Environmental Energetic and Economic optimization of Swiss Farms

Masters Project

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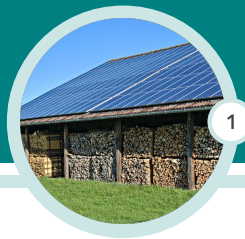
August, 2020

Outline



Abstract (2min)

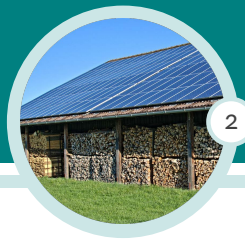
Introduction (3min)

Methodology (10min)
- Model requirements
- Information flow
- Assumptions
- Farm overview
- Model Description

Results (10min)

Discussion (3min)

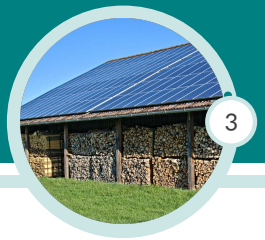
Abstract



A Mixed Integer Linear Programming (MILP) model describing a Farm Energy System (FES) is developed to explore optimal energy pathways for a small scale farm, located in Aadorf (TG), Switzerland. The full model, with additional results is available at `https://github.com/terborch/SFF` and `https://terborch.github.io/SFF`.

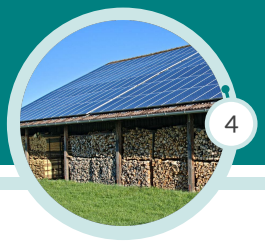
Outcome

- **Reduce emissions at no costs** - With AD and SOFC
- **Reach carbon neutrality is difficult** - Energy cons >> Biomass
- **PV potential** - at large scale
- **SOFC and ICE are cost equivalent** - Uncertainty



Global warming effects in Switzerland

Figure: Trient Glacier in Switzerland (VS). On the left, as it was in 1891, on the right, on Aug. 26, 2019.[1]



Global warming and the physiological limit

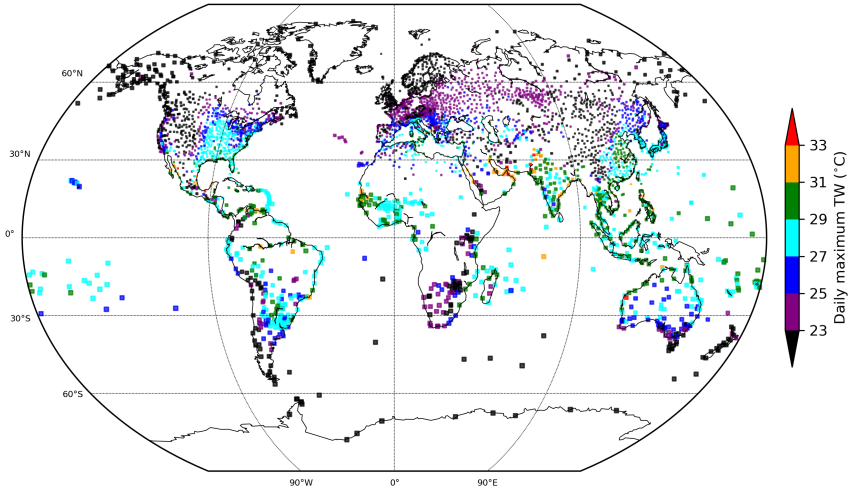
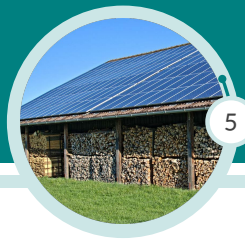


Figure: Wet-bulb daily maxium Temperature (TW) up to 2017[2]

- Physiological upper limit is 35°C
- The 2003 heatwave reached TW 28°C
- In 2050 TW 35°C may be common in the middle east and south-east Asia under the business as usual scenario

Introduction
From a problem to a solution



Anaerobic Digestion converts harmful waist to renewable energy

Swiss Biomass is highly localized

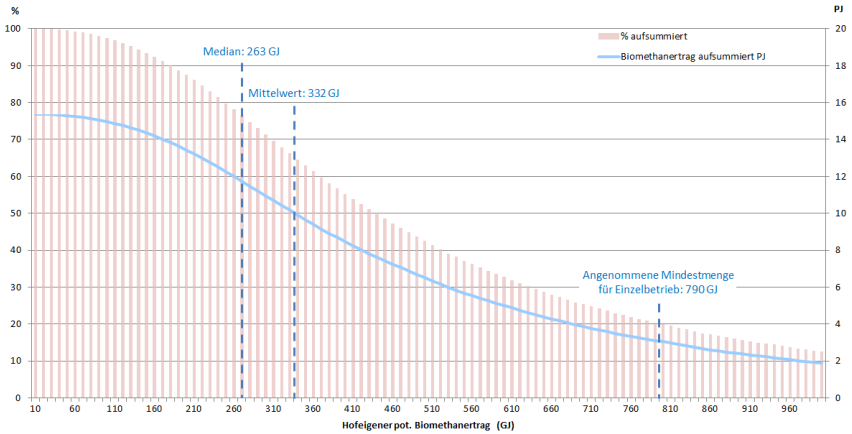
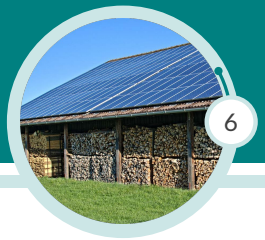


Figure: Biogas potential per farm in Switzerland[3]

- $26PJ$ Biomass available as Manure
- 80% Farms below $10kW_{el}$
- State of Art micro-CHP $\eta_{el} = 0.26$ to 0.32
- SOFC-biogas $\eta_{el} = 0.5$

Introduction
Many available solutions



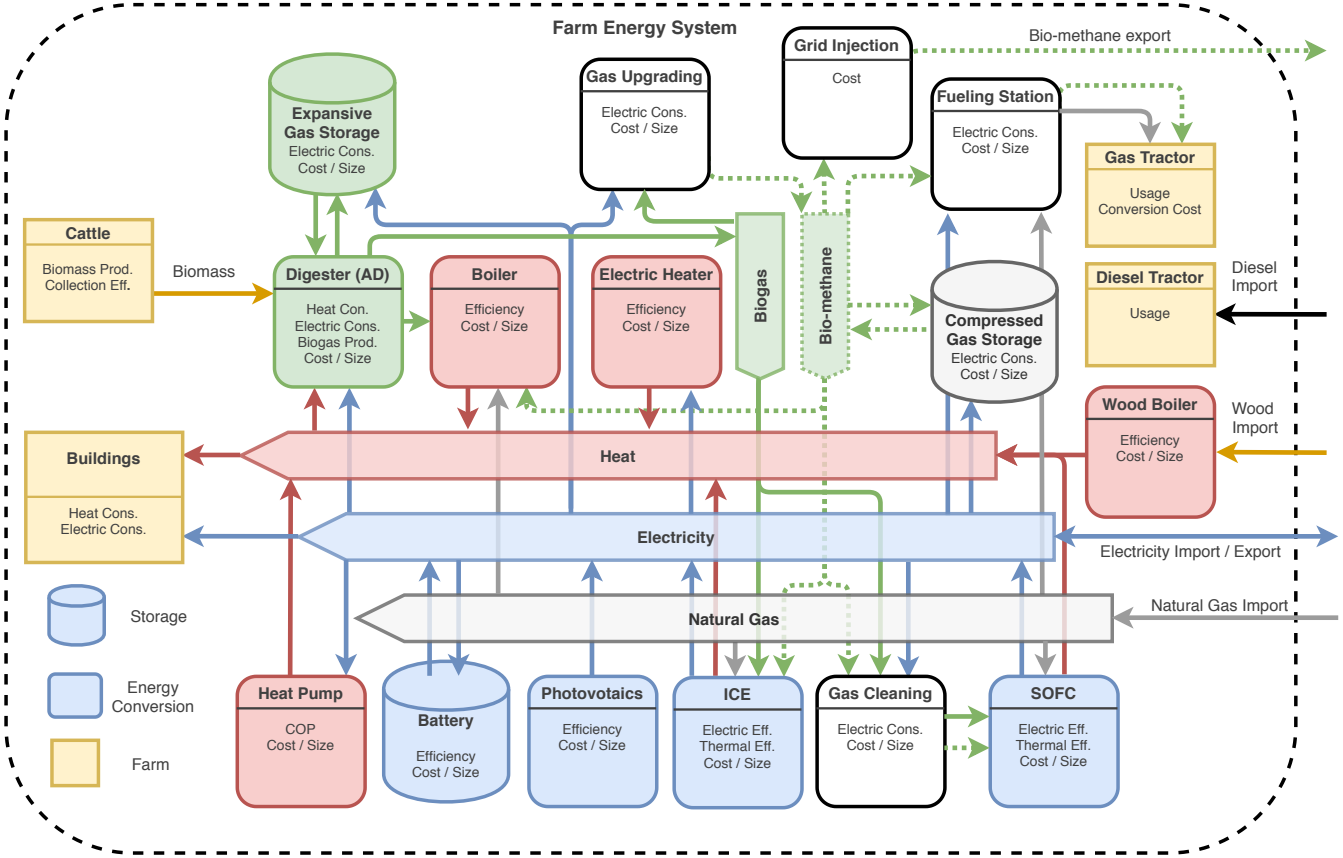


Figure: Flow diagram of the MILP energy model of a farm

Part I : Methodology

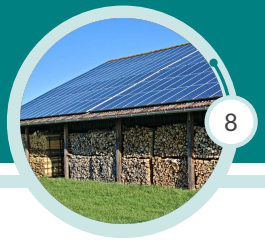
Model requirements

Model the Farm Energy System (FES) and search for optimal solutions in terms of costs and emissions

