameters are derived from Swiss architecture norms such as SIA 2024 or government statistics. He proposes multiple optimally controlled solutions to reduce both the cost and emissions for the end user. He concludes that the classic fossil based heating system is still the cheapest solution under current energy prices, but that with increasing carbon taxation, a Heat Pump (HP) combined with Photovoltaic (PV) panels is a promising optimal solution for the near future. Paul's energy system is by far the most complete and complex, which also makes it difficult to

modify, extend or apply to different contexts.

Many technologies used in the built environment can be applied to farms, therefore many technologies of the FES are based on Stadler's BES. Such as the building thermal model description (see section 3.3.2) and the daily profiles for electric consumption and building occupation. The principle of the mass balance equations and resource grids (see section 3.5), with a highly simplified heat balance. The model description of the Gas Boiler, Electric Heater, PV panels and Battery where all adapted from the BES.

This work is a continuation on the previous research on farm emissions and energy consumption, with a focus on designing and sizing a renewable energy system for a specific small scale farm. The energy models developed by Lauinger, Majerus and Stadler may be made available to students or other parties for use and modification by their author, but where not developed to be accessible. The FES was developed with accessibility in mind for future users and, with a unique and popular language handling everything from inputs to output graphs. The FES model relies on many simplifications to reduce its complexity which allows it to compare a broader spectrum of technologies than previous works.

3 Methodology

3.1 Modelling approach

The aim of this project is to compare a wide range of energy conversion and storage technologies in the context of farms, to identify optimal energy pathways and reduce emissions. For this, the Farm Energy System (FES) model is developed. The model is required to be to be deterministic and the time for solving the model fast, while being complex enough to accurately represent the reality and simple enough to include many technologies.

The model complexity is driven by the kind of mathematical description it uses. This is commonly LP (Linear Programming), MILP (Mixed-Integer LP) and NLP (Non-Linear Programming) and is arguably the most important choice for optimization modelling. LP models are fastest to solve but the problem description is limited to linear equations only. For a NLP model the solution may depend on initial conditions. MILP models use mostly linear constraints but also allow for binary and integer variables. The binary variables are often referred to as the decision variables and are useful when the model has to choose between different options. The next important choice is the time step. A shorter time step increase accuracy at the expense of solving time. The current state of the art for global energy optimization rely on a MILP approach. It allows to resolve complex optimization problems over a year or more with an hourly resolution in a few minutes. Unlike for NLP the solution is deterministic.

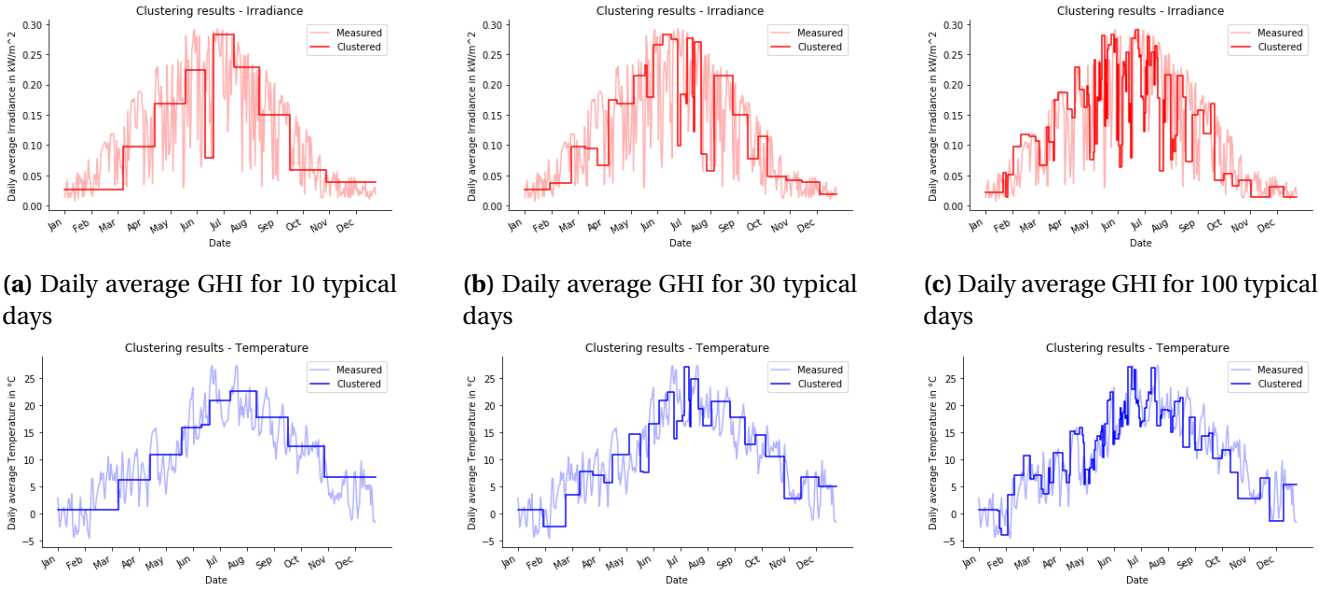
For the above-stated reasons, the chosen modelling approach is MILP. The time resolution is one hour. In an effort to increase accessibility, the model is written for the Gurobi solver, in the popular open-source Python language using the Gurobi's own Python module. The complete code is available at `https://github.com/terborch/SFF` and only requires a Gurobi licence to run. The versatile Python language allows the user automatically handle all inputs and outputs, the data management being as complicated as the modelling. With a few modifications, the model may be saved as a .lp (linear programming) file and solved using another MILP solver. The figure below, illustrates the information flow across the different parts of the FES. A user guide is proposed in Annex A.1.

FES information flow diagram

3.2 Clustering Typical Days

Without further data reduction, the model takes between 30 min and 10 hours to solve. Clustering some parameters can drastically reduce the solve time with a minimum impact on the solution. The main time dependent parameters, on which consumption and production of most units depend are external temperature and Global Horizontal Irradiance (GHI). Due to their nature, it is possible to cluster them on a daily basis. The default clustering when solving the FES is 10 typical days, unless specified otherwise.

Using a k-means algorithm from the sklearn python module, days are clustered together as to minimize the Mean Squared Error (MSE) between the clustered values and closest measured values. The instantaneous temperature and GHI are normalized to give equal weights to both parameters. The k-means algorithm takes



(a) Daily average GHI for 10 typical days

(b) Daily average GHI for 30 typical days

(c) Daily average GHI for 100 typical days

(d) Daily average temperature for 10 typical days

(e) Daily average temperature for 30 typical days

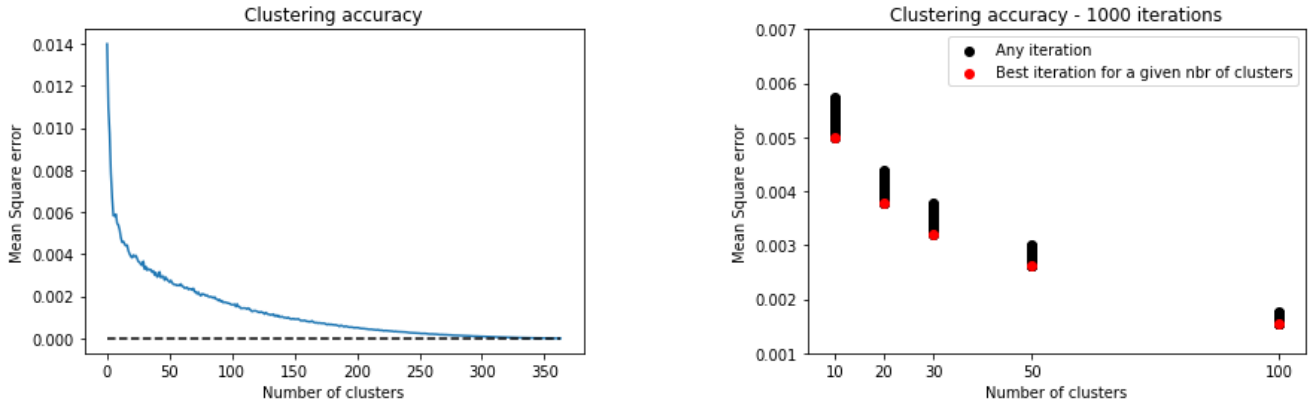
(f) Daily average temperature for 100 typical days

Figure 2 – Daily average values of temperature and GHI. Clustered values compared to measured values along the year 2019. Measurements come from the Liebensberg weather station.

less than a second to cluster a year into n typical days. To validate the assumption that more clusters means more precision, the MSE relative to the number of clusters is presented in Figure 3a. As predicted the MSE decrease with the number of clusters on average and reaches zero for 365. The algorithm is non deterministic and randomly initialized, taking advantage of the brief calculation time, 1'000 solutions are calculated for a select number of cluster sizes of 10, 20, 30, 50 and 100 typical days. The result is presented in Figure 3b and reveals that a good solution for 30 clusters is as accurate as the worst solution for 50 clusters. Time spent on getting better cluster results can help reduce future solve times by using a lower number of clusters for similar precision. Only the best solution for each number of clusters is kept.

When describing the reduced problem, typical periods are generally ordered such that one typical day only occurs once in a year and is repeated according to the number of days in that typical day's cluster. Having these periods in the right order is important for any storage longer than a day, like the heat stored by the building's thermal inertia. A brief and systematic sorting algorithm is written on the following principles. The list to sort contains 365 days where the position in the list is the day in the year and the value corresponds to the cluster number e.g. 1 to 30. Sorting results for daily average values of temperature and GHI are presented in Figure 2.

1. The list if filtered such that where many days of the same cluster surround a day of another cluster, the latter is replaced by the former. At least one day of each cluster must remain.
2. The least frequent cluster in the list is selected e.g. cluster number 12
3. The longest uninterrupted streak of 12's is replaced by a single 12
4. All other 12's in the list are removed
5. Repeat from step 2. until all clusters are replaced by a single value



(a) MSE as a function of cluster numbers

(b) MSE variation for a fixed cluster number

Figure 3 – (a) The MSE as a function of the number of clusters. In black 1′000 iterations of the k-means algorithm. In red, the best solution for each number of clusters. (b) In blue, the MSE as a function of the number of clusters for hourly values of Temperatue and GHI for each day in 2019, measured at the Libensberg weather station. The dashed black line highlights where the MSE is zero.

Table 1 – Solve time relative to the number of clusters for weather parameters and objective functions. The total solve time is the time required to solve the model ten times. The average may vary a lot, e.g. for 100 typical days, most solutions take 200 seconds to solve but a few solutions will take over one hour to solve.

Objectives	Typical Days	Average Solve Time	Total Solve Time
OPEX-CAPEX	10	1min 6s	11min
	20	1min 17s	13min
	30	3min 30s	34min
	50	7min	1h 9min
	100	15min	2h 30min
ENVEX-TOTEX	10	2min 35s	26min
	20	3min 16s	33min
	30	15min	2h 30min
	50	30min	5h
	100	2h	20h

3.3 Swiss Future Farm Overview

The model is tailored to a small scale farm (139 LSU[14]) located in Aadorf, Switzerland. The farm's heating system is connected with nearby housing apartments, together the annual heat consumption is $1.6GWh$ [16]. Heat is the main energy consumption, followed by electricity at $0.8GWh$ for buildings and $8'000l$ of diesel for 4 tractors. The available biomass is $0.74GWh$ and is exclusively animal slurry, unused at present. A sky view of the site is presented in Figure 4

Figure 4 – A sky view of the Swiss Future Farm buildings [17]. The farm is located on the upper side off the image and is connected to commercial and housing buildings on the lower side. The Church is not part of the analysis.

[14]A Live Stock Unit help relate animal sizes, a milk cow has an LSU of 1.

3.3.1 Meteorological Parameters

The main energy consumption is heat and the parameters driving heat consumption are the meteorological parameters. The external temperature in $°C$ and GHI in Wh/m^2 is obtained from the nearest available weather station, i.e. Liebensberg, for the past ten years are available at `http://www.agrometeo.ch/fr/meteorology/datas`. Measurements are taken every 10 minutes, the temperature is averaged over an hour and the GHI is summed and converted to kW/m^2.

3.3.2 Heat Consumption

Heat is the main energy consumption and is therefore driving the system's behaviour. The annual heat load is given but the hourly heat load profile has to be calculated. The drivers of the heat consumption is external temperature, solar gains and human gains. Hot water consumption is neglected. Human activities vary during the day but also in the week (week-ends) and the year (holidays). For simplicity these variations are neglected and an average daily profile of building occupation is used.

The building heat load is pre-calculated in a separate LP model, relative to the non clustered weather data for 2019 and the building thermal parameters. The annual heat load and the peak load are minimized. The building heat requirement model is a 0 dimension, bulk temperature model, with a heat capacity, heat resistance and gains as in equation 1 [15]. Because of the heat capacity, the temperature of the previous day will influence the next day. Therefore this model is solved over 365 days without clustering. Note that by pre-calculating the heat load, it is no longer a problem variable and therefore predictive control or using the building heat capacity as storage is no longer possible. However, the generated profile comes from a "perfectly" controlled heating system. This is one possible explanation for why the actual heat demand is almost twice the modelled heat demand and has to be corrected (see following paragraphs).

$$C_b(T_{b,next(d,h)} - T_{b,d,h}) = U_{b,d}(T_{b,d,h} - T_{ext,d,h}) + \dot{Q}^{+}_{b,d,h} + \dot{Q}^{+gains}_{b,d,h} \qquad [kW/m^2] \qquad (1)$$

$$T_{b,min} \leq T_{b,d,h} \leq T_{b,max} \qquad [C^\circ] \qquad (2)$$

$$\dot{Q}^{+}_{b,d,h} \geq f_{b,Q_{min}} \cdot max(\dot{Q}^{+}_{b,d,h}) \qquad [kW/m^2] \qquad (3)$$

$$MINIMIZE: \sum_{d,h}^{365,24} \dot{Q}^{+}_{b,d,h} + max(\dot{Q}^{+}_{b,d,h}) \cdot 8760 \qquad [kW/m^2] \qquad (4)$$

The variables are the building temperature T_b and the heating load $\dot{Q}^{+}_{b}$. The superscript + and − is energy entering respectively leaving the system, in this case heat entering the building. The subscript b refers to the buildings while d and h refers to days and hours respectively. $next(d,h)$ is a python function that gives the next time period after (d,h). C_b and U_b are the building heat capacity and conductivity per heated square meter of heated area. T_{ext} is the external temperature. $\dot{Q}^{+gains}_{b}$ is the sum of the heat gains in kW/m^2. Eq. 2 limit the temperature of the building, since no active cooling is considered only the lower limit is important [16]. The smallest heating system part load is constrained by equation 3, where the heater part load $f_{b,Q_{min}}$ is 20%. Eq. 4 is the objective function and handles the system control. It seeks to minimize the peak heat load and the

[15] Each equation number is directly referenced into the model's python code to make the model more reusable

[16] To prevent the simulated building temperature from going above the upper limit, $U_{b,d}$ takes the default value of 0.002 during normal days, i.e. days where the average temperature is below 25°. For other days it will be divided by half, as to simulate many open windows during hot days. Note that if the model is infeasible due to eq. 2 a new attempt is automatically made with a lower $U_{b,d}$ for hot days.

annual heat load. The heat gains are calculated with the following eq. 10.

$$\dot{Q}^{+ppl}_{b,h} = \dot{Q}^{+ppl}_{b,peak} \cdot \hat{P}_{occup,h} \qquad [kW/m^2] \tag{5}$$

$$\dot{Q}^{+ppl}_{b,peak} = \frac{Q^{+ppl}_{b,annual}}{8760 \cdot mean(\hat{P}_{occup,h})} \qquad [kW/m^2] \tag{6}$$

$$\dot{Q}^{+EL}_{b,d,h} = \dot{E}^{+EL}_{b,d,h} \cdot \frac{f_{b_{Q/EL}}}{A_{b,heated}} \qquad [kW/m^2] \tag{7}$$

$$A_{b,heated} = \sum_{b} N_{floors} \cdot A_{b,ground} \qquad [m^2] \tag{8}$$

$$\dot{Q}^{+I}_{b,d,h} = I_{d,h} \cdot \alpha_b \qquad [kW/m^2] \tag{9}$$

$$\dot{Q}^{+gains}_{b,d,h} = \dot{Q}^{+ppl}_{b,h} + \dot{Q}^{+EL}_{b,d,h} + \dot{Q}^{+I}_{b,d,h} \qquad [kW/m^2] \tag{10}$$

$$f_b, Q_{real}/Q_{model} = \sum_{d,h}^{d_{typical},h} \frac{\dot{Q}^{+}_{b,real}}{\dot{Q}^{+}_{b,d,h} \cdot f_d} \qquad [-] \tag{11}$$

Human gains $\dot{Q}^{+ppl}_{b,h}$ are calculated using eq. 5. They are based on an annual value $Q^{+ppl}_{b,annual}$ spread over each day using a normalized occupation profile $\hat{P}_{occup,h}$ [17]. The heat gains per active person is approximately $100W$. Using eq. 6, the daily peak value $\dot{Q}^{+ppl}_{b,peak}$ is calculated. In eq. 7 electric gains $\dot{Q}^{+EL}_{b,d,h}$ derive from the electricity consumed by buildings $\dot{E}^{+EL}_{b,d,h}$, assuming all of it is used inside the heated buildings. A loss factor $f_{b,Q/EL}$ account for light emissions as in [11]. $A_{b,heated}$ is the building heated area [18], i.e. the number of floors times the ground area of each building, as per eq. 8. In eq. 9, the solar gains $\dot{Q}^{+I}_{b,d,h}$ is simply the GHI times a building absorptance α_b related to the heated area. Finally the sum of all gains is expressed in eq. 10. Once the heat profile is calculated, days outside the clustered days are discarded. Then the annual heat load is approximately half of the actual heat consumption. This is due to a predictive and perfectly controlled system as well as uncertainties on the building thermodynamic parameters, a bulk temperature description and variations when clustering. Therefore $\dot{Q}^{+}_{b,d,h}$ is increased by a correction factor $f_b, Q_{real}/Q_{model}$ from equation 11, where f_d is the frequency of each clustered day. The resulting heat load profile $\dot{Q}^{+}_{b,d,h}$ has the same annual heat consumption as SFF in 2019.

The monthly heat consumption is available. Figure 5 highlights the difference between the monthly average measured heat load (transparent red) and modelled heat load (red) for a 10-day weather cluster. During the first typical period, the heat load is too high, and during summer, too low. This will lead to an overestimation for the installed capacity of heating units. The monthly heat consumption is not included in the FES but could be used in a future version to improve the modelled heat load profile.

3.3.3 Extreme conditions

This previously calculated heat load profile does not take into account extreme weather phenomenons or system failures. The coldest day recorded in the past 10 years at Liebensberg is $-14C°$ (daily average) while is it 0° in the 10-days cluster. To ensure the sustained operating of the heating system under extreme conditions, the following scenario is theorized:

1. $-20C°$ external temperature (12h average)

[17] $\hat{P}_{occup,h}$ is adapted from [15] and is based on the Swiss building norm SIA 2024

[18] The buildings size and year of construction are available at `https://map.geo.admin.ch/`. Heated and non heated buildings were categorized according to [16].

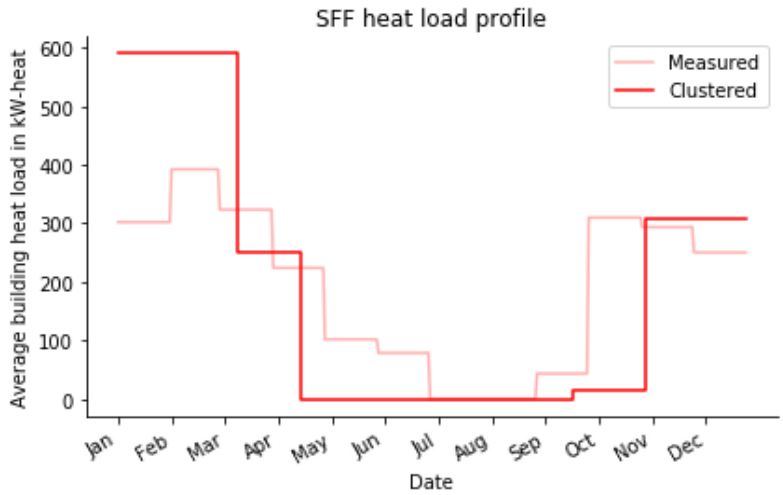


Figure 5 – Comparison between the average monthly measured heat load [16] and daily average modeled heat load, for ten typical days over 2019.

2. No heat gains
3. No wood supply for the wood boiler
4. The air sourced Heat Pump cannot operate at this temperature
5. Cogeneration Heat and Power (CHP) units are not operating
6. An eventual additional heat load for the Anaerobic Digester (AD) is not considered

Equation 12 ensures that under these conditions the interior building temperature is maintained at $T_{b,min} = 18C°$. The parameter $T_{ext,extreme}$ is fixed at $-20C°$ and the variables S_{EH}, S_{GBOI}, S_{GHP} are the installed capacity in kW-heat of the Electric Heater, Gas Boiler and Geothermal Heat Pump respectively.

$$A_b \cdot U_b \cdot (T_{b,min} - T_{ext,extreme}) \leq S_{EH} + S_{GBOI} + S_{GHP} \qquad [kW] \qquad (12)$$

Table 2 – Summary of parameters related to the building heat load profile calculation. Note that all values presented in the tables are rounded to improve readability.

Name	Symbol	Value	Units	Source
Absorptance	α_b	0.08	–	Tuned[19]
Heat capacity	C_b	0.12	$kWh/C°/m^2$	[15]
Heat conductivity	U_b	0.002	$kW/C°/m^2$	[15]
Electric heat gains	$f_{b_{Q/EL}}$	0.9	–	[11]
Human heat gains	$Q^{+ppl}_{b,annual}$	26	$kWh/m^2/year$	[15]
Heated area	$A_{b,heated}$	14705	m^2	[17]
Heater part load	$f_{b,Q_{min}}$	0.2	–	Setting[20]
Max interior temperature	$T_{b,max}$	34	$C°$	Setting
Min interior temperature	$T_{b,min}$	18	$C°$	Setting
Extreme temperature	$T_{ext,extreme}$	−20	$C°$	Setting

3.3.4 Electricity Consumption

Electricity consumption for the entire site is obtained for the year 2019. The daily consumption profile is presented in Figure 6. It is obtained by applying the measured annual electric consumption of SFF to a normalized electricity consumption profile for commercial buildings[21] in a similar fashion to 6. Variations during weekends and vacation periods are neglected.

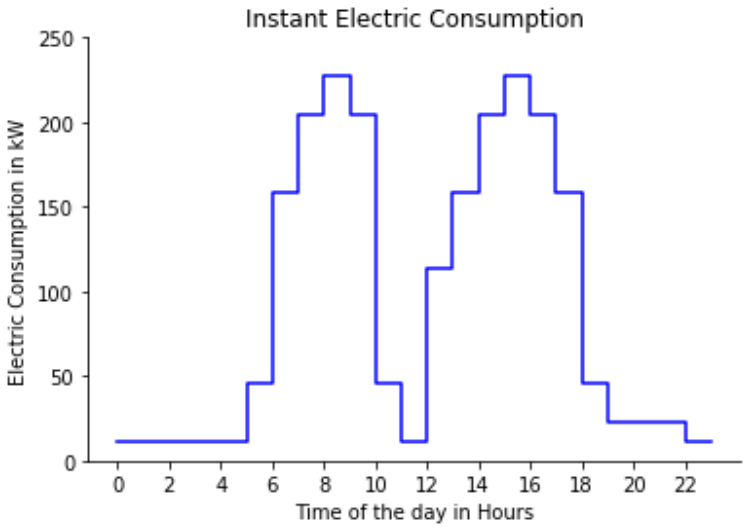


Figure 6 – Buildings electricity consumption profile. Adapted from [15]

3.3.5 Biomass Production

The biomass produced is a function of the number and type of animals present on the farm. One adult dairy cow corresponds to 1 Livestock Unit (LSU), other animals have lower LSU values depending on their species and age. In the FES, the manure can only be used in the Anaerobic Digester (AD). The complex digestion process produces different methane yields for different animal manure. It is more accurate to look up the methane yield for each animal as presented by [18] instead of taking the Lower Heating Value (LHV) of the manure. The authors of [18] only take into account the recoverable fraction of manure, i.e. manure produced while the animals are in the stables. The manure recovered is assumed to be constant through the year although it may increase in winter when animals spend more time in stables. Other sources of biomass such as crop remains or nearby food industry waist are not considered.

$$\dot{E}_{farm}^{-Biomass} = \frac{1}{8760 \cdot \eta_{AD}} \sum_{a}^{animals} \frac{N_a}{LSU_a} \cdot \dot{E}_a^{-BG} \qquad [kW] \qquad (13)$$

Equation 13 relates the biomass produced $\dot{E}_{farm}^{-Biomass}$ with the number of animals $\frac{N_a}{LSU_a}$ and their respective methane potential $\dot{E}_a^{-BG}$. Subscript a denotes an animal category. The AD efficiency η_{AD} is used to convert the methane value to input of biomass. All parameter used are presented in Table 3.

According to Prapasponsa et al. [6] when left to decompose, manure will emit methane emissions which have a Global Warming Potential (GWP) 30 times larger than CO_2. The emissions per tonne of manure will

[19] *Tuned* means the value was selected based on trial and error.
[20] *Setting* means the value is based on a modelling choice.
[21] Adapted from [15]

depend on the treatment process. A common practice is to store the manure in an anaerobic lagoon before spreading it on the fields. This process generates approximately $110kg$ of equivalent CO_2 emissions per tonne of pig manure (average value). The authors estimate net negative emissions of $-40kgCO_2$ per tonne manure when using an AD to capture biogas and generate electricity. Since a CO_2 credit for exporting renewable electricity is already included in the model, the value of $-40kgCO_2$ cannot be directly used. Details on the calculation of the manure emissions are presented in Annex A.3.

Instead the difference in CO_2 emissions between no treatment and combustion of the biogas from $1t$ of pig manure is calculated, without accounting for renewable electricity. The methane potential of a pig is known, so is the amount of manure it produces [18]. From the chemical balance equation, $1kg$ of CH_4 produces $2.74kg$ of CO_2 during combustion. The CO_2 already present in the biogas is added. The result is $45kg$ of CO_2 per tonne of pig manure and is assumed to be similar for all other animals. This means using an AD reduces emissions from 110 to 45 kg equivalent CO_2 per tonne of manure, when the biogas is combusted, without accounting for renewable electricity generation. Alternatively it can be expressed as a 60% reduction in manure related emissions. For explicit equations, see Annex A.4.

Table 3 – The number of animals present at the farm [16]. Methane potential by animal when using the manure in an AD and manure yield [18].

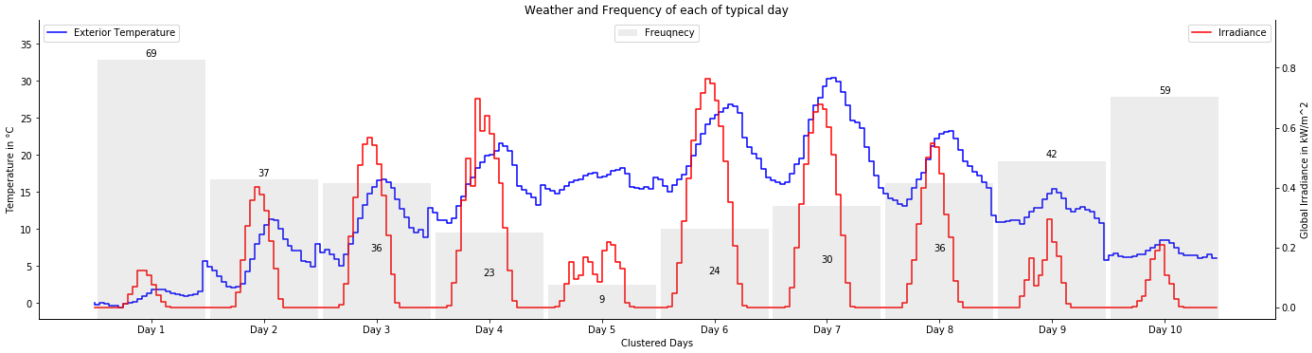
Animals	**Number of animals** N_a **[LSU]**	**Size** LSU_a **[LSU/head]**	**Methane Potential** $\dot{E}_a^{-BG}$ **[kWh/head/year]**	**Manure Potential** $\dot{m}_a^{-manure}$ **[t/head/year]**
Calves	0.4	0.5	396	2.9
Dairy cows	65	1	3017	19.3
Pigs	40	0.3	236	1.6
Sows	27.5	0.5	577	4
Sheeps	3	0.1	262	0.5
Goats	3	0.1	262	0.5

3.3.6 Diesel consumption

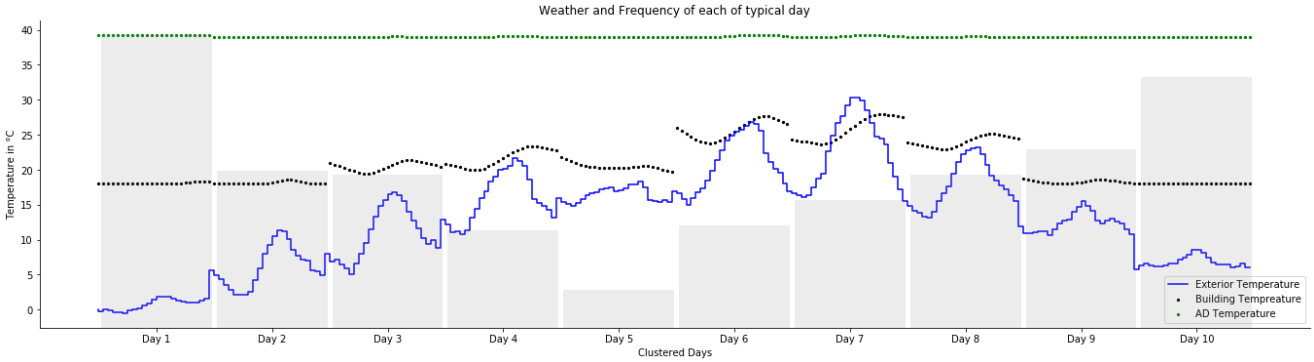
The diesel consumption on the farm is approximately $8'000$ liters per year with 4 tractors operating [16]. Assuming most of the field work is done during the warmer part of the year, fuel requirement will be higher in spring and summer. This is an opportunity to utilize biogas from the AD as a fuel when the heat load is low and co-generated heat would be wasted. The FES can either use a diesel only fleet, as is the case at present, or convert the entire fleet to run on Natural Gas (NG) and Biomethane (BM). The second option requires a gas fueling station, which slowly charges utility vehicles overnight. A fuel consumption profile for gaseous fuel in kW-fuel is presented in figure 7d. Gas charging stations for utility vehicles slowly fills them overnight from 6 pm to 4 am. This corresponds to about $30kW$ of fuel consumption during 10 hours. The temperature limit below which tractors do not operate is set to be $5C^\circ$ (daily average).

3.4 Energy conversion units

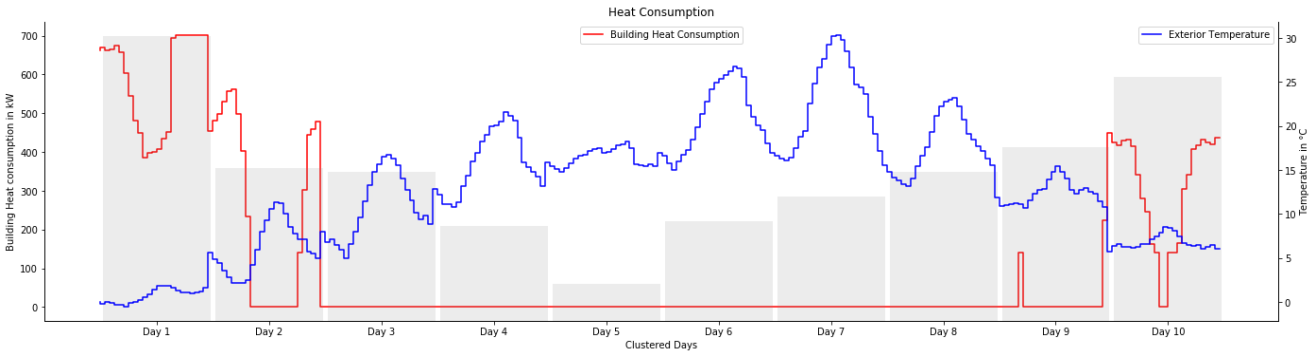
To satisfy the farm energy needs, the model can choose any combination of energy conversion units. These are 5 heaters, 2 cogeneration units, 2 energy production units, 3 storage units and 4 utilities. All of them linked together by energy balance equations as in figure 11. Their operation is driven by the farm consumption of heat, electricity and fuel, under a multitude of constraints and an objective to minimize costs or emissions.



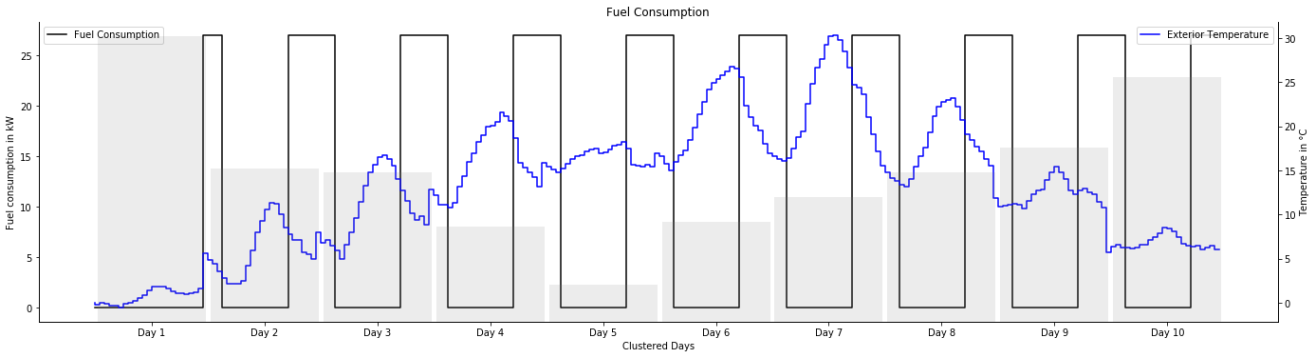
(a) Exterior Temperature and GHI clustered into 10 typical days. The frequency of each day appears in the background as a bar chart.



(b) Building and AD temperatures for each typical day. Exterior temperature and frequency added for comparison.



(c) Buildings heat consumption for each typical day. Exterior temperature and frequency added for comparison.



(d) Fuel consumption profile for a gas time fuelling station. The fuel consumed can either be Diesel or a combination of NG and biogas. The profile is only relevant for gaseous fuels. Exterior temperature and frequency added for comparison. Note that the only period without refueling is the first period, but it is repeated 69 times in the year.

Heating units include an Electric Heater (EH), a Gas Boiler (GBOI), a Wood Boiler (WBOI), a Air-Air Heat Pump (AHP) and a Geothermal Heat Pump (GHP). Cogeneration is either provided by a Solid Oxide Fuel Cell (SOFC) or an Internal Combustion Engine (ICE). An Anaerobic Digester (AD) can produce biogas and Photovoltaic Panels (PV) may produce electricity. A battery (BAT) can store electricity while a Compressed Gas Tank (CGT) can store bio-methane in the long term. A Biogas Storage (BS) allows short term storage of raw biogas. Utilities include a deep Gas Cleaning unit for SOFC applications (GCSOFC), a Gas Fueling Station (GFS) for tractors running on gaseous fuels, a Biogas Upgrading (BU) unit to remove CO_2 from biogas and Grid Injection (GI) to control and inject bio methane into the grid.

Each energy conversion unit in the FES has the following set of variables. An installed capacity S_u in kW or kWh for storage units, where the subscript u indicates the unit's abbreviation. A binary decision variable Z_u taking a value of 1 if the unit is installed and 0 otherwise. Every unit consumes and produces at least one resource and has one variable for each resource produced and consumed expressed in kW. The notation $\dot{E}^{+r}_{u,d,h}$ is used, where E indicates an energy flow, alternatively Q a heat flow, the superscript $+r$ and $-r$ indicate that the unit consumes respectively produces the resource r. The subscripts indicate the time period corresponding to the typical day d and the hour h in that typical day. For storage units an additional variable $SOC_{u,p}$ represent the state of charge in kWh relative to a time period p which is always divided in $8'760$ steps, one for each hour in the year. Clarifications concerning cost parameters are available in the Annex, section A.2.

In the following sections, each technology is represented by a schematic drawing, with consumed resources on the left and produced resources to the right. Auxiliary inputs are are added below. Losses and exchanges with the environment are added above. The color scheme, follow the flow diagram 11, with blue for electricity, red for heat, green for biogas, grey fro natural gas and beige for biomass or wood. The values are normalized for 100 units of input. For storage, a day of storage is used. Not all possible inputs are represented, only the most common.

3.4.1 Resources and grids

Some resources can be bought from the grid or sold to the grid. Electricity (EL) is the only resource that can be both bought and sold. Natural Gas (NG), Diesel and wood can only be bought from the grid, while Bio-methane (BM) can only be sold to the grid. Heat, Biogas (BG) and biomass cannot be exchanged with the grid. Each resource except for electricity has a waste stream. Resources have a fixed purchase price based on the OFS annual energy price report for a medium (size 3) consumer [19] for the year 2019.

Production of renewable electricity often benefit from feed-in tariffs. In Switzerland these tariffs have lately been removed for small PV installations and biogas installations [20]. The tariffs on electricity produced from biomass at farms used to be as high as $0.48 CHF/kWh$ [21], not including bonuses for reusing heat. Since 2018, it is no longer possible to benefit from these tariffs [20]. The base case scenario will therefore not include favourable feed-in tariffs. For electricity, the revenue for selling to the grid is fixed at $0.12 CHF/kWh$, a value specific to Aadorf for PV[22]. For simplicity, feed-in tariff for electricity is the same regardless of the source (PV, ICE or SOFC). For the injection of BM into the grid, no current value could be found in the literature. An estimate at 20% below the retail price of NG is used.

Each imported or exported resource has an associated emission. For electricity in Switzerland, the associated emissions can greatly vary according to imports from neighbouring countries and domestic production. As in figure 8 the variation is significant, from 0.06 to $0.4 kgCO_2/kWh$ depending on the season. The source of NG, diesel and wood is assumed to not vary during the year, their emissions are fixed and based on the Life Cycle Assessment (LCA) of the production of each resource. Table 4 summarizes resource cost and emissions. Emissions from waste streams are neglected except for unused manure. In practice, the model minimizes waste therefore only a significant amount of heat is lost via cogeneration in summer.

Resource in the FES may have the following variables. $\dot{E}^{+r}_{grid,d,h}$ and $\dot{E}^{-r}_{grid,d,h}$ the energy consumed by respectively produced by the grid of that resource in kW. $\dot{E}^{+r}_{waste,d,h}$ the energy flow that is not used. As well as E^{+r}_{grid}, E^{-r}_{grid} and E^{+r}_{waste} the corresponding annual total energy flow in kWh.

Table 4 – Cost and emissions associated with buying a resource from the grid or selling a resource to the grid. The subscript $_r$ replace the resource name for readability

Resource	Name	Symbol	Value	Units	Source
EL	Selling price	c^{sell}_r	0.12	CHF/kWh	[22]
	Purchase cost	c^{buy}_r	0.21	CHF/kWh	[19]
	Associated emissions	$m^{buy}_{CO_2\,r}$	0.2 [22]	tCO_2/MWh	[23]
NG	Selling price	c^{sell}_r	-	CHF/kWh	Not sold
	Purchase cost	c^{buy}_r	0.1	CHF/kWh	[19]
	Associated emissions	$m^{buy}_{CO_2\,r}$	0.21 [23]	tCO_2/MWh	[24]
Wood	Selling price	c^{sell}_r	-	CHF/kWh	Not sold
	Purchase cost	c^{buy}_r	0.07	CHF/kWh	[19]
	Associated emissions	$m^{buy}_{CO_2\,r}$	0.01	tCO_2/MWh	[25]
Diesel	Selling price	c^{sell}_r	-	CHF/kWh	Not sold
	Purchase cost	c^{buy}_r	0.15	CHF/kWh	[19]
	Associated emissions	$m^{buy}_{CO_2\,r}$	0.27 [24]	tCO_2/MWh	[5]
BM	Selling price	c^{sell}_r	0.08 [25]	CHF/kWh	Setting
	Purchase cost	c^{sell}_r	-	CHF/kWh	Not bought
	Associated emissions	$m^{buy}_{CO_2\,r}$	0.21 [26]	tCO_2/MWh	Setting

[22] Average value of the hourly data by [23]. For the swiss grid in the year 2015.

[23] Ratio between the emissions from natural gas and the consumed natural gas for Switzerland in 2017. As verification, NG combustion emissions are calculated to be $0.198[kgCO2/kWh] = 2.75[kgCO2/kgCH4] \cdot \frac{50[MJ/kgCH4]}{3.6[kWh/MJ]}$

[24] As verification, Diesel combustion emissions are calculated to be $0.269[kgCO2/kWh] = 2.68[kgCO2/liter] \cdot \frac{35.86[MJ/liter]}{3.6[kWh/MJ]}$

[25] The selling price of BM without feed-in tariff is fixed at 80% of the purchase cost of NG.

[26] BM is considered to be a renewable resource. When exported to the grid, it will replace NG and save an equivalent amount of emissions.

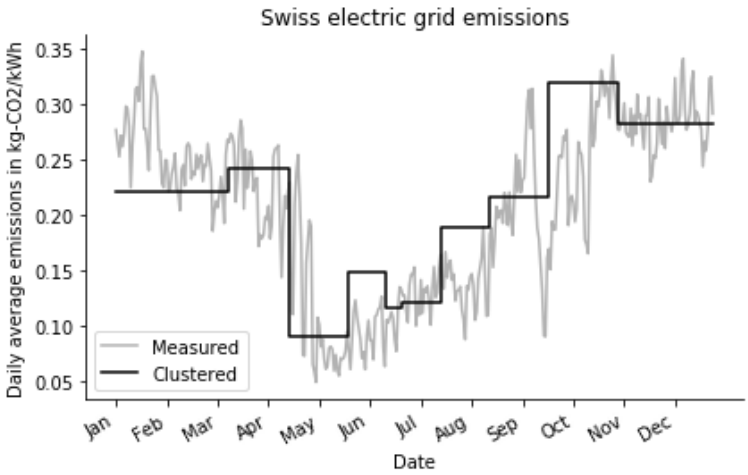
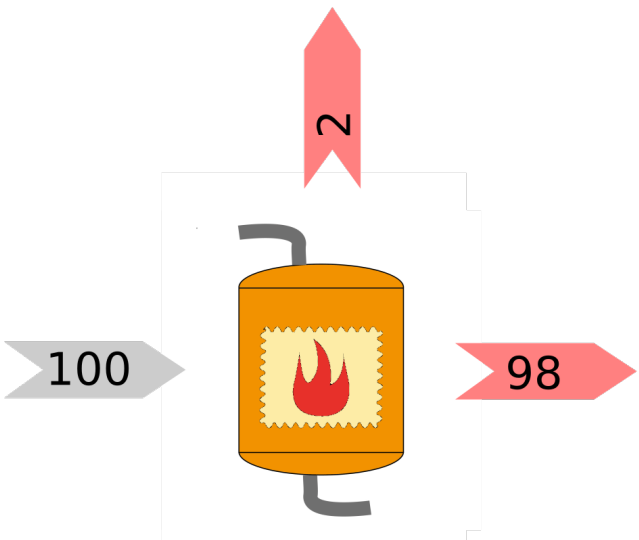


Figure 8 – Emissions associated with importing electricity from the Swiss grid as a function of time. The data used in the model is hourly, it is presented as a daily average for better visibility. The measured data was produced by [23] from February of 2015 to February of 2016. For the clustered data, the typical days and their order are the same as for the weather parameters.

3.4.2 Gas Boiler



Credit: Haruka Ogawa

The GBOI represent a modern, high efficiency natural gas boiler. Equation 14 gives the heat produces relative to the gaseous fuel inputs. The efficiency of burning NG, BG or BM are assumed to be equivalent. Variable $\dot{Q}^{-}_{GBOI,d,h}$ is the heat output of the GBOI, variables $\dot{E}^{+NG}_{GBOI,d,h}$, $\dot{E}^{+BG}_{GBOI,d,h}$ and $\dot{E}^{+BM}_{GBOI,d,h}$ are the inputs of NG, BG and BM respectively. The boiler efficiency is η_{GBOI}. The variable S_u is the installed capacity of the GBOI in kW output of heat. Equation 15 holds for all of the heaters except the AHP. Parameters and costs for this unit are summarized in table 5.

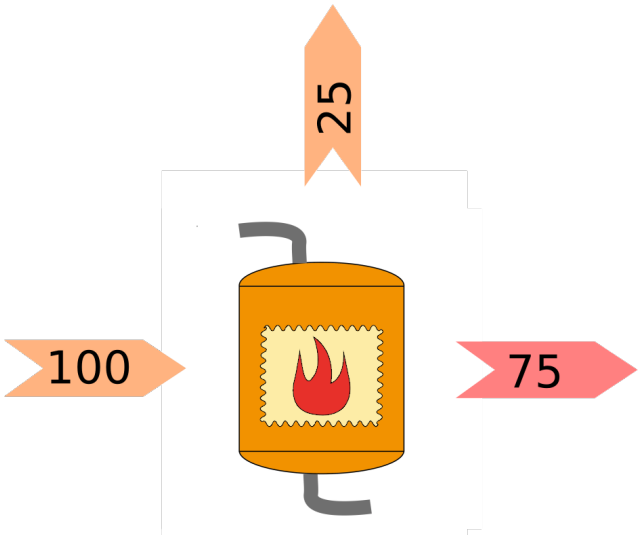
$$\dot{Q}^{-}_{GBOI,d,h} = \eta_{GBOI} \cdot (\dot{E}^{+NG}_{GBOI,d,h} + \dot{E}^{+BG}_{GBOI,d,h} + \dot{E}^{+BM}_{GBOI,d,h}) \qquad [kW] \qquad (14)$$

$$\dot{Q}^{-}_{u,d,h} \leq S_u \qquad [kW] \qquad (15)$$

Table 5 – GBOI: Parameters used for the modelling of the Gas Boiler. The subscript u is used in place of $GBOI$ to improve readability.

Name	Symbol	Value	Units	Source
Efficiency	η_u	0.98	–	[26]
Cost multiplier	c_u^{mult}	1.8	–	[15]
Specific investment cost	c_u^{size}	0.105	$kCHF/kW$	[15]
Fixed investment cost	c_u^{fixe}	3.8	$kCHF$	[15]
LCA emissions	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	[26]
Life	n_u	20	$Years$	[15]
Maintenance	c_u^{maint}	0.05	–	[26]
Smallest size[27]	S_u^{min}	5	kW	Setting
Reference size	S_u^{ref}	50	kW	[15]

3.4.3 Wood Boiler



Credit: Haruka Ogawa

The WBOI is very similar to the gas boiler. It burns wood pellets to generate heat. The nature of the fuel limits the efficiency of the WBOI. The heat generated $\dot{Q}^{-}_{WBOI,d,h}$ depends on the wood consumed $\dot{E}^{+Wood}_{WBOI,d,h}$ and the efficiency η_{WBOI} as per eq. 16. The size of the heater is also limited by equation 15. Table 6 lists the parameters used.

$$\dot{Q}^{-}_{WBOI,d,h} = \eta_{WBOI} \cdot \dot{E}^{+Wood}_{WBOI,d,h} \qquad [kW] \tag{16}$$

Wood can be considered as a renewable resource, provided every tree consumed is replaced, the emissions during combustion will be compensated by the CO_2 captured during the tree's life. As is the case in Switzerland

[27] The smallest possible installed capacity has two roles. First, to limit the number of possibilities the model has to reduce the solve time by cutting off installed capacities close to zero. Second, for very small sizes efficiency may be reduced or costs may increase exponentially, which this limit prevents.

where the forest covered area is approximately 32% and has been increasing since 1991 [27]. It is important to consider wood as limited and useful resource for many other applications such as construction. Only waist wood will be considered as a renewable resource. Even then, some wood work waist can be used in the making of composite wood panels. Steubing et al. [28] have estimated that the remaining renewable wood biomass to be $15.2PJ$ per year in Switzerland. Out of $1'100PJ$ total primary energy supply in 2019 [7] 40% can be attributed to the domestic use and a further 83% of that share for heating. 69% of the heating in Switzerland are from heavy oil (mazout) and natural gas [15]. This represent $250PJ$ of heating from direct fossil combustion. If all remaining renewable wood is used for heating via combustion it would represent 6% of the heating supply.

Wood pellets like any resource has Life Cycle (LCA) emissions, due to transport and the use of energy during production. Sikkema et al. [25] calculated the LCA emissions of wood pellets for district heating in Sweden and arrived at a value of $10.15kg$ equivalent CO_2 per MWh_{LHV} of fuel. An order of magnitude below NG.

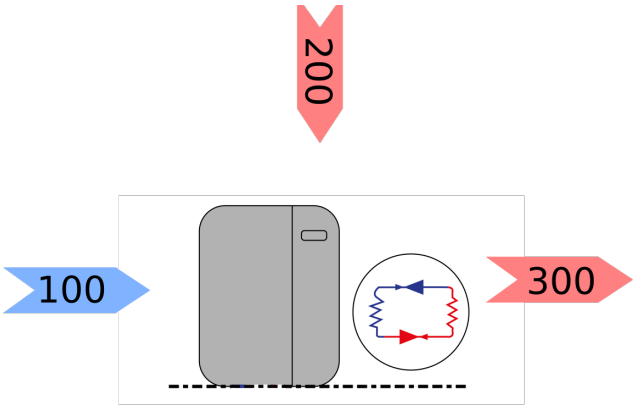
Table 6 – WBOI: Parameters used for the modelling of the Wood Boiler.

Name	Symbol	Value	Units	Source
Efficiency	η_u	0.85	–	[26]
Cost multiplier [28]	c_u^{mult}	1.8	–	Default
Specific investment cost [29]	c_u^{size}	0.148	$kCHF/kW$	[26]
Fixed investment cost	c_u^{fixe}	5.4	$kCHF$	[26]
LCA emissions	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	[26]
Life	n_u	17	$Years$	[26]
Maintenance	c_u^{maint}	0.017	–	[26]
Smallest size	S_u^{min}	5	kW	Setting
Reference size	S_u^{ref}	100	kW	[26]

[28] When no other value is available, the cost multiplier is fixed at 1.8 for foreign based costing analysis. In order to account for an increased investment cost when installing a technology in Switzerland relative to Europe or north America.

[29] In most of the literature only a total cost for the technology is given. To split this value into fixed and specific costs, 30% of the total cost is attributed to the fixed cost and the remaining 70% is attributed to the specific cost. As reference the share of the fixed cost for the GBOI in [15] is 36% at the ref size.

3.4.4 Air-Air Heat Pump



Credit: Haruka Ogawa

A Heat Pump (HP) can transfer heat from a cold source, i.e. outside temperature air, to a hot source, i.e. air inside the house. The advantage compared to an electric heater is that only a third or a forth of electricity is needed to produce the same heat load. This is achieved by an electric compressor, Heat Exchangers (HE) and an expansion valve. The working fluid, a refrigerant, is compressed increasing its temperature. It then releases its heat by condensing on the high temperature HE. It is then expanded through the expansion valve and condenses on the cold HE, recovering heat from the cold air. The performance of the HP is expressed by the Coefficient of Performance (COP). The COP depends on the temperature difference between the hot and cold source and system efficiency. It can be estimated by the following equation. Where $\frac{T_{hot}}{T_{hot}-T_{cold}}$ is the ideal efficiency and η_{HP} is specific to the HP for a certain temperature range. Generally η_{HP} is close to 0.5.

$$COP = \eta_{HP} \cdot \frac{T_{hot}}{T_{hot} - T_{cold}} \tag{17}$$

The Air sourced heat pump (AHP) is designed for a domestic scale. The exterior air is cooled down and the interior is directly heated via one or more heating panels (the hot HE). The COP is fixed at 3 for simplification, although it will vary depending on the outside temperature. Equation 18 relate the heat load $\dot{Q}^{-}_{AHP,d,h}$ to the electric load $\dot{E}^{+EL}_{AHP,d,h}$ and the COP. Unlike other heaters, the installed capacity of the unit S_u is relative to the electric consumption as in eq. 19. All parameters related to the AHP are presented in table 7.

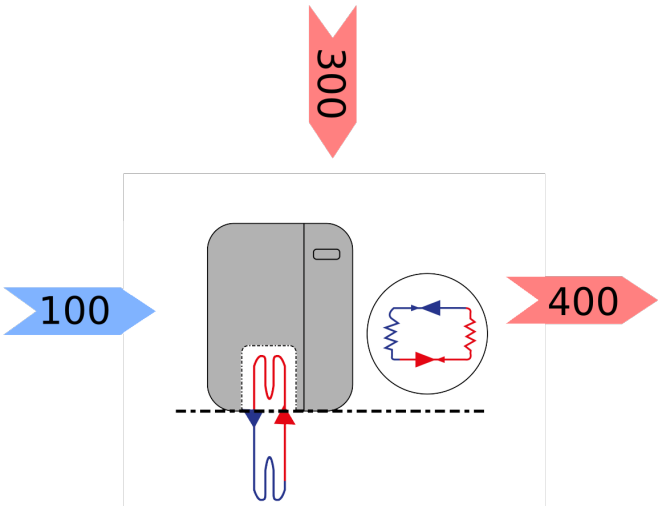
$$\dot{Q}^{-}_{AHP,d,h} = COP_{AHP} \cdot \dot{E}^{+EL}_{AHP,d,h} \qquad [kW] \tag{18}$$

$$\dot{E}^{+EL}_{AHP,d,h} \leq S_{AHP} \qquad [kW] \tag{19}$$

Table 7 – AHP: Parameters used for the modelling of the Air-Air Heat Pump

Name	Symbol	Value	Units	Source
Coefficient of Performance	COP_u	3	–	[26]
Cost multiplier	c_u^{mult}	1.8	–	[15]
Specific investment cost	c_u^{size}	1.24	$kCHF/kW$	[15]
Fixed investment cost	c_u^{fixe}	5.68	$kCHF$	[15]
LCA emissions [30]	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	Default
Life	n_u	20	$Years$	[15]
Maintenance	c_u^{maint}	0.02	–	[15]
Smallest size	S_u^{min}	5	kW	Setting
Reference size	S_u^{ref}	10	kW	[15]

3.4.5 Geothermal Heat Pump



Credit: Haruka Ogawa

The GHP is based on the same principle as the AHP, except the heat source is not the exterior air but ground heat. It uses bore holes on the order of 100 meters deep and a closed water circuit. Perego et al. [29] studied the use of GHP in Ticino, Switzerland and concluded that on average 15 meters of borehole produced $1kW$ of heat via the GHP. The COP is on average 4 (minimum 3 and maximum 5) and is assumed to be constant. At 100 depth, the ground temperature remains stable through the year between 11 and $14°C$ depending on the region, for low altitudes ($500m$). Drilling increases the system initial investment. Its therefore more suited for centralized heating systems rather than individual systems. Blum et al. [30] estimate the cost of drilling to be equal to the cost of the HP. The bore hole has a life span of 50 years or more[31] while the HP part is estimated at 25 years [30]. Setting a life span of 33 years is equivalent to annualizing half the costs over 25 years and the other half over 50 years. The maintenance costs relative to initial investment are half of the AHP because the

[30] When no value is available, the LCA emissions of any unit (except the Battery) is by default $0.02tCO_2/kW$ as for the GBOI and WBOI.

[31] According to `dandelionenergy.com` a GHP provider

bore hole is assumed to not require maintenance. It is important to note that the COP and cost of drilling will depend on the geological aspects of the ground.[32]

Equation 20 is rigorously the same as for the AHP. The installed capacity of the unit S_{GHP} is expressed in kW of heat output like other heaters, as in eq. 21. All parameters for the unit are presented in table 8.

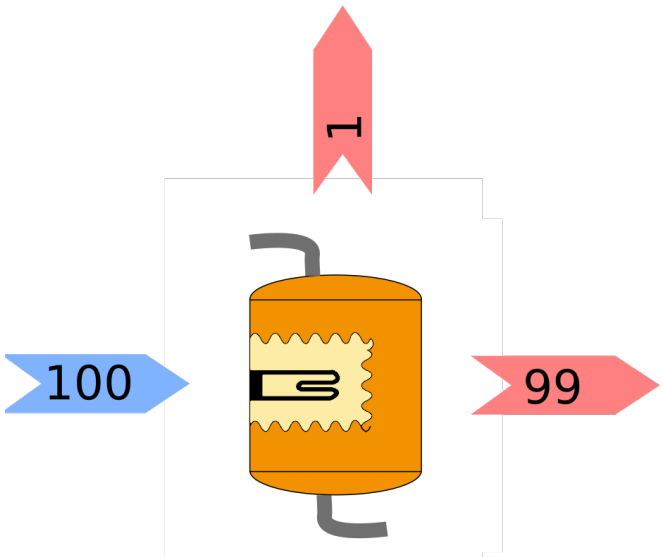
$$\dot{Q}^{-}_{GHP,d,h} = COP_{GHP} \cdot \dot{E}^{+EL}_{GHP,d,h} \qquad [kW] \tag{20}$$

$$\dot{Q}^{-}_{GHP,d,h} \leq S_{GHP} \qquad [kW] \tag{21}$$

Table 8 – GHP: Parameters used for the modelling of the Geothermal Heat Pump

Name	Symbol	Value	Units	Source
Coefficient of Performance	COP_u	4	–	[29]
Cost multiplier	c_u^{mult}	1	–	[29]
Specific investment cost	c_u^{size}	2.1	$kCHF/kW$	[29]
Fixed investment cost	c_u^{fixe}	22.5	$kCHF$	[29]
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life	n_u	33	$Years$	Calc
Maintenance	c_u^{maint}	0.01	–	[30, 15]
Smallest size	S_u^{min}	25	kW	[29]
Reference size	S_u^{ref}	25	kW	[29]

3.4.6 Electric Heater



Credit: Haruka Ogawa

[32] Rough geological aspects and temperatures are available at `maps.geo.admin.ch` but relating them to the cost and COP is outside the scope of this study.

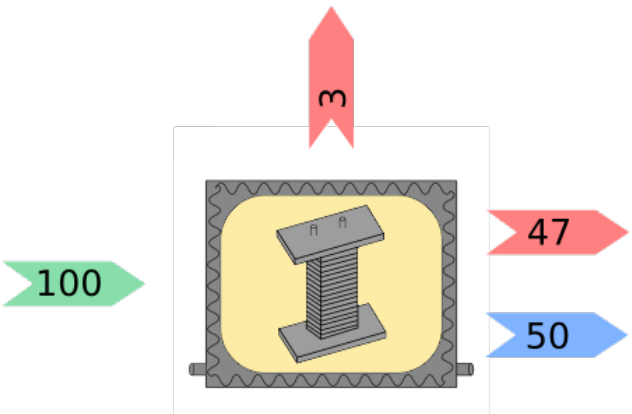
The Electric heater dissipates electricity through a resistance to generate heat. Its advantage is to be the cheapest heater per installed capacity, however it is the least efficient heater from the perspective of exergy. Its resource is also expensive. The heat produced $\dot{Q}^{-}_{EH,d,h}$ is almost equivalent to the electricity consumed $\dot{E}^{+EL}_{EH,d,h}$. Its capacity in kW-heat is constrained by 15. Parameters for the HE are presented in Table 9.

$$\dot{Q}^{-}_{EH,d,h} = \eta_{EH} \cdot \dot{E}^{+EL}_{EH,d,h} \qquad [kW] \tag{22}$$

Table 9 – EH: Parameters used for the modelling of the Electric Heater

Name	Symbol	Value	Units	Source
Efficiency	η_u	0.99	–	[15]
Cost multiplier	c_u^{mult}	1	–	[15]
Specific investment cost	c_u^{size}	0.013	$kCHF/kW$	[15]
Fixed investment cost	c_u^{fixe}	0.97	$kCHF$	[15]
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life	n_u	20	$Years$	[15]
Maintenance	c_u^{maint}	0.02	–	[15]
Smallest size	S_u^{min}	5	kW	Setting
Reference size	S_u^{ref}	100	kW	[15]

3.4.7 Solid Oxide Fuel Cell



Credit: Haruka Ogawa

The SOFC consume gaseous fuels (BG, BM or NG) to cogenerate heat and power. The main advantage of the SOFC is its high electric efficiency even for a small installed capacity. However, the technology is not yet commercialized on a large scale, making it relatively expensive. The SOFC operates at high temperature ($800°C$) allowing it to reduce oxygen on the air side and oxidize methane on the fuel side without the need for rare earth metals, like low temperature cells consuming hydrogen. Due to the high operating temperature it cannot be turned on and off in a short time without degradation. Since the FES model has an hour time step, no limit start-up time is set. Unlike a combustion engine it can operate efficiently at part load.

Being a catalyst, it is very sensitive to contaminants in the fuel. Biogas often contains sulfur like H_2S on the order of $10ppm$ to $1'000ppm$ and siloxanes on the order of $100ppb$ as well as other contaminants [31]. The SOFC may be regenerated after the deposition of a small amount ($10ppm$) of sulfur but siloxane will accumulate over time reducing the efficiency of the SOFC. These contaminants need to be removed through biogas gas cleaning for SOFC applications (GCSOFC).

The efficiency of the SOFC depends on the quality of the fuel consumed. Biogas with its high content of CO_2 causes a drop in efficiency compared to NG or BM. Equation 23 relate the electricity produced by the SOFC $\dot{E}^{-EL}_{u,d,h}$ to each fuel consumed $\dot{E}^{+BG}_{u,d,h}$, $\dot{E}^{+BM}_{u,d,h}$ and $\dot{E}^{+NG}_{u,d,h}$ and their respective electric efficiency $\eta_{u,EL-BG}$ and $\eta_{u,EL-NG}$. Because BM is similar to NG in methane content, it is assumed to have the same efficiency $\eta_{u,EL-NG}$. However, like biogas it needs to be deep cleaned before it is consumed by the SOFC. The subscript u is used in place of $SOFC$ to shorten the notations. In eq. 24 the heat produced $\dot{Q}^{-}_{u,d,h}$ is a function of the energy losses and the thermal efficiency $\eta_{u,Q}$, which corresponds to the fraction of heat losses that can be recovered as heat for the heating system. The installed capacity S_u corresponds to the electric output capacity as per eq. 25. Table 10 presents the SOFC parameters and costs.

$$\dot{E}^{-EL}_{u,d,h} = \eta_{u,EL\text{-}BG} \cdot \dot{E}^{+BG}_{u,d,h} + \eta_{u,EL\text{-}NG} \cdot (\dot{E}^{+NG}_{u,d,h} + \dot{E}^{+BM}_{u,d,h}) \quad [kW] \tag{23}$$

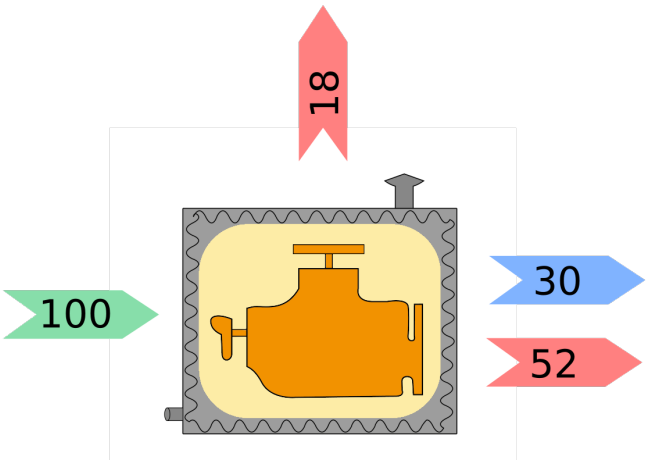
$$\dot{Q}^{-}_{u,d,h} = \eta_{u,Q} \cdot \left((1-\eta_{u,EL\text{-}BG}) \cdot \dot{E}^{+BG}_{u,d,h} + (1-\eta_{u,EL\text{-}NG}) \cdot (\dot{E}^{+NG}_{u,d,h} + \dot{E}^{+BM}_{u,d,h})\right) \quad [kW] \tag{24}$$

$$\dot{E}^{-EL}_{u,d,h} \leq S_u \quad [kW] \tag{25}$$

Table 10 – SOFC: Parameters used for the modelling of the Solid Oxide Fuel Cell

Name	Symbol	Value	Units	Source
Electric efficiency for BG	$\eta_{u,EL-BG}$	0.5	–	[9]
Electric efficiency for NG	$\eta_{u,EL-NG}$	0.6	–	[9]
Thermal efficiency	$\eta_{u,Q}$	0.9	–	[9]
Cost multiplier	c^{mult}_u	1.8	–	[15]
Specific investment cost	c^{size}_u	2.1	$kCHF/kW$	[15]
Fixed investment cost	c^{fixe}_u	15.5	$kCHF$	[15]
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life	n_u	10	$Years$	[15]
Maintenance	c^{maint}_u	0.05	–	[15]
Smallest size	S^{min}_u	1	kW	[15]
Reference size	S^{ref}_u	5	kW	[15]

3.4.8 Internal Combustion Engine



Credit: Haruka Ogawa

As a cogeneration unit, the ICE is similar to the SOFC. It consumes gaseous fuel and produces heat and electricity. At large scales the ICE can reach efficiencies close to 40 % [33]. However at small and very small scales (below $50kW$), the efficiency is drastically reduced. Part-load efficiency is also an issue for the ICE but it is not accounted for in the FES model. The technology is mature and costs are lower than for SOFC installations. Although some biogas cleaning and drying is commonly used for an ICE running on biogas, it is neglected in the present model. The high maintenance cost accounts for degradation from biogas contaminants like sulfur. Performance with biogas may be slightly lower than for NG but the difference is neglected. Equation 26 relates the electricity produced to the fuel consumed and the ICE electric efficiency $\eta_{u,EL}$. The heat produced is related to the thermal efficiency $\eta_{u,Q}$ as a fraction of the heat losses as per eq. 27. ICE size S_u is expressed in terms of installed electric capacity. Table 11 shows the ICE related parameters.

$$\dot{E}^{-EL}_{u,d,h} = \eta_{u,EL} \cdot (\dot{E}^{+BG}_{u,d,h} + \dot{E}^{+NG}_{u,d,h} + \dot{E}^{+BM}_{u,d,h}) \qquad [kW] \qquad (26)$$

$$\dot{Q}^{-}_{u,d,h} = \eta_{u,Q} \cdot (1 - \eta_{u,EL})(\dot{E}^{+BG}_{u,d,h} + \dot{E}^{+NG}_{u,d,h} + \dot{E}^{+BM}_{u,d,h}) \qquad [kW] \qquad (27)$$

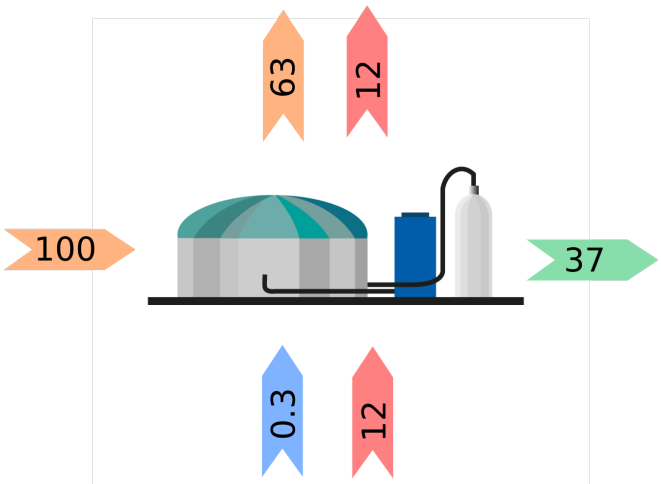
$$\dot{E}^{-EL}_{u,d,h} \leq S_u \qquad [kW] \qquad (28)$$

[33] A 150kW ICE in Palézieux reaches 37% running on biogas [32]

Table 11 – ICE: Parameters used for the modelling of the Internal Combustion Engine

Name	Symbol	Value	Units	Source
Electric efficiency	$\eta_{u,EL}$	0.3	–	[12], [33]
Thermal efficiency	$\eta_{u,Q}$	0.75	–	[12], [33]
Cost multiplier	c_u^{mult}	1	–	[12]
Specific investment cost	c_u^{size}	1.4	$kCHF/kW$	[12], [33]
Fixed investment cost	c_u^{fixe}	6	$kCHF$	[12], [33]
LCA emissions	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	Default
Life	n_u	20	$Years$	[12]
Maintenance	c_u^{maint}	0.085	–	[32], [33]
Smallest size	S_u^{min}	10	kW	Setting
Reference size	S_u^{ref}	20	kW	[12]

3.4.9 Anaerobic Digester



Credit: Haruka Ogawa

An Anaerobic Digester (AD) produces biogas (BG) from biomass. BG is on average 60% of methane with 40%CO_2 [9] but this value is often higher for BG produced from animal manure. Many different AD processes exist, for a small scale system, a single stage, continuously stirred, mesophilic reactor is common [34]. To achieve anaerobic digestion the AD is maintained at a temperature of 40°C, to promote the right bacterial activity for methane production. Under these conditions, the retention time is approximately 30 days [35]. The process requires heat and electricity to run. The efficiency can vary drastically relative to operating conditions, nature of inputs and contaminants since it depends on the bacterial activity. The time to reach full load from start up is at least 30 days and often more. Once the digestion process is complete, the digestate can be used as fertilizer [36].

To model this complex system with a set of simple linear constraints the following assumptions are made. If installed, the AD operates at full load at all time, consuming all the available biomass. The startup time is neglected. The efficiency is assumed constant. Under these assumptions, the following constraints 29 to 33

describe the AD behaviour. Equation 29 gives $\dot{E}^{-BG}_{AD,d,h}$, the biogas produced, with η_{AD} the biomass to biogas conversion efficiency and $\dot{E}^{+Biomass}_{AD,d,h}$ the biomass consumed by the AD. Eq. 30 forces all the available biomass $\dot{E}^{-Biomass}_{Farm,d,h}$ to be consumed at all times if the AD is installed. The condition is represented by the binary decision variable Z_{AD} which will be 1 if the AD is installed and 0 otherwise. The electricity consumed is a function of the biogas produced and a factor $f_{AD_{EL/BG}}$ as per eq. 31. The AD heat load through the year changes depending on weather. It is modelled and precalculated using the same equations as the buildings thermal model with different heat capacity, conductivity and gains. A detailed description of the AD sizing and thermodynamic model is available in Annex A.3. Eq. 32 says the heat load will be $\dot{Q}^{+precalc}_{AD,d,h}$ if the AD is installed and 0 otherwise. The installed capacity of the AD is expressed relative to the biogas output in kW of BG as per eq. 33. Table 12 summarises the AD performance and cost parameters, parameters relative to the heat load calculation are presented in the annex.

$$\dot{E}^{-BG}_{AD,d,h} = \eta_{AD} \cdot \dot{E}^{+Biomass}_{AD,d,h} \qquad [kW] \tag{29}$$

$$\dot{E}^{+Biomass}_{AD,d,h} = \dot{E}^{-Biomass}_{Farm,d,h} \cdot Z_{AD} \qquad [kW] \tag{30}$$

$$\dot{E}^{+EL}_{AD,d,h} = f_{AD_{EL/BG}} \cdot \dot{E}^{-BG}_{AD,d,h} \qquad [kW] \tag{31}$$

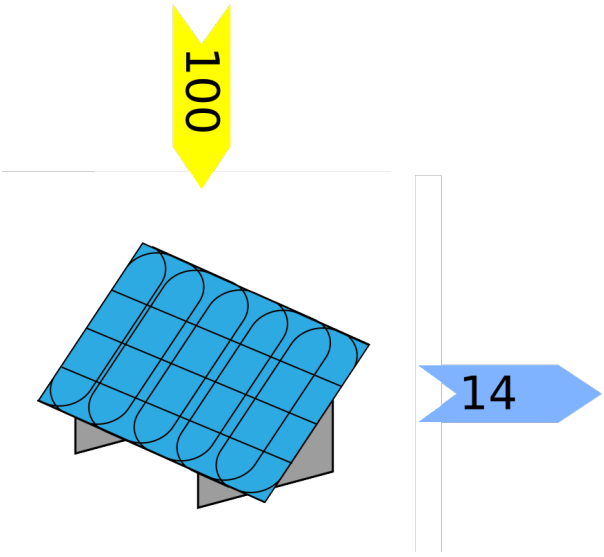
$$\dot{Q}^{+}_{AD,d,h} = \dot{Q}^{+precalc}_{AD,d,h} \cdot Z_{AD} \qquad [kW] \tag{32}$$

$$\dot{E}^{-BG}_{AD,d,h} \leq S_{AD} \qquad [kW] \tag{33}$$

Table 12 – AD: Parameters used for the modelling of the Anaerobic Digester

Name	Symbol	Value	Units	Source
Efficiency	η_u	0.37	–	[1]
Electric consumption	$f_{u_{EL/BG}}$	0.008	–	[37]
Heat consumption	$f_{u_{Q/BG}}$	0.32	–	[1]
Cost multiplier	c^{mult}_u	1.8	–	[31]
Specific investment cost	c^{size}_u	1.5	$kCHF/kW$	[31]
Fixed investment cost	c^{fixe}_u	5	$kCHF$	[31]
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life	n_u	20	$Years$	[31]
Maintenance	c^{maint}_u	0.1	–	[31]
Smallest size	S^{min}_u	20	kW	[34]
Reference size	S^{ref}_u	100	kW	[31]

3.4.10 Photovoltaic Panels



Credit: Haruka Ogawa

PV panels convert solar irradiation to electricity. It is currently a cheapest way to produce electricity, especially at small scales. In 2017 it reached an average of $0.1 USD/kWh$ compared to 0.07 for fossil and 0.06 for onshore wind [38]. PV installations are commonly composed of a multitude of fixed modules mounted directly on building roofs. For simplification, the amount of radiation received by the PV panel is assumed equal to the GHI measurement and not dependent of the panels orientation. Equation 34 represents the electricity produced $\dot{E}^{-EL}_{PV,d,h}$ as a function of average efficiency η_{PV}, surface covered $\frac{S_{PV}}{\rho_{PV}}$ and GHI $\cdot I_{d,h}$. ρ_{PV} is the energy density of the panel and S_{PV} the installed capacity in kW electricity produced under nominal conditions, i.e. a GHI of $1 kW/m^2$. The installed capacity S_{PV} is limited by the available roof area. The fraction of roof available for PV installations $f_{PV,roof}$, is set to be half of the buildings ground area A^b_{ground}. See table 13 for all PV related parameters.

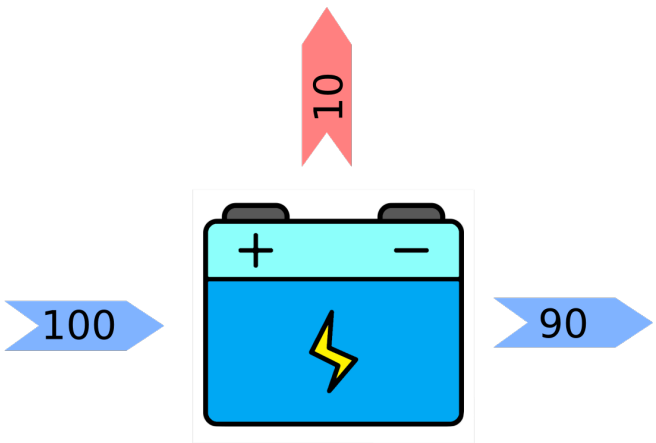
$$\dot{E}^{-EL}_{PV,d,h} = \eta_{PV} \cdot I_{d,h} \cdot \frac{S_{PV}}{\rho_{PV}} \qquad [kW] \qquad (34)$$

$$S_{PV} \leq A_{b,ground} \cdot f_{PV,roof} \cdot \rho_{PV} \qquad [kW] \qquad (35)$$

Table 13 – PV: Parameters used for the modelling of the Photovoltaic Panels

Name	Symbol	Value	Units	Source
Efficiency	η_u	0.14	–	[15]
Energy density	ρ_u	0.2	kW/m^2	[39]
Available area ratio	$f_{A_{PV}/A_{b,ground}}$	0.5	–	Setting
Cost multiplier	c_u^{mult}	1.33	–	[15]
Specific investment cost	c_u^{size}	2.65	$kCHF/kW$	[15]
Fixed investment cost	c_u^{fixe}	2.5	$kCHF$	[15]
LCA emissions	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	Default
Life	n_u	20	$Years$	[15]
Maintenance	c_u^{maint}	0.02	–	[15]
Smallest size	S_u^{min}	5	kW	Setting
Reference size	S_u^{ref}	10	kW	[15]

3.4.11 Battery



Credit: Haruka Ogawa

Lithium-ion batteries (BAT) is still an emerging technology. They can store a high amount of electricity for a prolonged time in a relatively small volume. The disadvantage is that they are at present difficult to recycle and therefore they have the highest life-cycle emissions of all the FES units. In the future, numerous used electric vehicle batteries may be available for energy storage with a lower environmental impact. Alternatively, technologies to recycle lithium may reduce the LCA emissions. The highest value presented [40] for BAT LCA emissions corresponding to the current scenario .

The linear model for batteries presented below is based on the models by P. Stadler [15] and D. Lauinger [11]. No limits on depth of discharge are set. The life of the battery is fixed and is not dependant on operating conditions or temperature. The discharge rate is not limited, while the model time step is 1 hour, the effective maximum discharge rate is $1C_{rate}$ which is acceptable.