- **Deterministic** - unique optimal solution
- **Fast** - multi-objective
- **Realistic** - representative
- **Accessible** - reusable by others

Mixed Integer Linear Programming (MILP) with Guroby on Python
Code available on GitHub `https://github.com/terborch/SFF`

Information flow



1. Inputs

1. Parameters, Settings
2. Cluster weather
3. Pre-calculate heat-loads
4. Save inputs

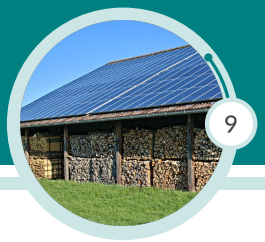
2. Model

1. Load inputs
2. Define variables
3. Write constraints
4. Set objective
5. Solve model
6. Save results

3. Post-processing

1. Load results
2. Draw graphs
3. Draw tables
4. Draw Pareto

Assumptions



Assuming the following is representative of 20 years of operation

Time discretization

- 1 year (2019)
- 10 typical days
- 1 extreme hour
- 1 hour time-step

Anaerobi Digester

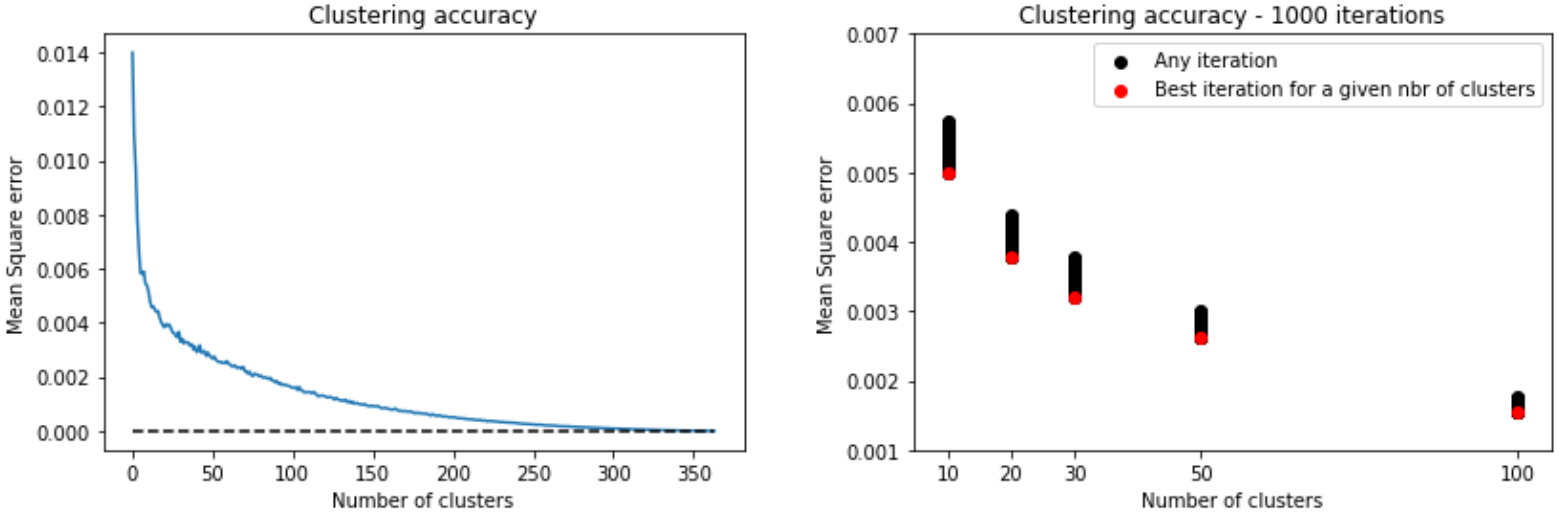
- operates at max capacity
- startup time is neglected
- single stage, semi buried reactor[4]

All technologies

- 8′760 operating hours per year
- Linear equations can describe operation
- Predictive control

Inputs

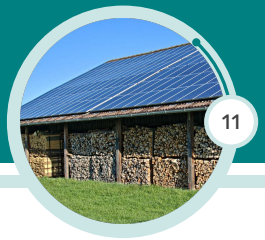
Clustering weather

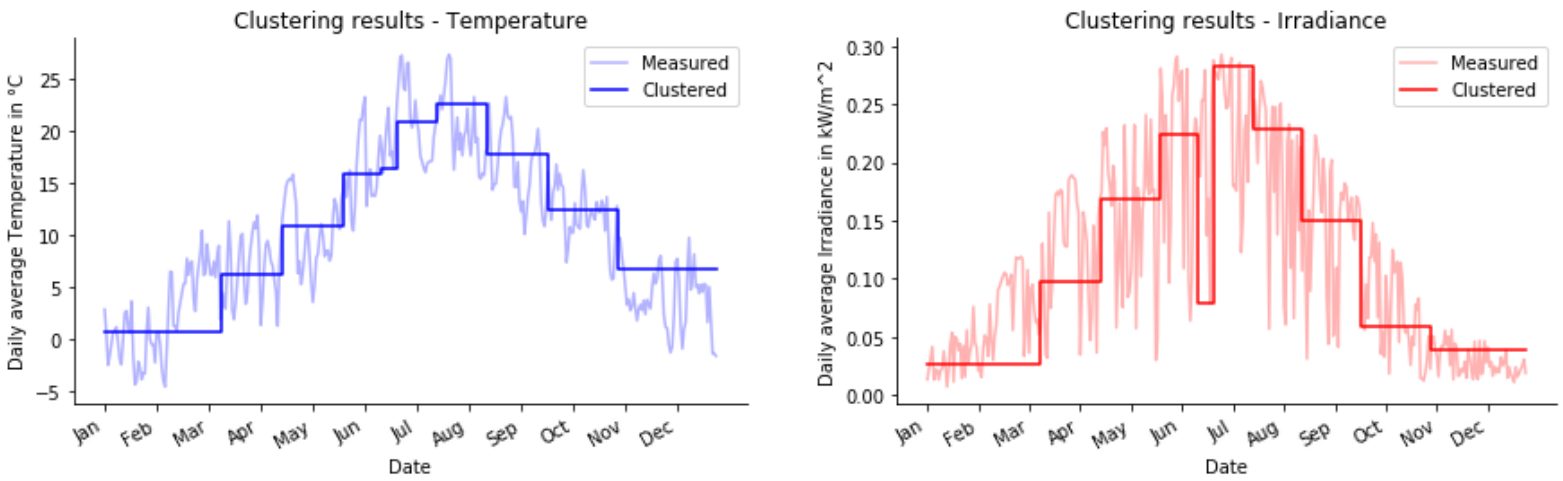


(a) (b)

Figure: (a) Clustering into n typical days using a k-means algorithm (sklearn for python). (b) Clustering into 10, 20, 30, 50 and 100 typical days iterated 1'000 times each to measure variance.