Batteries are short term storage devices, they are usually modelled on a daily cycle. It is however possible

to use a battery to store electricity over more than a day. For the FES model and to tune the self discharge parameter, it is assumed to be not viable to store electricity longer than a month. To take this possible medium term storage into account, the variable for the SOC is discretized over the whole year, i.e. 8′760 hours, instead of a number of typical days only. The SOC is the only variable that requires this discretization, all other variables, such as charging and discharging, depend on the reset of the model's behaviour, which will be identical for each typical day. In the model and in the result graphs the SOC is in kWh.

$$SOC_{BAT,p+1} - (1 - r_{sd}) \cdot SOC_{BAT,p} = (\sqrt{\eta_{BAT}} \cdot \dot{E}^{+EL}_{BAT,t(p)} - \frac{1}{\sqrt{\eta_{BAT}}} \cdot \dot{E}^{-EL}_{BAT,t(p)}) \quad [kWh] \quad (36)$$

$$SOC_{u,0} = SOC_{u,last(p)} \quad [kWh] \quad (37)$$

$$Z^{\dot{E}^{+EL}}_{u,d,h} + Z^{\dot{E}^{-EL}}_{u,d,h} \leq 1 \quad [-] \quad (38)$$

$$Z^{\dot{E}^{+EL}}_{u,d,h} \cdot M \geq \dot{E}^{+EL}_{u,d,h} \cdot dt \quad [kWh] \quad (39)$$

$$Z^{\dot{E}^{-EL}}_{u,d,h} \cdot M \geq \dot{E}^{-EL}_{u,d,h} \cdot dt \quad [kWh] \quad (40)$$

$$SOC_{u,p} \leq S_u \quad [kWh] \quad (41)$$

$$\dot{E}^{+EL}_{u,d,h} \cdot dt \leq S_u \quad [kWh] \quad (42)$$

$$\dot{E}^{-EL}_{u,d,h} \cdot dt \leq S_u \quad [kWh] \quad (43)$$

In equation 36, the SOC $SOC_{BAT,p}$ is dependent on the charge and discharge, $\dot{E}^{+}_{BAT,t(p)}$ and $\dot{E}^{-}_{BAT,t(p)}$ in the last hour as well as the self discharge and losses as in [15]. The equation combines two different time periods, p which is 8′760 distinct hours and d, h which is the usual number of days and hours relative to the desired number of typical days. $t(p)$ is a function that gives the period d, h corresponding to any period p. The timestep dt of one time period p is 1 hour. r_{sd} is the self discharge rate per hour. A single efficiency η_{BAT} is used for charging and discharging as per [11]. The effect of the self-discharge is visible in figure 9. Constraint 37 forces the first value of SOC to be equal to the last over the entire year, to satisfy energy conservation.

Equations 39 40 and 38 with two binary variables $Z^{\dot{E}^{+}}_{BAT,d,h}$ and $Z^{\dot{E}^{-}}_{BAT,d,h}$ for "now charging" and "now discharging" prevent the battery from simultaneously charging and discharging. The installed capacity S_{BAT} is the storage capacity in kWh-electric. Table 14 presents the battery related parameters.

Table 14 – BAT: Parameters used for the modelling of the Battery

Name	Symbol	Value	Units	Source
Efficiency	ηu	0.9	–	[15]
Self discharge rate [34]	$r_{u_{sd}}$	0.003	–	Tuned
Energy density	ρ_u	230	kWh/m^3	[41]
Cost multiplier	c_u^{mult}	1.33	–	[15]
Specific investment cost	c_u^{size}	0.97	$kCHF/kWh$	[15]
Fixed investment cost	c_u^{fixe}	0.62	$kCHF$	[15]
LCA emissions	$m^{LCA}_{CO_2,u}$	0.2	tCO_2/kWh	[40]
Life	n_u	10	$Years$	[15]
Maintenance	c_u^{maint}	0.02	–	[15]
Smallest size	S_u^{min}	1	kWh	Setting
Reference size	S_u^{ref}	10	kWh	[15]

[34] The self discharged rate is tuned such that a full charge is approximately 90% depleted after a month of inactivity.

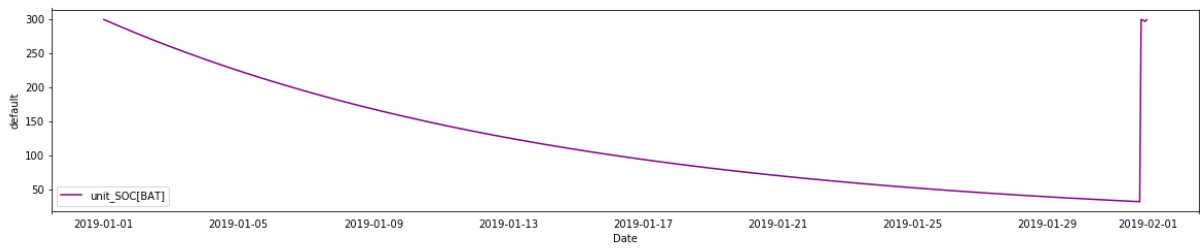
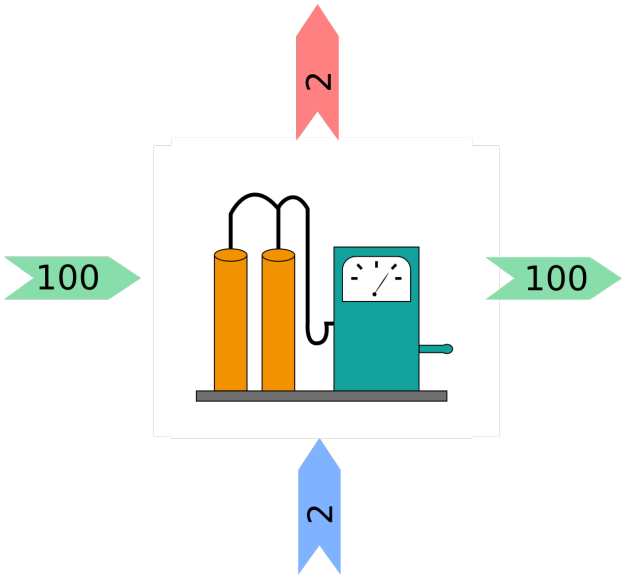


Figure 9 – The SOC of the battery is plotted against time, to highlight the self discharge rate modelled, the battery starts at full charge and is unused during one month, up until the last time steps where the BAT charges to full to satisfy a monthly cycling constraint, only used for this graph.

3.4.12 Compressed Gas Tank



Credit: Haruka Ogawa

A CGT stores compressed gas for extended periods of time, using only electricity for compression. The CGT is modelled after a $180bar$ NG storage tank, where electricity consumed by the compressor is 2% of the energy content of the NG input [42]. Only Bio-methane is considered for compression storage since NG has an unlimited availability from the grid at a fixed price. The storage model is similar to the battery, in fact equations 37 to 43 are identical for both units. Losses and self discharge are neglected for the CGT. No BM pretreatments are modelled, although some level of drying and filtering may be required depending on tank and compressor specifications to avoid corrosion from sulfur.

$$SOC_{CGT,p+1} - SOC_{CGT,p} = (\dot{E}^{+BM}_{CGT,t(p)} - \dot{E}^{-BM}_{CGT,t(p)})dt \qquad [kWh] \qquad (44)$$

$$\dot{E}^{+EL}_{CGT,d,h} = f^{comp}_{CGT_{EL/NG}} \cdot \dot{E}^{+BM}_{CGT,d,h} \qquad [kW] \qquad (45)$$

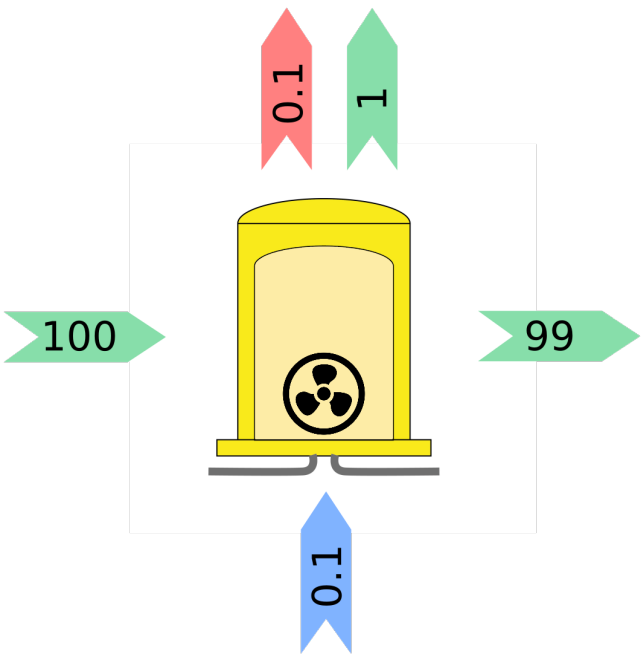
Equations 44 and 45 are specific to the CGT. The first calculates the SOC in kWh-BM without losses. The electricity consumed by the compressor $\dot{E}^{+EL}_{CGT,d,h}$ is proportional to the BM compressed $\dot{E}^{+BG}_{CGT,d,h}$. $f^{comp}_{CGT_{EL/NG}}$

is the fraction of electricity consumed relative to the energy of NG compressed. See table 15 for a full list of parameters. The energy density of the system is $2MWh/m^3$, for comparison the energy density of diesel is about $10MWh/m^3$.

Table 15 – CGT: Parameters used for the modelling of the Compressed Gas Tank

Name	Symbol	Value	Units	Source
Electric consumption	$f^{comp}_{u_{EL/NG}}$	0.02	–	[42]
Energy density [35]	ρ_u	2	MWh/m^3	Calc
Cost multiplier	c^{mult}_u	1.8	–	Default
Specific investment cost	c^{size}_u	0.0009	$kCHF/kWh$	[43]
Fixed investment cost	c^{fixe}_u	71.6	$kCHF$	[43]
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kWh	Default
Life	n_u	25	$Years$	[43]
Maintenance	c^{maint}_u	0.02	–	[43]
Smallest size	S^{min}_u	100	kWh	Setting
Reference size	S^{ref}_u	4300	kWh	[43]

3.4.13 Biogas Storage



Credit: Haruka Ogawa

[35] The energy density is calculated for methane under $180bar$ of pressure. Under these conditions the density of methane is $142.5kg/m^3$ [44] with an LHV of methane at $50MJ/kg$.

Biogas is assumed to contain 60%CH_4 and 40%CO_2. The CO_2 fraction cannot be stored in high pressure vessels because it will liquefy and pose problems during compression. To be able to store raw biogas requires a near atmospheric storage vessel. The BS is made of an inflatable reservoir, usually enclosed by an external steel casing. An electric blower fills the reservoir and maintains pressure at all time. The storage pressure is near atmospheric [45] and the biogas energy density is low, approximately 1′400 times lower than diesel. 1% of the biogas stored escapes during a day [45]. The high volume and daily losses makes this solution a short term storage solution. Storing biogas produced by the AD at the scale of SFF for 12 hours (biogas potential of $30kW$) would require approximately $50m^3$ of storage capacity.

Equations 37 to 43 from the battery model are identical and therefore are not repeated below. Equation 46 compute the SOC of the BS for each of the 8′760 time periods p, with $r_{BS_{sd}}$ the hourly self discharge rate. Eq. 47 represents the continuous operation of the fan as a function of installed capacity S_{BS} in kWh biogas, with $f^{fan}_{BS_{EL/BG}}$ the electricity consumed by the fan relative to storage capacity.

$$SOC_{BS,p+1} - (1 - r_{BS_{sd}}) \cdot SOC_{BS,p} = (\dot{E}^{+BG}_{BS,t(p)} - \dot{E}^{-BG}_{BS,t(p)})dt \qquad [kWh] \qquad (46)$$

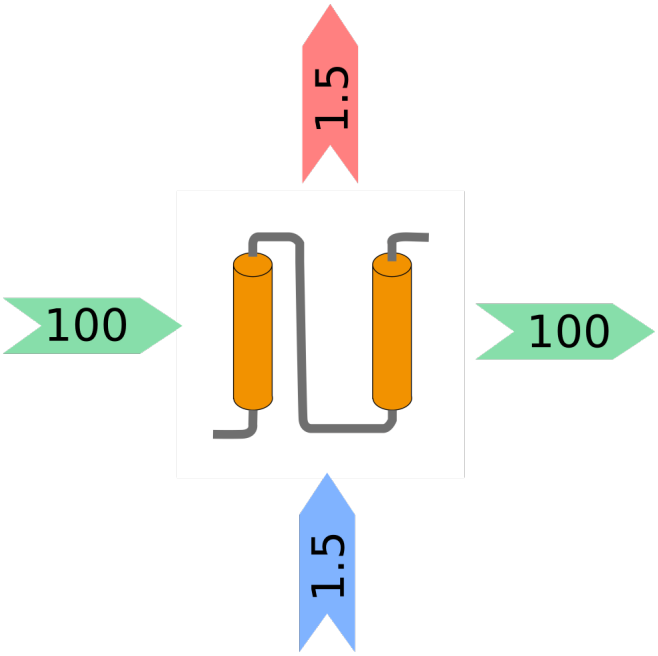
$$\dot{E}^{+EL}_{BS,d,h} = 10^{-3} \cdot f^{fan}_{BS_{EL/BG}} \cdot S_{BS} \qquad [kW] \qquad (47)$$

Table 16 – BS: Parameters used for the modelling of the Biogas Storage

Name	Symbol	Value	Units	Source
Electric consumption	$f^{fan}_{u_{EL/BG}}$	0.063	–	[45]
Self discharge rate	$r_{u_{sd}}$	0.0004	–	[45]
Energy density	ρ_u	6.8	kWh/m^3	[46]
Cost multiplier[36]	c^{mult}_u	5.2	–	Scaling
Specific investment cost	c^{size}_u	0.012	$kCHF/kWh$	[45]
Fixed investment cost	c^{fixe}_u	1.6	$kCHF$	[45]
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kWh	Default
Life	n_u	20	$Years$	[45]
Maintenance	c^{maint}_u	0.024	–	[45]
Smallest size	S^{min}_u	30	kWh	Setting
Reference size	S^{ref}_u	18700	kWh	[45]

[36]The BS capacity in the analysis by [45] was made for an installed capacity of $18700kWh$ or $2750m^3$ whereas the scale of SFF would require a storage on the order of $50m^3$. Therefore the scaling factor $gamma = 0.6$ is applied and results in the specific cost being 5.2 times larger at small scale, i.e. $300kWh$ than at large scale, i.e. $18'700kWh$.

3.4.14 Gas Cleaning for SOFC



Credit: Haruka Ogawa

Gas Cleaning (GC) of biogas for SOFC is a specific process of drying followed by ultra filtration of biogas to prevent contamination of the SOFC anode, i.e. fuel side. The main contaminants are sulfur and siloxanes, the first can be controlled and reduced during the digestion process, the second is unavoidable and has to be filtered. Both vary greatly in concentration from one location to another. The technology is still emerging and a setup has to be designed for a specific biogas source and SOFC size, using market available filtration solutions. The setup usually consists of a freeze dryer, activated carbon filter columns and a fan to compensate the pressure drop. A primary filtration step for sulfur only may be desirable if the BG has a high sulfur content. Regularly changing the filters is the largest cost contribution [31]. For reference, a $6kW$ SOFC and its biogas cleaning installation can fit in a container, leaving room for maintenance.

Equation 48 is a simple energy balance without losses, where the gas input $\dot{E}^{+r}_{u,d,h}$ and output $\dot{E}^{-r}_{u,d,h}$ can be either BG or BM. The unit will have to filter any BG or BM before it enters the SOFC. The electricity consumed by the dryer and the fan is calculated by eq. 49 as a function of the gas throughput and $f_{u_{EL/BG}}$ the electricity over gas throughput ratio. The volume fraction of methane present in the biogas x_{BG}, is applied to the flow of BM since the system parameter and costs are estimated for biogas, including its CO_2 fraction. The size of the unit S_u is expressed in kW of gas throughput.

$$\dot{E}^{-r}_{u,d,h} = \dot{E}^{+r}_{u,d,h} \qquad [kW] \qquad (48)$$

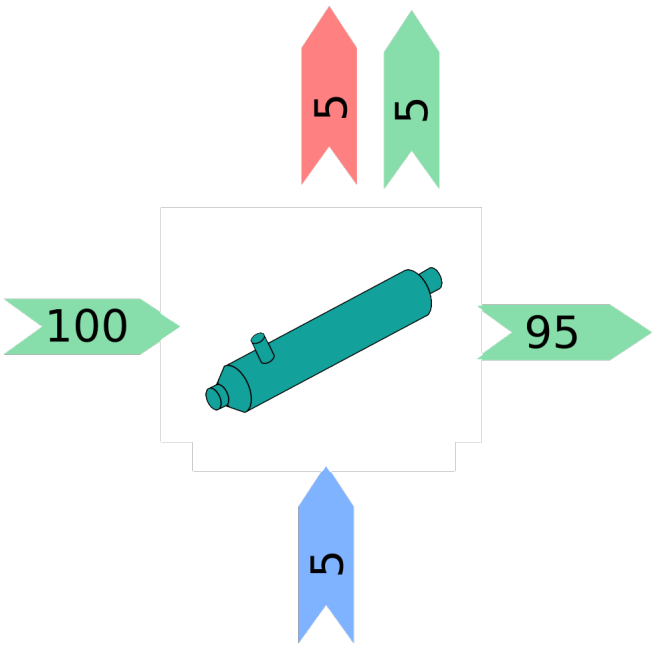
$$\dot{E}^{+EL}_{u,d,h} = f_{u_{EL/BG}} \cdot (\dot{E}^{-BG}_{u,d,h} + x_{BG} \cdot \dot{E}^{-BM}_{u,d,h}) \qquad [kW] \qquad (49)$$

$$\dot{E}^{-BG}_{u,d,h} + x_{BG} \cdot \dot{E}^{-BM}_{u,d,h} \leq S_u \qquad [kW] \qquad (50)$$

Table 17 – GCSOFC: Parameters used for the modelling of the Gas Fueling Station

Name	Symbol	Value	Units	Source
Electric consumption	$f_{GCSOFC_{EL/BG}}$	0.015	–	[31]
Biogas methane fraction	x_{BG}	0.6	–	[9]
Cost multiplier	c_u^{mult}	1	–	[31]
Specific investment cost	c_u^{size}	0.56	$kCHF/kW$	[31]
Fixed investment cost	c_u^{fixe}	2.8	$kCHF$	[31]
LCA emissions	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	Default
Life	n_u	10	$Years$	[31]
Maintenance	c_u^{maint}	0.185	–	[31]
Smallest size	S_u^{min}	1	kW	Setting
Reference size	S_u^{ref}	50	kW	[31]

3.4.15 Biogas Upgrading



Credit: Haruka Ogawa

The CO_2 fraction in Biogas reduces the energy density and poses problems during compression. For this reason there are limits on gas methane content for gas grid injection and gas vehicle fuel. In the USA they are 97% and 95% respectively [46]. To reach these limits, BG has to be upgraded to Biomethane (BM). The upgrading process is usually derived from large scale NG applications, it can be based on Water scrubbing, Pressure Swing Adsorption, Organic physical scrubbing, Amine scrubbing, and Membranes[46]. For small scale applications, i.e. below $1'000 m^3/h$ of BM production capacity, membrane based upgrading technologies have the lowest cost. They are safe and easy to operate and can achieve high recovery rates of up to 99.5%. An electric compressor creates a pressure difference and allows some gasses to be transported across a polymer

membrane (CO_2 and some H_2S) while others (CH_4) do not permeate. The system is simple but multiple steps may be required to achieve an acceptable methane content.

$$\dot{E}^{-BM}_{BU,d,h} = \eta_{BU} \cdot \dot{E}^{+BG}_{BU,d,h} \quad [kW] \quad (51)$$

$$\dot{E}^{+EL}_{BU,d,h} = f_{u_{EL/BM}} \cdot \dot{E}^{-BM}_{u,d,h} \quad [kW] \quad (52)$$

$$\dot{E}^{-BM}_{BU,d,h} \leq S_{BU} \quad [kW] \quad (53)$$

Equation 51 gives the BM output $\dot{E}^{-BM}_{BU,d,h}$ with η_{BU} the methane recovery rate and $\dot{E}^{+BG}_{BU,d,h}$ the BG entering the system. Eq. 52 describes the electricity consumed, with $f_{u_{EL/BM}}$ the electricity consumption of the compressor per kW of BM produced. And the unit installed capacity S_{BU} is a function of the produced BM in kW thermal as per eq. 53. The methane content of the final product is assumed to be 97% (average value [46]).

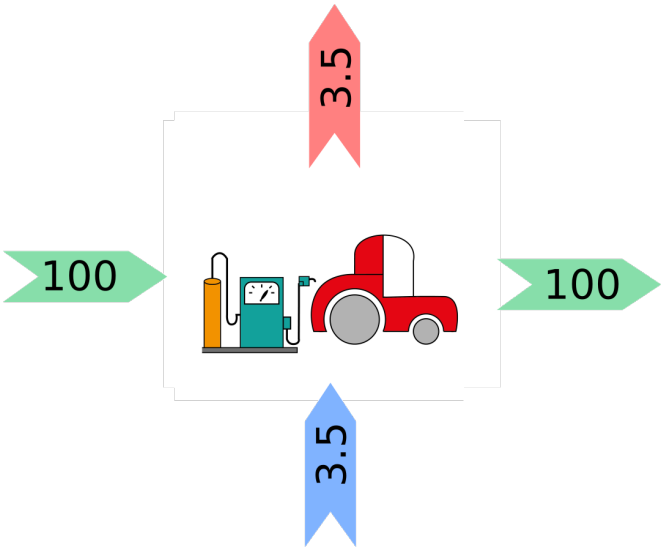
The cost of upgrading biogas is significant, at small scale it is equivalent to the cost of producing biogas. The smallest installed membrane upgrading facility in 2012 had a capacity of $10m^3/h$ or $94kW$ of BM production capacity [46]. Upgrading all the biogas potential at SFF, the maximum BM production capacity would be $30kW$. Parameters for the BU are presented in Table 18.

Table 18 – BU: Parameters used for the modelling of the Biogas Upgrading

Name	Symbol	Value	Units	Source
Efficiency	η_u	0.95	–	[46]
Electric consumption	$f^{comp}_{u_{EL/BM}}$	0.045	–	[46]
Cost multiplier [37]	c^{mult}_u	5.1	–	Scaling
Specific investment cost	c^{size}_u	0.89	$kCHF/kW$	[46]
Fixed investment cost	c^{fixe}_u	11.4	$kCHF$	[46]
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life	n_u	15	$Years$	[47]
Maintenance	c^{maint}_u	0.02	–	[46]
Smallest size	S^{min}_u	10	kW	Setting
Reference size	S^{ref}_u	1000	kW	[46]

[37] Similar to the BS, the BU is derived from large scale applications, therefore a scaling law with $\gamma = 0.6$ gives a 5.1 cost multiplier for the specific cost.

3.4.16 Gas Fueling Station



Credit: Haruka Ogawa

There are two types of gas fueling station, fast charge and time fill. Fast charge stations fills a vehicle tank in 3 min using high pressure and adapted filling equipment. These are adapted for commercial gas fueling station where many vehicles have to be charged during one day. The time fill station uses a small pressure differential and the fueling process takes between 6 and 10 hours [43]. The latter is cheaper and adapted for utility vehicles, parked and charging overnight every night. In the case of SFF, 4 tractors require fuel, for which a time fill station is better suited. The model is based on an economic analysis for a Compressed Natural Gas (CNG) vehicle time fill station for 4 to 5 utility vehicles by Smith et al. [43]. In order to consume BM, each tractor engine has to be converter. This is feasible but may be expensive. The autonomy of a converted CNG vehicle, without increasing the fuel tank volume is 175 km with NG compared to 400 km with diesel [48]. Performance with BM is assumed to be equivalent to NG, although some drying and desulfurization may be required.

The fuel considered for converted gas tractors are NG or BM and not biogas due to compression into the CNG tank. Although Owczuk et al. [49] tested the use of raw biogas on tractors using 30% diesel and 60% biogas and concluded that biogas (after removing contaminants) is a suitable fuel in a dual fueled diesel engine. A gas fueling station requires electricity for drying and compressing the gas up to $250bar$ (typical for CNG vehicles [43]). The energy of the fuel is conserved and there are no losses through the GFS as in equation 54, where r can either be NG or BM. The electricity consumed is described by equation 55, where $f^{comp}_{u_{EL/NG}}$ is the fraction of energy required for NG compression and $f^{dry}_{u_{EL/BG}}$ is the fraction of energy required for drying BG, corrected by the methane content of BG x_{BG}. The installed capacity is the sum of fuel throughput as in eq. 56.

$$\dot{E}^{-r}_{u,d,h} = \dot{E}^{+r}_{u,d,h} \qquad [kW] \qquad (54)$$

$$\dot{E}^{+EL}_{u,d,h} = (f^{comp}_{u_{EL/NG}} + f^{dry}_{u_{EL/BG}} \cdot x_{BG}) \sum_{r}^{(BM,NG)} \dot{E}^{+r}_{u,d,h} \qquad [kW] \qquad (55)$$

$$\sum_{r}^{(BM,NG)} \dot{E}^{-r}_{u,d,h} \leq S_u \qquad [kW] \qquad (56)$$

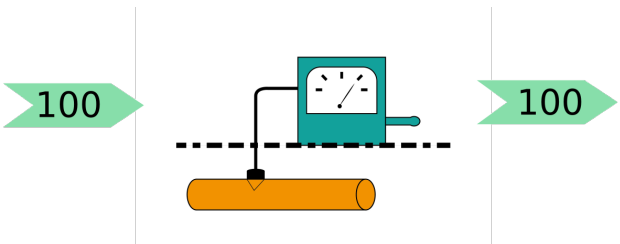
Like the AD, this unit will either be installed at full capacity, i.e. enough to fuel 4 tractors overnight or not at all. Because of the Fueling profile and how it can slightly vary from one number of typical days to another,

the installed capacity will vary by a few percent. The unit cost is corrected to ensure that it always is exactly the Total cost. The other costs are presented for the typical size of $30kW$ [38]. Table 19 summarizes the values for the GFS including costs related to the diesel to NG engine conversion for a large diesel engine.

Table 19 – GFS: Parameters used for the modelling of the Gas Fueling Station

Name	Symbol	Value	Units	Source
Typical size [39]	S_u^{typ}	30	kW	Calc
Total cost at S^{typ} [40]	c_u^{total}	41	$kCHF$	Calc
Conversion cost [41]	$c_u^{convert}$	48	$kCHF/Tractor$	[48]
Electric consumption compressor	$f_{u_{EL/NG}}^{comp}$	0.03	–	[42]
Electric consumption dryer	$f_{u_{EL/BG}}^{dry}$	0.008	–	[31]
Fueling time	$t_{slow-fuel}$	10	h	[43]
Minimum operating temperature [42]	T_u^{oper}	5	$°C$	Setting
Cost multiplier	c_u^{mult}	1.8	–	Default
Specific investment cost	c_u^{size}	1.03	$kCHF/kW$	[43] [36]
Fixed investment cost	c_u^{fixe}	12.3	$kCHF$	[43] [36]
LCA emissions	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	Default
Life	n_u	25	$Years$	[43]
Maintenance [43]	c_u^{maint}	0.02	–	Default
Smallest size	S_u^{min}	10	kW	[43]
Reference size	S_u^{ref}	30	kW	[43]

3.4.17 Grid Injection



Credit: Haruka Ogawa

The natural gas grid is a very efficient energy transport and storage system. Grid injection of biomethane is attractive in many European countries where favourable feed-in tariffs are in place like France and the Uk

[38] Installed capacity for 4 tractors consuming $8'000l$ of diesel over $10h$ per day circa 300 days per year

[39] Size adapted to the case of SFF.

[40] Cost at the typical size, also responding to the a 4 to 5 slow fill utility vehicles GFS as presented in [43]

[41] The upper bound value presented in [48] for personal vehicle diesel to NG conversion cost, is multiplied by 2 to account for the size of the tractor engine. The the 1.8 factor is applied to account for increased conversion costs is Switzerland.

[42] The tractors are assumed to be unused and not fueled below this temperature

[43] When not maintenance cost is specified, the default value is 2% of the CAPEX per year.

[21]. The Swiss natural gas grid connects users via the low pressure transportation grid at $5bar$ or the distribution grid between 0.01 and 0.2 bar [50]. Specifications for injection are reported in table 10. SFF is already connected to the gas grid as a consumer, to be able to inject gas costs for metering and monitoring equipment are expected. Upgrading biogas and injecting it into the grid is expensive and is generally only viable at larger scales with the help of feed-in tariffs. Yet it is a very energy efficient way to produce and distribute a carbon neutral vehicle fuel for CNG vehicles.

It is assumed that no loss occur during injection as presented by equation 57. No electricity is consumed, not even for compression, because the gas is expected to reach 5 to 7 bar after upgrading and satisfy the grid specifications without further treatment. The size of the unit is equivalent to the BM throughput as in eq. 58.

$$\dot{E}^{-BM}_{GI,d,h} = \dot{E}^{+BM}_{GI,d,h} \qquad [kW] \qquad (57)$$

$$\dot{E}^{-BM}_{GI,d,h} \leq S_{GI} \qquad [kW] \qquad (58)$$

Components	Requirements
Methane	$CH_4 \geq 96$ vol%
Hydrogen	$H_2 \leq 2$ vol%
Carbon Dioxide	$CO_2 \leq 4$ vol%
Water	Dew point at – 8 °C at pressure level of injection point of the gas grid

Figure 10 – Gas grid specifications for the Swiss natural gas grid as reported in [50]. Values originally from Schweizerischer Verein des Gas und Wasserfaches (SVGW) for the year 2016.

Table 20 – GI: Parameters used for the modelling of Grid Injection

Name	Symbol	Value	Units	Source
Cost multiplier	c_u^{mult}	5.1	–	Default
Specific investment cost [44]	c_u^{size}	0.11	$kCHF/kW$	[50]
Fixed investment cost	c_u^{fixe}	1.4	$kCHF$	[50]
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life [45]	n_u	20	$Years$	Default
Maintenance	c_u^{maint}	0.02	–	Default
Smallest size	S_u^{min}	10	kW	Setting
Reference size	S_u^{ref}	1300	kW	[50]

[44] The specific cost and investment cost were computed using a scaling factor $\gamma = 0.6$.
[45] When no system life expectancy is available the default value is 20 years.

3.5 Mass and Energy Balance

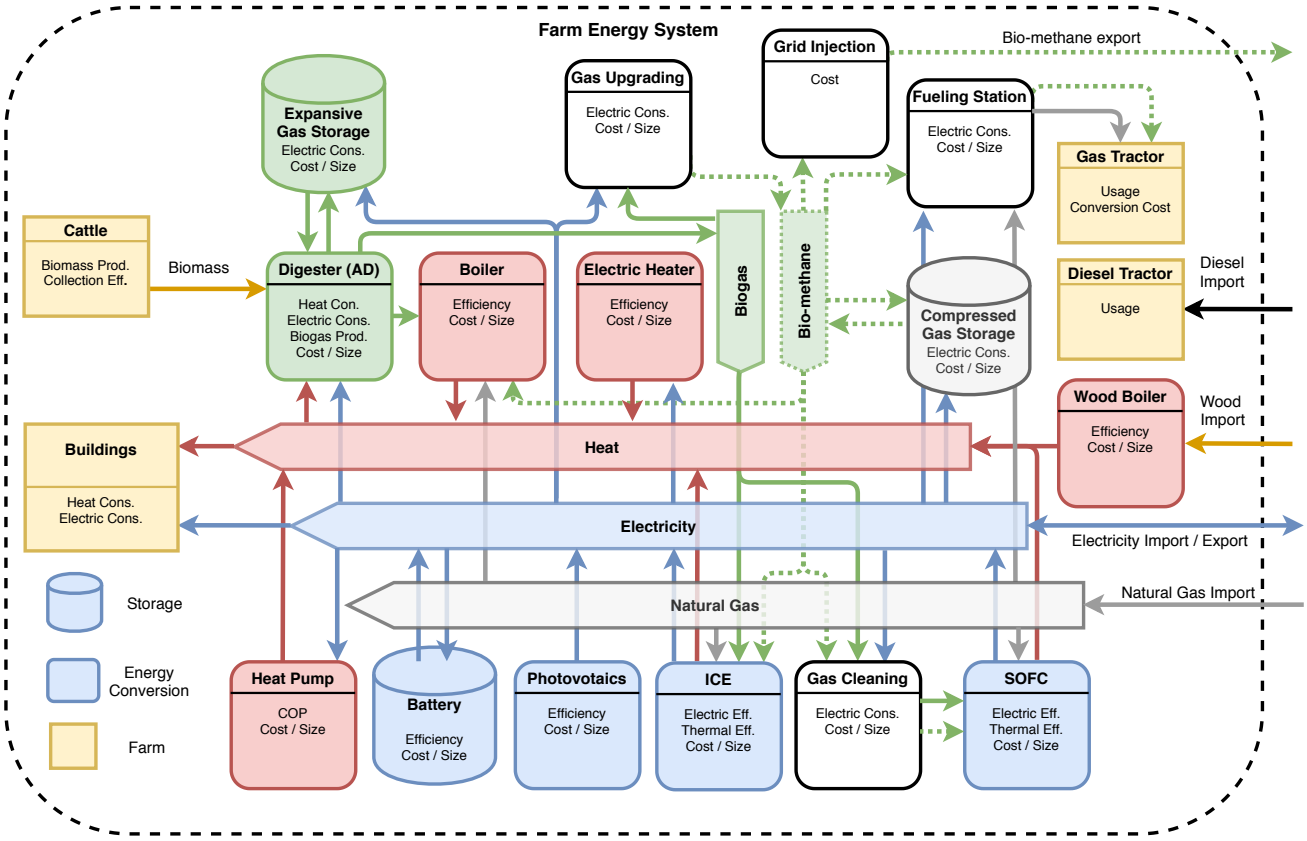


Figure 11 – Overall process flow diagram highlighting the energy balance between all units. Colours represent resources. Heat is red, Electricity is blue, Biogas and Bio-methane are green, with dashed lines representing bio-methane. Manure and Wood are orange, Natural gas is grey and diesel black. The shapes differentiate energy conversion technologies (round edge square) storage technologies (cylinders) and farm systems (square). Their color depends on the main resource they produce or store, white is for utilities.

Resources considered in the model are Heat, Electricity (EL), Natural Gas (NG), Biogas (BG), Biomethane (BM) Biomass [46] (BG), Wood [47] and Diesel. Only EL, NG, Wood and Diesel can be purchased from the grid and only EL and BM can be sold.

The **electricity** balance in equations 59 is simply equating the sum of all sources (the electricity bought from the grid $\dot{E}^{-EL}_{grid,d,h}$ and produced by the units $\sum_u^{Units} \dot{E}^{-EL}_{u,d,h}$) to the sum of all sinks (the electricity sold to the grid $\dot{E}^{+EL}_{grid,d,h}$, consumed by the units $\sum_u^{Units} \dot{E}^{+EL}_{u,d,h}$ and by the buildings $\dot{E}^{+EL}_{b,d,h}$). The balance is applied for every hour of every typical day. Electricity does not have a waste stream. An additional constraint 60 seek to prevent the battery from charging with EL when associated emissions are low and selling it when they are high. $\sum_u^{BAT \notin Units} \dot{E}^{-EL}_{u,d,h}$ is the electricity produced by all units except the battery. Since EL can be both sold to and bought from the grid, eq. 61, 62 and 63 prevent EL from being simultaneously sold and purchased from the grid. $Z^{\dot{E}^{+EL}}_{grid,d,h}$ is a binary decision variable on whether electricity is sold or not sold to the grid associated

[46] Specifically animal manure produced on the farm
[47] Specifically wood pellets bought for the Wood boiler

via a big-M constraint to $\dot{E}^{+EL}_{grid,d,h}$ the electricity sold to the grid in that instant.

$$\dot{E}^{-EL}_{grid,d,h} + \sum_{u}^{Units} \dot{E}^{-EL}_{u,d,h} = \dot{E}^{+EL}_{grid,d,h} + \sum_{u}^{Units} \dot{E}^{+EL}_{u,d,h} + \dot{E}^{+EL}_{b,d,h} \qquad [kW] \qquad (59)$$

$$\dot{E}^{+EL}_{u,d,h} \leq \sum_{u}^{BAT \notin Units} \dot{E}^{-EL}_{u,d,h} \qquad [kW] \qquad (60)$$

$$Z^{\dot{E}^{+EL}}_{grid,d,h} + Z^{\dot{E}^{-EL}}_{grid,d,h} \leq 1 \qquad [-] \qquad (61)$$

$$Z^{\dot{E}^{+EL}}_{grid,d,h} \cdot M \geq \dot{E}^{+EL}_{grid,d,h} \qquad [kW] \qquad (62)$$

$$Z^{\dot{E}^{-EL}}_{grid,d,h} \cdot M \geq \dot{E}^{-EL}_{grid,d,h} \qquad [kW] \qquad (63)$$

The **biogas** balance in eq. 64 is again sources equals to sinks, where $\sum_{u}^{GCSOFC \notin Units} \dot{E}^{-BG}_{u,d,h}$ is the BG produced by each unit except for the GCSOFC and $\sum_{u}^{SOFC \notin Units} \dot{E}^{+BG}_{u,d,h}$ the BG consumed by each unit except the SOFC. A waste stream $\dot{E}^{+BG}_{waste,d,h}$ represent BG flaring, however its emissions are neglected because the model tends to not waste BG. The GCSOFC consumes BG and BM and produces clead BG and BM for the SOFC only as in eq. 65.

$$\sum_{u}^{GCSOFC \notin Units} \dot{E}^{-BG}_{u,d,h} = \sum_{u}^{SOFC \notin Units} \dot{E}^{+BG}_{u,d,h} + \dot{E}^{+BG}_{waste,d,h} \qquad [kW] \qquad (64)$$

$$\dot{E}^{-r_{GCSOFC}}_{GCSOFC,d,h} = \dot{E}^{+r_{GCSOFC}}_{SOFC,d,h} \qquad [kW] \qquad (65)$$

For the **biomethane** balance in eq. 66 the sources are the CGT and the BU and the sinks are each BM consuming unit except the SOFC. The waste stream represents flaring. Constraint 67 allows the BM produced by the GI to be exported. Constraint 68 ensure the tractor fuel requirement $\dot{E}^{+Fuel}_{tractors,d,h}$ is met by the GFS supply of BM and NG if the GFS is installed, with Z_{GFS} a decision variable that is 1 if the GFS is installed and 0 otherwise.

$$\dot{E}^{-BM}_{CGT,d,h} + \dot{E}^{-BM}_{BU,d,h} = \sum_{u}^{SOFC \notin Units} \dot{E}^{+BM}_{u,d,h} + \dot{E}^{+BM}_{waste,d,h} \qquad [kW] \qquad (66)$$

$$\dot{E}^{-BM}_{GI,d,h} = \dot{E}^{+EL}_{grid,d,h} \qquad [kW] \qquad (67)$$

$$\dot{E}^{-BM}_{GFS,d,h} + \dot{E}^{-NG}_{GFS,d,h} = \dot{E}^{+Fuel}_{tractors,d,h} \cdot Z_{GFS} \qquad [kW] \qquad (68)$$

Equation 69 is a simplistic **heat** balance. The source of heat are the heaters and CHP units while the sinks are the buildings and digester and wasted heat $\dot{Q}^{+}_{waste,d,h}$. This simplification is possible because the heat produced by the heaters and the CHP engines is at a temperature high enough to supply heat to both the AD or the buildings. Old building heating systems require heat at about $65°C$, while air has to heated to a maximum of $30°C$. The minimum temperature difference between the supply temperature and used temperature is called the ΔT_{min}. This value is high for old houses but will be much lower for the AD. Assuming the ΔT_{min} of the AD is $15°C$, the minimum supply temperature is $55°C$ to be able to keep it at $40°C$. Which is lower than the building supply temperature. Under this assumption each heat source can supply each heat sink and eq. 69 holds.

$$\sum_{u}^{Units} \dot{Q}^{-}_{u,d,h} = \dot{Q}^{+}_{b,d,h} + \dot{Q}^{+}_{AD,d,h} + \dot{Q}^{+}_{waste,d,h} \qquad [kW] \qquad (69)$$

Equation 70 is the **biomass** balance, where it is either consumed by the AD or wasted. Emissions from untreated biomass are accounted for using a constraint in the objective function. A constraint in the AD unit

forces it to consume all available biomass $\dot{E}^{-Biomass}_{Farm,d,h}$ if it is installed. Equation 71 is the **natural gas** balance. The only source of NG is the grid and the sinks are $\sum_u^{Units} \dot{E}^{+NG}_{u,d,h}$, i.e. any unit consuming NG. Equation 72 is the **wood** balance. The only source is the grid, the only sink the WBOI. Equation 73 is the **diesel** balance. It is dependant on whether or not the GFS is installed. If the GFS is installed $(1-Z_{GFS}) = 0$ and no diesel imports are required. If the GFS is not installed $(1-Z_{GFS}) = 1$ and all fuel requirements are met with diesel imports. Finally eq. 74 compute the annual sum of imports, exports and wastes $\dot{E}^{\pm r}_{g,d,h}$ of each resource r, where subscript g stands for grids and wastes. The daily sum has to be multiplied by f_d the frequency of day d, i.e. the number of times that typical day is repeated in a year. The factor 10^{-3} simply changes the units to MWh to stay within the 10^4 variable upper bound M and prevent numerical errors.

$$\dot{E}^{-Biomass}_{Farm,d,h} = \dot{E}^{+Biomass}_{AD,d,h} + \dot{E}^{+Biomass}_{waste,d,h} \qquad [kW] \qquad (70)$$

$$\dot{E}^{-NG}_{grid,d,h} = \sum_u^{Units} \dot{E}^{+NG}_{u,d,h} \qquad [kW] \qquad (71)$$

$$\dot{E}^{-Wood}_{grid,d,h} = \dot{E}^{+Wood}_{WBOI,d,h} \qquad [kW] \qquad (72)$$

$$\dot{E}^{-Diesel}_{grid,d,h} = \dot{E}^{+Fuel}_{tractors,d,h} \cdot (1 - Z_{GFS}) \qquad [kW] \qquad (73)$$

$$E^{\pm r}_{g} = 10^{-3} \sum_d^{Days} \left(\sum_h^{Hours} \dot{E}^{\pm r}_{g,d,h} \cdot f_d \right) \qquad [MWh] \qquad (74)$$

3.6 Optimization

Once the model parameter and constraints are in place, an objective[48] is chosen. Minimizing the objective within the given constraints will ultimately control the value of all other variables. The Gurobi MILP solver is deterministic and will only return a solution that is a global optimum, i.e. no better solution exists. The search for the optimal solution by the solver fixes the installed capacity of each of the 16 technologies and controls their hourly operation.

The FES is a multi-objective problem, meaning more than one objective needs to be optimized. It is only possible to solve a MILP with a single objective at a time. For multi-objective optimization, the MILP is solved multiple times using the different objectives and constraints on the objective that are not active.

The first objective is environmental, expressed as the total annual CO_2 emissions (ENVEX), the second is economic expressed as total annual costs (TOTEX). Two alternative objectives, capital investment costs (CAPEX) and operational costs (OPEX) are also considered. In this work, only two pairs of objectives, i.e OPEX-CAPEX and ENVEX-TOTEX, are used for multi-objective optimization and no other combinations. If one of the two objectives is constrained, e.g. CAPEX, then the other objective, i.e. OPEX is minimized. An unconstrained OPEX minimization is to minimize the OPEX only, without constraining the CAPEX.

The costs contributions are buying or selling resources from the grids, i.e. OPEX and investing in technologies that may or may not reduce resource imports, i.e. CAPEX. To calculate **CAPEX**, the decision variable to Z_u install or not each unit is fixed using two big-M constraints eq. 75 and 76. The latter using a tight variable bound of 10 to prevent numerical errors. Equation 77 indicates that if a unit is installed, it has to be at least the size of S^{min}_u, the minimum installed capacity. Equation 78 gives the investment costs of each installed unit $CAPEX_u$, where c^{mult}_u [49] is a multiplication factor, c^{size}_u is the specific cost and c^{size}_u the fixed cost. The specific and fixed costs produce a linear relation between installed capacity and capital costs, although the relationship between costs and size are not linear in general, they can be considered linear for small size increments, as is the case for P. Stadler's BES [15]. To be able to compare the CAPEX and the OPEX, the CAPEX of each unit

[48] The objective is the model variable that will be minimized or maximized. In the case of FES objectives will always be minimized.
[49] Similar to the installation related Bare Module Factor often noted F_{BM}.

is expressed as an annual cost, by applying an annualization factor τ. τ is defined in eq. 82, with n the lifetime of each unit and an interest rate of $i = 2.5\%$. The total annual OPEX is simply the sum of the annual OPEX of each unit as in eq. 79.

The **OPEX** is calculated in equation 80, which is the sum of resources bought minus the resources sold, and a contribution of maintenance costs. The cost to buy a resource is c_r^{buy} and the price at which it is sold is c_r^{sell}. These prices do not vary so they can be applied to $E_{grid}^{\pm r}$ the total annual import and export of each resource. The maintenance cost c_u^{maint} is expressed in per-cent of investment cost per year, and has to multiply the initial investment cost. The **TOTEX** is simply the sum of the OPEX and the annualized CAPEX, as in equation 81.

The total annual costs are calculated using equation 78 to 81. Eq. 75 and 76 fix the "unit is installed" decision variable Z_u for each unit. The second equation was added with a smaller bound of 10 to prevent numerical errors. The operating expenses are the costs for buying resources and maintenance costs for the units. It is calculated in eq. 80 where c_r^{buy} and c_r^{sell} are the costs of buying or selling a resource in $kCHF/MWh$. These are specific for a medium consumer for the year 2019 in Switzerland. Finally the **TOTEX** is the sum of the CAPEX and OPEX. A contribution for grid injection is added if grid injection takes place.

$$Z_u \cdot M \leq S_u \qquad [kW] \qquad (75)$$

$$Z_u \cdot 10 \leq CAPEX_u \qquad [kW] \qquad (76)$$

$$S_u \leq S_u^{min} \cdot Z_u \qquad [kW] \qquad (77)$$

$$CAPEX_u = 10^{-3} \cdot c_u^{mult}(c_u^{size} \cdot S_u + c_u^{fixe} \cdot Z_u)\tau_u \qquad [MCHF/year] \qquad (78)$$

$$CAPEX = \sum_u^{Units} CAPEX_u \qquad [MCHF/year] \qquad (79)$$

$$OPEX = 10^{-3} \sum_r^{Resources} \left(c_r^{buy} \cdot E_{grid}^{-r} - c_r^{sell} \cdot E_{grid}^{+r}\right) + \sum_u^{Units} \left(c_u^{maint} \cdot \frac{CAPEX_u}{\tau_u}\right) \qquad [MCHF/year] \qquad (80)$$

$$TOTEX = OPEX + CAPEX \qquad [MCHF/year] \qquad (81)$$

$$\tau_u = \frac{i(1+i)^{n_u}}{(1+i)^{n_u} - 1} \qquad [-] \qquad (82)$$

Emissions contributions are the resources exchanged with the grid as well as a small fraction of LCA emissions from installing a technology. When selling a resource produced on the farm, like renewable electricity or BM, it replaces some fossil resource that would otherwise have to be produced to balance the grid. Therefore the farm emissions are reduced when selling renewables to the grids.

The **ENVEX** is calculated with equations 83 to 85. The emissions from electricity are calculated separately because the emission factor $m_{CO_2,EL,d,h}^{buy}$ for buying electricity from the grid, is a time dependent value as shown in Figure 12. The source of electricity in Switzerland varies depending on the supply. Some times a large fraction of power is renewable like hydraulic or PV power. Other times the largest fraction comes from fossil power, like imported coal power from Germany. For exports, the electricity produced at the farm is considered renewable. However a factor $f_{CO_2}^{sell} = 0.95$ is added to promote self consumption and prevent numerical errors when minimizing TOTEX. Other resources such as BM, NG, Diesel and Wood have a fixed emission factor $m_{CO_2,r}^{buy}$ and each of their contribution are calculated separately in equation 84 using their annual total imports and/or exports.

The ENVEX is calculated in equation 85 and includes construction related emissions $m_{CO_2,u}^{LCA}$ often called grey emissions, related to the installed capacity of each unit. The LCA emissions are annualized by simply dividing them by the life (in year) of the unit. The ENVEX also includes manure emissions $m_{CO_2,manure}$, which corresponds to the emissions from untreated animal manure. If the AD is installed, then $Z_{AD} = 1$ and the

manure related emissions are reduced by a factor $f_{CO_2}^{AD_{reduction}} = 0.59$ because all the manure is treated by the AD.

$$ENVEX_{EL} = 10^{-6} \cdot \sum_{d}^{Days} \sum_{h}^{Hours} m_{CO_2,EL,d,h}^{buy} \cdot (\dot{E}_{grid,d,h}^{-EL} - f_{CO_2}^{sell} \cdot \dot{E}_{grid,d,h}^{+EL}) \cdot f_d \quad [ktCO_2/year] \tag{83}$$

$$ENVEX_r = 10^{-3} \cdot m_{CO_2,r}^{buy} \cdot (E_{grid}^{-r} - f_{CO_2}^{sell} \cdot E_{grid}^{+r}) \quad [ktCO_2/year] \tag{84}$$

$$ENVEX = \sum_{r}^{Resources} ENVEX_r + 10^{-3} \cdot \sum_{u}^{Units} \left(\frac{m_{CO_2,u}^{LCA}}{n_u} \cdot S_u \right) + (1 - f_{CO_2}^{AD_{reduction}} \cdot Z_{AD}) \cdot m_{CO_2,manure} \quad [ktCO_2/year] \tag{85}$$

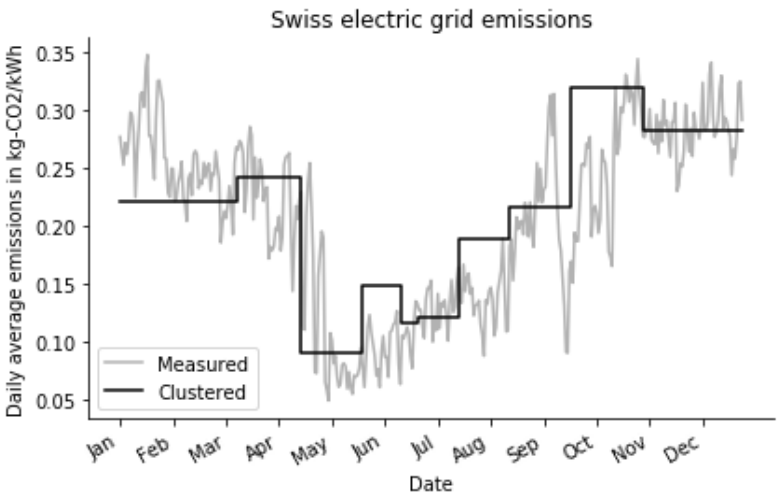


Figure 12 – Average daily electricity emissions factor. The measured value was calculated by Vuarnoz et al. [23] specifically for the end consumer of the Swiss electric grid, for a year starting February 2015. Note that the emissions factor was not part of the weather data k-means clustering.

3.7 Sensitivity analysis: One At a Time method

The sensitivity analysis is an essential part of many MILP models. For example, investment costs in the FES model are first estimates based on the literature and have therefore an uncertainty of ±50%. The sensitivity analysis will show how sensitive a solution is to the change of one parameter, using a common method called "One At a Time". One parameter is modified while all others are set at their default value, then the model is solved and it is possible to measure the change in the output result relative to the change in the input parameter. This method has the advantage to isolate the change in one parameter and evaluate its impact on the solution. The disadvantage is that the effect of many parameters changing at the same time will can not be measured. Note that the resulting value of "change in output over change in input" hides the fact that any change to a model parameter will have non-linear relation with the change in input.

To reduce the complexity of the analysis only the objectives and the aggregated change in installed capacity will be considered. Equation 86 is used to calculate how sensitive the objective Obj is to a change of parameter p. $\frac{Obj_{new}}{Obj_{default}} - 1$ and $\frac{p_{new}}{p_{default}} - 1$ are the changes in the objective output and parameter input such that the result is in % change of output per % change of input. Because many different combinations of units may give a similar objective value, the change in the overall system setup is calculated using Equation 87. The aggregated

change in installed capacity of each unit $\delta S_{\delta p}$ related to the change in parameter p. The right hand side is similar to a normalized euclidean distance, where a unit is a dimension and the installed capacity the distance on this dimension. This distance $S_{\delta p}$ is a measure of how different two solutions are in terms of the installed capacity of each unit.

$$\delta Obj_{\delta p} = \frac{\frac{Obj_{new}}{Obj_{default}} - 1}{\frac{p_{new}}{p_{default}} - 1} \tag{86}$$

$$\delta S_{\delta p} = \left(\sum_{u}^{Units} \left(\frac{S_{u,new} - S_{u,default}}{S_{u,max}} \right)^2 \right)^{\frac{1}{2}} \tag{87}$$

For every parameter included in the sensitivity analysis, the FES model has to be solved twice, once for the upper bound and once for the lower bound of the uncertainty on that parameter. The system about 250 input parameters in total, therefore only the parameters that are likely to have a direct impact on the solution are included in the analysis. These parameters are presented in Table 21 and 22 and add up to a total of 53. Weather profiles, heat load profiles and their related parameters as well as the electric consumption profile is not part of this sensitivity analysis. Unit lifetime and maintenance are not tested, because their impact is similar to or dependent on the cost multiplication factor. Unit LCA does not have significant impact on total emissions, see section 4.5.2. For simplicity, the variation for each parameter is assumed symmetric and changes are expressed in % relative to the default value. The amount of variation depend on their physical bounds, e.g. any unit efficiency has to remain below 1 and on theoretical assumptions, e.g investment costs estimations have a large uncertainty.

3.8 Sensitivity analysis: Monte Carlo method

The cumulative effect of many parameters changing at the same time can be captured with a Monte Carlo (MC) approach. The principle is to randomly change all of the parameters at once and solve the problem. When this process is repeated enough times a statistically significant probability distribution of outputs appears representing a sample of all possible combinations of parameters. The number of iterations required depend on the problem but it is usually above $1'000$ and below $10'000$. This may seem like a lot, but compared to trying solve every single combination one by one, i.e. $50! = 10^64$, it is nothing. The FES model is only fast enough for this analysis when solved along a single unconstrained objective.

The chosen objective to minimize is TOTEX. The problem is solved $2'500$ times in the span of 20 hours and for each iteration the 50 parameters are slightly varied according to their default value and uncertainty as presented in Tables 21 and 22. The resulting normal distribution of the ICE electric efficiency is given in Figure 13 as an example representative of all other parameters. Note that the same upper and lower bounds as in the OAT method are used, however due to probabilities, these bounds may be violated. The disadvantage of the MC analysis is that no single parameter can be identified as causing a variation.

3.9 Case study of a medium scale energy producer in Palézieux

A second farm situated in Palézieux is modeled using a different set of input parameters. This site differs from SFF in scale, the installed capacity of the CHP is $150kW$ electric while for SFF a classic CHP would have an installed capacity of $10kW$. The farm in Palézieux houses 300 milking cows and a biomass co-digestion process is in operation since early 2015. The manure from cows is recovered via concrete grids on the barn

Table 21 – Summary of parameters included in the sensitivity analysis. Part 1/2

Category	Full Name	Symbol	Uncertainty	Minima	Maxima
AD	Cost multiplier	c_u^{mult}	50%	2.7	0.9
	Efficiency	η_u	50%	0.55	0.18
	Electric consumption	$f_{u_{EL/BG}}$	25%	0.01	0.006
	Heat consumption	$f_{u_{Q/BG}}$	25%	0.48	0.16
AHP	Coefficient of Performance	COP_u	20%	3.6	2.4
	Cost multiplier	c_u^{mult}	50%	2.7	0.9
BAT	Cost multiplier	c_u^{mult}	50%	2	0.67
	Efficiency	η_u	10%	0.99	0.81
	Self dischanrge rate	$r_{u_{sd}}$	10%	0.004	0.003
BS	Cost multiplier	c_u^{mult}	50%	7.8	2.6
	Electric consumption	$f_{u_{EL/BG}}^{fan}$	10%	0.07	0.057
	Self dischanrge rate	$r_{u_{sd}}$	10%	0.0005	0.0004
BU	Cost multiplier	c_u^{mult}	50%	7.6	2.5
	Efficiency	η_u	10%	1	0.85
	Electric consumption	$f_{u_{EL/BM}}^{comp}$	10%	0.05	0.041
CGT	Cost multiplier	c_u^{mult}	50%	2.7	0.9
	Electric consumption	$f_{u_{EL/NG}}^{comp}$	10%	0.022	0.018
EH	Cost multiplier	c_u^{mult}	50%	1.5	0.5
	Efficiency	η_u	0%	0.99	0.99
GBOI	Cost multiplier	c_u^{mult}	50%	2.7	0.9
	Efficiency	η_u	0%	0.98	0.98
GCSOFC	Cost multiplier	c_u^{mult}	50%	1.5	0.5
	Electric consumption	$f_{u_{EL/BG}}$	10%	0.017	0.013
GFS	Conversion cost	$c_u^{convert}$	50%	72	24
	Cost multiplier	c_u^{mult}	50%	2.7	0.9
	Electric consumption compressor	$f_{u_{EL/NG}}^{comp}$	10%	0.033	0.027
	Electric consumption dryer	$f_{u_{EL/BG}}^{dry}$	10%	0.008	0.007
GHP	Coefficient of Performance	COP_u	20%	4.8	3.2
	Cost multiplier	c_u^{mult}	50%	1.5	0.5

Table 22 – Summary of parameters included in the sensitivity analysis. Continued part 2/2

Category	Full Name	Symbol	Uncertainty	Minima	Maxima
GI	Cost multiplier	c_u^{mult}	50%	1.5	0.5
ICE	Cost multiplier	c_u^{mult}	50%	1.5	0.5
	Electric efficiency	$\eta_{u,EL}$	10%	0.33	0.27
	Thermal efficiency	$\eta_{u,Q}$	10%	0.83	0.67
	Cost multiplier	c_u^{mult}	50%	2	0.67
PV	Efficiency	η_u	50%	0.21	0.7
	Available area	$f_{u_{A_{PV}/A}}$	20%	0.6	0.4
	Energy density	ρ_u	10%	0.22	0.18
	Cost multiplier	c_u^{mult}	50%	2.7	0.9
SOFC	Electric efficiency for BG	$\eta_{u,EL-BG}$	10%	0.55	0.45
	Electric efficiency for NG	$\eta_{u,EL-NG}$	10%	0.66	0.54
	Thermal efficiency	$\eta_{u,Q}$	10%	0.99	0.81
	Cost multiplier	c_u^{mult}	50%	2.7	0.9
WBOI	Efficiency	η_u	10%	0.94	0.76
	Annual interest rate	i	10%	0.028	0.022
Other	Manure emissions AD reduction	$f_{CO_2/manure}^{AD}$	30%	0.77	0.41
	Manure emissions untreated	$f_{CO_2/manure}$	30%	140	77
	Selling price	c_{BM}^{sell}	20%	0.094	0.063
Resources	Purchase cost	c_{Diesel}^{buy}	25%	0.18	0.12
	Selling price	c_{Elec}^{sell}	50%	0.18	0.059
	Purchase cost	c_{Elec}^{buy}	15%	0.23	0.19
	Purchase cost	c_{Gas}^{buy}	15%	0.11	0.088
	Purchase cost	c_{Wood}^{buy}	15%	0.082	0.067

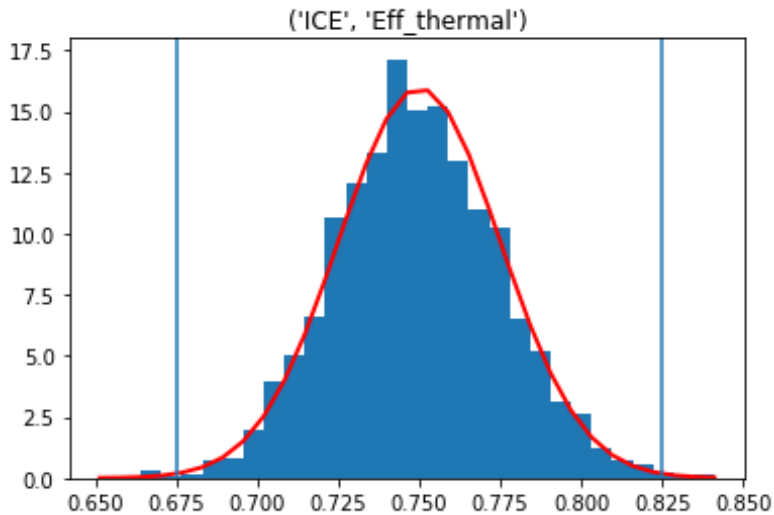


Figure 13 – Example distribution for the electric efficiency of the ICE, generated with 2'500 random samples normally distributed around the default value (on the x-axis). The vertical lines represent the 5th and 95th percentile.

floor and flows towards the digester where it is pumped in. The main share of biomass comes from nearby food processing waste and some green waste. It represent the equivalent of manure from an addition 700 milk cows. It is transported by truck and loaded into a shredder, before it enters the digester. The AD itself is a two stage digester, with pre and post digestion at $35°C$ to $42°C$. The total volume of the AD is $1'500m^3$ and the residence time is 60 days. The biogas leaves the second stage and is dried and filtered before entering the ICE. The ICE produces $150kW$ of electricity and $183kW$ of heat for $8'300$ hours per year on average. An areal picture of the farm and biogas installation is presented in Figure 14

Figure 14 – A sky view of the Palézieux biogas installation and farm buildings from [17]. The nearby school supplied with excess heat from the CHP is not included in the picture.

The following simplifications to fit this scenario into the existing FES model are made. The clustered weather parameters for Liebensberg are assumed representative of the weather at Palézieux. The size and residence time of the AD are not accounted for, since the AD heat load will be corrected relative to the measured heat consumption. The operating time of all units in the FES model is $8'760$ hours per year and can not

easily be changed. Instead the available biomass calculated is such that the net produced electricity will be equal to the real-world installation.

The selling price of renewable electricity from PV and the ICE are not known, moreover the FES model does not include the option for a separate price for solar or biogas generated electricity. Instead two scenarios are modeled, one for an energy producer similar to the situation in Palézieux and one for an energy consumer similar to the situation at SFF.

The **energy producer scenario** represent a farm whose energy production exceeds its energy consumption, similar to Palézieux. In this scenario, the FES is not allowed to import NG or Electricity, while the feed-in tariffs of electricity and biomethane grid injection are favourable. Additionally, the use of PV is blocked, to prevent the model from selling solar electricity at the higher price of biogas electricity.

The **energy consumer scenario** represent a farm whose energy consumption exceeds its energy production, similar to SFF. In this scenario, the FES is unchanged, the feed-in tariffs remain low and no additional constraints are added.

The parameters used for both scenarios[50] are presented in Tables 23 and 24. Parameters not presented in these tables, or where the source is marked as Default, keep their original value. Note that the AD maintenance cost was corrected from 10% to 2% CAPEX per year. The original maintenance cost is too high to be representative of a large scale AD and would produce an annual maintenance cost of almost 300′000 CHF.

Table 23 – Performance parameters redefined to apply the FES model to the case of Palézieux. All parameters not presented in this table keep the value defined in the methodology. 'Default' in the source column refers to the a value already defined in the methodology, when no value from the partners at Palézieux was available.

Category	Full name	Symbol	Value	Units	Source
AD	Efficiency	η_{AD}	0.37	–	Default
	Electric consumption	$f_{AD_{EL/BG}}$	0.04	–	[32]
	Heat consumption	$f_{AD_{Q/BG}}$	0.14	–	[32]
	Digester volume	V_{AD}	1500	m^3	[32]
	BG Methane volume fraction	$f_{BG_{CH_4/CO_2}}$	0.6	–	Default
ICE	Electric efficiency	$\eta_{ICE,EL}$	0.372	–	[32]
	Thermal efficiency	$\eta_{ICE,Q}$	0.734	–	[32]
PV	Efficiency	η_{PV}	0.14	–	Default
	Energy density	ρ_{PV}	0.197	kW/m^2	Default
	Available area	$f_{PV_{A_{PV}/A}}$	1	–	[32]
	Available roof area for PV	$A_{b,ground}$	3560	m^2	[17]
Buildings	Number of LSU	LSU_{farm}	300	LSU	[32]
	Annual electric consumption	E_b^{+el}	880	$MWh/year$	[32]
	Annual heat consumption	$\dot{Q}_{b,real}^{+}$	606	$MWh/year$	[32]
	Annual diesel consumption	$\dot{E}_{tractors}^{+diesel}$	8000	$l/year$	Default
	Number of tractors	$N_{tractors}$	4	$Tractor$	Default

[50] Except for the feed-in tariffs which are only representative of the energy producer scenario.

Table 24 – Economic parameter redefined in order to apply the FES to the case of Palézieux. All parameters not presented in this table keep the value defined in the methodology. 'Default' in the source column refers to the a value already defined in the methodology, when no value from the partners at Palézieux was available. The specific and fixed investment cost are derived from the total investment cost by attributing 90% of the costs to the specific cost and the 10% remaining to fixed cost, due to the larger scale of units.

Category	Full name	Symbol	Value	Units	Source
AD	Cost multiplier	c_u^{mult}	1	–	[32]
	Specific investment cost	c_u^{size}	6.5	$kCHF/kW$	[32]
	Fixed investment cost	c_u^{fixe}	290	$kCHF$	[32]
	LCA emissions	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	Default
	Life	n_u	20	$Years$	Default
	Maintenance	c_u^{maint}	0.02	–	Assumption
	Smallest size	S_u^{min}	100	kW	Setting
	Reference size	S_u^{ref}	403	kW	[32]
ICE	Cost multiplier	c_u^{mult}	1	–	[32]
	Specific investment cost	c_u^{size}	1.8	$kCHF/kW$	[32]
	Fixed investment cost	c_u^{fixe}	30	$kCHF$	[32]
	LCA emissions	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	Default
	Life	n_u	20	$Years$	Default
	Maintenance	c_u^{maint}	0.12	–	[32]
	Smallest size	S_u^{min}	50	kW	Setting
	Reference size	S_u^{ref}	150	kW	[32]
PV	Cost multiplier	c_u^{mult}	1	–	[32]
	Specific investment cost	c_u^{size}	2	$kCHF/kW$	[32]
	Fixed investment cost	c_u^{fixe}	122	$kCHF$	[32]
	LCA emissions	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	Default
	Life	n_u	20	$Years$	Default
	Maintenance	c_u^{maint}	0.02	–	Default
	Smallest size	S_u^{min}	100	kW	Setting
	Reference size	S_u^{ref}	552.5	kW	[32]
EL	Selling price	c_{Elec}^{sell}	0.28	CHF/kWh	[21]
	Purchase cost	c_{Elec}^{buy}	-	CHF/kWh	Not purchased
	Associated emissions	$m_{CO_2\,Elec}^{buy}$	0.2	tCO_2/MWh	Default
BM	Selling price	c_r^{sell}	0.26	CHF/kWh	[21]
	Purchase cost	c_r^{sell}	-	CHF/kWh	Not bought
	Associated emissions	$m_{CO_2\,r}^{buy}$	0.21	tCO_2/MWh	Default

4 Results

4.1 Results summary

To use the FES to its full potential, multiple scenarios and optimization approaches are applied to the default FES model and slight variations of the FES model. The 7 scenarios used, i.e. 6 variations of the FES model and one default version, are presented in Table 25. Constraints on the units for each scenario is presented in the Annex, Table 31. All the results where produced using an hourly discretization over a period of ten typical days, clustered according to weather measurements from Liebensberg, representing the year 2019.

Scenario A in section 4.2 represents the current situation at SFF, a small scale farm only relying on fossil. This result in low investment costs but high operating costs and maximum emissions.

Scenario B is the default FES model with all units active and designed around a small scale consumer farm like FFS. It is explored in sections 4.3, 4.4 and 4.5. The Pareto principle, i.e. 20/80 rule is found to be applicable to FES (section 4.4). Emissions are drastically reduced at no cost by replacing the Gas Boiler (GBOI) by a Wood Boiler (WBOI) (if wood is considered renewable) and installing an Anaerobic Digester (AD) (section 4.6). The Internal Combustion Engine (ICE) is more profitable than the Solid Oxide Fuel Cell (SOFC), but the different is very small (section 4.4.1). The SOFC is more cost effective for reducing emissions than the PV(section 4.5). A solution less costly than Scenario A includes a $16kW$ SOFC and a AD of $5m^3/h$ biogas (section 4.5.3). Other technologies like storage or the biomethane pathway only appear close to the ENVEX minimum due to high costs. The optimal solutions for scenario B are compared with Scenario A in section 4.6, almost all of the results from scenario B have lower costs and emissions than scenario A.

The **One At a Time sensitivity analysis** (section 4.7) shows that the price of wood pellets is the most influencing parameter on the FES model, a problem for predictions because the price of wood pellets has been recently fluctuating more than other resources[19]. Reducing the cost of PV will also influence the model results, again this poses problems since the price of PV will depend on the installed capacity with a non-linear scaling law.

The **Monte Carlo sensitivity analysis** (section 4.8) reveals that due to the uncertainty inherent to the FES model, the previous conclusions are much less clear cut than they seem. The SOFC is shown to be as profitable as the ICE the cumulative effect of uncertainty on all parameters is considered.

Scenario C is Scenario B without a wood boiler, see section 4.9. The next best solution for heating in terms of costs and emissions (or best solution of wood pellets want to be avoided) is found to be the Geothermal Heat Pump (GHP), supported by the Air Heat Pump (AHP) for peak loads.

Scenario D is Scenario B with half the cost for PV. This sets the PV in a range similar to that observed at Palézeiux results in PV being profitable, even at a low feed-in tariff.

A possible **maximum theoretical RE** estimation is performed (section 4.11). With the technologies available in FES, even under favourable assumptions and no cost limits, it is impossible to reach energy neutrality at SFF, due to the low available biomass and high energy consumption. A second estimation using Power to Gas and hydro-thermal gasification allows the system to produce all the energy it consumes.

Scenario E represents the current situation at Palézieux, a medium scale farm producing power via biogas since 2015. (section 4.12.1) A variation on the default FES model takes the measured consumption, performance and costs into account and fixes the relevant units at their installed capacity. For a medium producer, better feed-in tariffs are applied, the PV is deactivated and imports of electricity and NG are forbidden. Scenario E is used for comparison with scenario G. Differences in observation regarding the Palézieux installation compared to the model result highlights the limits of the FES model and the importance of scale. The FES is

rather conservative and meant for small scales, this result in a non profitable installation, i.e. positive TOTEX whereas the real Palézieux installation is profitable.

Scenario F represents a medium scale consumer. It is scenario E, without constraints on imports and PV. The feed-in tariffs are at their default value, i.e. less favourable . It is used to compare medium and small scale farms.

Scenario G is scenario E, with all units active except for the PV. It is used to look for optimal solutions for a medium scale producer (section 4.12.3). The SOFC and storage solutions (BS and CGT) are part of the solution much closer to the TOTEX minima than for scenario B, but the overall priority order for technologies is preserved.

The effects of **Feed-in tariffs** for a medium scale consumer (scenario G) is investigated in section 4.12.6, by minimizing TOTEX with a decreasing value for electricity feed-in tariffs. The minimum feed-in tariff to make the SOFC profitable is $0.37 CHF/kW$, close to the previously in place tariff for small ($> 50kW$) biogas installations. The lowest feed-in tariff for profitability regardless of technology is $0.29 CHF/kW$.

Table 25 – Summary of the different scenarios used in the results sections.

	SFF	**Palézieux**	
	Small scale consumer	Medium scale producer	Medium scale consumer
Current Situation	Scenario A	Scenario E	Scenario F
Default	Scenario B	Scenario G	-
No Wood Boiler	Scenario C	-	-
Cheaper PV	Scenario D	-	-

4.2 Scenario A: Current situation at Swiss Future Farm

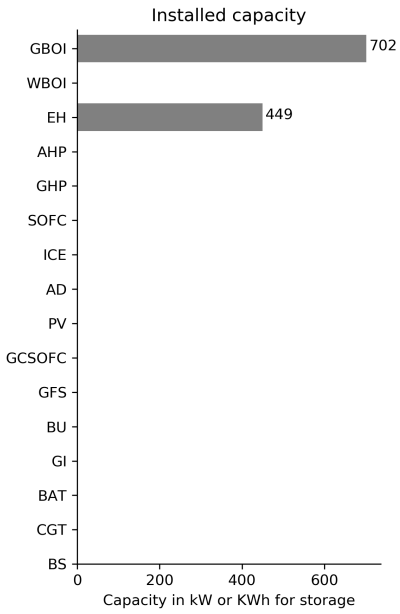
Currently, the Swiss Future Farm (SFF) is only equipped with a Natural Gas Boiler (GBOI) for heating and all resources come from the grids. **Scenario A** is the SFF reference point and is devised based on the current situation at SFF. The aim of this scenario is not to accurately represent the current situation, rather to have a reference point to compare the optimization results with. Only the EH and the GBOI are active and the optimization objective is to minimize TOTEX. The optimizer and Farm Energy System (FES) model constraints handles the sizing of the units and their operation.

The resulting installed capacity, as presented in Figure 15 is an EH of $450kW$[51] heat production capacity, that is never used during the simulation period but is necessary to satisfy the extreme case scenario, see section 3.3.3. The GBOI can produce $700kW$ of heat. The strength of this scenario is a low initial investment cost as shown in Figures 15b. The drawbacks are increased operating expenses and emissions, see Figures 15c and 15d. The bulk of the OPEX comes from importing electricity and natural gas at 165′000 CHF/year each. Untreated manure will release methane (see section 3.3.5), a potent GHG, surpassing emissions from importing electricity. Here, the AD is an opportunity to both reduce the manure emissions and fossil imports, turning harmful waste into useful energy. A result comparison is presented in section 4.6.

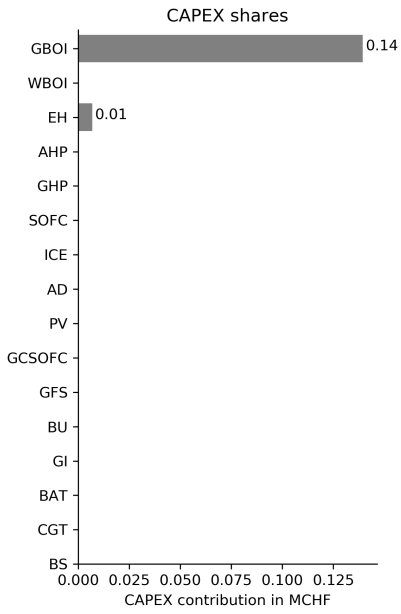
4.3 Scenario B: Multi-objective optimization

The result of single objective optimization is one optimum solution. Under dual-objective optimization the result is a continuous line between the unique solutions of each objective. A Pareto graph is a representa-

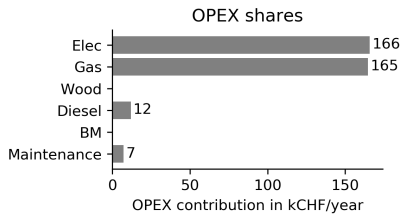
[51] Installed capacity values are rounded based on the exact values of the graphs.



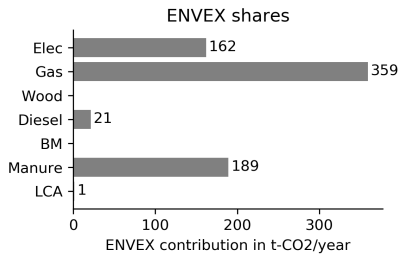
(a) Installed capacity



(b) Investment costs



(c) Operating costs



(d) Emissions

Figure 15 – Results for **Scenario A**: Reference small scale scenario based on the current situation at SFF. Figure (a) shows the size of each technologies, expressed in kW for non storage units and in kWh for storage units. Figure (b) shows the initial investment cost for each technology in Million CHF. Figure (c) is the OPEX contribution from exporting and importing each resource and the cumulative maintenance of all units in kCHF/year. Figure (d) is the ENVEX contributions from exporting and importing each resource, from manure according to treatment and from the cumulative LCA of all units. Note that the installed capacity and units does not match the actual installed capacity at SFF, however results on emissions and costs are useful to compare with other optimization results.

tion of this line, using a discrete number of intermediary solutions. MILP models are often used for equipment sizing and costing. The classical approach is to minimize the operating costs (OPEX) under a maximum investment cost (CAPEX) constraint, in order to analyse the model behaviour and identify promising solutions. Because of the nature of the OPEX and CAPEX, this approach yields good solutions. Specifically both objectives have few parameters in common, the only one being the maintenance cost, which is often only a small contribution to the OPEX.

The OPEX-CAPEX is made by first minimize OPEX without additional constraint, then minimize CAPEX while constraining the OPEX slightly above the unconstrained minimum (1% in this case). This gives the first true[52] minimum for the OPEX and the first point on the Pareto graph, see point 1 on Figure 16a. By minimizing OPEX with CAPEX constrained at slightly above its unconstrained minimum value yields point 21. All other intermediary points is the result of minimizing one objective while constraining the other at different intermediary values.

To reduce the number of points and the time to produce a Pareto graph, an even distribution is important. Points 1 and 21 are found first. Using a short in-house python function, the euclidean distance and slope between the two points is then calculated. If the slope is steeper than -1, the y-axis objective is constrained at the middle of the distance between the two points. If the slope is less steep than -1, the x-axis objective is constrained at the midpoint. The unconstrained objective is minimized. Each additional point is then placed in between the two points on the graph that are furthest apart according to the euclidean distance. The final product is a relatively evenly distributed set of points as seen on Figure 16a.

Using the aforementioned method, two Pareto graphs are computed by repeatedly solving the default FES model, i.e. **Scenario B** with default settings. The first Pareto graph uses the classical approach and looks at costs only, while the second graph looks at total costs and emissions. In total, 42 optimal solutions are derived, 21 for each graph. In sections 4.4 and 4.5 will highlight the general system evolution along each Pareto graph, then select three promising solutions to explore in more details. In section 4.4, they are solutions 9, 14 and 21 representing the minimum CAPEX, TOTEX and OPEX respectively on the the OPEX-CAPEX Pareto graph. In section 4.4, they are solutions 4 representing the minimum TOTEX, 5 representing the minimum TOTEX with an SOFC and 15 representing the minimum ENVEX on the ENVEX-TOTEX Pareto graph. Finally a comparison is made between these points and the current scenario, highlighting their cost and emissions saving potential.

4.4 Scenario B: Minimizing costs

The first approach to the optimizing the FES is the classical approach, i.e. using the OPEX and CAPEX as objectives. The resulting Pareto distribution is shown in Figure 16a. The shape of the graph is an almost a perfect $y = \frac{1}{x}$ function. The graph shows that by increasing the CAPEX, it is possible to reduce the OPEX. Furthermore slightly increasing the CAPEX from its minimum (from point 1 to point 9) will greatly reduce the OPEX. The reverse is also true to some degree. The line drawn by the 21 optimal solutions separate all feasible solutions on the right and all unfeasible solutions on the left.