Inputs
Clustering results

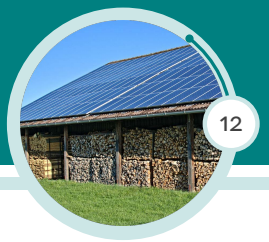


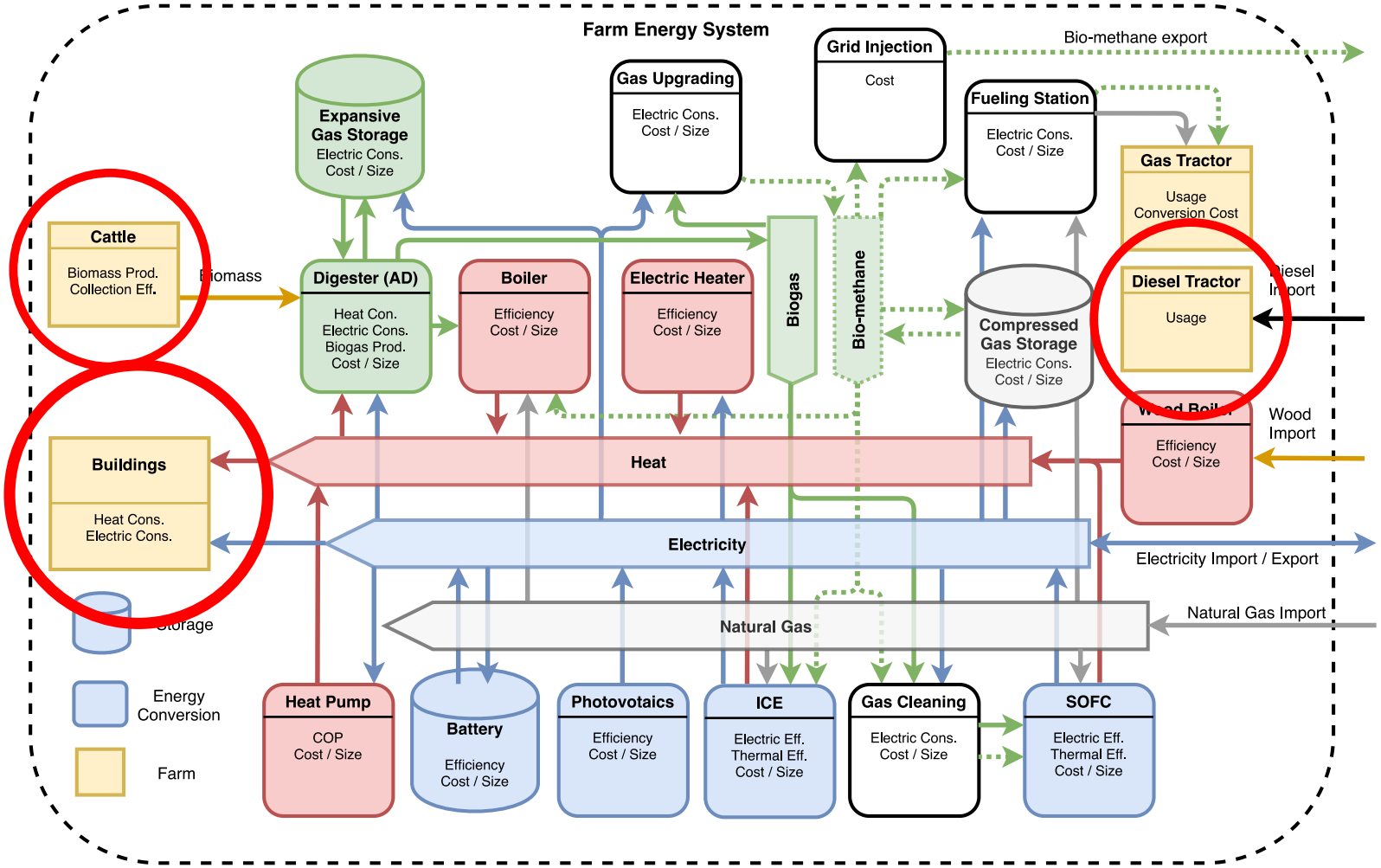


(a) (b)

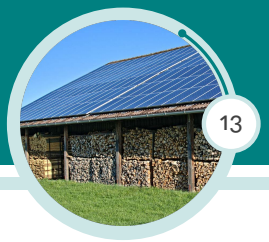
Figure: Clustering results on average daily weather for 10 typical days. After applying a in-house sorting algorithm. (a) Daily average Temperature (b) Daily average Irradiance.

Inputs
Farm overview





Inputs
Farm overview



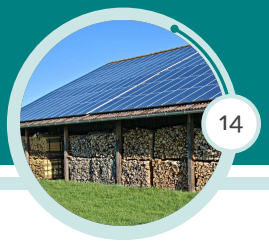
Farm located in Aadorf - Thurgau. 139 LSU, 81ha crops. $14'700m^2$ heated area, $6600m^2$ roof. Nearby residential buildings included.

- **Heating** - Natural gas - $1.6GWh/year$
- **Electricity** - Grid - $0.8GWh/year$
- **Diesel** - 4 tractors - $8'000l/year$
- **Biomass** - unused - $0.74GWh/year$

Potential to install a $16kW$ biogas fed SOFC

Figure: A sky view of SFF from `map.geo.admin.ch`.

Inputs
Heat load profile



Heat load profiles for the buildings and the AD are pre-calculated in a separate LP with a 1R1C model[5]. Resulting profiles are corrected to match the measured building heat load and estimated AD heat loads.

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

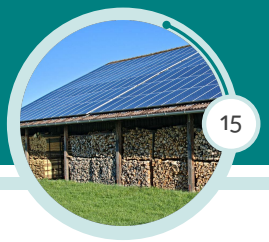
$$T_{b,min} \leq T_{b,d,h} \leq T_{b,max} \quad [C^{\circ}] \quad (2)$$

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

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

Inputs

Electric load profile and average heat consumption



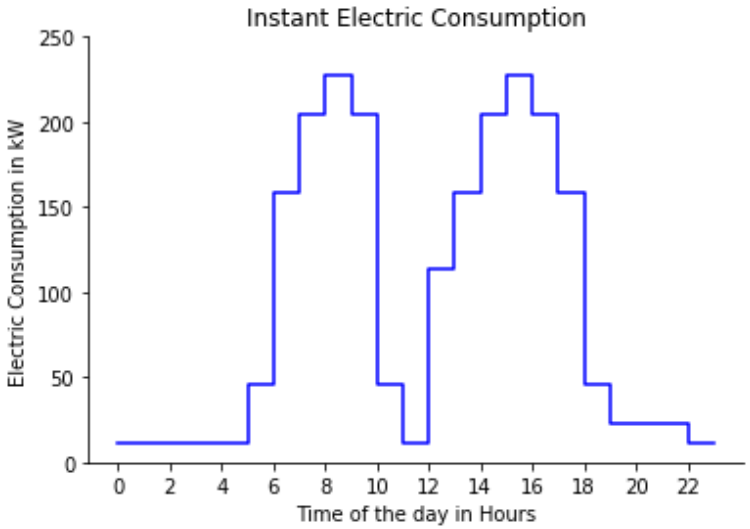


Figure: Daily building electricity consumption based on SIA 2024 load profile for commercial buildings

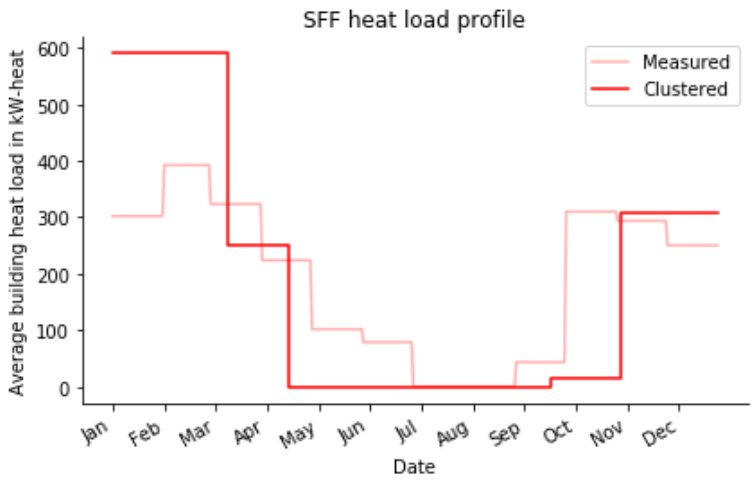
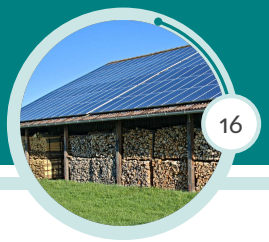
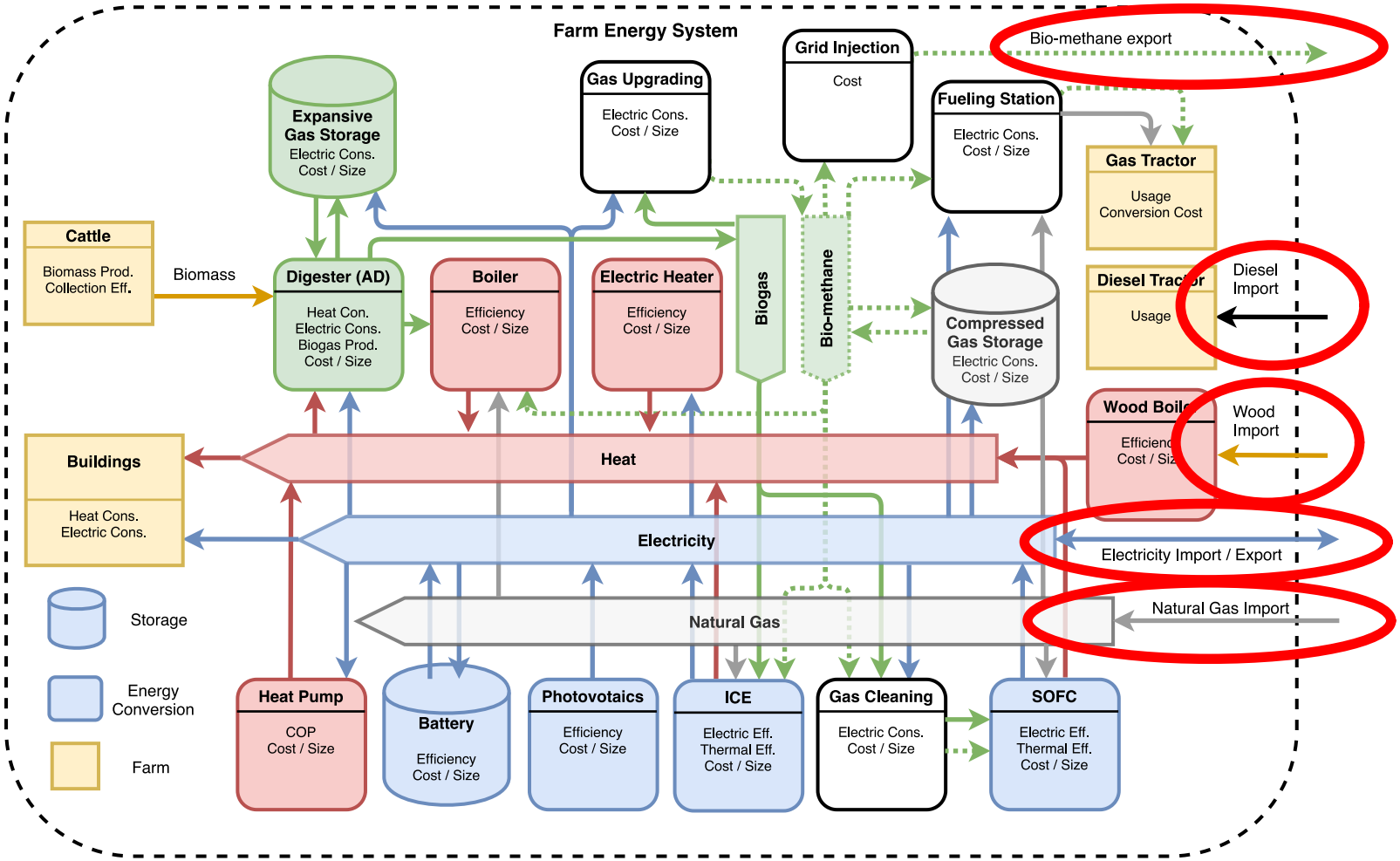


Figure: Measured monthly average heat load consumption, compared to the daily average modeled heat load profile.

Model Description

Resources





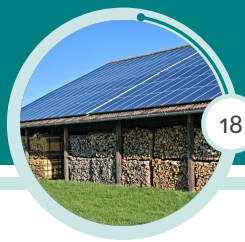
Model Description

Resources

Resource	Name	Symbol	Value	Units	Source
EL	Selling price	c_r^{sell}	0.12	CHF/kWh	vese.ch
	Purchase cost	c_r^{buy}	0.21	CHF/kWh	OFS
	Associated emissions	$m_{CO_2\ r}^{buy}$	0.2	tCO_2/MWh	Vuarnoz 2018
NG	Selling price	c_r^{sell}	-	CHF/kWh	Not sold
	Purchase cost	c_r^{buy}	0.1	CHF/kWh	OFS
	Associated emissions	$m_{CO_2\ r}^{buy}$	0.21	tCO_2/MWh	iea.org
Wood	Selling price	c_r^{sell}	-	CHF/kWh	Not sold
	Purchase cost	c_r^{buy}	0.07	CHF/kWh	OFS
	Associated emissions	$m_{CO_2\ r}^{buy}$	0.01	tCO_2/MWh	Sikkema 2010
Diesel	Selling price	c_r^{sell}	-	CHF/kWh	Not sold
	Purchase cost	c_r^{buy}	0.15	CHF/kWh	OFS
	Associated emissions	$m_{CO_2\ r}^{buy}$	0.27	tCO_2/MWh	epa.gov
BM	Selling price	c_r^{sell}	0.08	CHF/kWh	Setting
	Purchase cost	c_r^{sell}	-	CHF/kWh	Not bought
	Associated emissions	$m_{CO_2\ r}^{buy}$	0.21	tCO_2/MWh	Setting

Model Description

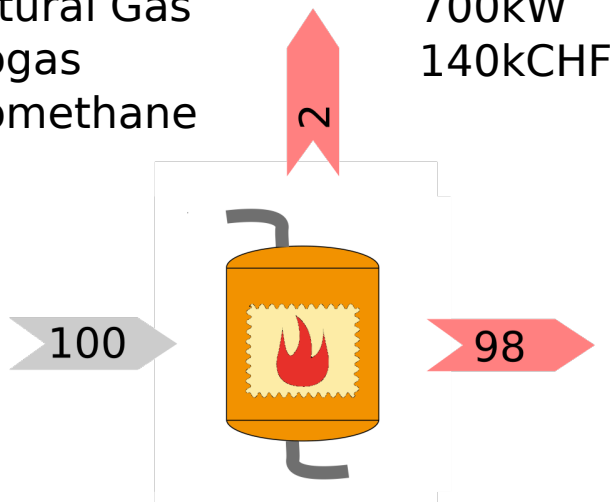
Heater: Gas Boiler

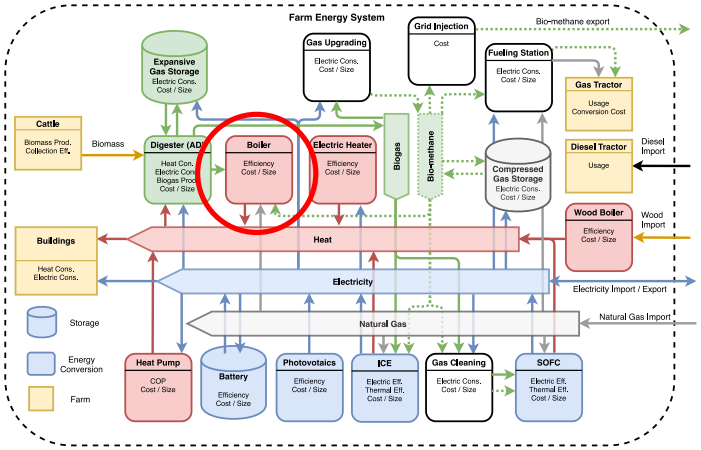


GBOI

<u>Inputs:</u>
Natural Gas
Biogas
Biomethane

<u>Typical size:</u>
700kW
140kCHF

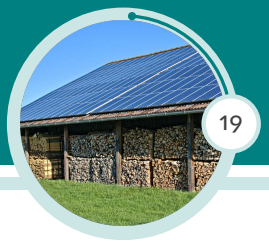




Credit: Haruka Ogawa

Model Description

Heater: Gas Boiler



$$\dot{Q}^{-}_{GBOI,d,h} = \eta_{GBOI} \cdot (\dot{E}^{+NG}_{GBOI,d,h} + \dot{E}^{+BG}_{GBOI,d,h} + \dot{E}^{+BM}_{GBOI,d,h}) \quad [kW] \quad (5)$$

$$\dot{Q}^{-}_{u,d,h} \leq S_u \quad [kW] \quad (6)$$

Name	Symbol	Value	Units	Source
Efficiency	η_u	0.98	—	Energyscope
Cost multiplier	c_u^{mult}	1.8	—	P. Stadler PHD
Specific investment cost	c_u^{size}	0.105	$kCHF/kW$	P. Stadler PHD
Fixed investment cost	c_u^{fixe}	3.8	$kCHF$	P. Stadler PHD
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Energyscope
Life	n_u	20	*Years*	P. Stadler PHD
Maintenance	c_u^{maint}	0.05	—	Energyscope
Smallest size	S_u^{min}	5	kW	Setting
Reference size	S_u^{ref}	50	kW	P. Stadler PHD

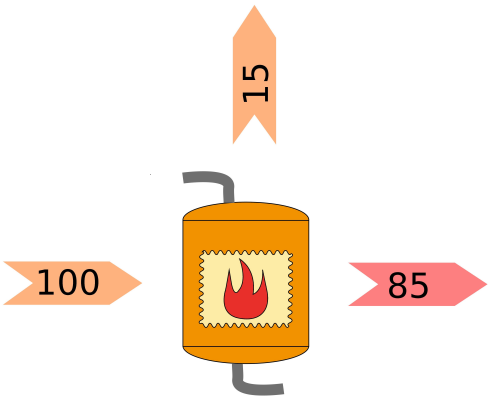
Model Description

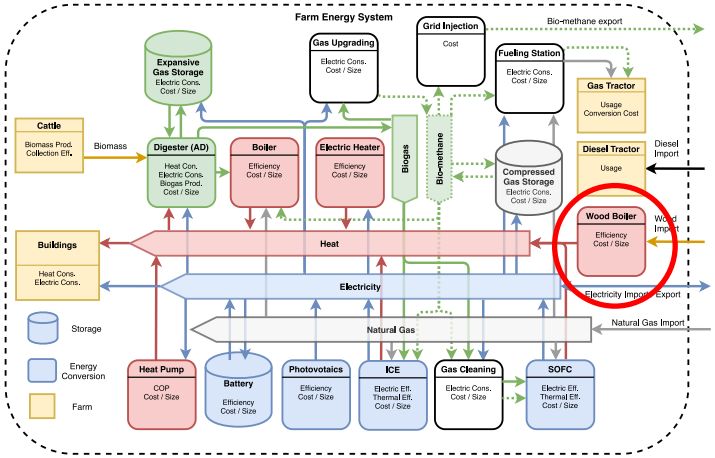
Heater: Wood Boiler

WBOI

<u>Inputs:</u>
Wood pellets

<u>Typical size:</u>
700kW
200kCHF

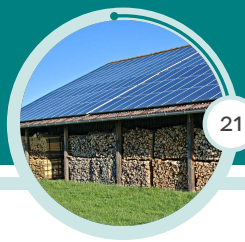




Credit: Haruka Ogawa

Model Description

Heater: Wood Boiler



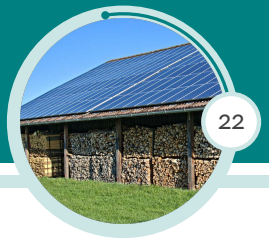
$$\dot{Q}^{-}_{WBOI,d,h} = \eta_{WBOI} \cdot \dot{E}^{+Wood}_{WBOI,d,h} \qquad [kW] \qquad (7)$$