The Pareto principle, often called the 80/20 rule is described as "80% of the effects come from 20% of the causes"[53]. Two dashed lines are drawn on Figure 16a to emphasize that an increase in CAPEX by 20% from its true minimum will decrease OPEX by 80% resulting in a much lower TOTEX.

The two dotted lines on Figure 16a cross by chance at exactly **point 14** on the graph. This point is also the inflexion point and may be considered as a promising trade-off between both objectives. Furthermore, point

[52] The first minimum, which is 1% lower than the so called true minimum is not a very interesting solution and will often be an outlier on the Pareto graph. For example, without any incentive to minimize CAPEX many technologies will be installed at maximum scale even if they are used only once.

[53] Bunkley, Nick (March 3, 2008). "Joseph Juran, 103, Pioneer in Quality Control, Dies". The New York Times.

14 corresponds to the global TOTEX minimum. Another promising solution is **point 9**, the last point of the initial linear trend from points 1 to 9. The same linear trend does not appear close to the minimum OPEX, therefore the last point of interest is the minimum OPEX itself, i.e. **point 21**. Detailed results for each Pareto point, in terms of installed capacity for each unit, emissions and TOTEX, are presented in the form of a parallel coordinate graph in Annex[54].

Figure 16c and 16e show the evolution of the technologies deployed along the Pareto graph. Naturally, cheaper and less efficient technologies like the GBOI are selected close to the CAPEX minimum (point 1). Gradually more expensive technologies replaces them when moving towards the OPEX minimum (point 21). Looking at heaters, the GBOI is initially replaced by the WBOI, which is then gradually replaced by the GHP. The AHP is almost completely absent, while the EH is always selected but rarely used to produce heat. Looking at renewable energy production, the AD appears at the inflexion point (point 14), along with an ICE consuming all the biogas. The very next solution (point 15) includes a large SOFC (50kW) to cogenerate heat and power from NG only. Then at point 16, the ICE is replaced by a larger SOFC (110kW) and a biogas cleaning unit. From then on, the installed capacity of PV increases until the OPEX minimum.

This evolution shows that even under exclusively economic objectives, renewable energy sources like the AD and PV as well as novel and more efficiency energy conversion systems like the SOFC and GHP are part of the solution, even without the incentive from feed-in tariffs. With low feed-in tariffs, the system leans towards self consumption, however, storage is never part of the solution, which highlights that imported energy is cheaper than localized production combined with storage.

The AHP is virtually absent from both Pareto solutions. The fact that the AHP is discarded can be attributed to two three factors. First the scale of the AHP model is suited for a single house, whereas the heat load at SFF is on the order of a small housing district. Second, a reversible AHP may be more beneficial if there was a cooling load during hot periods. Third, the COP of the AHP is low and could be improved if modeled as a function of external temperature.

4.4.1 TOTEX minimum (point 14)

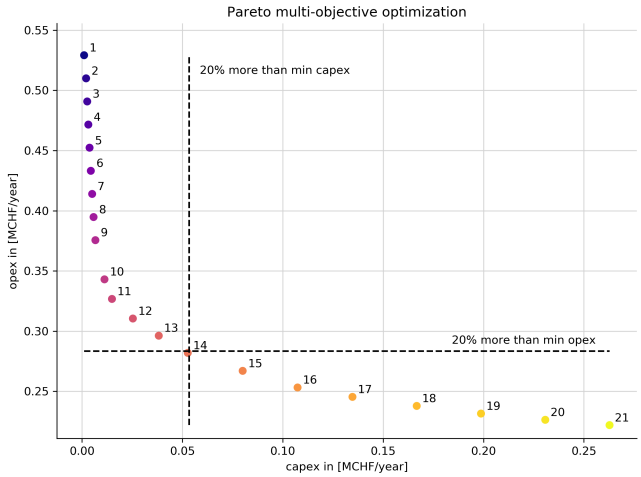
At the inflexion point on the OPEX-CAPEX Pareto graph, the FES model chooses the combination of a $300kW$ wood boiler (WBOI) and a $400kW$ Geothermal Heat Pump (GHP) for heating, as presented in Figure 17a. Both operate during cold periods with a priority for the GHP, while the WBOI only active once the GHP reaches full capacity. The Electric Heater (EH) is never used but is necessary to satisfy the extreme scenario constraint.

An Anaerobic Digester (AD) consumes all the available biomass, producing about $30kW$ of biogas or $5m^3/h$[55]. All the biogas produced is consumed by an Internal Combustion Engine installed at its minimum size of $10kW$ electric capacity. The resulting heat is fully used during cold periods. The ICE consumes some Natural Gas (NG) ($< 1kW$) during colder periods to reach full capacity. A total of $50MWh$ of heat is lost during the warmer part of the year due to cogeneration while $146MWh$ of heat is produced in total with $83kWh$ of electricity.

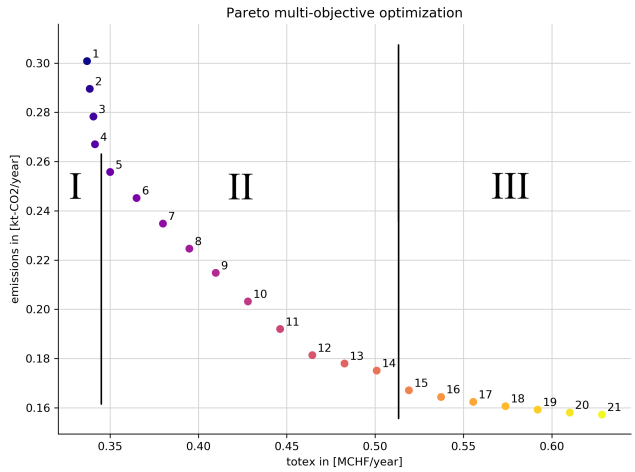
Concerning heaters, the GHP and WBOI are more expensive than the GBOI. However they are cheaper to operate. The TOTEX minimum of the FES, show that in the long term, the most cost efficient heater is the GHP, followed by the WBOI. Provided the cost of the resources stay the same during the lifetime of the heaters. While the price of electricity has slowly but steadily been increasing, the price of wood is fluctuating[19]. In the

[54] An interactive version of all parallel coordinate plots are available online at `https://terborch.github.io/SFF/`. As well as additional graphs for each result analysed

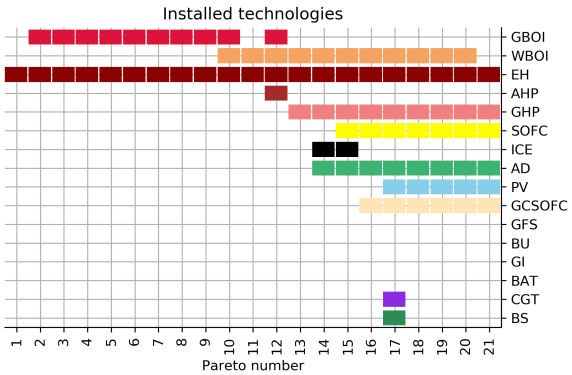
[55] Assuming a biogas energy density of $21.5mJ/m^3$ [46]



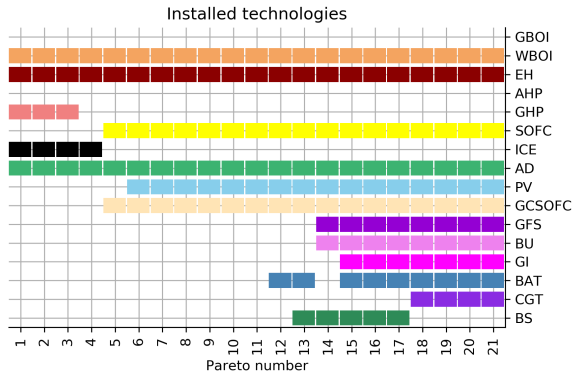
(a) OPEX-CAPEX Pareto graph `LINK`



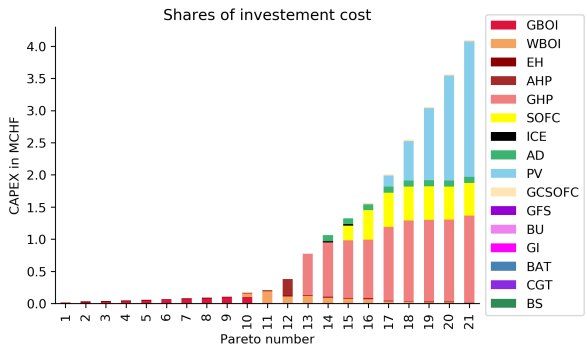
(b) ENVEX-TOTEX Pareto graph `LINK`



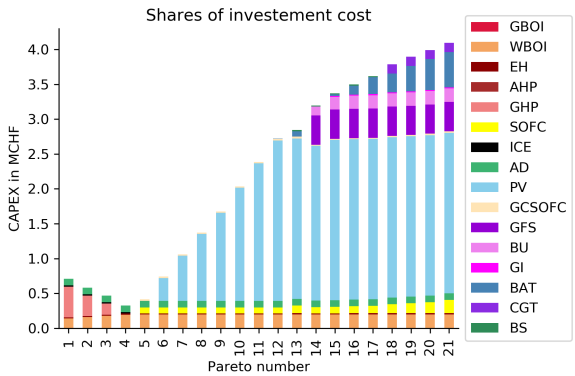
(c) OPEX-CAPEX Installed technologies



(d) ENVEX-TOTEX Installed technologies



(e) OPEX-CAPEX Share of investment costs



(f) ENVEX-TOTEX Share of investment costs

Figure 16 – Optimization results for **Scenario B**: Figures (a), (c) and (e) result from a OPEX and CAPEX multi-objective optimization. Figures (b), (d) and (f) result from a ENVEX and TOTEX multi-objective optimization. Both set of results where produced with the default FES model, i.e. no technologies are blocked or limited and all parameters and constraints are according to the model description and 10 typical days weather clustering. The color on the points of the Pareto graphs correspond to the colors on the lines of the Parallel Coordinate graphs presented in the Annex and a link to the interactive version of these graves is added below each Pareto graph. Figure (a) has additional dashed lines to highlight the Pareto principle. Figure (b) is split into three parts to highlight the different system evolution. Figures (c) and (d) show whether or not a technology is installed for a given Pareto point. Figure (e) and (f) show the total CAPEX in MCHF with the share of each technology for each Pareto point.

authors opinion, the GHP will therefor be the safest solution for reducing TOTEX, relying on the most stable resource for heat supply.

To better understand the units operation, Figure 18c shows what each unit and grid produced (negative value) and consumed (positive value) over the simulated year. The total sum of electricity, heat and diesel is equal to the building's electric load, building's heat load and tractor fuel load respectively, which are not represented on this graph. The graphs shows that the biogas produced by the AD is entirely consumed by the ICE. A fourth of the heat generated by the ICE is lost during warmer periods, underlining the advantage of the SOFC with higher electric efficiency. Over half of the heat produced by the CHP is consumed by the AD. Almost a third of the GHP electric consumption can be supplied by the CHP. This last observation leads to the question, how much of the heat supply could be produced from the available biomass in a best case scenario? Which is answered in section 4.11.

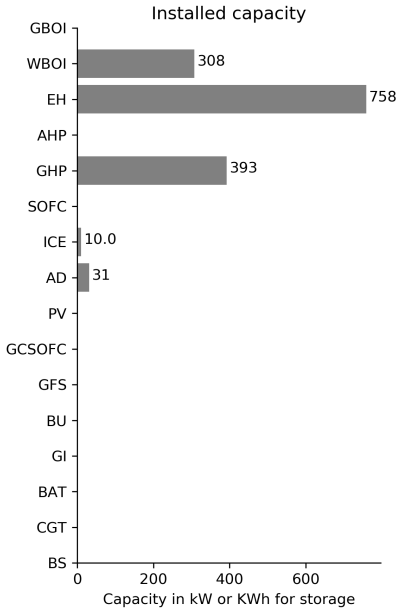
The largest share of investment costs 17b comes from the GHP at 850′000 CHF, followed by the AD at close to 100′000 CHF and the WBOI on the same order. The ICE alone would cost 20′000 CHF while the EH only cost 11′000 CHF. The total investment cost would be 1 Million CHF. It is important to note that the cost estimates of each technology may vary by as much as 50%, i.e. from 0.5 to 1.5 million CHF in total. The cost approximation of some technologies are better than others, in the authors opinion, the cost approximation for the GHP, based on a recent Swiss techno-economic study [29], is very accurate compared to that of other technologies based on large scale reference size.

The largest contribution to emissions is from electricity imports at $220 tCO_2/year$ followed by treated[56] manure at $80 tCO_2/year$, higher than diesel imports for tractors at $20 tCO_2/year$. Wood and grey or LCA emissions from installing all units only account for 5 and $1.5 tCO_2/year$ respectively. The system consumes $1 GWh/year$ of electricity, the largest consumer being the GHP. Wood represent $450 MWh/year$. The remaining manure emissions are unavoidable and are largely compensated by the renewable electricity produced and consumed on site [6].

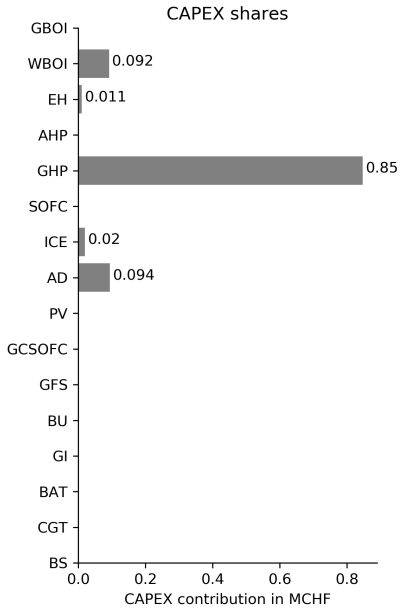
The largest contribution to OPEX is again electricity imports, costing 215′000 CHF/year followed by wood at 33′000, while diesel is only 12′000 CHF/year. Contributions from the maintenance cost of all units is estimated at 21′000 CHF/year but may vary greatly depending on each unit and its operation.

Overall this particular solution represents a good trade-off between a high initial investment cost and annual operating costs. It relies on mature technologies and uses electricity as its main resource. If the electricity's grid share of renewables increase over time, this set-up will benefit from both a reduction in emissions and costs. If the price of electricity increases over time, the owner may benefit from installing PV panels. Treating the manure using an AD represents an important reduction in emissions and a source of renewable electricity and heat. However emissions could be much further reduced. No surplus renewables is injected into the grid. Which is expected due to low feed-in rates, pushing the FES towards self consumption.

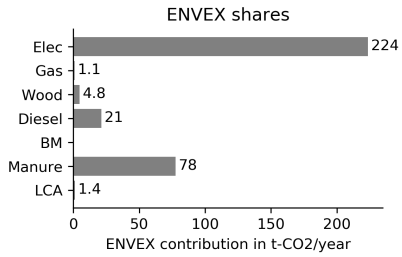
[56] Treated via anaerobic digestion.



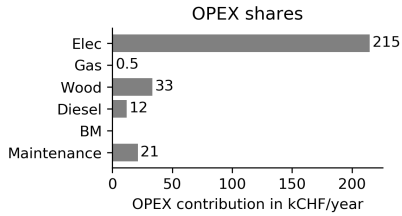
(a) Installed capacity



(b) Investment costs



(c) Operating costs



(d) Emissions

Figure 17 – Result details optimal solutions of **Scenario B**: for **point 14** on the OPEX-CAPEX Pareto graph.

4.4.2 Near CAPEX minimum (point 9)

Near the CAPEX minimum, the situation is close to the current SFF scenario. A GBOI of $460kW$ produces 80% of the heat and an EH supplement it during the peak heat load. In terms of emissions the NG contributes by $300tCO_2/year$ and electricity by $220tCO_2/year$. The reverse is observed for OPEX, where electricity imports account for $220'000$ CHF/year, 25% of which is dissipated in the EH.

The strength of this scenario is the low investment cost. The heating system would only cost $100'000$ CHF. However, this leads to a higher TOTEX, such that after 20 years of operation, this setup would have cost 1 Million CHF more than solution 14. Moreover, without the AD emissions from untreated manure rise to $190tCO_2/year$.

4.4.3 Near OPEX minimum (point 21)

Near the OPEX minimum, most of the heat is produced by a $640kW$ GHP supplemented by a large scale SOFC of $130kW$ electric capacity. The AD is installed, along with a GCSOFC, since all the biogas is consumed in the SOFC. At the OPEX minimum, almost all of the available roof[57] is used for an installed peak capacity of $600kW$.

In therms of energy produced, the GHP generates 80% of the heat and the SOFC another 20% by consuming $850MWh$ of NG. 25% of the heat generated by the SOFC is lost. The SOFC produces $650MWh$ of electricity, more than the PV at $420MWh$ and almost twice the GHP consumption. $150MWh$ of electricity is sold to the grid, at a fixed tariff of $0.06CHF/kWh$ regardless of the source.

Looking at costs, the PV installation is worth $2.1MCHF$, the GHP $1.4MCHF$ and the SOFC $0.5MCHF$. The GCSOFC only cost $20'000$ CHF but contributes a significant amount to the maintenance costs. The largest

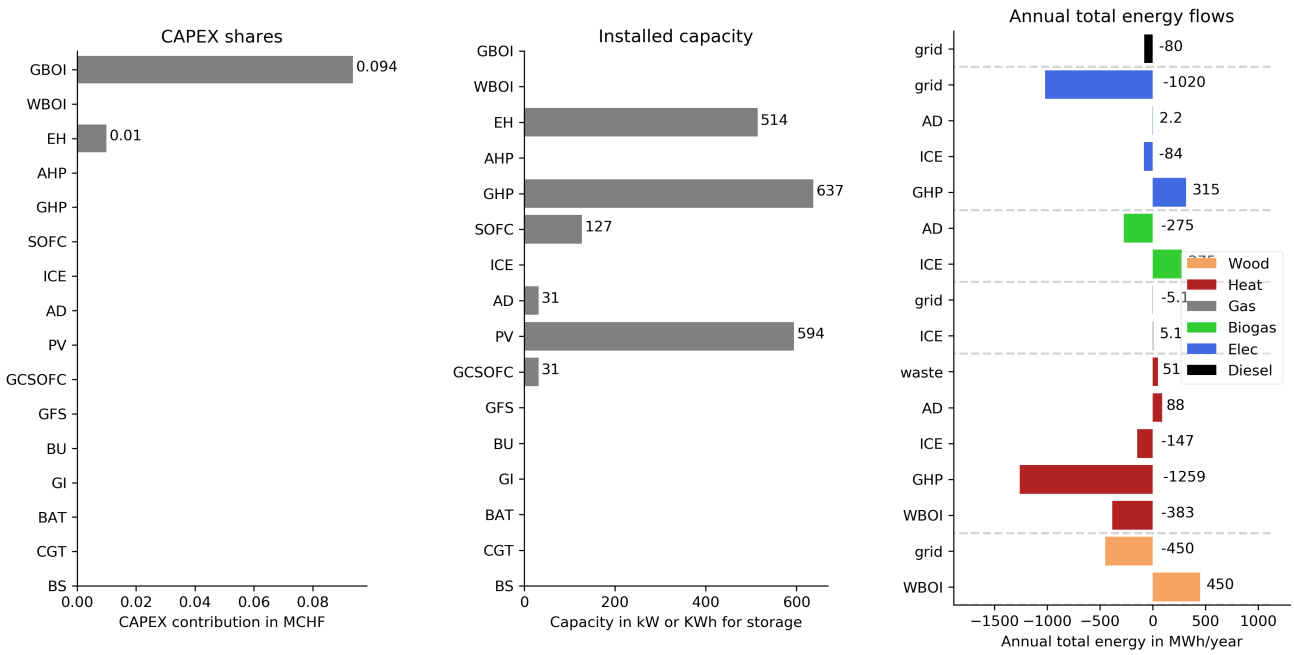
[57] The roof surface available for PV installation was estimated at 50% of the total building ground area, i.e. $3'300m^2$.

share of OPEX are the sum of all maintenance costs at 94′000 CHF/year. NG and electricity contribute by 83′000 and 33′000 CHF/year respectively.

From the perspective of OPEX only, PV is the best choice, having a low maintenance cost and not requiring any energy put to produce electricity. The AD with higher maintenance cost, is also a great option. Cogenerating heat and electricity from NG during cold periods, is cheaper than directly importing the electricity to run the GHP. Which in turn is cheaper than simply burning NG or wood in a boiler.

The strength of this scenario is the low operating cost at only 222′000 CHF/year compared to 350′000 CHF/year for the current SFF scenario. The CAPEX is often considered the most important factor when designing a heating system. Considering how many years a boiler may operate past its 17 years of average lifetime, minimizing the CAPEX may be sighted and will impact the TOTEX negatively. Minimizing OPEX is advantageous for long lived systems. If we consider that the lifetime of some units can be increased by a factor two, a probable assumption for PV, the GHP borehole and the AD structure, then this solution may compete with solution 14 in terms of TOTEX.

The risks are that new technologies or changes in energy prices will render the current system obsolete, even if it does not simply break down early. The author would argue that this risk of increasing energy prices may be higher than the risk of having to replace the system early.



(a) Pareto point 9 - Investment cost

(b) Pareto point 21 - Installed capacity

(c) Pareto point 14 - Resource flows

Figure 18 – Result details for optimal solutions of **Scenario B**: for different points on the OPEX-CAPEX Pareto graph.

4.5 Scenario B: Minimizing emissions and costs

Up to this point, the FES was only optimized according to costs. However, this project aims to minimize emissions and costs if possible. To do so, a second Pareto graph is computed with ENVEX and TOTEX as objectives and presented in Figure 16b. The shape on the graph is less even, with and middle section close to a $y = -1x$ linear function, which is the result of two strongly linked objectives. Indeed the main contributor to

both objectives is the the amount of resources imported and exported.

The graph is divided in three parts to better understand the system evolution. Part **I** is the early steep decrease of emissions from point 1 to 4. Part **II** is the less steep middle section from point 5 to 12. In part **III**, from point 15 to 21 the slope decrease further reaching an almost flat line. The slope of each section is important, it allows to quantify the cost increase necessary to reduce the annual emissions by $1tCO_2$ relative to the minimum TOTEX at point 1. In part **I**, emission mitigation costs only $121CHF/tCO_2$, available from 300 to $260tCO_2/year$. In part **II**, this cost increases to $1'520CHF/tCO_2$, when reducing emissions from 260 to $170tCO_2/year$. Finally the cost increases to $10'900CHF/tCO_2$ in part **III** to suppress the last $10tCO_2/year$. Highlighting again the Pareto principle, a small effort in **I** leads to a big result, and a big effort in **III** produces a very small result.

The system evolution, as shown through figures 16d and 16f, is in some ways similar to the result in section 4.4, but goes further towards self sufficiency, using almost all available technologies. The situation at point 1 is very similar to point 14 on the OPEX-CAPEX graph because point 1 corresponds to the TOTEX minimum. The heat load is shared by the WBOI and GHP along with an AD and ICE cogeneration system. At point 4 the GHP is removed and all the heat is supplied by the WBOI. From then on, the heating will be wood based, because wood was attributed a very low emissions factor. Then at point 5, the ICE is replaced by an SOFC and Gas Cleaning, increasing the CHP electric efficiency. The linear slope from point 6 to 12 can be attributed to a steadily increasing installed PV capacity until PV covers all of the available roof at point 12. Different kinds of storage start appearing, first the Battery (BAT), then the Biogas Storage (BS). The Gas Fueling Station (GFS) and Biogas Upgrading (BU) appears at point 14 providing the tractors with biomethane instead of diesel. It is difficult to explain the step from point 14 to 15, but it may come from the BAT reappearing at point 15, which slowly increase in size until the ENVEX minimum. The last unit to be installed is the Compressed Gas Tank (CGT) able to store biomethane in the long term and replacing the raw biogas storage.

The essential information, the ENVEX-TOTEX graph informs us on is the priority list of technologies to install in order to reduce emissions at the lowest expense. The list as follows and is derived from graphs 16b, 16d and 16f. This list does not include the heating solution, as the WBOI is present for most of the Pareto points. A notable result is that the SOFC appears before the PV. This means replacing the ICE by an SOFC is more cost effective for emissions reduction than installing PV panels, under current feed-in tariffs.

1. Anaerobic Digestion with Internal Combustion Engine
2. Anaerobic Digestion with Solid Oxide Fuel Cell
3. Photovoltaïc panels
4. Small sized Battery
5. raw Biogas Storage
6. Biogas Upgrading with a Gas Fueling Station and convert tractors to use biomethane as fuel
7. Grid Injection
8. A large scale battery
9. Compressed gas tank to store biomethane

Point 4, is chosen as a promising solution for the same reason as point 9 was chosen on the OPEX-CAPEX graph, it is close to the TOTEX minimum but with a significant reduction in emissions. Next to it, point 5 is also chosen as point of interest since it is the earliest Pareto solution that includes the SOFC. Comparing these

two points is a way to compare the classical AD and ICE system with the novel AD and SOFC system, suited for small scale applications. Point 15 is chosen as the best solution if the design goal is to minimize emissions. A justification for this choice is provided in the next section.

4.5.1 Near ENVEX minimum (point 15)

Using the default FES, the true ENVEX minimum at point 21 is neither realistically attainable, nor desirable since it involves a large scale battery. A storage solution that is not yet considered renewable because of the difficulty of recycling lithium. Choosing whether or not to install a large battery involves measuring the minute to minute electric load profile onsite over many days and taking degradation under specific operating conditions into consideration. Because none of these parameters are taken into account uncertainties regarding large scale battery costs and performance have to be taken into account. The evolution from point 15 to point 21 are driven by the increasing size of the battery. This evolution may under unfavourable circumstances drive both emissions and costs up. Therefore the recommended scenario to reduce emissions as much as possible is point 15.

Result details for point 15 are presented in figure 19. Concerning the installed capacity, figure 19a shows a total of 11 different technologies operating in conjuncture. This means the system operation is rather complex and difficult to explain without looking at the hourly load profile of each resource of each unit. To better understand the system, the heaters and PV are considered separately as their scale and operation depends mainly on the size and number of buildings. All other units, except for the BAT, rely directly on the available biomass and operate therefore on a smaller scale.

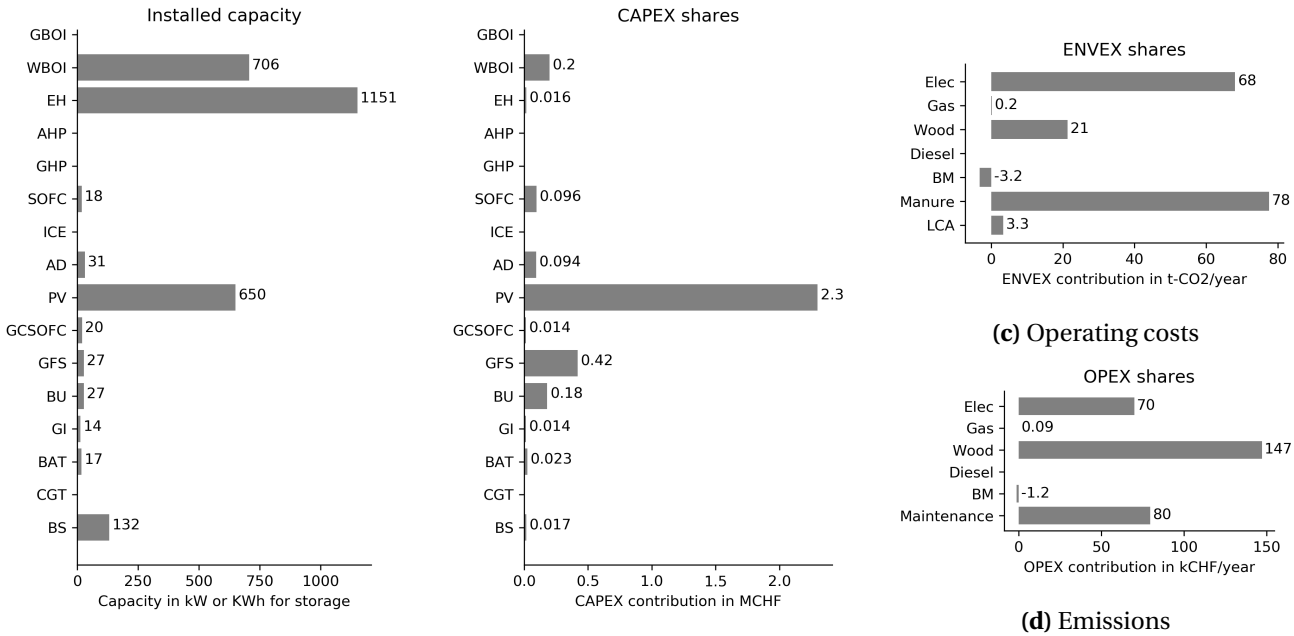
The heat load is almost completely covered by a $700kW$ WBOI, with a $1.1MW$ EH as emergency heater only. The heat produced by the SOFC is not even enough to cover the AD heat load. The PV covers all of the $3'300m^2$ of available roof for a peak capacity of $650kW$. The PV dwarfs all other units in terms of investment cost at 2.3 MCHF, compared to the WBOI at 200′000 CHF.

The biogas subsystem consist of a AD producing $30kW$ of biogas, a BU converting 80% of the biogas into $27kW$ of biomethane, a $18kW$ SOFC that consumes both BG and BM. Some of the biogas is stored in a short term BS storage of $130kWh$ or $22m^3$ capacity. A GFS provides 4 converted gas tractors with exclusively biomethane. A Grid Injection system (GI) injects $16MWh/year$ of biomethane into the NG grid. A small $17kWh$ battery store some of the surplus electricity from either the PV or the SOFC. The most expensive of the small systems is the GFS at 420′000 CHF including tractor conversion, followed by the BU at 180′000 CHF or twice the cost of the AD.

Looking at the annual resource production and consumption graph 20c, waste heat is reduced to only $8MWh/year$, because the CHP no longer has to always operate at full capacity. During hot periods, some biogas can be stored short term, some can be converted and injected into the grid or used as tractor fuel. In the end, the SOFC consumes 18% of the BG produced and 50% of the BM. While close to 40% of the BM is used as tractor fuel and only 7% is sold to the grid. Some biogas losses occur during upgrading, and most notably, the BU consumes $10MWh$ of electricity, three times more than any other unit. Although the SOFC has a small installed capacity, its mostly continuous operation produces $90MWh$ of renewable electricity, compared to $450MWh$ for the PV. The FES imports $2GWh$ of wood pellets, $420kWh$ of electricity, almost no NG and no Diesel. $160MWh$ of electricity is exported.

The many installed units induce a high maintenance cost of 80′000 CHF/year as shown in Figure 19c. Wood is the most significant contribution to OPEX with 150′000 CHF/year. Electricity only amount to 70′000 CHF/year, the benefit of producing almost half of the electricity consumed via PV or SOFC and selling some to the grid.

Concerning emissions from diesel imports, i.e. $21 tCO_2/year$, they are completely negated by the GFS, which only consumes biomethane. It is important to note that the combination of biomethane and gas engine is the only current solution for carbon neutral individual transport that does not rely on batteries. Even with a low emissions factor, the wood grey emissions are non negligible, at $20 tCO_2/year$ as shown in Figure 19d. The manure emissions can not be fully compensated unless more electricity or biomethane is exported to the grid. In other words the system has reached its limits in terms of emissions and would require more space for PV, more biomass or other technologies to reach carbon neutrality.



(a) Installed capacity

(b) Investment costs

(c) Operating costs

(d) Emissions

Figure 19 – Result details for optimal solutions of **Scenario B**: for **point 15** on the ENVEX-TOTEX Pareto graph, calculated using the default FES setting, with 10 typical days.

4.5.2 Near TOTEX minimum (point 4)

As with most solutions on the ENVEX-TOTEX graph, the wood boiler is the main source of heat. Solution 4 also includes an AD, a $10kW$ ICE and an EH for emergency only. The ICE consumes all of the available biogas, plus some NG during peak heat or electric load to reach its maximum capacity. The ICE provides 10% of the heat and 8% of the electricity. As is the case with a continuously operating ICE, $50MWh$ of heat is lost.

The strength of this solution is a low CAPEX of 330′000 CHF. As shown in figure 20a, the most expensive unit is the large wood boiler, and the CHP represent only a fifth of the biogas subsystem CAPEX. The OPEX is less favourable , with 300′000 CHF/year for electricity and wood. The contributions to OPEX of diesel and maintenance is less than 10%. For emissions, Wood and Diesel only account for $20 tCO_2$, with electricity at $140 tCO_2$ per year.

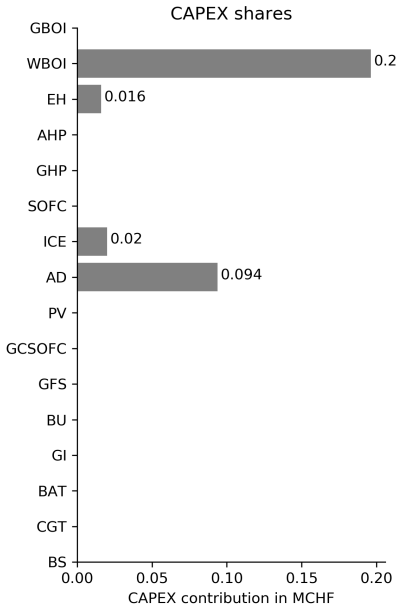
The LCA emissions reach $2 tCO_2/year$, close to that of point 15 at $3 tCO_2/year$ although point 15 has over 11 technologies installed. This observation highlights that apart from the battery, the emissions from LCA of installing technologies could be safely neglected as they do not vary or contribute to the ENVEX by a significant amount.

4.5.3 Near TOTEX minimum with SOFC (point 5)

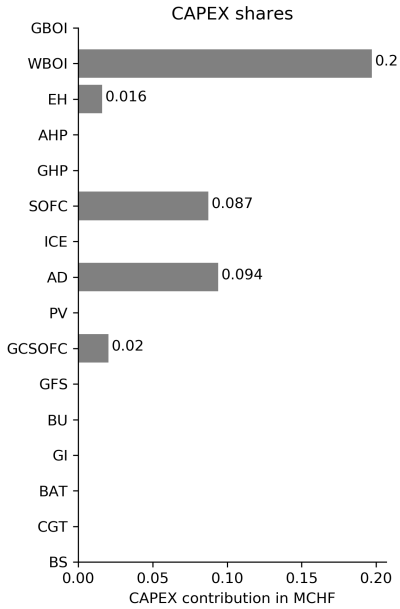
Solution 5 uses an SOFC as CHP unit and is identical in every other aspect to solution 4. When replacing the $10kW$ ICE with a SOFC consuming the same amount of biogas, the electric capacity of the SOFC is $16kW$ due to an increased electric efficiency. The amount of electricity produced is increased by 64%, to $140MWh$, while $4MWh$ is consumed by gas cleaning section, necessary for the SOFC. This allows the system to export some surplus electricity. The heat produced is of course reduced, although the high temperature of the SOFC is an advantage for heat recovery. The SOFC produces 14% less heat, for a total of $124MWh$, just enough to cover the AD heat load and losses. Heat losses are reduced by 25%.

Increasing electricity and lower heat losses come at a cost. The SOFC and GCSOFC cost $110'000$ CHF to purchase, compared to $20'000$ CHF for the ICE. However, the OPEX is slightly more favourable . When comparing points 4 and 5, the SOFC system reduces the electric costs by $10'000$CHF/year, while the maintenance is increased by $6'000$ CHF/year, mainly due to gas cleaning. Over the ten years life span of the system, the cost SOFC system will be approximately $90'000$[58] CHF more than the ICE system. Over the same time $110tCO_2$ may be saved by the SOFC system. Equating to a cost of $800CHF/tCO_2$ for emissions reduction. Pilorgé et al. [51] estimated in 2020 that the cost of capturing $CO2$ could be reduced to $40\$/tCO_2$. However their cost analysis applies to large scale industrial process streams, producing emissions on the order of $600ktCO_2/year$. SFF operates on a much smaller scale and emits about $0.25ktCO_2/year$, or $2'400$ times less than the industrial scale process. Applying the scaling factor $\gamma = 0.6$ to Piorgé et al's value, leads to a cost of $900\$/tCO_2$ captured for a small scale process stream emitting $250tCO_2/year$. In other words, the cost of reducing emissions by replacing a small scale ICE and AD system by a small scale SOFC and AD system is on the same order as state of the art carbon capture technologies but does not require further energy inputs.

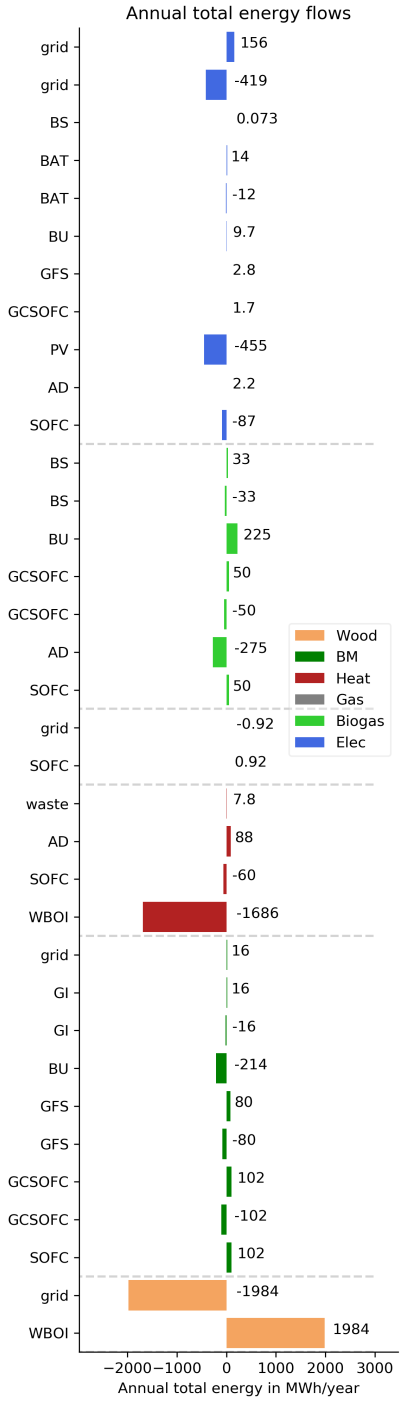
[58] Using the TOTEX difference between scenario 4 and 5.



(a) Pareto point 4 - Investment cost



(b) Pareto point 5 - Investment cost



(c) Pareto point 15 - Resource flows

Figure 20 – Result details for different optimal solutions of **Scenario B**: points on the ENVEX-TOTEX Pareto graph, calculated using the default FES setting, with 10 typical days.

4.6 Results comparison between Scenarios A and B

The following Table shows the different objective values for each of the Pareto points discussed above, and compares them to the current Scenario for SFF. Apart from point 9 of the OPEX-CAPEX graph (section 4.4), every Pareto optimum reduces emissions by over 50%. All the scenarios except scenario 9 are also equipped with an AD and CHP system. A maximum reduction of 77% is observed at the ENVEX minimum (section 4.5.1), saving $570 tCO_2/year$ compared to the current scenario. Values in the ENVEX column highlight the advantage of the unconventional ENVEX-TOTEX Pareto optimization (section 4.5), from the emissions perspective. Indeed, all of the ENVEX values are lower using the ENVEX-TOTEX approach than those of using the OPEX-CAPEX approach.