$$\dot{Q}^{-}_{WBOI,d,h} \leq S_{WBOI} \qquad [kW] \qquad (8)$$

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

Model Description

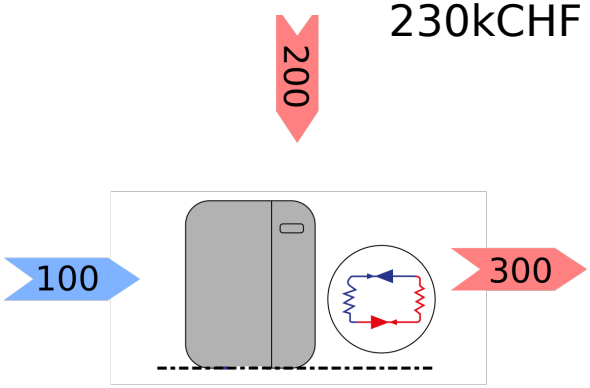
Heater: Air-Air Heat Pump

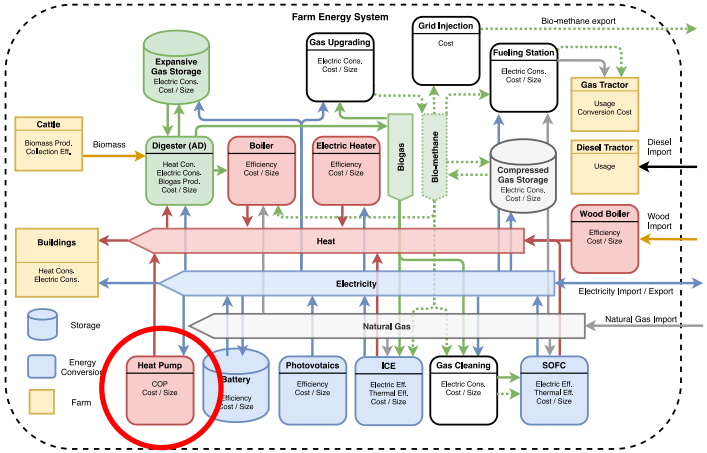


AHP

<u>Inputs:</u>
Electricity

<u>Typical size:</u>
100kW
230kCHF





Credit: Haruka Ogawa

Model Description

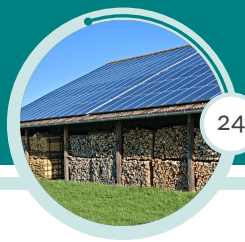
Heater: Air-Air Heat Pump

$$\dot{Q}^{-}_{AHP,d,h} = COP_{AHP} \cdot \dot{E}^{+EL}_{AHP,d,h} \qquad [kW] \qquad (9)$$

$$\dot{E}^{+EL}_{AHP,d,h} \leq S_{AHP} \qquad [kW] \qquad (10)$$

Name	Symbol	Value	Units	Source
Coefficient of Performance	COP_u	3	—	Energyscope
Cost multiplier	c_u^{mult}	1.8	—	P. Stadler PHD
Specific investment cost	c_u^{size}	1.24	$kCHF/kW$	P. Stadler PHD
Fixed investment cost	c_u^{fixe}	5.68	$kCHF$	P. Stadler PHD
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life	n_u	20	*Years*	P. Stadler PHD
Maintenance	c_u^{maint}	0.02	—	P. Stadler PHD
Smallest size	S_u^{min}	5	kW	Setting
Reference size	S_u^{ref}	10	kW	P. Stadler PHD

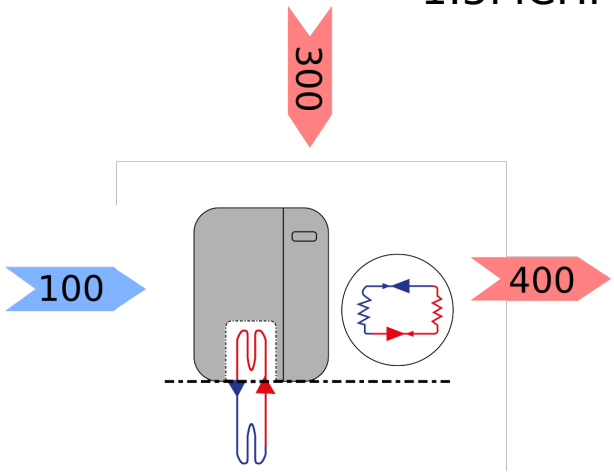
Model Description
Heater: Geothermal Heat Pump

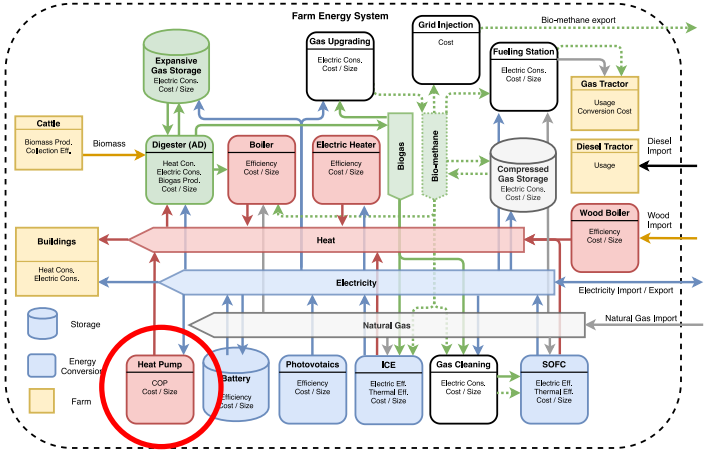


GHP

<u>Inputs:</u>
Electricity

<u>Typical size:</u>
700kW
1.5MCHF





Credit: Haruka Ogawa

Model Description

Heater: Geothermal Heat Pumpp

$$\dot{Q}^{-}_{GHP,d,h} = COP_{GHP} \cdot \dot{E}^{+EL}_{GHP,d,h} \qquad [kW] \qquad (11)$$

$$\dot{Q}^{-}_{GHP,d,h} \leq S_{GHP} \qquad [kW] \qquad (12)$$

Name	Symbol	Value	Units	Source
Coefficient of Performance	COP_u	4	—	Perego 2019
Cost multiplier	c_u^{mult}	1	—	Perego 2019
Specific investment cost	c_u^{size}	2.1	$kCHF/kW$	Perego 2019
Fixed investment cost	c_u^{fixe}	22.5	$kCHF$	Perego 2019
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	—	Blum 2011, P. Stadler PHD
Smallest size	S_u^{min}	25	kW	Perego 2019
Reference size	S_u^{ref}	25	kW	Perego 2019

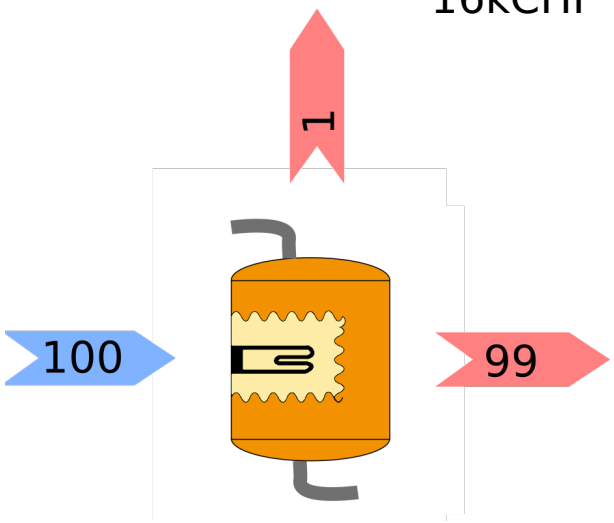
Model Description

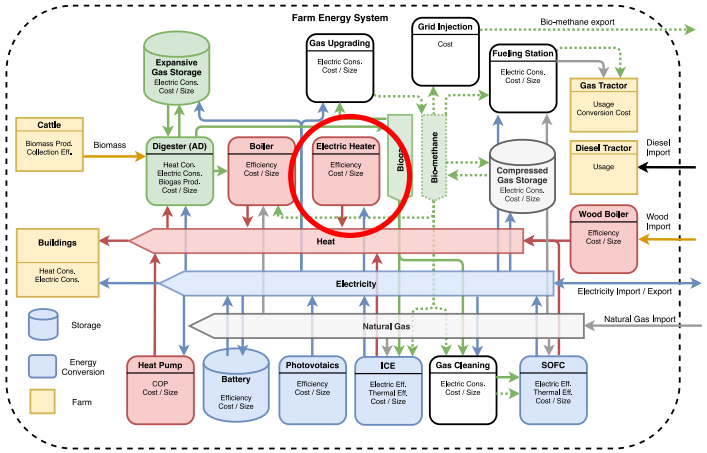
Heater: Electric Heater

EH

<u>Inputs:</u>
Electricity

<u>Typical size:</u>
1100kW
16kCHF

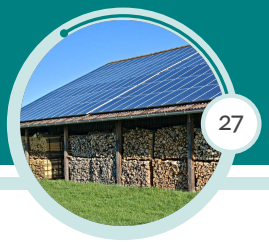




Credit: Haruka Ogawa

Model Description

Heater: Electric Heater



$$\dot{Q}^{-}_{EH,d,h} = \eta_{EH} \cdot \dot{E}^{+EL}_{EH,d,h} \qquad [kW] \qquad (13)$$

$$\dot{Q}^{-}_{EH,d,h} \leq S_{EH} \qquad [kW] \qquad (14)$$

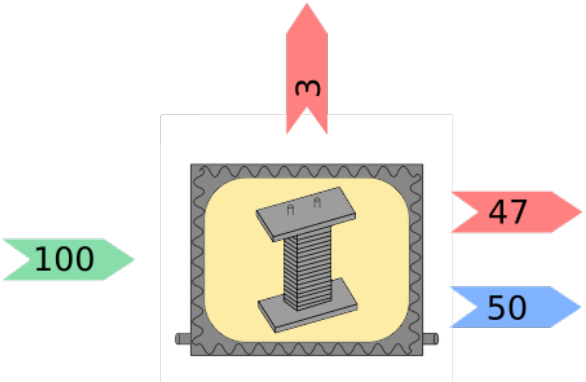
Name	Symbol	Value	Units	Source
Efficiency	η_u	0.99	—	P. Stadler PHD
Cost multiplier	c_u^{mult}	1	—	P. Stadler PHD
Specific investment cost	c_u^{size}	0.013	$kCHF/kW$	P. Stadler PHD
Fixed investment cost	c_u^{fixe}	0.97	$kCHF$	P. Stadler PHD
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life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