The TOTEX does not vary by more than 10% for most optimal solutions. Without the inclusion of future projections on energy prices, the addition of feed-in tariffs or a CO_2 tax the change in total costs will not be extremely favourable when producing renewable energy. This is worse for scenarios 21 and 15, where large amounts of renewables are produced, increasing their TOTEX by about 50%. Nevertheless, solutions 14, 4 and 5 all produce renewables, all make use of the AD and ICE or SOFC and all have a lower TOTEX than the reference case. The TOTEX may be reduced by as much as 7% at point 14 (section 4.4.1), saving 24′000 CHF/year.

The OPEX improves for all solutions, except at the CAPEX minimum. It may be reduced by as much as 37% or 128′000 CHF/year at the minimum (section 4.4.3). The OPEX and ENVEX are both driven by the import and export of resources, however they are not interdependent. For example, solutions 4 and 21 are close in terms of ENVEX but not in terms of OPEX. The solutions from the OPEX-CAPEX approach (section 4.4) favour OPEX at the expense of ENVEX and the opposite is true for the solutions from the ENVEX-TOTEX approach (section 4.5).

The CAPEX column is where the drawbacks of reducing emissions and operating costs start to show. The only solution with a lower CAPEX has worse emissions than the current scenario. Surprisingly, the solutions 4 and 5 from the ENVEX-TOTEX minimization (section 4.5) have a much more affordable CAPEX than solutions 14 and 21 form the OPEX-CAPEX minimization (section 4.4). Still, for scenario 5 (section 4.5.3), investing in an SOFC and reducing the farm emissions by 65% will only amount to an investment of 410′000 CHF compared to 150′000 CHF for the current heating system. The lower TOTEX indicates that the system will cost less over time.

It is important to note that each optimal solution is the result of perfect system operation using predictive control. Therefor any application of this solution will likely yield worse results, even with uncertainty taken into account. Hence the importance to consider the FES optimal solutions relative to each other, derived using the same optimization approach. Rather than comparing the FES solutions to the actual expenses and emissions. All large changes on the objectives are therefore shown in percent. The absolute values for cost an emissions are presented for scale only and are therefore rounded.

Comparison between the different optimal solutions. Changes in ENVEX, TOTEX and OPEX are noted in percent relative to the current SFF scenario. Changes in CAPEX is noted as a factor.

Objective	Scenario	ENVEX [$tCO_2/year$]	TOTEX [$kCHF/year$]	OPEX [$kCHF/year$]	CAPEX [$kCHF/year$]
TOTEX	Current SFF	733	359	350	0.15
OPEX-CAPEX	9	738	382	376	0.1
OPEX-CAPEX	14	330 55	335	282 19	1.1 -7
OPEX-CAPEX	21	315 57	485 55	222 37	4.1 -27
ENVEX-TOTEX	4	267 64	341	319	0.33 -2
ENVEX-TOTEX	5	256 65	350	316 10	0.41 -3
ENVEX-TOTEX	15	167 77	519 46	296 15	3.4 -23

4.7 Sensitivity analysis of Scenario B: One At a Time method

As discussed in section 4.3 the FES model needs to be solved 23 times for a complete multi-objective solution. To reduce computation time, only the two solution, (see section 5.1) that will be recommended to the partners are analysed. In order to approximate these solutions without computing the entire Pareto graph a set of additional constraints are formulated, for each.

Solution 5 (see section 4.5.3) is approximated with the following logic. *Minimize ENVEX without increasing the the TOTEX compared to the reference case for SFF.* For every change of every parameter, the TOTEX upper limit is calculate by solving the reference case under TOTEX minimization. Then the FES model is solved under ENVEX minimization with a constrained TOTEX and yields the output objective and installed capacity for this parameter change.

Solution 15 (see section 4.5.1) is approximated with the following constraint. *Minimize TOTEX, near the ENVEX minimum.* First the ENVEX of the default model is minimized, without constraint. Then the TOTEX is minimized, with a constrained ENVEX at 7% above its minimum. The 7% value is derived by observing the ENVEX-TOTEX Pareto graph 16b.

The result of these assumptions are presented in Figure 21. The position of the approximated solution 5 on the Pareto graph is rather accurate, while that of solution 15 is a bit too high, when comparing with its original position on graph 16b. The fact that solution 5 vary most along the y-axis while solution 15 vary the most along the x-axis can be attributed to their constraints on TOTEX and ENVEX respectively.

Figure 22 show the variation in installed capacity and the two most changing objectives for solutions 5 and 15. When comparing figures 22a and 22b, variation at point 5 is overall much larger than at point 15. The difference is likely explained by the overall larger installed capacity of units at solution 15, therefore their change relative to maximum installed capacity is lower. When comparing figures 22c, 22e, 22d and 22f point 5 remains the solution most affected by the sensitivity analysis. Only the two objectives with largest variations are presented for each solution. The TOTEX of solution 5 will vary less because it is linked with the reduced model representing the SFF current scenario. The ENVEX of solution 15 will vary less because it is linked with the ENVEX minimum, which is not sensitive to changes in cost.

Looking at all graphs of figure 22, it is clear that only a small number of parameters have a large effect on the model. Performance parameters are virtually absent, while the cost of resources appear systematically in

the top three of each chart. Followed by the investment cost of different units. It highlights the importance for very accurate estimates of energy costs, and accurate estimates of unit investment costs. On the other hand, parameter performance is generally less uncertain due to physical bounds and these small changes does not affect the model significantly.

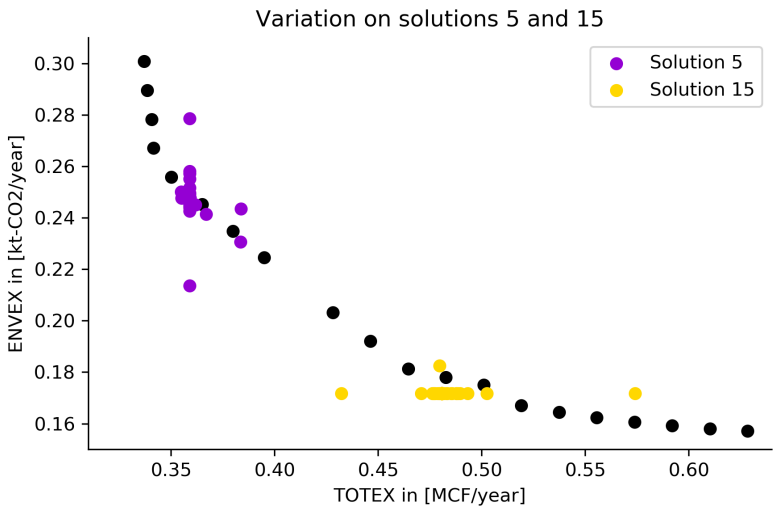


Figure 21 – Comparing each result of the sensitivity analysis with the original ENVEX-TOTEX Pareto graph from Scenario B. The purple dots are an approximation of solution 5 from graph 16b in section 4.5, while the golden dots approximate solution 15. The black dots are the original Pareto solutions of graph 16b.

4.7.1 Sensitivity of solution 5

Wood pellets price has by far the most impact on what units will be installed and their size, as shown in Figure 22a. Increasing the cost of wood by as little as 15% will force the system to user other sources of heating. Therefore, a second Pareto ENVEX-TOTEX graph will be computed in section 4.9 without the wood boiler, to better asses how point 5 would change. **Reducing the price of PV** will lead to the largest change in installed capacity, for any unit price change. This observation will also be further explored in a separate Pareto graph. Increasing the price of units already installed at solution 5, like the AD or SOFC will also lead to changes in installed capacity.

Figure 22c shows that increasing the cost of wood pellets by 1% will lead to an increase in ENVEX by 0.75%, due to the FES relying more on fossil for heating. increasing the cost of NG by 1% reduces the ENVEX by 0.5%, the color red represent this inverse tendency. Although the effect is small, increasing the price of electricity by 1% will reduce ENVEX by about 0.1%. In absolute values, the ENVEX will decrease by $250 kgCO_2/year$ if the electricity price is increased by $0.2 ct/KWh$. Figure 32 shows that $660 MWh$ are imported, translating into an annual cost of 1′300 CHF, or a relative carbon reduction cost of $5 CHF/kgCO_2$ avoided.

Figure 22e shows that increasing the cost of NG by 1% will increase the CAPEX by 5%. While increasing the price of wood pellets by the same amount will decrease the CAPEX by 2%. Even the CAPEX is most affected by the price of energies. CAPEX is the most sensitive objective, due to the changes in installed capacity and the kings of technologies used.

4.7.2 Sensitivity of solution 15

The **SOFC investment cost** has the most impact on the units installed according to figure 22b. At solution 15, the SOFC is central and its size is co-dependent on the volume of grid injection, biogas storage and GCSOFC. Resource costs have overall less impact on solution 15.

The maximum variation for any parameter on any objective is less than 0.5% per 1% change of the parameter. For TOTEX on Figure 22d, the largest impact comes from changing the investment cost of PV, since it is the largest share of CAPEX. The cost of wood pellets has the largest impact on OPEX on Figure 22f since it is the most imported resource.

4.8 Sensitivity analysis of scenario B: Monte Carlo method

The Monte Carlo (MC) analysis yields huge variations on objectives and installed capacities as shown in figures 23a and 24. This is due to the cumulative effect of changing all 50 principal parameters at the same time. The TOTEX varies from 280′000 to 370′000$CHF/year$ and the ENVEX varies even more, from 200 to 700$tCO_2/year$, almost the range of all optimal solutions for Scenario B.

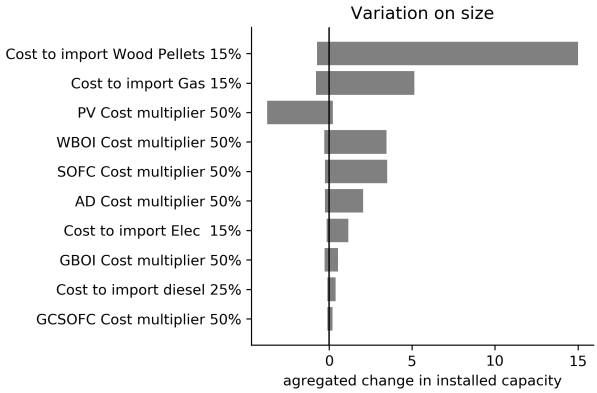
The installed capacity for all the units that appear a significant number of times are presented in figure 24, they should be compared with the default installed capacity for the unconstrained TOTEX minimum presented in figure 23b. The most frequently occurring unit is the HE, followed by the WBOI. However, the WBOI is not always the cheapest heater. It is often be replaced or complemented by the GHP that appears frequently, as well as the AHP. The GBOI is less likely to be part of the TOTEX minimum than the AD. The most important observation, is that the SOFC (lower center) and the ICE (lower left) have a very similar probability to be installed. They are both part of the TOTEX minimum with equal frequency and can therefore be considered, on average, equivalent in terms of costs. The GFS has a fair chance (10%) of being part of the TOTEX minimum, while being close to the ENVEX minimum in previous results as in section 4.5.

4.9 Scenario C: Minimizing emissions and costs without a wood boiler

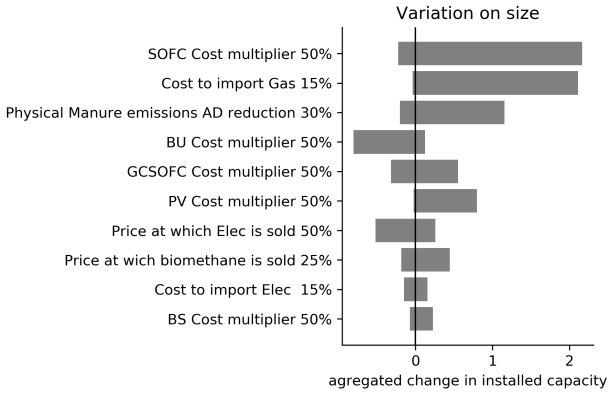
As discussed in section 3.4.1, wood pellets may not be considered a renewable resource depending on the location, supply chain and the other uses of wood waste. However most of the reduction in emissions when comparing the current scenario to other optimal solutions are due to the Wood boiler. Professor F. Maréchal [52] would argue that burning wood pellets is a wasteful practice, for a limited resource that may be better integrated in other processes like paper making or gassification. Previous calculations showed that 6% of the fossil energy for domestic heating could be replaced by wood pellets (section 3.4.3). However, in the lifespan of the boiler (17 years) the resource may become scarce or increase in price.

Using the default FES model, virtually all of the solution on the ENVEX-TOTEX Pareto rely on wood for heating, due to a low cost and emissions factor. However, section 4.7 showed that the cost of wood pellets is the most influencing parameter on the model behaviour. Therefore a slight variation on the default model is formulated, where the **wood boiler is removed from the analysis**. Then an ENVEX-TOTEX multi-objective is performed and presented in Figure 26.

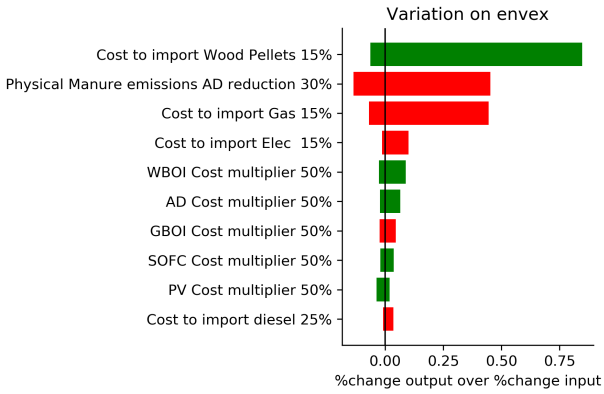
Compared to the original ENVEX-TOTEX Pareto in figure 16b, the new Pareto in figure 26a has a similar shape except for the early steep slope, which is now gone. Looking at figures 26c and 26e, the wood heating system has been replaced by a combination of Geothermal and Air based heat pumps. Progressing from points 1 to 12 on the Pareto graph 26a, the AHP is slowly replaced by the GHP, until all of the heat load is covered by the GHP.



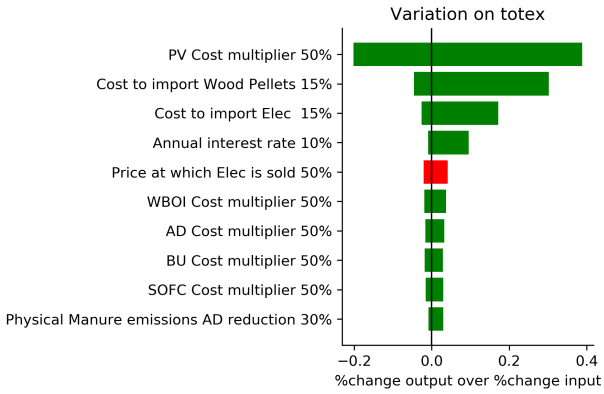
(a) Point 5 - Installed capacity sensitivity



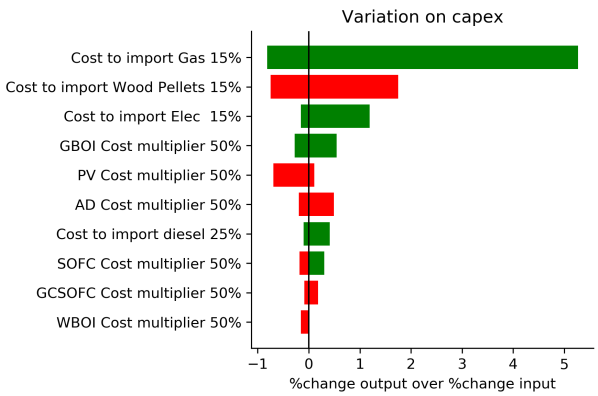
(b) Point 15 - Installed capacity sensitivity



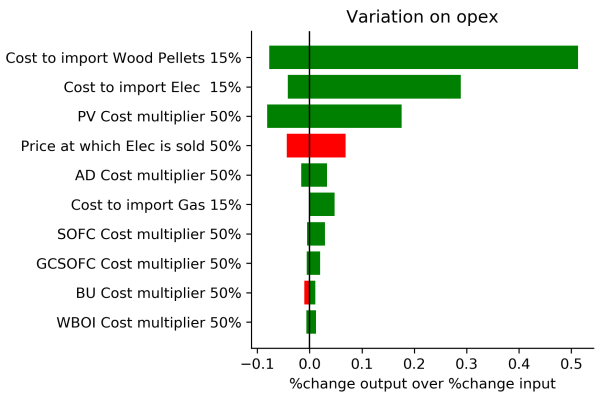
(c) Point 5 - ENVEX sensitivity



(d) Point 15 - TOTEX sensitivity

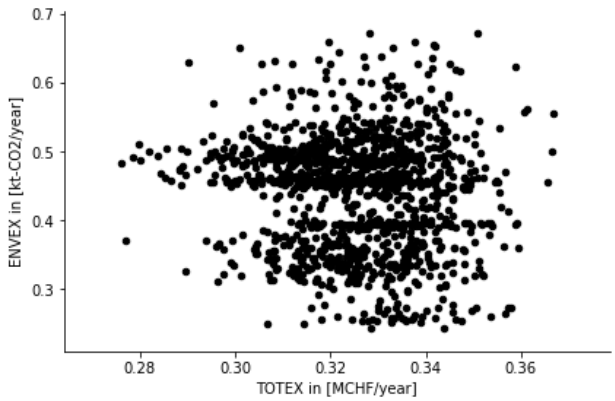


(e) Point 5 - CAPEX sensitivity

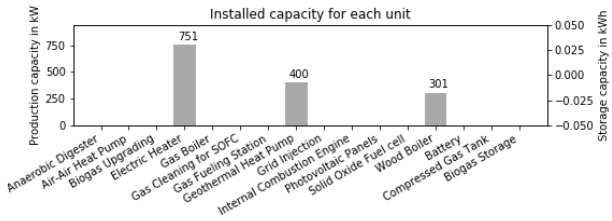


(f) Point 15 - OPEX sensitivity

Figure 22 – Figures (a), (c) and (e) result from the sensitivity analysis around point 5 on the ENVEX-TOTEX Pareto graph. Figures (b), (d) and (f) result from the sensitivity analysis around point 15 on the same graph. Both set of results where produced with the default FES model, i.e. scenario B, by either increasing or decreasing the value of one parameter at a time. Figure (a) and (b) show a total variation in installed capacity of all units, for any change of parameter (not relative to the amount of change). Figures (c) (d) (e) and (f) show the relative change in an objective value for any change of parameter. All charts are sorted by large variation (top) to small variation (bottom) and only show the ten largest variations. Left of zero is the variation caused by a decrease of the parameter value while the right of zero is the result of increasing the same parameter. Green means and increased input causes an increase in results while red means an increase in the input cause a decrease in the result.



(a) Variation on the objectives



(b) Installed capacity for scenario B by minimizing TOTEX only

Figure 23 – Sensitivity analysis on the objective via the Monte Carlo method. Performed by minimizing the TOTEX (unconstrained) using scenario B with normal probability distributions on each of the 50 parameters. The default installed capacity for scenario B is added for comparison.

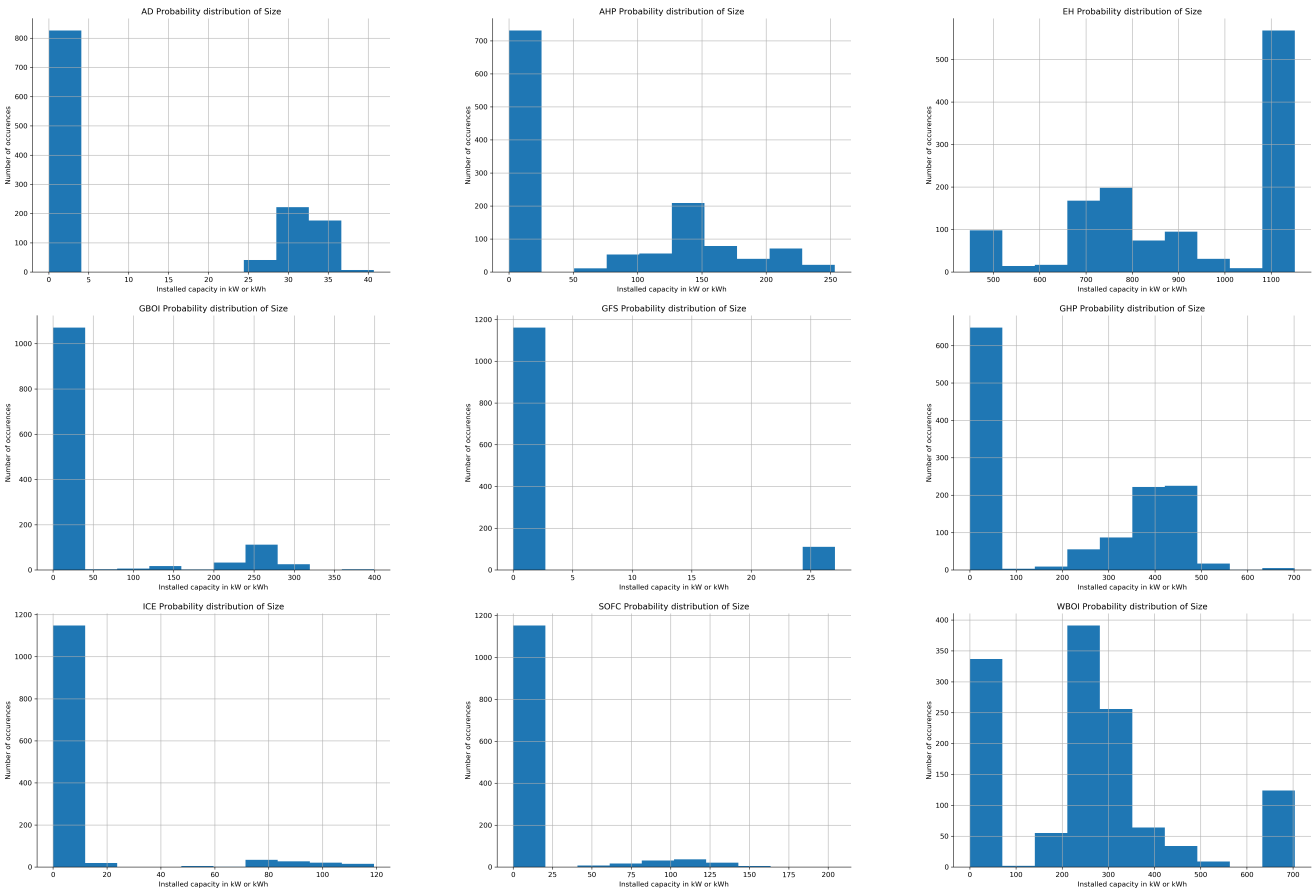
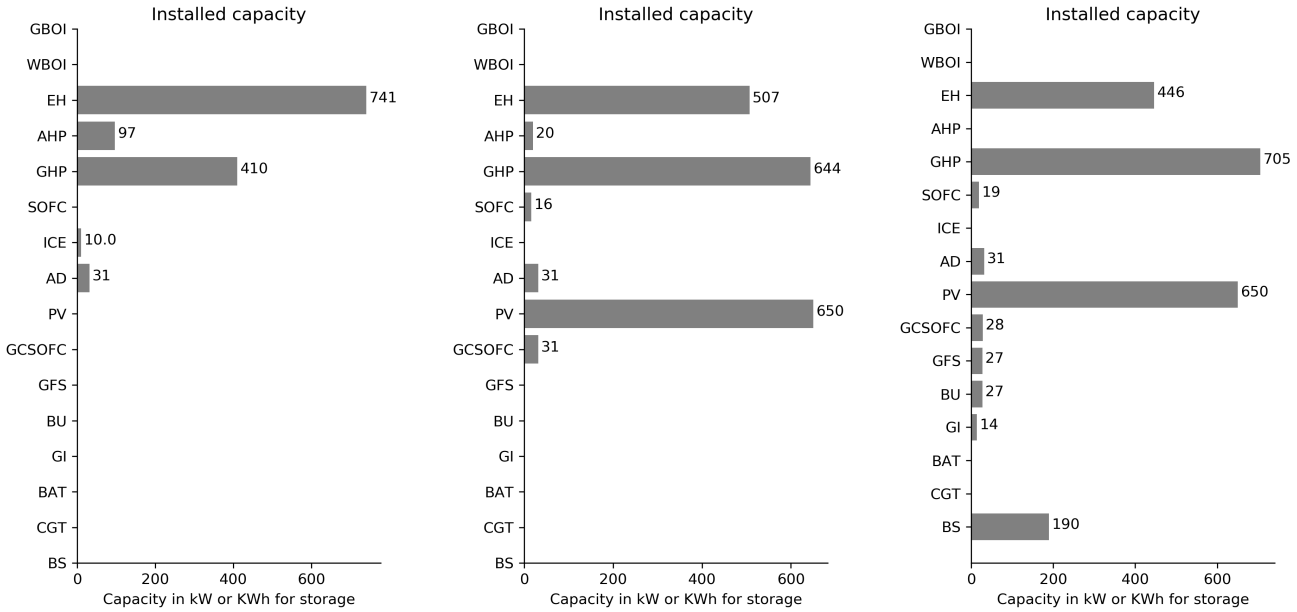


Figure 24 – Sensitivity analysis on the Units installed capacity via the Monte Carlo method. Performed by minimizing the TOTEX (unconstrained) using scenario B with normal probability distributions on each of the 50 parameters. A total of 2′500 where computed within 20 hours with a random variation on all parameters for each.

Figure 25 show the installed capacity at solutions 1, 12 and 15 on the Pareto graph. Most of the heat is provided by the GHP, while the AHP serves as emergency heater. The HE is always present but never used. Concerning PV, storage and auxiliary units, the progression is very similar to that of the original ENVEX-TOTEX Pareto graph. (see section 4.5) At solution 1, the GHP produces 75% of the heat, with an initial investment cost of 880′000 CHF, and a maximum electric consumption of $100kW$. At solution 12 the share of heat produced by the GHP increases to 95%.

Removing the wood boiler from the analysis shows that the next best solution for heating is the geothermal heat pump, in terms of reducing costs and emissions. The AHP is used as a secondary heater to handle peak heat loads. The SOFC is never used as a heater via imports of Natural Gas. Note that a $100kW$ electric load may benefit from medium voltage tariffs and potential offers to be supplied by only renewable electricity. In which case the GHP would always be a better option than the WBOI. With increasing renewable deployment, the cost of electricity is expected to decrease along with its carbon intensity, which would also promote the GHP.



(a) No Wood Boiler - solution 1 **(b)** No Wood Boiler - solution 12 **(c)** No Wood Boiler - solution 15

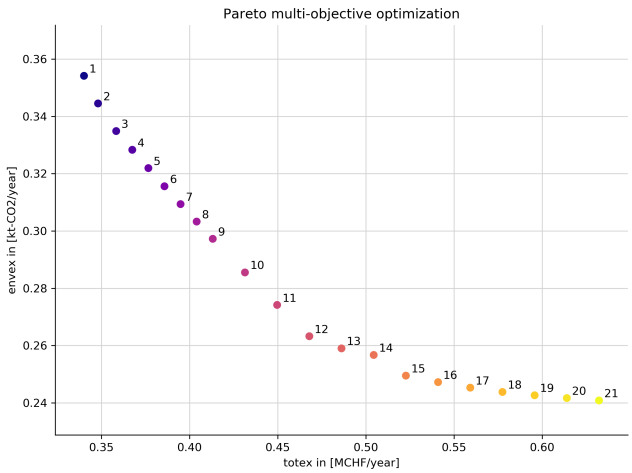
Figure 25 – Scenario C: Result details for different points on the ENVEX-TOTEX Pareto graph for the No Wood Boiler scenario 26a.

4.10 Scenario D: Minimizing emissions and costs with cheap PV

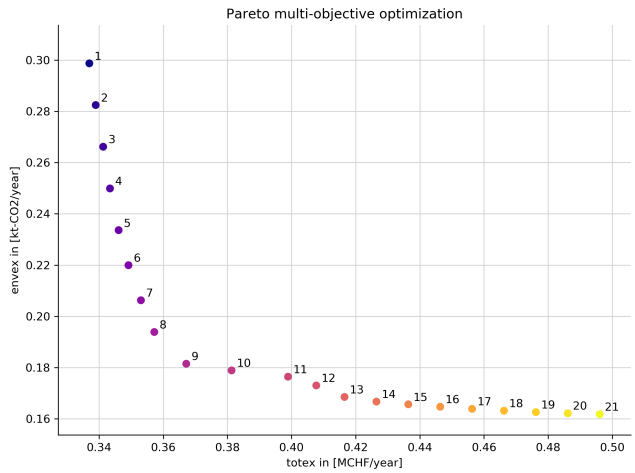
Section 4.7 showed that deducing the cost of PV had an important effect on the units installed. Moreover, section 3.9 highlighted that the cost of PV in the FES model is likely an overestimate for medium scale installations (above $100kW$ peak). Therefor slight variation on the default FES model is formulated, where **the cost of PV is divided by two**, bringing it down to 1.8 KCHF/kW. Then an ENVEX-TOTEX multi-objective is performed and presented in Figure 26.

Compared to the original ENVEX-TOTEX Pareto in figure 16b, the new Pareto in figure 26b show a very steep initial slope, until it reaches a plateau at solution 9. The system evolution, presented in Figures 26d and 26f show that the early decrease in emissions comes from an increasing installed capacity of PV, covering all the available roof surface at point 9.

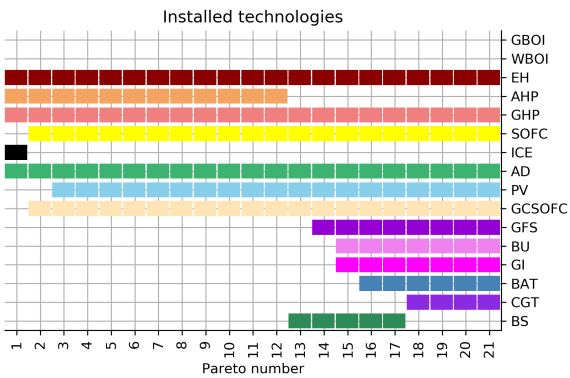
The low PV price makes it economically viable in therms of total costs. At solution 1, the TOTEX minimum, the installed capacity of PV is 78 kW, producing $55 MWh/year$ of renewable electricity (mostly self consumed) with an initial investment cost of 100′000 CHF. The SOFC only replace the ICE once the PV reached its maximum installed capacity at solution 9 on the Pareto graph.



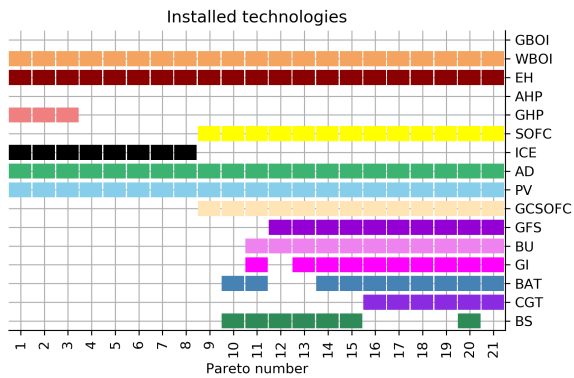
(a) ENVEX-TOTEX Pareto graph



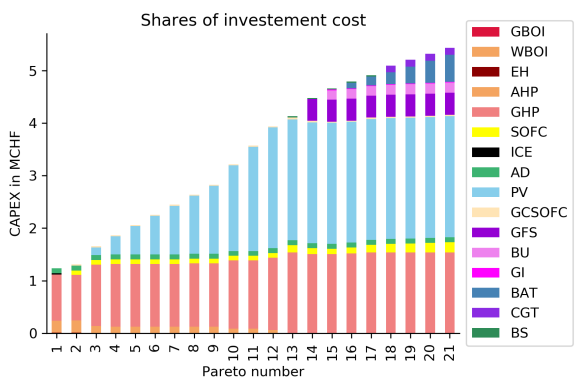
(b) ENVEX-TOTEX Pareto graph



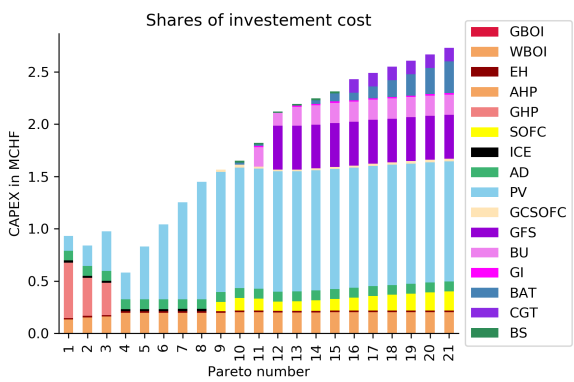
(c) ENVEX-TOTEX Installed technologies



(d) ENVEX-TOTEX Installed technologies



(e) ENVEX-TOTEX Share of investment costs



(f) ENVEX-TOTEX Share of investment costs

Figure 26 – Figures (a), (c) and (e) result from **Scenario C**, a ENVEX and TOTEX multi-objective optimization, with the size of the wood boiled fixed at 0. Figures (b), (d) and (f) result from **Scenario D**, a ENVEX and TOTEX multi-objective optimization with the cost of PV divided by two.

4.11 Estimating the maximum renewable energy production of SFF

SFF is a particular case in terms of biogas production. Most farms with an AD have a large number of livestock for a small number of houses connected to the heating system. This means the CHP will generally overproduce heat and export most of the electricity, like it is the case for the Palézieux biogas installation. SFF has a annual heat load ($1.6GWh$) over twice as high as the available biomass ($0.74GWh$). Nevertheless, reaching net negative emissions and net positive energy balance is possible using proven technologies.

4.11.1 Using only the technologies present in the FES model

In the optimal system for heat production, the AD turn biomass into biogas, the CHP converts it into electricity which in turn is converted into heat via a heat pump. The efficiency of the AD is modeled to be 37%, and can produce $275MWh$ of biogas per year. This efficiency is an average value, that under favourable circumstances, i.e. with animal manure only may be improved. Adding pre-treatment may also push this value higher. Assuming the AD can reach an efficiency of 47%, producing $350MWh$ of biogas, the next concern is storage, since the production is constant but the heat requirement vary. The only possibility to store biogas produced during the summer until winter is via compression or liquefaction. Compression requires biogas upgrading. The SOFC has the highest electric and thermal efficiency. When fed with BM it can reach an electric efficiency of 60% [9]. The electricity produced has to be converted to heat using the most efficient heat pump, i.e. the GHP. The reference scale for the GHP parameters is $25kW$ of heat, whereas SFF requires close to $1MW$. Such a large scale geothermal plant at low altitude could reach a COP of 5 according to [29].

A short calculation gives just above $1.1GWh$ heat produced close to but not quite reaching the $1.6GWh$ of heat consumed in 2019, with the CHP directly contributing to 10% of the heat load. Reaching self sufficiency in therms of heat consumption, without increasing the available biomass, would require producing additional electricity with PV or heat from solar thermal panels.

4.11.2 Using other technologies

The AD waste product is digestate, a moist dirt-like mass that is usually composted before it is used as fertilizer. The digestate is still rich in energy when it leaves the AD. Using Hydro-thermal gasification integrated with an SOFC may recover 67% of the remaining energy content in the digestate as electricity, and separate the CO_2 [53]. This may provide the system with an additional $90MWh$ of renewable electricity.

The CO_2 stream from this process and the membrane upgrading can be used in combination with hydrogen to produce more carbon neutral methane. This process is called Power to Gas. One approach is to use a Solid Oxide Electrolyser (SOEC) to convert excess electricity from PV into Hydrogen. The theoretical upper limit of this technology is 100% efficiency [54]. Moreover, a reversible SOFC may be used in the future instead of the SOEC. Then the CO_2 and H_2 streams are mixed in a methanation catalyst, to form methane. The catalyst has thermodynamical maximum efficiency of 78% [54] but waste heat may be recovered. When necessary more CO_2 can be recovered at the SOFC exhaust.

In solution 15 (section 4.5.1) the excess electricity sold to the grid is $156MWh$. Using an SOEC, this would provide $156MWh$ of Hydrogen. And $120MWh$ of carbon neutral methane. The SFF electric consumption is $800MWh$, doubling the PV covered surface by covering more roof or unused ground surface would generate an annual $910MWh$ of electricity. To store this RE, the excess is converted into hydrogen and then methane to be stored in compressed gas tanks.

The SOFC requires $500MWh$ of methane to provide the GHP with enough electricity to heat the buildings

and AD, including $200MWh$ of heat directly generated by the SOFC. In total they produce $1.7GWh$ of heat. The AD produces $350MWh$ of biogas, an additional $150MWh$ of methane is produced with $200MWh$ of electricity. Assuming $400MWh$ of electricity from the PV as well as the $90MWh$ of electricity from gasification are directly consumed, the remaining $510MWh$ of electricity has to be stored in either batteries or via Power to Gas. With a storage round trip efficiency of 70% or more, the system becomes an energy producer. If all the CO_2 at the SOFC exhaust is captured and the excess is stored, the system can even be considered as a carbon capture and storage solution.

4.12 A medium scale farm case study: Palézieux

The default FES is modified to represent an existing medium scale biogas installation currently operating at a farm in Palézeiux as described in section 3.9. Additionally, two scenarios for a medium scale farm are formulated. The first scenario represent and energy producer and includes a better feed in tariff for renewable electricity of $0.28CHF/kWh$ produced from biogas and a feed in tariff of $0.27CHF/kWh$ of biomethane injected into the grid. This tariff is representative of existing biogas installations benefiting from an advantageous feed-in tariffs with bonuses for using cogenerated heat. To prevent the model from exporting PV generated electricity at the same price, PV is removed from the analysis. Imports of electricity and Natural gas are also forbidden.

The second scenario represent an energy consumer, with a default feed-in tariff of $0.12CHF/kWh$ for renewable electricity. This tariff is representative of near future installations no longer benefiting from advantageous feed-in tariffs. The use of PV and imports of electricity or NG is allowed.

4.12.1 Scenario E: Medium scale energy producer

The medium scale energy producer scenario represents the current situation at Palézeiux, can be used as reference case for the Palézieux multi-objective optimization. Detailed results for this scenario are presented in Figure 27. The unit sizes are fixed according to the current current biogas installation at Palézieux. The ICE provides most of the heat, a wood boiler still provides heat during peak heat loads. Table 26 summarizes the objective values. The modeled system is not profitable, i.e. the TOTEX is positive, whereas the real system is profitable. The FES model ignores any government support, favourable loan and other schemes promoting renewables. Moreover, the maintenance cost of the AD still amounts to 60′000 CHF/year even with the reduced maintenance cost.

The largest positive contribution to OPEX is maintenance at almost 100′000 CHF/year while renewable electricity exports of $1GWh$ amount to 280′000 CHF/year, as presented in Fugire 27b. Regarding ENVEX in Figure 27c, the treated emissions by the 300 cows surpass credits from exporting renewable electricity. This indicates that the emissions per tonne of treated manure, at $40kgCO_2/t$ cow manure is probably an overestimate. Alternatively, the reason for a net positive ENVEX lies in the low carbon intensity of the Swiss electric grid.

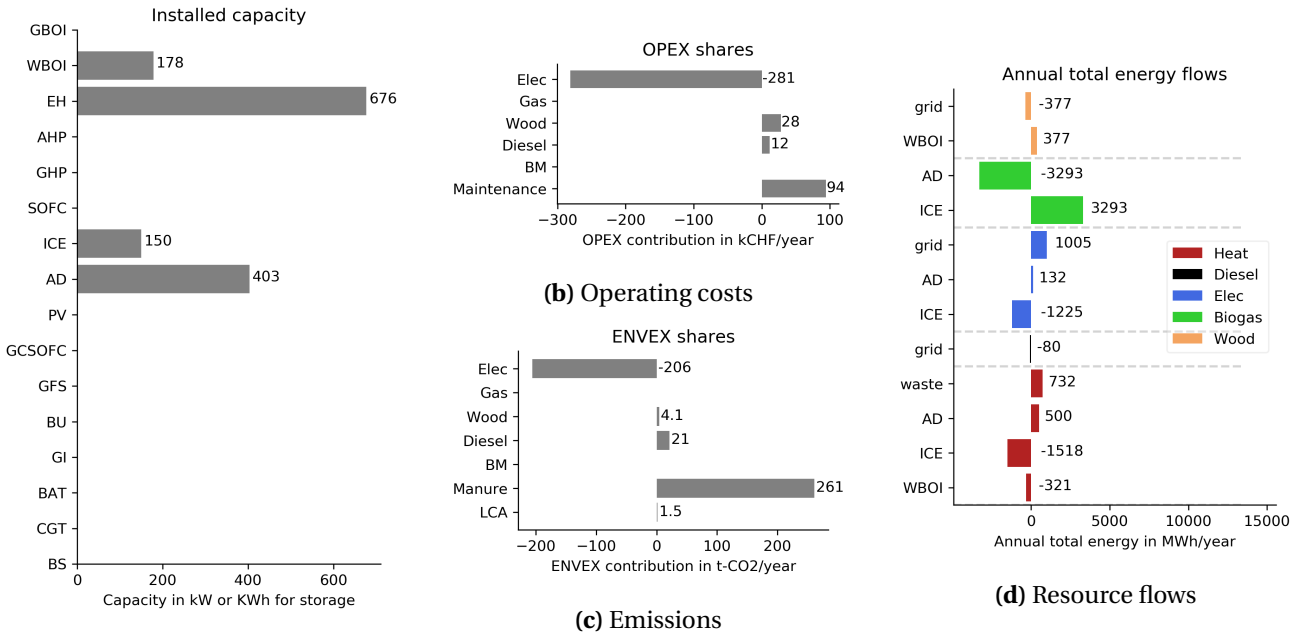
Concerning resource flows in Figure 27d, waste heat is considerable, amounting to $730MWh/year$, almost half of all the heat produced by the ICE. Considering only heat from the ICE is waster, the ICE provides half of the heat load to the buildings. In reality all of the buildings heat load is covered by the CHP, which means the FES heat load profile is fluctuating too much compared to reality, due to the chose building thermal parameters and the omission of domestic hot water in the heat balance.

the discrepancies between the results produces by the FES model and the real biogas installation at Palézieux, show that the FES model is rather conservative. A more accurate model description, including real time feed-

in tariffs, heat load profiles and any governmental support would make the current system profitable. Since the solutions including the SOFC are close to the TOTEX minimum on the Pareto graph (figure 28a), they may even become part of the profitable solutions.

Table 26 – Scenario E: Objective values for the medium scale energy producer.

Objective	Value	Units
ENVEX	82	t-CO2/year
TOTEX	63	kCHF/year
OPEX	-147	kCHF/year
CAPEX	3.3	MCHF



(a) Installed capacity

(b) Operating costs

(c) Emissions

(d) Resource flows

Figure 27 – Scenario E: Result details for the medium scale energy producer scenario, calculated using the FES adapted to Palézieux with favourable feed-in tariffs and limits on PV and resource imports, under TOTEX minimization.

4.12.2 Scenario F: Medium scale energy consumer

This scenario represent a medium scale farm under the current unfavourable policy regarding feed-in tariffs for renewable energy from biogas. Figures for this scenario are presented in the Annex in the Annex (section A.5, figure 30) Imports of resources are allowed. The have a fixed size according to their installed capacity at Palézeiux, including the PV, as shown on Figure 30a. Table 27 shows the objective values for this scenario.

The PV provides an additional $400MWh$ of renewable electricity per year, but due to low feed in tariffs, the revenue from selling electricity is only $160'000$ CHF/year. A part from the PV and the reduced revenu form selling electricity, this scenario is very similar to the energy producer scenario.

Table 27 – Scenario F: Objective values for the medium scale energy consumer.

Objective	Value	Units
ENVEX	23	t-CO2/year
TOTEX	283	kCHF/year
OPEX	-5	kCHF/year
CAPEX	4.5	MCHF

4.12.3 Scenario G: Multi-objective optimization

An ENVEX-TOTEX multi-objective optimization approach is applied to the case of Palézieux. The FES model is slightly changed as described in section 3.9, to match an existing biogas energy production site at Palézieux, with a medium scale biogas potential producing $150kW$ with an ICE. Figure 28 shows the system evolution along the Pareto graph. The graph 28a is split into three sections according to slope. The slope of part **I** and **II** are steeped than on the graph 16b for the default model. And while the default model never reaches carbon neutrality, it is achieved by the modified model at the point 3 already.

Looking at Figures 28c and 28e, the order of units installed is observed. Except for the missing PV and Battery, it is similar to that of the default model. However, the SOFC and storage are part of the solution much earlier. In part **I** The AD consumed the available biomass and the ICE transforms it into heat and electricity. Some raw biogas is stored in a low pressure tank. In part **II**, an SOFC consumes the available biogas as it is produced. Biomethane via Upgrading appears at solution 4 along with grid injection and a tractor gas fueling station. The slope from point 3 to 10 is mostly due to an increasing capacity of Biogas Upgrading. In part **III**, the slope decreases as long term storage (CGT) start appearing along with an increasing size of the SOFC.

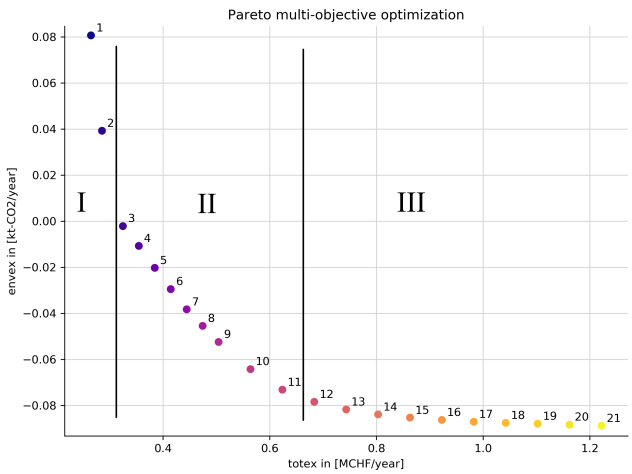
The electricity has a time dependent emissions factor. When exporting renewable electricity, this factor is relevant. In order to further reduce emissions in part **III**, the model uses long-term storage of biomethane to produce high amounts of electricity while the electric emissions factor is high. It is an interesting behaviour of grid load management applied to emissions, where renewables are stored until they are most needed to reduce the overall electric grid emissions intensity.

Overall the two most desirable solutions in terms of emissions reduction is solution 3 when minimizing the TOTEX is most important and solution 11, when minimizing the emissions is the priority. Both solutions use a large scale SOFC instead of the ICE to cogenerate heat and power.

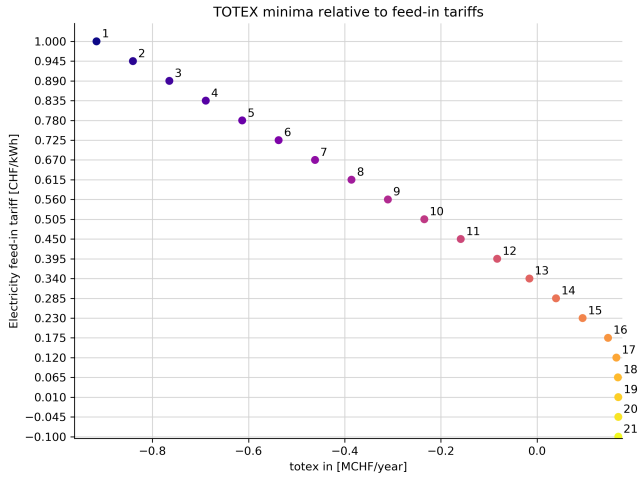
4.12.4 Near TOTEX minimum (solution 3)

Near the TOTEX minimum, a $215kW$ SOFC converts the biogas produced by the AD into heat and power. This additional efficiency allows the farm to reach a net carbon negative of $-1.7tCO_2/yaer$. However, this is only because the Palézieux farm imports two thirds of its biomass from the exterior. A low pressure biogas storage can store what the AD produces in two hours, in a volume of $100m^3$. The installed capacity of the AD, as presented in figure 29a, is lower than the real AD scale, because the operating time is assumed to be $8'760h/year$ of the AD CHP system. The difference between this solution and the small scale near TOTEX solution (see section 4.5.3) is the presence of Biogas Storage. Figure 29b, shows that the SOFC increases electricity generated by $420MWh/year$, the reduction in heat losses is only $50Mh$, despite storage and the SOFC.

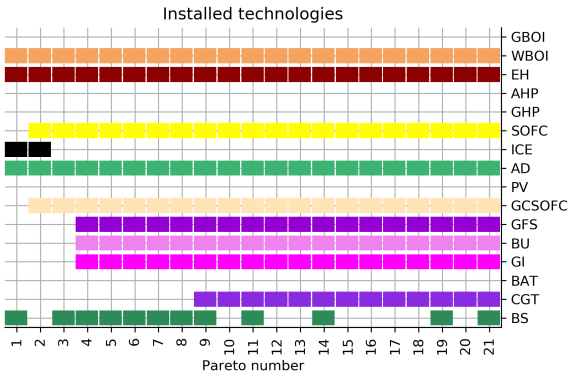
The the SOFC and gas cleaning system would cost 1 million CHF. The overall maintenance cost increases, with the addition of the GCSOFC, but it is compensated by additional revenues from electricity sales. Overall,



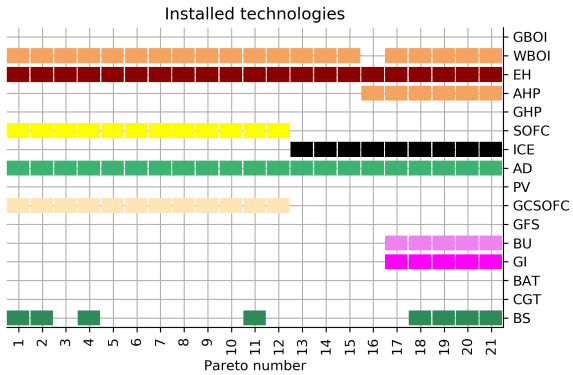
(a) ENVEX-TOTEX Pareto graph



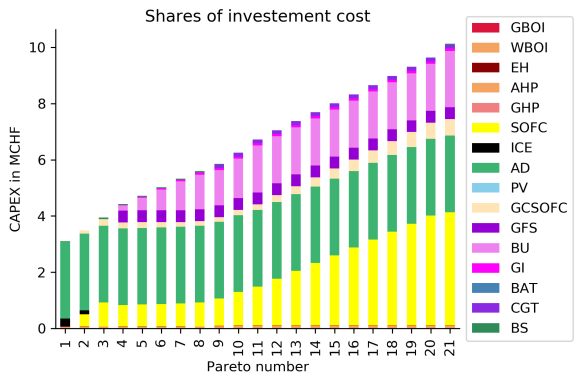
(b) TOTEX minimum and feed-in tariffs



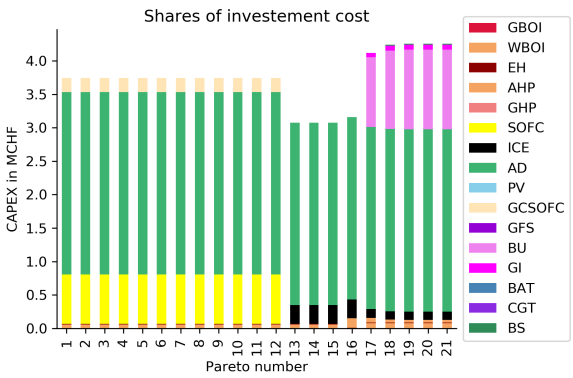
(c) ENVEX-TOTEX Installed technologies



(d) TOTEX-Tariffs Installed technologies



(e) ENVEX-TOTEX Share of investment costs



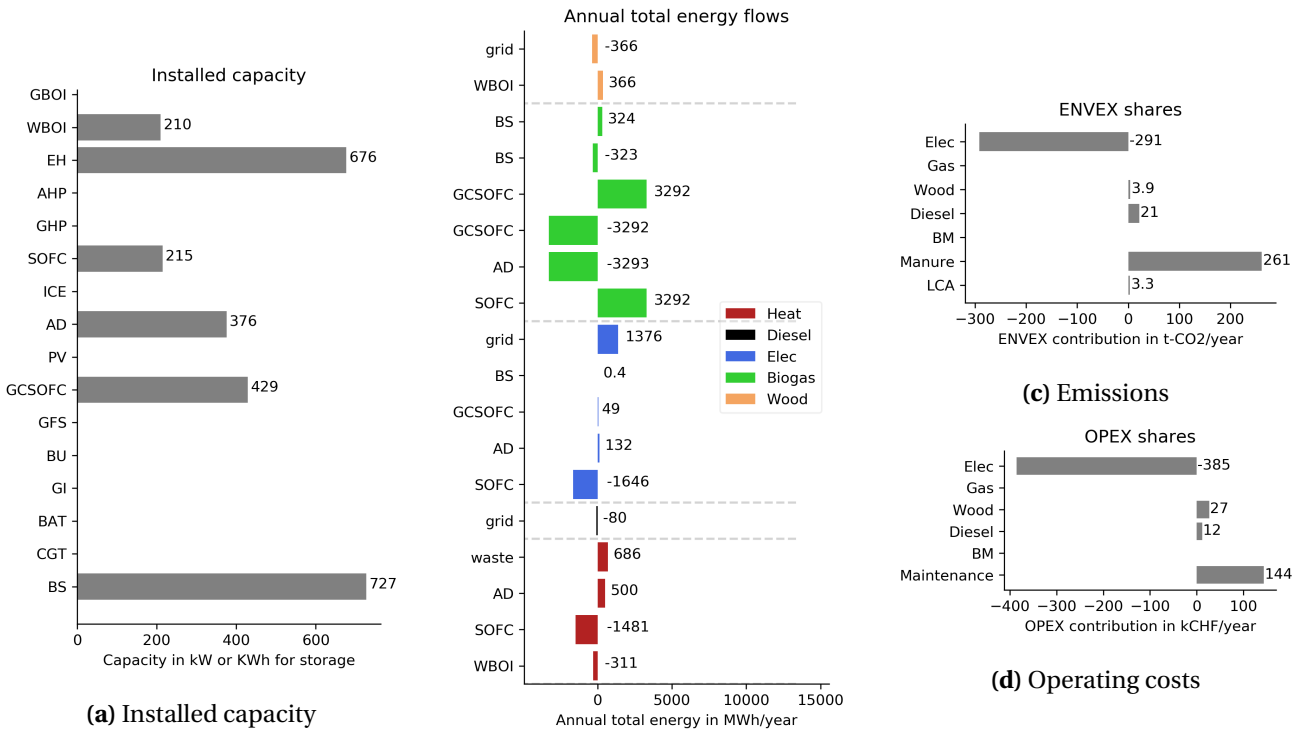
(f) TOTEX-Tariffs Share of investment costs

Figure 28 – Figures (a), (c) and (e) result from a ENVEX and TOTEX multi-objective optimization applied to **Scenario G**. Figures (b), (d) and (f) result from a unconstrained TOTEX minimization of **Scenario G**, with a changing electricity feed-in tariff. Both set of results are based on the medium scale energy producer scenario, i.e. PV is blocked, and no imports of NG and Electricity is allowed. Electricity and biomethane feed-in tariffs are favourable. Figure (a) is split into three parts to highlight the different system evolution. Figures (c) and (d) show whether or not a technology is installed for a given Pareto point. Figure (e) and (f) show the total CAPEX in MCHF with the share of each technology for each Pareto point.

the OPEX revenue is increase by 37% compared to the current scenario (4.12.1), while the total annual costs increase.

Table 28 – Scenario G: Objective values for the solution 3 on the Palézeiux ENVEX-TOTEX graph.

Objective	Value	Units
ENVEX	-1.7	t-CO2/year
TOTEX	105	kCHF/year
OPEX	-202	kCHF/year
CAPEX	3.9	MCHF



(a) Installed capacity

(b) Resource fllows

(c) Emissions

(d) Operating costs

Figure 29 – Result details for **solution 3** on the Palézieux ENVEX-TOTEX Pareto graph 28.

4.12.5 Near ENVEX minimum (solution 11)

Closer to the minimum emissions of a medium scale producer, the FES relies on biogas upgrading to fuel tractors, do biomethane grid injection and store the surplus under pressure. Figures concerning this scenario are presented in the Annex (section A.5, figure 31d). A membrane BU system of $360kW$ is installed, costing 1.7 MCHF. A larger SOFC of $360kW$ may increase its production at certain time thanks to the storage. The ENVEX reaches a net negative of $-73tCO_2/year$ while both OPEX and TOTEX increase.

The notable difference between this solution and the equivalent small scale scenario (see section 4.5.1) is the addition of long term storage. The compressed CGT can store up to 7 hours of biogas production, in a volume of just above $1m^3$. This and a larger SOFC allows the FES to produce more electricity and heat during certain times. However, the heat produced by the WBOI stays the same between solutions 3 and 11, indicating that the increased capacity of SOFC is not used to produce heat during peak demand. Because wood pellets

have low costs and emissions, the SOFC will produce a maximum of electricity when the carbon intensity of the electric grid is high. Allowing the FES to further reduce emissions, by exporting more during certain times. It is an interesting behaviour, similar to electricity producers increasing load when the price and demand increases. If the model was reformulated to account for hour to hour changes in the price of electricity, it is likely that the same behaviour occurs close to the TOTEX minimum of an energy produced, favouring storage.

Table 29 – Scenario G: Objective values for the solution 11 on the Palézeiux ENVEX-TOTEX graph.

Objective	Value	Units
ENVEX	-73	t-CO2/year
TOTEX	405	kCHF/year
OPEX	-129	kCHF/year
CAPEX	6.7	MCHF

4.12.6 Effect of feed-in tariffs on a medium scale producer

The feed-in tariff of renewable electricity is an essential part for renewable penetration. Assuming a medium scale commercial energy producer wants to maximize his profits, i.e. minimize the TOTEX, what would be the feed-in tariff necessary for biogas produced electricity to make the SOFC competitive? To answer this question, the medium scale energy producer model is solved by minimizing TOTEX, with a decreasing feed-in tariff. The tariff range is set from $1CHF/kWh$ to $-0.1CHF/kWh$ and discretized over 21 points. The resulting TOTEX-Tariff plot is presented in Figure 28b.

Looking at figures 28b and 28d, the switch from SOFC to ICE occurs between solutions 12 and 13. At $0.34CHF/kWh$ and below, the ICE is more profitable, at $0.39CHF/kWh$ and below, the SOFC becomes more profitable. A refined analysis pin points the necessary feed-tariff to make the SOFC more profitable than the ICE at $0.37CHF/kWh$. For comparison, biogas installations below $50kW$ used to benefit from a feed in tariff of $0.36CHF/kWh$ if waste heat was used [21].

Any increase of SOFC efficiency or decrease in ICE efficiency will lower the necessary feed-in tariff for a profitable SOFC. This is likely to occur for small scale installations. A large SOFC (of $10kW$) may reach up to 55% efficiency, while a small ICE (of $10kW$) would have a lower efficiency of about 30%.

The break-even feed-in tariff for any technology lie between 0.28 and $0.34CHF/kWh$. Close to the assumed feed-in tariff for the medium scale producer scenario. The system evolution, when going from a feed-in tariff of 1 to $-0.1CHF/kWh$ is represented in Figures 28d and 28f. For a high feed-in tariff the SOFC is used for cogeneration to maximize electricity production and exports. Biogas Storage appears and disappears, while the wood boiler provides the extra heat necessary. The SOFC is replaced by the ICE. Then at point 17, when the feed-in tariff reaches $0.12CHF/kWh$ the FES switches from electricity producer to biomethane producer via upgrading and grid injection. Indeed, the producer scenario requires the system to self produce all electricity and the biomethane grid injection tariff is maintained at $0.26CHF/kWh$. The FES is not impacted by a negative feed-in tariff as it can use the AHP to waste surplus electricity instead of exporting it.

5 Discussion

5.1 Recommendations to the project partners

Based on the optimization results derives from **Scenario B** (Sections 4.4 and 4.5), the recommended solution to implement at Swiss Future Farm will inevitably depend on the partner's objective. Two possibilities come to light, either reduce the carbon foot-print as much as possible or reduce the carbon foot-print without increasing costs.

Looking at the optimization results from the ENVEX-TOTEX approach (section 4.5) **solution 5** on the Pareto graph reduces emissions by 65% compared to the current scenario while keeping the total costs slightly below that of the current scenario. Therefore it is the recommended scenario to follow in order to reduce emissions, without increasing costs.

The recommended solution to reduce emissions as much as possible, would be **solution 15**, also on the ENVEX-TOTEX Pareto graph. This solution could potentially reduce emissions by as much as 77% but will increase total costs by 46%. However, these two solutions are only indications of the direction to follow and further analysis is necessary to find accurate costs and sizes of the future energy system at SFF. The two following sections offers a discussion on what could be adapted from the solutions 5 and 15.

5.1.1 Reducing emissions without increasing costs

Concerning the **heating system**, some solutions can be discarded. The Air-Air Heat Pump and Gas Boiler both show bad performance in terms of cost and emissions. Three possibilities remain, importing gas to co-generate heat and power, importing electricity to run the geothermal heat pump or using wood pellets. Solutions 5 and 15 both rely on the wood boiler, but the author would argue that the geothermal heat pump is neither more polluting, nor more expensive. Indeed, the solutions on the OPEX-CAPEX Pareto graph (section 4.4) show that the GHP is cheaper than the WBOI, by prioritizing the consumption of electricity over wood. The price of wood pellets was taken as the average value for 2019 but the "IPC prix moyens de l'énergie et des carburants" [19], show a large variation in wood prices over the past few years. Moreover, the increased renewable share of electricity is driving the carbon intensity of electricity down, while wood is a limited resource and could become scarce in the next decade, if overused. Thirdly, the GHP could consume electricity from PV generated on site, or an increased CHP load if more biomass is available in the future. Therefore the author would argue in favour of the GHP, unless large amounts of wood waste are produced on site, in which case the WBOI may be favourable.

Concerning **energy production**, Anaerobic Digestion is present in most solutions on both ends of the spectrum. Its implementation will reduce both costs and emissions, therefor it should be installed regardless of the partner's objective. Small scale PV however, is not economically viable with the current feed-in tariffs (see section 4.5.3). However, because the PV potential of SFF is on the order of $500kW$ it is worth to consult directly with local energy providers to possibly to obtain a better feed-in tariff. Moreover, $550kW$ PV installation at Palézeiux costs substantially less than the default value in the FES model. As shown in the OAT sensitivity analysis and section 4.10, when the investment cost of PV drops in the FES model the technology becomes profitable.

Concerning the **CHP**, solution 5 favours the Solid Oxide Fuel Cell and because the total cost of solution 5 is not higher than the current total cost, the author would argue in favour of the SOFC, due to its higher electric efficiency, resulting in lower heat losses. In spite of the SOFC high investment cost, the cost increase per tonne CO_2 saved is on par with carbon capture and storage (see section 4.5.3). Additionally, the FES shows that in terms of costs per emissions savings, the SOFC is better than PV, because the SOFC replaces the ICE before PV

panels appears on the ENVEX-TOTEX Pareto graph (ssection 4.5). At small scales, i.e. $10kW$ electric, Internal Combustion Engines are not efficient and the default electric efficiency in the model is rather generous. On the other hand, a $16kW$ electric SOFC is considered large scale (the commercially available SOFC range from < 1 to 6 kW) and performances should therefore be at least the same or above the default values. The Monte Carlo analysis (section 4.8) also showed that when uncertainty is taken into account the SOFC and ICE are equivalent in terms of costs. Additionally, such an installation would likely be considered state of the art in Switzerland for a long time, promoting the deployment of efficient and economic small scale biogas installations in the rest of the country.

Recovering all of the small scale biomass potential using a mass produces AD and SOFC system, would give access to $20PJ$ of biomass, producing $4.5PJ$ of electricity and $2.5PJ$ of heat, while saving $150kgCO_2/t$ of manure, according to [6]. Using the energy content of 1 tonne of cow manure from [18] this would lead a reduction in emissions of $5MtCO_2/year$ [59], i.e. 10% of Switzerland's annual carbon emissions.

5.1.2 Reducing emissions as much as possible

To move away from solution 5 and towards the emissions minima at solution 15 on the ENVEX-TOTEX graph, additional utilities to produce and distribute biomethane and store energy are required. The discussion on the heating system in section 5.1.1 is equally valid for the present scenario. With a stronger incentive to rely on the GHP, since allot of the electricity can be produced on site using PV. Concerning **energy production**, PV is an efficiency way of reducing emissions, through self consumption and exports. It should therefore cover every surface available.

Concerning **biomethane**, a substantial amount of emissions can be avoided by converting the diesel engines of tractors to gas engines and use biomethane as fuel with a time fill station. This requires upgrading biogas to biomethane using membranes. Although biomethane is available, the FES favours storing raw biogas, probably because the upgrading process consumes a lot of electricity. Grid injection on the other hand is a great solution to reduce emissions when the biomethane is unneeded. Indeed, the NG grid is considered as a great storage opportunity for renewable energy in the form of gas, its capacity is virtually unlimited and unlike the electric grid, it is not sensitive to peaks of production.

Concerning **storage**, a small scale battery may be part of the solution, when self consumed electricity is considered better in terms of emissions than the electricity exported to the grid. Finally the raw biogas storage is a simple solution to better distribute the resource and reduce heat losses in the short term. The losses of about 1% per day of the biogas stored have not been taken into account as emissions although they may impact the solution.

5.2 Model limitations

The **real-world** case study of an energy producer in Palézieux in section 4.12.3 highlights the weaknesses of the FES model when comparing it with reality. The real-world installation is profitable, however, the FES model never reaches a negative TOTEX value. The largest contribution to the TOTEX is the OPEX, where resource costs and feed-in tariffs are essential. Moreover, other forms of subsidies for renewable energy producers are not taken into account. It is useful to compare the real-world cost of units installed at Palézieux with the FES model values, keeping in mind the biogas potential at Palézieux is orders of magnitude above SFF. For the ICE, the specific cost is exactly the same at $2kCHF/kW$ however, due to scaling the ICE cost should be higher. For the PV, the model value is $3.8kCHF/kWp$ against $2.2kCHF/kWp$. However, the potential installed capacity

[59] Note that this calculation is highly simplified, since cow manure is not representative of other animal manure in terms of energy content and $150kgCO_2/t$ only holds for pig manure.

of PV at SFF is 650kW Therefore the cost of PV is likely overestimated. Concerning the AD, the small scale cost is only 3$kCHF/kW$ compared to 7.2$kCHF/kW$ for Palézieux. The AD cost was likely underestimated in the FES model. However, the co-digestion process allows to treat more biomass but requires a shredder. Moreover, a two-stage AD improves performance but requires two separate reactors.

Thermodynamics in FES are highly simplified. As shown in section 4.12.1, the simulated heat load profile does not accurately represent the reality. Moreover, the heat balance equation does not allow for the integration of heat pumps producing heat at lower temperatures with a better COP. This will penalize heat pumps and lead to an over-dimensioned heating system with more losses in summer for CHP. This issue can be mitigated by using the available monthly heat consumption to correct the heat load. The building heat load equation could be reformulated with more accurate parameters. A heat cascade and a COP of heat pumps that change according to the ΔT_{min} between heat sources and sinks, similar to [15], would better describe the thermodynamics and promote the use of heat pumps.

Linear equations reduce the fidelity of the model, since all of the unit behaviours are in reality non-linear. This is particularly problematic for unit cost scaling. This can be resolved either by constraining the units's size withing an acceptable range of size of no more than one order of magnitude. Or by integrating piece-wise linear constraints, which could allow the modelling of more farms of different scales.

10 typical days of a single year are not representative of the system behaviour over its entire lifetime, i.e. 10 to 20 years. Weather is a cyclical phenomenon, both on a daily basis and an annual basis. F. Maréchal [52] argues that clustering weather parameters over 7 typical days is enough to accurately model a heating system. But warns that a better approach to clustering is to not only cluster weather measurements from a single year, rather cluster it for the last 20 years. Such that the typical days represent all possible weather over a long period of time.

One hour time-step is common among many MIP models but is a rather arbitrary value. F. Maréchal (cite FM) would argue that a longer time-step can be used to reduce the model solve time, while D. Lauinger proposed that a shorter time step might promote storage solutions like the battery. Either way, testing the model with different time-steps would probably yield interesting results from the modelling perspective. Reducing the time step would require adding dynamic constraints like a minimum startup time for the SOFC of an hour, as well as minute-by minute profiles for electricity and weather.

Predictive control occurs because all information regarding future weather and consumption profiles are available to the solver. It causes the unit control and operation to be perfect and unrealistic. Real systems only react the inputs or at best future predictions. This one reason why the simulated heat load must be multiplied by a factor two, to match the real heat consumption. It is possible to prevent this by implementing a receding horizon on temporal parameters like the heat and electricity load and weather parameters, simulating instant measurements and the system's reaction.

PV profitability never occurs although the electric load of the farm is huge, meaning much of the PV electricity can be self consumed. A medium voltage installation of 100kW peak should be profitable. A refined analysis, taking roof size, roof orientation and real-time electric consumption into account should be conducted, and integrated into the FES to answer this potential issue.

Energy integration is key modern renewable energy systems. However, FES is made up of 16 separate technologies, without any though for advanced integration. For example, the gas fueling station requires electricity for compression, however, biomethane going from the compressed gas tank would already be at high pressure and require less compression to serve as fuel. Taking integration into account for all combinations of technologies would benefit the hard-to-reach solutions close to the ENVEX minima.

Time dependent parameters like the electric consumption profile or building heating profile have a rather arbitrary shape. However they are central to the system operation. When possible, measuring these profiles for

only a couple days on site would give a much better idea of their actual shape. Lauinger [11] used a weekly electric load profile, taking into account the difference between week days and week-ends. Stadler [15] included the use of domestic hot water over a typical day. Alternatively they should be included into the sensitivity analysis.

Economic parameters are central to the model decisions, as seen in section 4.7. Unfortunately they are the parameters with the highest uncertainty. Both unit costs and resource costs can be better estimated by getting quotes from manufacturers or contacting local energy providers. PV retribution schemes may also depend on local energy companies. Resource costs are particularly important, future predictions on energy prices specifically for Switzerland are available in the literature and could be user.

FES is not open source, due to the use of Gurobi. Commercial solvers are generally considered faster than free to use options like COIN-OR, but the gap is closing. Pulp is an open source python module (similar to the Gurobi-python module) that can be used to describe a MILP and the solve it using an open source solver like COIN-OR. The Open Energy Modelling Framework (OEMOF) developed by Hilpert et al. [55] relies on Pulp to make modelling of energy systems accessible and free-to-use. If this project had used OEMOF as a starting point, it could have both benefited from OEMOF and benefited to OEMOF.

5.3 Further development

The advantage of the FES model is its relative simplicity. This makes it accessible and easily modifiable. Inevitable errors are more easily found and corrected. A unit can be described and added within an hour or two, by adapting its performance and costs parameters from existing literature. The Python language is accessible and allows systematic automation. This simplicity allowed the author to produce numerous results in a matter of weeks. The FES model's simplicity is also its weakness. The key to developing the model further is to strike a balance between complexity and realism. Anything can be neglected, should be neglected. Adding essential layers of complexity will allow the user to produce more accurate results and take better decisions. Applying the FES model to different farms with their own unit situation will gradually improve the model and the results it produces.

Section 4.11 showed that reaching energy neutrality, even in the very unfavourable case of SFF is theoretically possible. Investigating the Power to Gas Cycle, at farms is interesting. If biogas is to be used as vehicle fuel, for grid injection or long term storage, the upgrading process will produce high quality CO_2. This is a great opportunity for methanation, since other means of carbon capture uses a lot of energy.

Many of the heated buildings at SFF are old, therefore improve the building thermal envelope through insulation and renovation would significantly lower the overall heat load. Integrating this aspect into the analysis may lead to interesting solutions and trade offs.

Evaluating the impact of the increasing carbon tax in Switzerland [60] would be interesting. The life of most units is long and a steadily increasing cost of resources may drastically shift the cost minimum towards more efficient technologies and more RE production.

Accurately evaluation the impact of the presented solution on the national level would give a better idea of the actual opportunity these solutions represent and whether government policies should focus on helping smaller scale biogas producers towards the energy transition.

[60] about $100 CHF/tCO_2$ today [61]

6 Conclusion

Previous studies [15], [12] demonstrated that currently, the SOFC is not cost competitive as a heating solution. In the context of small scale biogas production, [12] (see section 4.12.3) the SOFC if not more profitable than the ICE. However, when viewed as an opportunity to reduce emissions for a small scale biogas process, the SOFC is on par with or more cost efficient than state of the art carbon capture technologies and more cost efficient than PV, storage or any alternative technology modelled in the FES.

Moreover, the MC analysis reveals a layer of complexity and uncertainty that cannot be seen on the Pareto graphs. For example, the GFS, which is only active close to the ENVEX minimum on the Pareto graph has actually 10% of chance to be part of the TOTEX minimum solution. The analysis also highlights that the ICE and SOFC are equivalent in terms of cost. The MC analysis is a strong argument in favour of the SOFC, since it is more energy efficient than the ICE, but does not cost more on average.

The CAPEX column in the results comparison table (section 4.6) can be viewed as the main hurdle to the deployment of more energy efficient technologies and localized production of renewables, essential to tap the remaining available biomass. The CAPEX may be the main driver in the farm owner's decision. An investment that may or may not pay of twenty years from now is not appealing. A potential reduction in the TOTEX by a few per-cent is not enough to risk investing at the wrong time in a new and evolving technology. It shows the need for stronger incentives in the form of feed-in tariffs (as explored in section 4.12.6) or in other forms.

Today, the most favourable large scale agriculture sites for biogas production are already exploited or under consideration. The true potential to reduce emissions and produce large amounts of renewable energy lies in the many smaller farms [1]. Biomass, having a low energy density cannot be efficiently transported. Therefore, the only solution is a small scale decentralized solution, a solution which can rely on SOFCs as demonstrated in 2003 by Van Herle et al. [56] at a small scale farm in Lully, VD.

Reducing emissions by more than half, at a small scale, using available technologies at today's market's price comes already at virtually no cost. A small push by policy makers, would be enough to create a strong economic incentive to invest in energy efficient technologies. Reducing the pay-back time and removing uncertainty for the owner. Furthermore, small scale installations have the advantage to be numerous and similar in scale. Therefore, the solution design, once deployed to a handful of farms may be reused, refined and standardized, and even mass produced, slicing the system cost.

Deployment of technologies takes time, and the energy systems designed today will operate until 2040 at the very least. By that year, the IPCC estimates that the global average temperatures, under the business as usual model, will have increased by $1.5°C$. The IPCC argues that it is important to limit global warming by $1.5°C$ or face much worse outcomes if temperatures increase by $2°C$. The IPCC also states government incentives for deployment of renewable based technologies is an effective way of driving emissions down [2].

7 Bibliography

References

[1] Oliver Thees et al. *Biomassenpotenziale der Schweizfür die energetische Nutzung*. Tech. rep. ISSN 2296-3456. SCCER BIOSWEET, 2017. URL: https://www.dora.lib4ri.ch/wsl/islandora/object/wsl%5C%3A13277/datastream/PDF/view (visited on 02/25/2020).

[2] V Masson-Delmotte et al. *IPCC, 2018: Global Warming of 1.5°C*. EN. Tech. rep. IPCC, 2018. URL: https://www.ipcc.ch/sr15 (visited on 08/11/2020).

[3] Colin Raymond, Tom Matthews, and Radley M. Horton. "The emergence of heat and humidity too severe for human tolerance". en. In: *Science Advances* 6.19 (May 2020). Publisher: American Association for the Advancement of Science Section: Research Article. ISSN: 2375-2548. DOI: 10.1126/sciadv.aaw1838. URL: https://advances.sciencemag.org/content/6/19/eaaw1838 (visited on 06/08/2020).

[4] *Energy, Agriculture and Climate Change*. Tech. rep. Food and Agriculture Organization of the United Nations, 2016. URL: http://www.fao.org/3/a-i6382e.pdf (visited on 02/17/2020).

[5] EPA. *Greenhouse Gases Equivalencies Calculator - Calculations and References*. 2020. URL: https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references (visited on 07/27/2020).

[6] Trakarn Prapaspongsa et al. "LCA of comprehensive pig manure management incorporating integrated technology systems". en. In: *Journal of Cleaner Production* 18.14 (Sept. 2010), pp. 1413–1422. ISSN: 09596526. DOI: 10.1016/j.jclepro.2010.05.015. URL: https://linkinghub.elsevier.com/retrieve/pii/S0959652610002027 (visited on 07/07/2020).

[7] *SFOE - Energy Consumption in Switzerland 2019*. EN. Tech. rep. Swiss Federal Office of Energy SFOE, 2019. URL: https://www.newsd.admin.ch/newsd/message/attachments/61942.pdf (visited on 07/28/2020).

[8] Pietro Capaldi. "A high efficiency 10 kWe microcogenerator based on an Atkinson cycle internal combustion engine". en. In: *Applied Thermal Engineering*. Special Issue: MICROGEN III: Promoting the transition to high efficiency distributed energy systems 71.2 (Oct. 2014), pp. 913–920. ISSN: 1359-4311. DOI: 10.1016/j.applthermaleng.2014.02.035. URL: http://www.sciencedirect.com/science/article/pii/S1359431114001252 (visited on 06/09/2020).

[9] *Group of Energy Materials (GEM) EPFL. Personal communications with prof. J. Van Herle*. May 2020.

[10] Jürg Fischer. *Energy Inputs in Swiss Agriculture*. Tech. rep. 99-01. COMMON AGRICULTURAL POLICY REGIONAL IMPACT ANALYSIS, 1999. URL: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.707.6655&rep=rep1&type=pdf (visited on 02/18/2020).

[11] Dirk LAUINGER. "Projet de Master EPFL, OPTIMIZATION OF RESIDENTIAL ENERGY SYSTEMS FUEL CELL INTEGRATION". en. In: (2015).

[12] Samuel Joseph Christian Majerus. "Projet de Master EPFL, fueling a sofc with agricultural waste derived biogas". en. In: (2016). URL: https://infoscience.epfl.ch/record/221505.

[13] Samuel Majerus, Dirk Lauinger, and Jan Van herle. "Cost Requirements for a Small-Scale SOFC Fed From Agricultural-Derived Biogas". en. In: *Journal of Electrochemical Energy Conversion and Storage* 14.1 (Feb. 2017), p. 011002. ISSN: 2381-6872, 2381-6910. DOI: 10.1115/1.4035891. URL: https://asmedigitalcollection.asme.org/electrochemical/article/doi/10.1115/1.4035891/380532/Cost-Requirements-for-a-SmallScale-SOFC-Fed-From (visited on 02/17/2020).