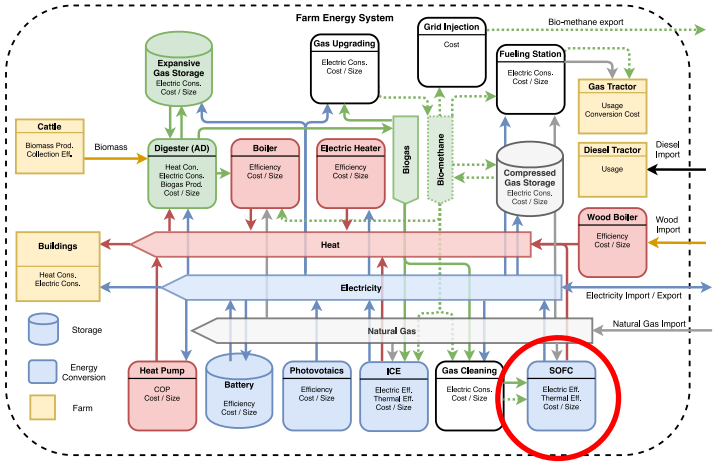
Model Description
Cogeneration: Solid Oxide Fuel Cell

SOFC

Inputs:
Biogas
Biomethane
Natural Gas

Typical size:
16kW
88kCHF

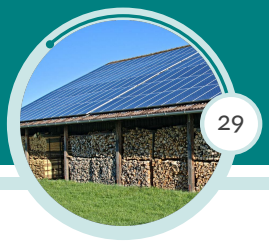




Credit: Haruka Ogawa

Model Description

Cogeneration: Solid Oxide Fuel Cell



$$\dot{E}^{-EL}_{u,d,h} = \eta_{u,EL\text{-}BG} \cdot \dot{E}^{+BG}_{u,d,h} + \eta_{u,EL\text{-}NG} \cdot (\dot{E}^{+NG}_{u,d,h} + \dot{E}^{+BM}_{u,d,h}) \quad [kW] \quad (15)$$

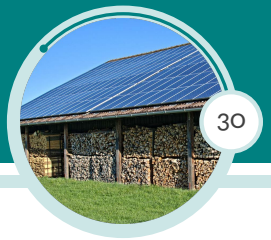
$$\dot{Q}^{-}_{u,d,h} = \eta_{u,Q} \cdot \Big((1 - \eta_{u,EL\text{-}BG}) \cdot \dot{E}^{+BG}_{u,d,h} + (1 - \eta_{u,EL\text{-}NG}) \cdot (\dot{E}^{+NG}_{u,d,h} + \dot{E}^{+BM}_{u,d,h}) \Big) \quad [kW] \quad (16)$$

$$\dot{E}^{-EL}_{u,d,h} \leq S_u \quad [kW] \quad (17)$$

Name	Symbol	Value	Units	Source
Electric efficiency for BG	$\eta_{u,EL\text{-}BG}$	0.5	—	J. Van Herle
Electric efficiency for NG	$\eta_{u,EL\text{-}NG}$	0.6	—	J. Van Herle
Thermal efficiency	$\eta_{u,Q}$	0.9	—	J. Van Herle
Cost multiplier	c_u^{mult}	1.8	—	P. Stadler PhD
Specific investment cost	c_u^{size}	2.1	$kCHF/kW$	P. Stadler PhD
Fixed investment cost	c_u^{fixe}	15.5	$kCHF$	P. Stadler PhD
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life	n_u	10	*Years*	P. Stadler PhD
Maintenance	c_u^{maint}	0.05	—	P. Stadler PhD
Smallest size	S_u^{min}	1	kW	P. Stadler PhD
Reference size	S_u^{ref}	5	kW	P. Stadler PhD

Model Description

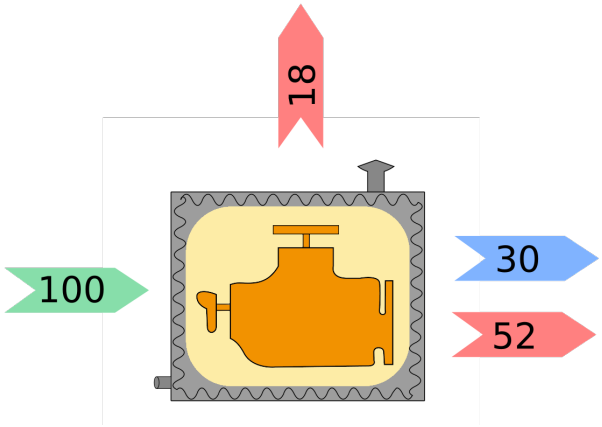
Cogeneration: Internal Combustion Engine

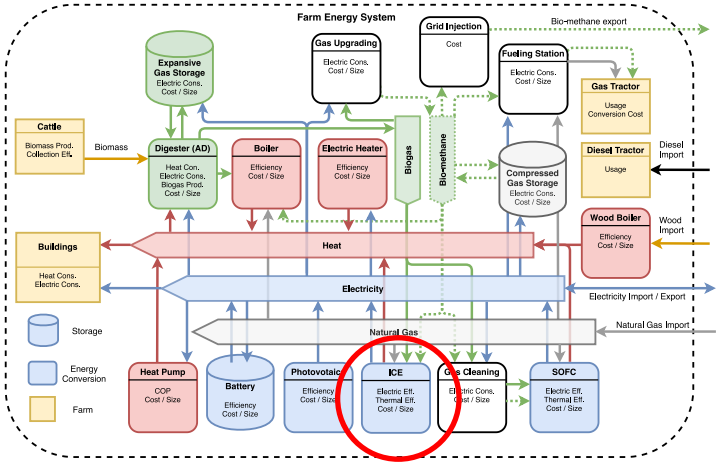


ICE

<u>Inputs:</u>
Biogas
Biomethane
Natural Gas

<u>Typical size:</u>
10kW
20kCHF

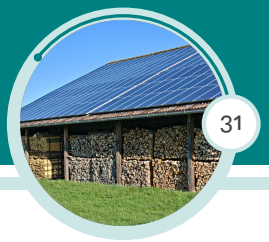




Credit: Haruka Ogawa

Model Description

Cogeneration: Internal Combustion Engine



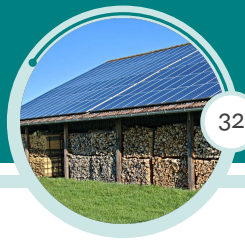
$$\dot{E}^{-EL}_{u,d,h} = \eta_{u,EL} \cdot (\dot{E}^{+BG}_{u,d,h} + \dot{E}^{+NG}_{u,d,h} + \dot{E}^{+BM}_{u,d,h}) \quad [kW] \quad (18)$$

$$\dot{Q}^{-}_{u,d,h} = \eta_{u,Q} \cdot (1 - \eta_{u,EL})(\dot{E}^{+BG}_{u,d,h} + \dot{E}^{+NG}_{u,d,h} + \dot{E}^{+BM}_{u,d,h}) \quad [kW] \quad (19)$$

$$\dot{E}^{-EL}_{u,d,h} \leq S_u \quad [kW] \quad (20)$$

Name	Symbol	Value	Units	Source
Electric efficiency	$\eta_{u,EL}$	0.3	—	S. Majerus PdM, Barragan 2020
Thermal efficiency	$\eta_{u,Q}$	0.75	—	S. Majerus PdM, Barragan 2020
Cost multiplier	c_u^{mult}	1	—	S. Majerus PdM
Specific investment cost	c_u^{size}	1.4	$kCHF/kW$	S. Majerus PdM, Barragan 2020
Fixed investment cost	c_u^{fixe}	6	$kCHF$	S. Majerus PdM, Barragan 2020
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life	n_u	20	*Years*	S. Majerus PdM
Maintenance	c_u^{maint}	0.085	—	Palézieux, Barragan 2020
Smallest size	S_u^{min}	10	kW	Setting
Reference size	S_u^{ref}	20	kW	S. Majerus PdM

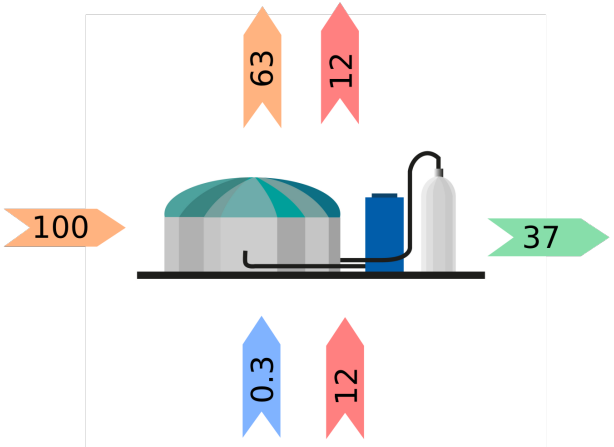
Model Description
Production: Anaerobic Digester

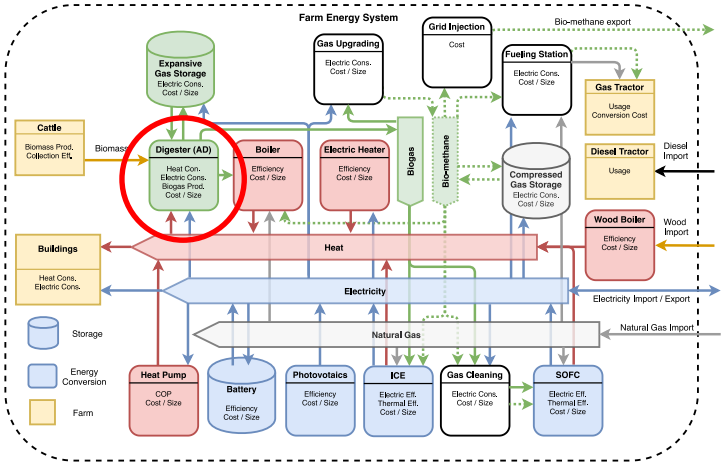


AD

<u>Inputs:</u>
Manure
Heat
Electricity

<u>Typical size:</u>
30kW
90kCHF

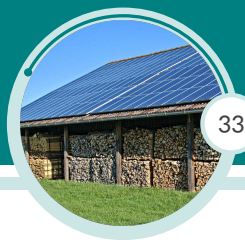




Credit: Haruka Ogawa

Model Description

Production: Anaerobic Digester



$$\dot{E}^{-BG}_{AD,d,h} = \eta_{AD} \cdot \dot{E}^{+Biomass}_{AD,d,h} \quad [kW] \quad (21)$$

$$\dot{E}^{+Biomass}_{AD,d,h} = \dot{E}^{-Biomass}_{Farm,d,h} \cdot Z_{AD} \quad [kW] \quad (22)$$

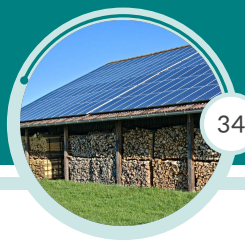
$$\dot{E}^{+EL}_{AD,d,h} = f_{AD_{EL/BG}} \cdot \dot{E}^{-BG}_{AD,d,h} \quad [kW] \quad (23)$$

$$\dot{Q}^{+}_{AD,d,h} = \dot{Q}^{+precalc}_{AD,d,h} \cdot Z_{AD} \quad [kW] \quad (24)$$

$$\dot{E}^{-BG}_{AD,d,h} \leq S_{AD} \quad [kW] \quad (25)$$

Model Description

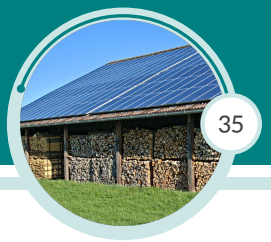
Production: Anaerobic Digester



Name	Symbol	Value	Units	Source
Efficiency	η_u	0.37	—	Thees 2017
Electric consumption	$f_{u_{EL/BG}}$	0.008	—	Carlini 2017
Heat consumption	$f_{u_{Q/BG}}$	0.32	—	Thees 2017
Cost multiplier	c_u^{mult}	1.8	—	N. Ter-Borch PdS
Specific investment cost	c_u^{size}	1.5	$kCHF/kW$	N. Ter-Borch PdS
Fixed investment cost	c_u^{fixe}	5	$kCHF$	N. Ter-Borch PdS
LCA emissions	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	Default
Life	n_u	20	*Years*	N. Ter-Borch PdS
Maintenance	c_u^{maint}	0.1	—	N. Ter-Borch PdS
Smallest size	S_u^{min}	20	kW	Dobbelaere 2015
Reference size	S_u^{ref}	100	kW	N. Ter-Borch PdS

Model Description

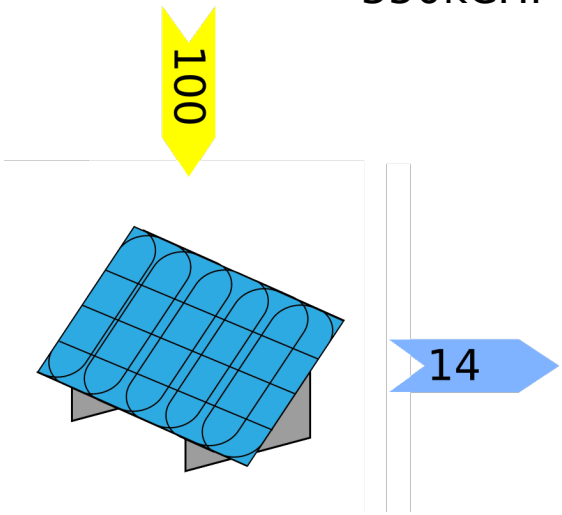
Production: Photo-voltaic Panels

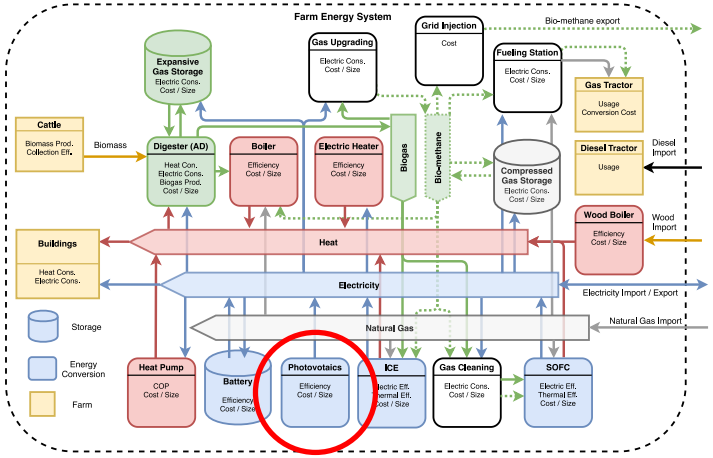


PV

<u>Inputs:</u>
None

<u>Typical size:</u>
100kW
350kCHF

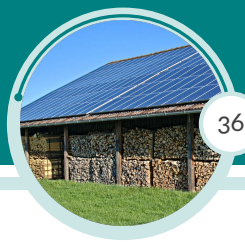




Credit: Haruka Ogawa

Model Description

Production: Photo-voltaic Panels



$$\dot{E}^{-EL}_{PV,d,h} = \eta_{PV} \cdot I_{d,h} \cdot \frac{S_{PV}}{\rho_{PV}} \qquad [kW] \qquad (26)$$

$$S_{PV} \leq A_{b,ground} \cdot f_{PV,roof} \cdot \rho_{PV} \qquad [kW] \qquad (27)$$

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

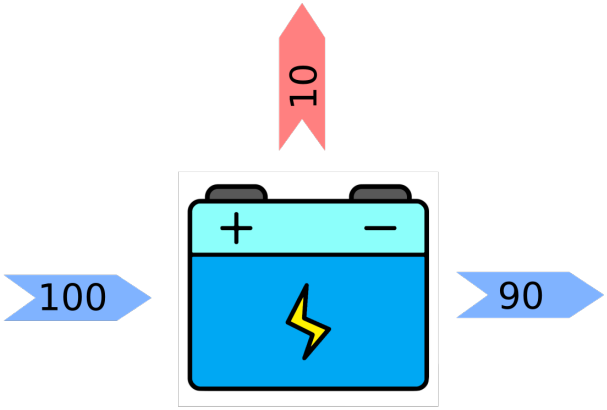
Model Description

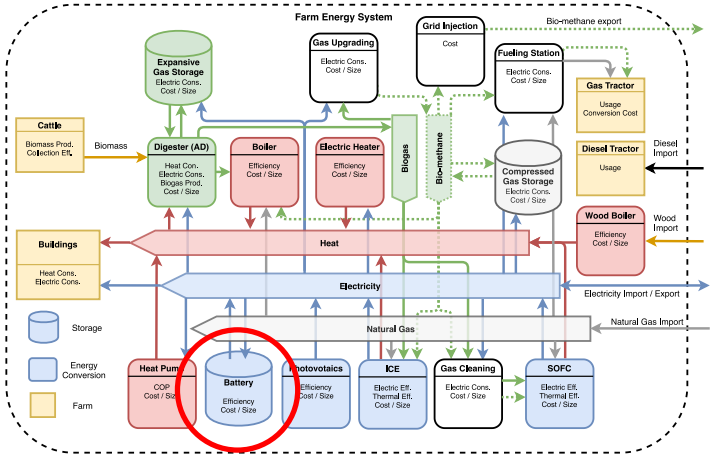
Storage: Battery

BAT

Inputs:
Electricity

Typical size:
20kWh
26kCHF





Credit: Haruka Ogawa

Model Description

Storage: Battery

$$SOC_{BAT,p+1} - (1 - r_{sd}) \cdot SOC_{BAT,p} = \left(\sqrt{\eta_{BAT}} \cdot \dot{E}^{+EL}_{BAT,t(p)} - \frac{1}{\sqrt{\eta_{BAT}}} \cdot \dot{E}^{-EL}_{BAT,t(p)}\right) \cdot dt \qquad [kWh] \qquad (28)$$

$$SOC_{u,o} = SOC_{u,last(p)} \qquad [kWh] \qquad (29)$$

$$Z^{\dot{E}+EL}_{u,d,h} + Z^{\dot{E}-EL}_{u,d,h} \leq 1 \qquad [-] \qquad (30)$$

$$Z^{\dot{E}+EL}_{u,d,h} \cdot M \geq \dot{E}^{+EL}_{u,d,h} \cdot dt \qquad [kWh] \qquad (31)$$

$$Z^{\dot{E}-EL}_{u,d,h} \cdot M \geq \dot{E}^{-EL}_{u,d,h} \cdot dt \qquad [kWh] \qquad (32)$$