[14] Souhil Harchaoui and Petros Chatzimpiros. "Can Agriculture Balance Its Energy Consumption and Continue to Produce Food? A Framework for Assessing Energy Neutrality Applied to French Agriculture". en. In: *Sustainability* 10.12 (Dec. 2018). ISSN: 2071-1050. DOI: 10.3390/su10124624. URL: http://www.mdpi.com/2071-1050/10/12/4624 (visited on 02/17/2020).

[15] Paul Michael STADLER. "Model-based sizing of building energy systems with renewable sources". en. In: (2019). ISSN: Thèse EPFL N° 9560. URL: https://infoscience.epfl.ch/record/267499?ln=en.

[16] *Swiss Future Farm. Personal communications with R. Bernet.* June 2020.

[17] Federal Office of Topography. *The federal geoportal.* URL: https://map.geo.admin.ch/ (visited on 07/25/2020).

[18] Nicolae Scarlat et al. "A spatial analysis of biogas potential from manure in Europe". en. In: *Renewable and Sustainable Energy Reviews* 94 (Oct. 2018), pp. 915–930. ISSN: 13640321. DOI: 10.1016/j.rser.2018.06.035. URL: https://linkinghub.elsevier.com/retrieve/pii/S1364032118304714 (visited on 07/06/2020).

[19] OFS. *IPC, prix moyens de l'énergie et des carburants, valeurs mensuelles (depuis 1993) et annuelles (depuis 1966).* fr. Library Catalog: www.bfs.admin.ch. June 2020. URL: https://www.bfs.admin.ch/asset/fr/su-f-05.02.91 (visited on 06/22/2020).

[20] Pronovo. *Organisme de certification accrédité pour la saisie de garanties d'origine (GO) et le traitement des programmes d'encouragement de la Confédération concernant les énergies renouvelables.* URL: https://pronovo.ch/fr/services/tarificateur/ (visited on 07/25/2020).

[21] Jörn Banasiak. *The website on regulations on renewable energy generation.* Feb. 18, 2019. URL: http://www.res-legal.eu/search-by-country/switzerland/single/s/res-e/t/promotion/aid/feed-in-tariff-1/lastp/396/#:~:text=The%5C%20feed%5C%2Din%5C%20tariff%5C%20is,3.1%5C%20of%3C%5C%20annexe%5C%201.3%5C%20EnFV). (visited on 07/25/2020).

[22] VESE. *Association des producteurs d'énergie indépendant.* URL: https://www.vese.ch/fr/pvtarif/#MapTitle (visited on 07/25/2020).

[23] Didier Vuarnoz and Thomas Jusselme. "Dataset concerning the hourly conversion factors for the cumulative energy demand and its non-renewable part, and hourly GHG emission factors of the Swiss mix during a one year period (2015–2016)". en. In: *Data in Brief* 21 (Dec. 2018), pp. 1026–1028. ISSN: 2352-3409. DOI: 10.1016/j.dib.2018.10.090. URL: http://www.sciencedirect.com/science/article/pii/S2352340918313076 (visited on 06/11/2020).

[24] IEA. *International Energy Agency - 2017 statistics for Switzerland.* 2018. URL: https://www.iea.org/data-and-statistics?country=SWITLAND&fuel=CO2%5C%20emissions&indicator=CO2%5C%20emissions%5C%20by%5C%20energy%5C%20source (visited on 07/25/2020).

[25] Richard Sikkema et al. "The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands". en. In: *Biofuels, Bioproducts and Biorefining* 4.2 (Mar. 2010), pp. 132–153. ISSN: 1932104X, 19321031. DOI: 10.1002/bbb.208. URL: http://doi.wiley.com/10.1002/bbb.208 (visited on 07/22/2020).

[26] Gauthier Limpens Stefano Moret. "ENERGYSCOPE, a novel open-source model for regional energy systems. Appl Energy 2019; Volume 255". en. In: (2018). ISSN: 10.1016/j.apenergy.2019.113729. URL: http://www.energyscope.ch/100-questions.

[27] Urs-Beat Brändli, Meinrad Abegg, and Barbara Allgaier Leuch. *Inventaire forestier national suisse. Résultats du quatrième inventaire 2009-2017.* fr. Tech. rep. Birmensdorf, Institut fédéral de recherches sur la forêt, la neige et le paysage WSL; Berne, Office fédéral de l'environnement., 2020. DOI: 10.16904/ENVIDAT.147. URL: https://www.envidat.ch/#/metadata/inventaire-forestier-national-suisse-2009-2017 (visited on 07/28/2020).

[28] B. Steubing et al. “Bioenergy in Switzerland: Assessing the domestic sustainable biomass potential”. en. In: *Renewable and Sustainable Energy Reviews* 14.8 (Oct. 2010), pp. 2256–2265. ISSN: 13640321. DOI: 10.1016/j.rser.2010.03.036. URL: https://linkinghub.elsevier.com/retrieve/pii/S1364032110000985 (visited on 07/22/2020).

[29] Rodolfo Perego, Sebastian Pera, and Antonio Galgaro. “Techno-Economic Mapping for the Improvement of Shallow Geothermal Management in Southern Switzerland”. en. In: *Energies* 12.2 (Jan. 2019), p. 279. ISSN: 1996-1073. DOI: 10.3390/en12020279. URL: http://www.mdpi.com/1996-1073/12/2/279 (visited on 07/20/2020).

[30] Philipp Blum, Gisela Campillo, and Thomas Kölbel. “Techno-economic and spatial analysis of vertical ground source heat pump systems in Germany”. en. In: *Energy* 36.5 (May 2011), pp. 3002–3011. ISSN: 03605442. DOI: 10.1016/j.energy.2011.02.044. URL: https://linkinghub.elsevier.com/retrieve/pii/S036054421100140X (visited on 07/20/2020).

[31] Nils Ter-Borch. “Semester Project EPFL, Cleaning of biomass derived gasses for Solid Oxide Fuel Cell applications”. en. In: (2020).

[32] *SI-REN SA. Personal communications with F. Huissoud.* Apr. 2020.

[33] Antonio Barragán-Escandón et al. “Assessment of Power Generation Using Biogas from Landfills in an Equatorial Tropical Context”. en. In: *Sustainability* 12.7 (Mar. 2020), p. 2669. ISSN: 2071-1050. DOI: 10.3390/su12072669. URL: https://www.mdpi.com/2071-1050/12/7/2669 (visited on 06/29/2020).

[34] Anke De Dobbelaere et al. “Small-scale anaerobic digestion : case studies in Western Europe”. en. In: (2015). DOI: 10.13140/RG.2.1.1502.0883. URL: http://rgdoi.net/10.13140/RG.2.1.1502.0883 (visited on 01/04/2020).

[35] Rainier Hreiz et al. “Modeling and simulation of heat transfer phenomena in a semi-buried anaerobic digester”. en. In: *Chemical Engineering Research and Design* 119 (Mar. 2017), pp. 101–116. ISSN: 0263-8762. DOI: 10.1016/j.cherd.2017.01.007. URL: http://www.sciencedirect.com/science/article/pii/S0263876217300096 (visited on 04/08/2020).

[36] Max Åhman. “Biomethane in the transport sector—An appraisal of the forgotten option”. en. In: *Energy Policy* 38.1 (Jan. 2010), pp. 208–217. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2009.09.007. URL: http://www.sciencedirect.com/science/article/pii/S0301421509006909 (visited on 02/18/2020).

[37] Maurizio Carlini et al. “An Economical Evaluation of Anaerobic Digestion Plants Fed with Organic Agro-Industrial Waste”. en. In: *Energies* 10.8 (Aug. 2017), p. 1165. ISSN: 1996-1073. DOI: 10.3390/en10081165. URL: http://www.mdpi.com/1996-1073/10/8/1165 (visited on 03/10/2020).

[38] *IRENA - Renewable power generation costs in 2017.* en. 2018, p. 160. ISBN: 978-92-9260-040-2. URL: https://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017.

[39] Panasonic. *Photovoltaic module HIT® KURO.* en. Tech. rep. Panasonic Eco Solutions Europe, Mar. 2019. URL: https://eu-solar.panasonic.net/cps/rde/xbcr/solar_en/VBHN320_325_330KJ01_KURO_Datasheet_EN.pdf.

[40] Erik Emilsson and Lisbeth Dahllöf. “Lithium-Ion Vehicle Battery Production”. en. In: (), p. 47. URL: https://www.ivl.se/download/18.14d7b12e16e3c5c36271070/1574923989017/C444.pdf.

[41] *Energy density and Specific Energy of Battery.* Sept. 12, 2019. URL: https://sinovoltaics.com/learning-center/storage/energy-density-and-specific-energy-of-battery/ (visited on 07/27/2020).

[42] J.E. Sinor. *Comparison of CNG and LNG Technologies for Transportation Applications.* Tech. rep. NREL, Dec. 1991. URL: https://afdc.energy.gov/files/pdfs/2451.pdf.

[43] M. Smith and J. Gonzales. *Costs Associated With Compressed Natural Gas Vehicle Fueling Infrastructure*. en. Tech. rep. DOE/GO-102014-4471, 1156975. Sept. 2014, DOE/GO–102014–4471, 1156975. DOI: 10.2172/1156975. URL: http://www.osti.gov/servlets/purl/1156975/ (visited on 04/29/2020).

[44] NIST. *Thermodynamic properties of fluids*. 2020. URL: https://webbook.nist.gov/chemistry/ (visited on 07/27/2020).

[45] Henning Hahn et al. "Cost analysis of concepts for a demand oriented biogas supply for flexible power generation". en. In: *Bioresource Technology* 170 (Oct. 2014), pp. 211–220. ISSN: 09608524. DOI: 10.1016/j.biortech.2014.07.085. (Visited on 07/20/2020).

[46] Xiao Yuan Chen et al. "Membrane gas separation technologies for biogas upgrading". en. In: *RSC Advances* 5.31 (2015), pp. 24399–24448. ISSN: 2046-2069. DOI: 10.1039/C5RA00666J. URL: http://xlink.rsc.org/?DOI=C5RA00666J (visited on 07/20/2020).

[47] Xuezhong He et al. "Carbon molecular sieve membranes for biogas upgrading: Techno-economic feasibility analysis". en. In: *Journal of Cleaner Production* 194 (Sept. 2018), pp. 584–593. ISSN: 09596526. DOI: 10.1016/j.jclepro.2018.05.172. URL: https://linkinghub.elsevier.com/retrieve/pii/S095965261831518X (visited on 07/21/2020).

[48] S Clarke, DeBruyn, and J DeBruyn. "FactSheet Vehicle Conversion to Natural Gas or Biogas". en. In: (2012), p. 8. ISSN: 1198-712X. URL: http://www.omafra.gov.on.ca/english/engineer/facts/12-043.pdf.

[49] Marlena Owczuk et al. "Evaluation of Using Biogas to Supply the Dual Fuel Diesel Engine of an Agricultural Tractor". en. In: *Energies* 12.6 (Mar. 2019), p. 1071. ISSN: 1996-1073. DOI: 10.3390/en12061071. URL: https://www.mdpi.com/1996-1073/12/6/1071 (visited on 02/24/2020).

[50] Serge Biollaz et al. *SFOE - Direct Methanation of Biogas*. English. Tech. rep. PSI, Aug. 2017, p. 78. URL: https://www.aramis.admin.ch/Default.aspx?DocumentID=45656&Load=true (visited on 07/23/2020).

[51] Hélène Pilorgé et al. "Cost Analysis of Carbon Capture and Sequestration of Process Emissions from the U.S. Industrial Sector". en. In: *Environmental Science & Technology* 54.12 (June 2020), pp. 7524–7532. ISSN: 0013-936X, 1520-5851. DOI: 10.1021/acs.est.9b07930. URL: https://pubs.acs.org/doi/10.1021/acs.est.9b07930 (visited on 08/03/2020).

[52] *Industrial Process and Energy Systems Engineering (IPESE) EPFL. Personal communications with prof. F. Maréchal*. May 2020.

[53] Emanuele Facchinetti et al. "Process integration and optimization of a solid oxide fuel cell – Gas turbine hybrid cycle fueled with hydrothermally gasified waste biomass". en. In: *Energy*. 23rd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS 2010 41.1 (May 2012), pp. 408–419. ISSN: 0360-5442. DOI: 10.1016/j.energy.2012.02.059. URL: http://www.sciencedirect.com/science/article/pii/S0360544212001739 (visited on 08/14/2020).

[54] Manuel Götz et al. "Renewable Power-to-Gas: A technological and economic review". en. In: *Renewable Energy* 85 (Jan. 2016), pp. 1371–1390. ISSN: 0960-1481. DOI: 10.1016/j.renene.2015.07.066. URL: http://www.sciencedirect.com/science/article/pii/S0960148115301610 (visited on 08/14/2020).

[55] S. Hilpert et al. "The Open Energy Modelling Framework (oemof) - A new approach to facilitate open science in energy system modelling". en. In: *Energy Strategy Reviews* 22 (Nov. 2018), pp. 16–25. ISSN: 2211-467X. DOI: 10.1016/j.esr.2018.07.001. URL: http://www.sciencedirect.com/science/article/pii/S2211467X18300609 (visited on 08/13/2020).

[56] Jan Van herle et al. “Energy balance model of a SOFC cogenerator operated with biogas”. en. In: *Journal of Power Sources*. Scientific Advances in Fuel Cell Systems 118.1 (May 2003), pp. 375–383. ISSN: 0378-7753. DOI: 10.1016/S0378-7753(03)00103-4. URL: http://www.sciencedirect.com/science/article/pii/S0378775303001034 (visited on 02/17/2020).

[57] S. Fujishima, T. Miyahara, and T. Noike. “Effect of moisture content on anaerobic digestion of dewatered sludge: ammonia inhibition to carbohydrate removal and methane production”. en. In: *Water Science and Technology* 41.3 (Feb. 2000). Publisher: IWA Publishing, pp. 119–127. ISSN: 0273-1223. DOI: 10.2166/wst.2000.0063. URL: https://iwaponline.com/wst/article/41/3/119/9106/Effect-of-moisture-content-on-anaerobic-digestion (visited on 05/26/2020).

[58] Tomasz Janusz Teleszewski and Mirosław Żukowski. “Analysis of Heat Loss of a Biogas Anaerobic Digester in Weather Conditions in Poland”. In: *Journal of Ecological Engineering* 19.4 (July 2018). Publisher: Polish Society of Ecological Engineering (PTIE), pp. 242–250. ISSN: 2299-8993. DOI: 10.12911/22998993/89660. URL: http://www.jeeng.net/Analysis-of-Heat-Loss-of-a-Biogas-Anaerobic-Digester-in-Weather-Conditions-in-Poland,89660,0,2.html (visited on 04/07/2020).

A Appendix

A.1 Farm Energy System user guide

The Farm Energy System (FES) was developed with the programming language Python, using the Gurobipython module provided by the Gurobi optimization software under academic licence. The FES model is available at GitHub[62], and is free to use or modify, provided a licence for GitHub can be obtained by the user. Feel free to contact me via GitHub and get my permission to branch this project. This user guide will give a short overview of the model structure in terms of folders, files and functions, then give a couple examples of how the FES could be used. Files that are not mentioned by the guide are not necessary to the default FES model.

A foreword regarding the python code. It follows some but not all PEP8 guidelines. Comments where added to most functions and modules to describe them. The unit abbreviations are the same as in the report. When in doubt, all abbreviations are directly available in the `global_set.py` module. The first letter of parameters, dictionaries and lists is an upper case letter to distinguish them from Gurobi variables which all start with a lower case. Python functions start with a lower case as per PEP8.

A.1.1 Description of the essential files and folders

The GitHub root directory or "Origine" contains mostly project metadata that can be safely ignored and the folder `sff_mip` which contains the FES in the form of 9 .py files. The FES receives input data and settings located in the `inputs` folder and produces outputs stored in the `results`[63] folder.

FES information flow diagram

Concerning inputs, `settings.csv` controls the solve time limit, variable bounds and may be used to activate or deactivate units. Unit performance parameters are stored in `parameters.csv`, cost and emissions related parameters are stored in `cost_param.csv`, while parameters that where pre-calculated are stored in either `calc_param.csv` (signle values) or `inputs.h5` (time dependent values). The `profiles` folder, `animals.csv`, `heat_load_param.csv` and `clusters.h5` contains parameters only relevant to the pre-calculation and not the FES per-say.

Concerning outputs, they will be saved (according to specifications by the user) to a daily `year-month-day` folder, inside `results`.

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

The `data.py` module declares a number of data handling related functions used in all other modules to read parameter values from input files, read weather data, modify input files or pass data from one format to

[62] `https://github.com/terborch/SFF`
[63] This folder may have to be manually created by the user, since it is not shared on GitHub due to its size.

another. Generally this module contains functions that are use full for multiple modules. This module has no local dependencies.

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

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

The `heat_load_param.csv` module is only called by `write_inputs.py` to generate the heat load profile of the buildings and the AD, also stored in `inputs.h5`.

The `read_inputs.py` module will read the settings, parameters and profiles from `settings.csv`, `parameters.csv`, `cost_param.csv`, `calc_param.csv` and `inputs.h5` and pass them on for the model description.

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

The `variables.py` module declares all the unit related variables according to the sets from `global_set.py`.

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

The `run.py` module is used to solve the FES model once or multiple times, using default or custom settings regarding inputs, objectives, and outputs. Its *run* function will solve the model once along a given objective and store the solution results into a new folder. Its *pareto* function will solve the model *n* times between two objectives, store each intermediary solution in single folder along with the relevant graphs.

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

The `results.py` model is called by `run.py` to plot graphs of all kind. Alternatively graphs of inputs may be directly generated by this module.

A.1.2 Example: Adding a unit to the model

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

1. Chose an abbreviation, e.g. TS
2. Add the efficiency to `parameters.csv` and the related costs to `cost_param.csv`
3. Add the unit to the tuple *Units* in `global_set.py`
4. Add the unit and the resource it consumes and produces to the dictionaries *U_cons* and *U_prod*, execute `global_set.py` and check that *U_res* contains the right information for TS. Use the existing PV for comparison.

5. Create a new function in `units.py` called *ts* and describe the unit using the Gurobi python syntax[64] and the new variables that where automatically generated by changing `global_set.py`. Since the TS is similar to the PV, simply copy the *pv* function and change the relevant information. Use the pandas series *P* to access the unit parameters you entered into the .csv files.

6. In `model.py`, call the function you just wrote with *units.ts(...)* inside of the *model_units* function.

7. Execute the `model.py` module to check for errors.

8. Make sure the unit is part of the right energy balance, in this case it produces heat only and will be automatically added to the right constraint if it is part of the *Heat* subset in the *U_prod* set. And keep in mind all other technologies produce and consume in kW-resource.

9. Execute a single run in the `run.py` module with 'envex' as the objective. If the TS does not appear in the results, try constraining its size to any reasonable value inside of the `settings.csv` file to force it to be installed.

A.1.3 Debugging

MILP modelling is complicated. In my (short) experience with Gurobi, I have encountered my fair share of "model infeasible", here is how I dealt with them. Look up the last function in `run.py`, it may be usefull.

The best practice to avoid problems is to code in small chunks. Write down on paper exactly what you want before you code it. For every single change you make to the model, make a run and check the solution to catch problems early. Problems only occur after something has been modified, so make sure not to to many modifications at once or else it will be very complicated to walk back and find the problem.

When Gurobi throws "model infeasible" error, it could often be solved by relaxing the setting *Bound* or *Tight* in the `settings.csv` file. Then searching for a variable with a large value will allow you to find the culprit. This error usually comes from an error in a constrain or a confusion with physical units e.g. Watt instead of kW.

When Gurobi solves for over 1'000s under a 10 typical days temporal clustering, something has gone wrong. If the console does not write "Warning..." messages, the problem is likely due to an unconstrained objective, that can get smaller and smaller while many variables reach their Bounds due to an error in the model description. Use a short limit on the solve time, e.g. 100s to terminate the solving process early. Gurobi will return a premature solution. Use it to look for large variables and identify your problem. (Usually, when the number of unexplored nodes keep increasing, the solution is nowhere near)

When Gurobi solves for long times, and or the solutions look weird the problem may come from numerical errors. Some "Large M variables" constrain binary variables to continuous variables. These constraints can be violated if the Bounds (*Bound* or *Tight* in the `settings.csv` file) become too large compared to the continuous variable they constrain (See the Gurobi documentation on numerical errors). The solver should also start throwing warning while solving. The solution to this problem is to keep the bounds as low as possible (less than 100 for Tight and 10'000 for Bound) by changing reformulating the problem.

A note on performance. The performance of the FES model and its observed solve time without the use of clustered time periods is not acceptable. This is most likely due to a large difference of scale in the coefficient matrix. The smallest coefficient is on the order of $10^{-}8$ while the largest, the upper bound M is on the order of

[64] The online Gurobi documentation is available at `https://www.gurobi.com/documentation/9.0/`. I highly recommend using it extensively and trying a few of their examples.

10^3. This will cause numerical issues for the solver and slow down the optimization. A rescaling of some of the model variables will often solve this problem and could greatly enhance the performance of the FES.

A.2 Clarification on cost estimates

Projected investment costs for each unit are presented in section 3.4. The costs are all in $kCHF$ 2019. Costs from before 2019 are corrected using the Chemical Engineering Plant Index (CEPCI) of 2019 and the year of the study. Costs in another currency are converted using a 10 year average exchange rate. Cost estimations based on studies from outside Switzerland are increased by a factor $c_u^{mult} = 1.8$ unless specified otherwise, to account for an increased purchase and installation cost. Where c stand for cost and subscript u is a unit. Each unit has a fixed cost c_u^{fixed} added once if the unit is installed and a size related cost c_u^{size} multiplied by S_u the installed capacity. For large scale unit, only the size related cost becomes relevant so the fixed costs is often not available in the literature. In this case it is calculated using equation 88. As an example, the gas fueling station's cost come from an American based study of 2014. The calculation is presented in equation 89. The maintenance cost c^{maint} is expressed in per-cent of CAPEX per year. The CAPEX of each unit is annualized relative to its life span and an interest rate of $i = 2.5\%$ before it is added to the TOTEX.

A special case concerns the BU, BS and GI are based on very large scale installations. A scaling factor of $\gamma = 0.6$ is used to correct their cost and is applied in the form of a large cost multiplication factor as per equation 90.

It is important to note that all costs values are first estimates based on the literature, meaning they have an associated uncertainty of ±50%. A sensitivity analysis will evaluate the impact of this uncertainty on the model results. Further precision is difficult to achieve without dimensioning units and requesting quotes from potential manufacturers.

$$c_u^{fixed} = 0.36 \cdot c_u^{size} \cdot S_u^{ref} \qquad [kCHF] \qquad (88)$$

$$c_{CHF_{2019}} = c_{USD_{2014}} \cdot \frac{CEPCI_{2019}}{CEPCI_{2014}} \cdot \bar{r}_{USDtoCHF}^{exchange} \qquad [kCHF] \qquad (89)$$

$$c_{S^{SFF}} = c_{S^{ref}} \cdot \left(\frac{S^{SFF}}{S^{ref}}\right)^{\gamma} \qquad [kCHF] \qquad (90)$$

A.3 Anaerobic Digester sizing and heat load calculation

To operate, an AD requires to stay above a certain temperature. Although the walls are usually well insulated much heat is lost through the cap. To model the heat requirements as a function of external weather, a thermodynamic model similar to that of the buildings is written for the AD. The shape of the modeled AD is a single stage semi-buried cylinder with a soft dome shaped cap on top.

$$C_{AD}(T_{d,h}^{AD} - T_{next(d,h)}^{AD}) = U_{AD}(T_{d,h}^{AD} - T_{d,h}^{ext}) + \dot{Q}_{AD,d,h}^{+} + \dot{Q}_{AD,d,h}^{+gains} - \dot{Q}_{AD,d,h}^{-loss} \qquad [kW] \qquad (91)$$

$$\dot{Q}_{AD,d,h}^{+gains} = \alpha_{AD,cap} \cdot I_t \cdot A_{ground}^{AD} + \dot{E}_{AD,d,h}^{+} \qquad [kW] \qquad (92)$$

$$\dot{Q}_{AD,d,h}^{-loss} = \dot{E}_{AD,d,h}^{+biomass} \cdot \frac{C_p^{water}(T^{AD,mean} - T^{ext,mean})}{HHV_{manure}(1 - f_{biomass,water}) \cdot 10^3} \qquad [kW] \qquad (93)$$

$$C_{AD} = C_p^{water} \cdot V_{sludge}^{AD} + C_b \cdot A_{ground}^{AD} \qquad [kW/°C] \qquad (94)$$

$$U_{AD} = A_{cap}^{AD} \cdot U_{cap}^{AD}(1 + f_{U_{walls}^{AD}}) \qquad [kW/°C] \qquad (95)$$

From the literature the values C_{AD} and U_{AD} can be calculated for the shape of this AD. The heat capacity C_{AD} strongly depends on the volume of fluid inside of the AD and therefore the installed capacity S_{AD} which

is a variable. However the coefficients C_{AD} and U_{AD} cannot be variables in a linear model. In reality, due to a large initial investment, the size of the AD does not need to vary, it will either be installed at the maximum capacity according to the available biomass or not installed at all. The parameters C_{AD} and U_{AD} are calculated for that maximum size.

Equation 91 is the 1R1C model of the AD with the bulk temperature $T^{AD}_{d,h}$, heat capacity and conductance C_{AD} and U_{AD}, heating load, gains and losses $\dot{Q}^{+heating}_{AD,t}$, $\dot{Q}^{+gains}_{AD,d,h}$ and $\dot{Q}^{-loss}_{AD,d,h}$. The gains are modeled using the absoptivity of the AD cap, $\alpha_{AD,cap}$ and the AD ground area A^{AD}_{ground}. The losses arise from the cold biomass entering the AD, this value in kW of biomass is converted to kW of heat using the C_p of water, the Higher Heating Value (HHV) of the biomass, HHV_{manure} the fraction of water in the biomass $f_{biomass,water}$ and the temperature difference $T^{AD,mean} - T^{ext,mean}$ which cannot be a variable. Therefore the mean temperature for one year is used.

The heat capacity of the AD is made up of the sludge and the structure. The structure is assumed to be similar to the walls of a building. The sludge is 90% water and and only that part is accounted for. 90% of the heat losses are through the cap (Hereiz 2017 and Teleszewski 2018). The area of the cap A^{AD}_{cap} is multiplied by the surface specific heat transfer coefficient U^{AD}_{cap} available in the literature and the small fraction of heat lost through the walls $f_{U^{AD}_{walls}}$ is added.

The sludge volume and cap area are calculated using the available daily biomass, its water content, a 30 day retention time and typical digester dimensions, such as height to diameter ratio for a given sludge volume as is presented in (Hereiz 2017). All input parameters for the AD model, dimensioning and heat load calculation are presented in Table 30.

Table 30 – Addition parameters concerning the Anaerobic Digester heat load calculation and sludge volume sizing.

Name	Symbol	Value	Units	Source
Biomass water content	$f_{AD_{Water/BM}}$	0.93	–	[57]
Cap volume ratio	$f_{AD_{V_{cap}/V_{dig}}}$	0.4	–	[35]
Cap absorptance	$\alpha_{AD_{cap}}$	0.9	–	[35]
Cap height ratio	$f_{AD_{cap_{rad/h}}}$	2.2	–	[35]
Cylinder fill	$f_{AD_{V_{cyl}/V_{dig}}}$	0.9	–	[35]
Efficiency	η_{AD}	0.37	–	[1]
Electric consumption	$f_{AD_{EL/BG}}$	0.008	–	[37]
Ground heat losses	$U_{AD_{ground}}$	0.06208	kW/m^2	[35]
Heat consumption	$f_{AD_{Q/BG}}$	0.32	–	[1]
Heater part load	$f_{AD,Q_{min}}$	0.2	–	Setting
Number of LSU	LSU_{farm}	139	LSU	[16]
Manure HHV	HHV_{BM}	3.694444	$kWh/kg-dry$	[37]
Manure per cattle	$f_{BM/LSU}$	7.3	$kg-dry/day/LSU$	[37]
Residence time	$t_{AD,resid}$	30	day	[35]
Max temperature	$T_{AD,max}$	40	$C°$	[35]
Min temperature	$T_{AD,min}$	39	$C°$	[35]
Cap heat conductivity	$U_{AD_{cap}}$	0.00208	$kW/C°/m^2$	[58]

A.4 Manure emissions potential

Emissions from manure are calculated using the following equations. With $f_{CO_2/manure} = 110 tCO_2/t$ of pig manure manure. Equation 97 is the volume of biogas produced with one tonne of pig manure, via the AD. The CO_2 emissions from the combustion of all of this biogas is calculated with equation 98.

$$\dot{m}^{-CO_2}_{manure,raw} = f_{CO_2/manure} \sum_{a}^{animals} \frac{N_a}{LSU_a} \cdot \dot{m}^{-manure}_{a} \qquad [tCO_2/year] \tag{96}$$

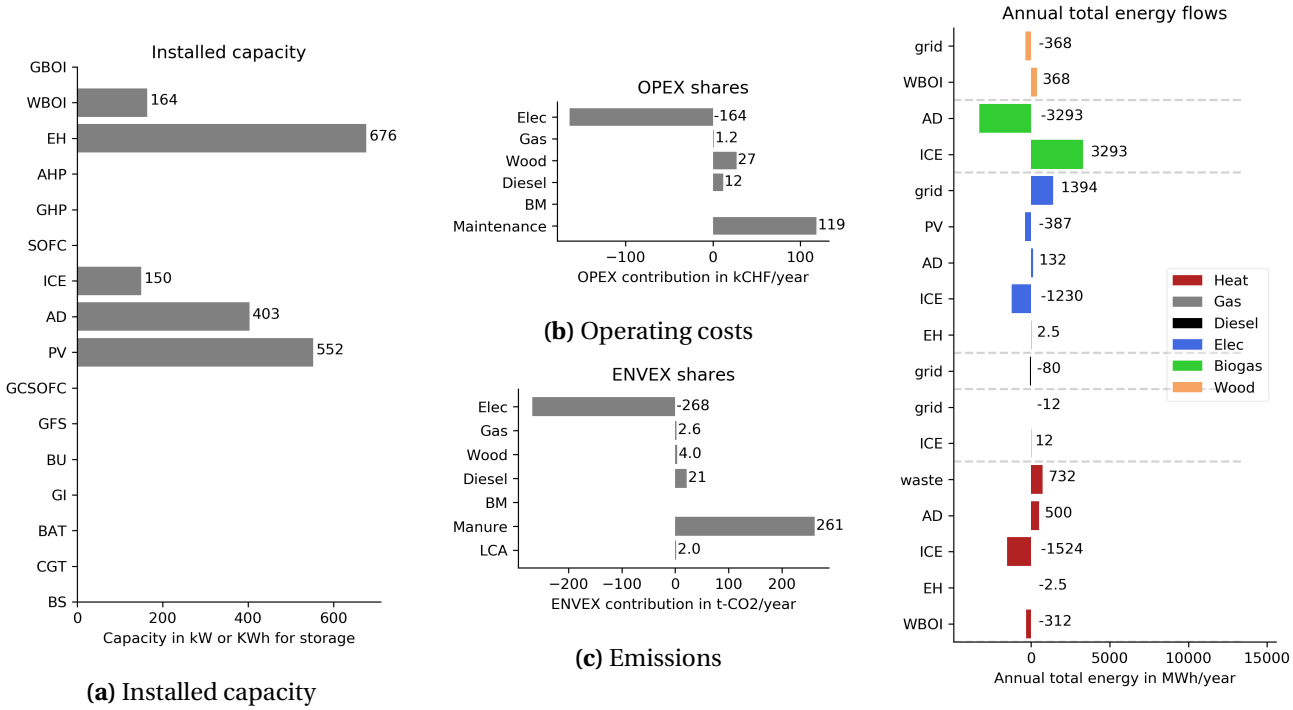
$$\dot{V}^{-CH_4} = \frac{\dot{E}^{-BG}_{pig}}{\dot{m}^{-manure}_{pig}} \cdot \frac{1}{36} \qquad [m^3 - BG/year] \tag{97}$$

$$\dot{m}^{-CO_2}_{manure,AD} = 0.657 \cdot \dot{V}^{-CH4} + 2 \cdot \frac{0.4}{0.6} \cdot \dot{V}^{-BG} \qquad [tCO_2/year] \tag{98}$$

A.5 Supplementary result figures and tables

Table 31 – Details on the different scenarios used in the results sections.

		Scenario	Active (A) or Fixed-size (F) Units															
			GBOI	WBOI	AHP	GHP	EH	SOFC	ICE	AD	PV	BAT	CGT	BS	GCSOFC	BU	GFS	GI
		Scenario A	A				A											
SFF	S cons.	Scenario B	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
		Scenario C	A		A	A	A	A	A	A	A	A	A	A	A	A	A	A
		Scenario D	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Palezieux	M prod.	Scenario E	A	A			A		F	F								
		Scenario G	A	A	A	A	A	A	A	A		A	A	A	A	A	A	A
	M cons.	Scenario F	A	A			A		F	F	F							



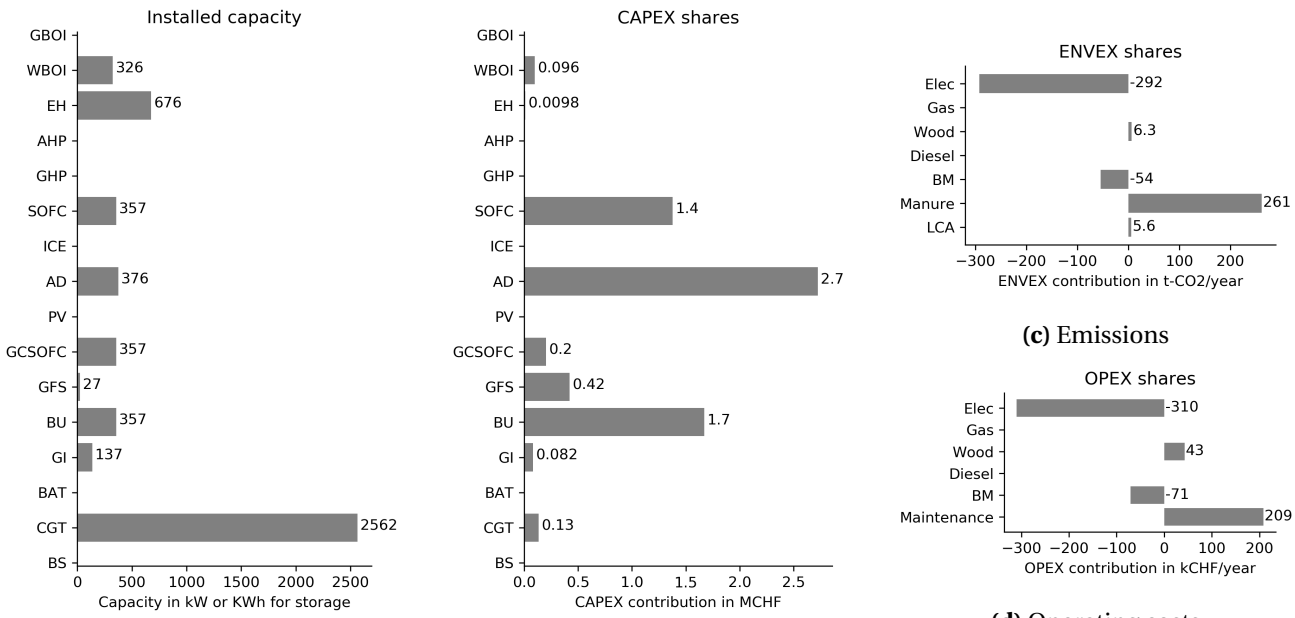
(a) Installed capacity

(b) Operating costs

(c) Emissions

(d) Resource flows

Figure 30 – Result details for **Scenario F**, the medium scale energy consumer scenario, calculated using the FES adapted to Palézieux without favorable feed-in tariffs or limits on PV and resource imports, under TOTEX minimization.



(a) Installed Capacity

(b) Investment cost

(c) Emissions

(d) Operating costs

Figure 31 – Result details for **Scenario G solution 11** on the Palézieux ENVEX-TOTEX Pareto graph 28.

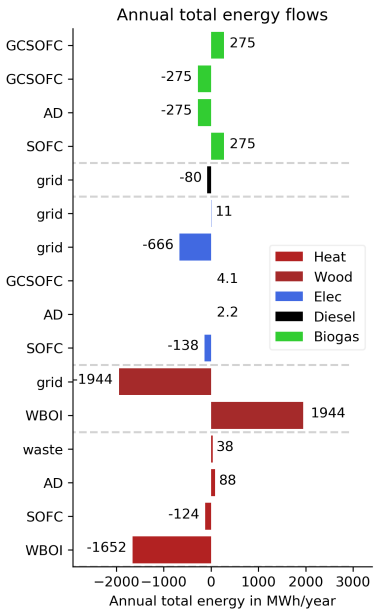


Figure 32 – Scenario B Resource flow at point 5 on the ENVEX-TOTEX Pareto graph.

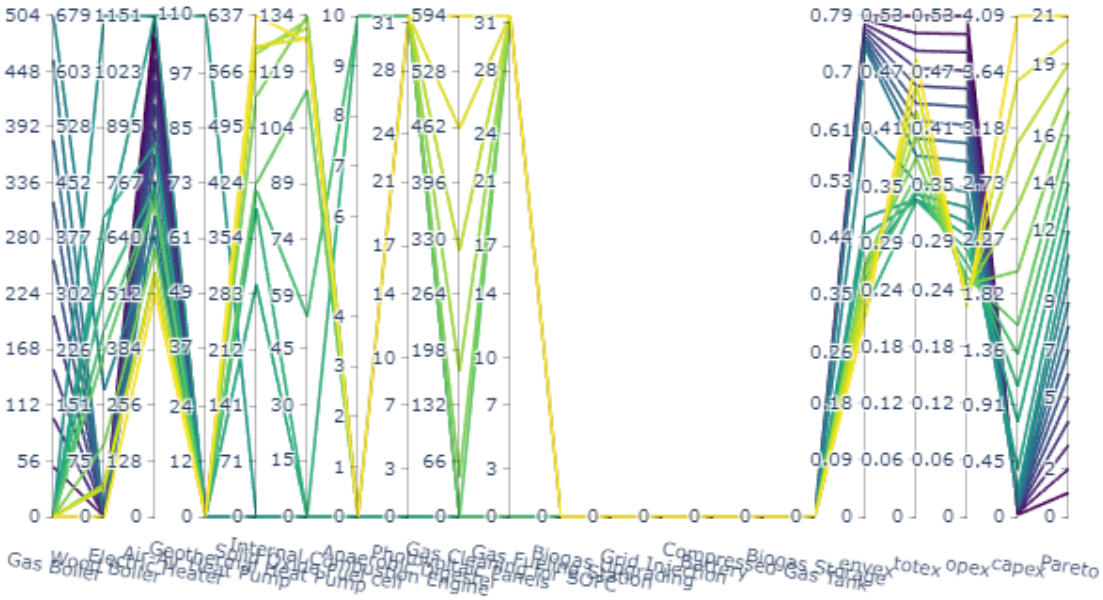


Figure 33 – Scenario B Parallel coordinate graph of the ENVEX-TOTEX pareto for scenario B. An interactive high resolution version is hosted on GitHub `LINK to the interactive graph`