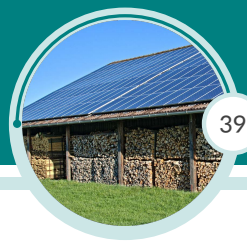
$$SOC_{u,p} \leq S_u \qquad [kWh] \qquad (33)$$

$$\dot{E}^{+EL}_{u,d,h} \cdot dt \leq S_u \qquad [kWh] \qquad (34)$$

$$\dot{E}^{-EL}_{u,d,h} \cdot dt \leq S_u \qquad [kWh] \qquad (35)$$

Model Description

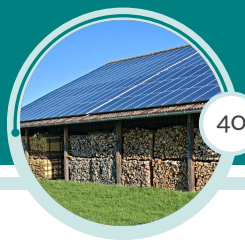
Storage: Battery



Name	Symbol	Value	Units	Source
Efficiency	η_u	0.9	—	P. Stadler PhD
Self discharge rate	$r_{u_{sd}}$	0.003	—	Tuned
Energy density	ρ_u	230	kWh/m^3	Sinovoltaics.com
Cost multiplier	c_u^{mult}	1.33	—	P. Stadler PhD
Specific investment cost	c_u^{size}	0.97	$kCHF/kWh$	P. Stadler PhD
Fixed investment cost	c_u^{fixe}	0.62	$kCHF$	P. Stadler PhD
LCA emissions	$m_{CO_2,u}^{LCA}$	0.2	tCO_2/kWh	Emilsson 2019
Life	n_u	10	$Years$	P. Stadler PhD
Maintenance	c_u^{maint}	0.02	—	P. Stadler PhD
Smallest size	S_u^{min}	1	kWh	Setting
Reference size	S_u^{ref}	10	kWh	P. Stadler PhD

Model Description

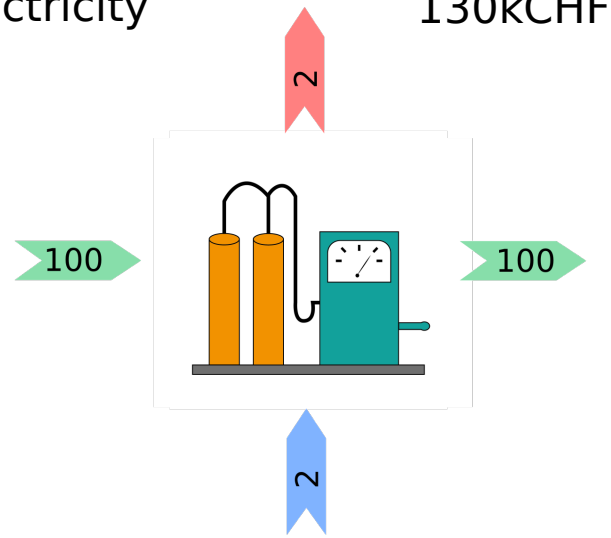
Storage: Compressed Gas tank

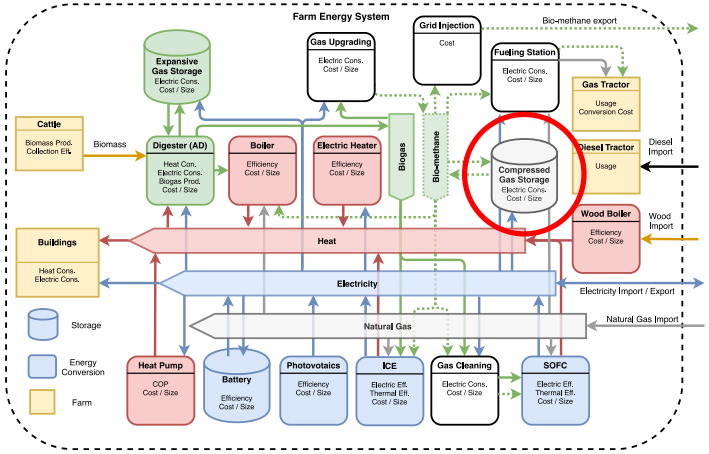


CGT

<u>Inputs:</u>
Biomethane
Electricity

<u>Typical size:</u>
3'400kWh
130kCHF





Credit: Haruka Ogawa

Model Description

Storage: Compressed Gas tank

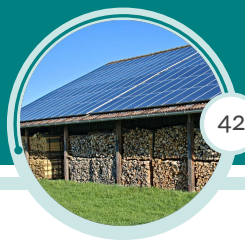
$$SOC_{CGT,p+1} - SOC_{CGT,p} = (\dot{E}^{+BM}_{CGT,t(p)} - \dot{E}^{-BM}_{CGT,t(p)})dt \qquad [kWh] \qquad (36)$$

$$\dot{E}^{+EL}_{CGT,d,h} = f^{comp}_{CGT_{EL/NG}} \cdot \dot{E}^{+BM}_{CGT,d,h} \qquad [kW] \qquad (37)$$

Name	Symbol	Value	Units	Source
Electric consumption	$f^{comp}_{u_{EL/NG}}$	0.02	—	Sinor 1991
Energy density	ρ_u	2	MWh/m^3	Calc
Cost multiplier	c^{mult}_u	1.8	—	Default
Specific investment cost	c^{size}_u	0.0009	$kCHF/kWh$	Smith 2014
Fixed investment cost	c^{fixe}_u	71.6	$kCHF$	Smith 2014
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kWh	Default
Life	n_u	25	*Years*	Smith 2014
Maintenance	c^{maint}_u	0.02	—	Smith 2014
Smallest size	S^{min}_u	100	kWh	Setting
Reference size	S^{ref}_u	4300	kWh	Smith 2014

Model Description

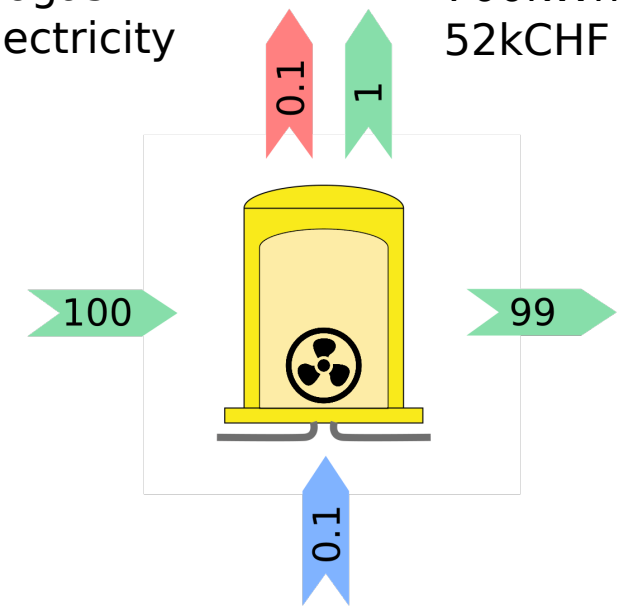
Storage: Biogas Storage

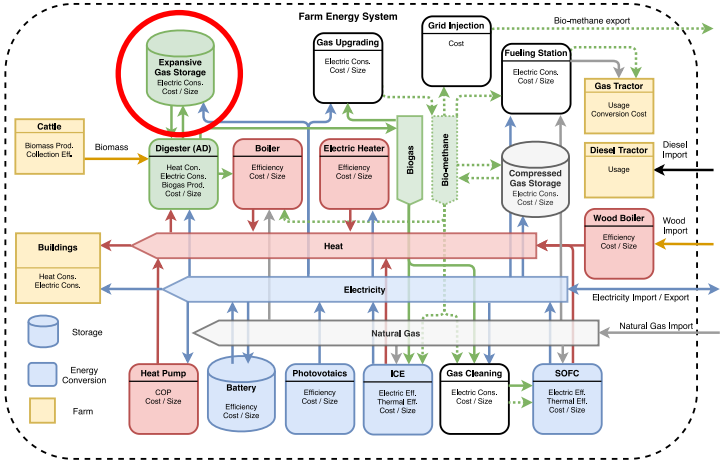


BS

Inputs:
Biogas
Electricity

Typical size:
700kWh
52kCHF

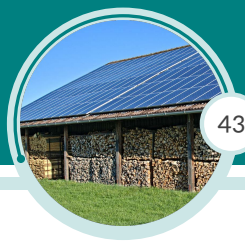




Credit: Haruka Ogawa

Model Description

Storage: Biogas Storage



$$SOC_{BS,p+1} - (1 - r_{BS_{sd}}) \cdot SOC_{BS,p} = (\dot{E}^{+BG}_{BS,t(p)} - \dot{E}^{-BG}_{BS,t(p)})dt \qquad [kWh] \qquad (38)$$

$$\dot{E}^{+EL}_{BS,d,h} = 10^{-3} \cdot f^{fan}_{BS_{EL/BG}} \cdot S_{BS} \qquad [kW] \qquad (39)$$

Name	Symbol	Value	Units	Source
Electric consumption	$f^{fan}_{u_{EL/BG}}$	0.063	—	Hahn 2014
Self discharge rate	$r_{u_{sd}}$	0.0004	—	Hahn 2014
Energy density	ρ_u	6.8	kWh/m^3	Chen 2015
Cost multiplier	c^{mult}_u	5.2	—	Scaling
Specific investment cost	c^{size}_u	0.012	$kCHF/kWh$	Hahn 2014
Fixed investment cost	c^{fixe}_u	1.6	$kCHF$	Hahn 2014
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kWh	Default
Life	n_u	20	*Years*	Hahn 2014
Maintenance	c^{maint}_u	0.024	—	Hahn 2014
Smallest size	S^{min}_u	30	kWh	Setting
Reference size	S^{ref}_u	18700	kWh	Hahn 2014

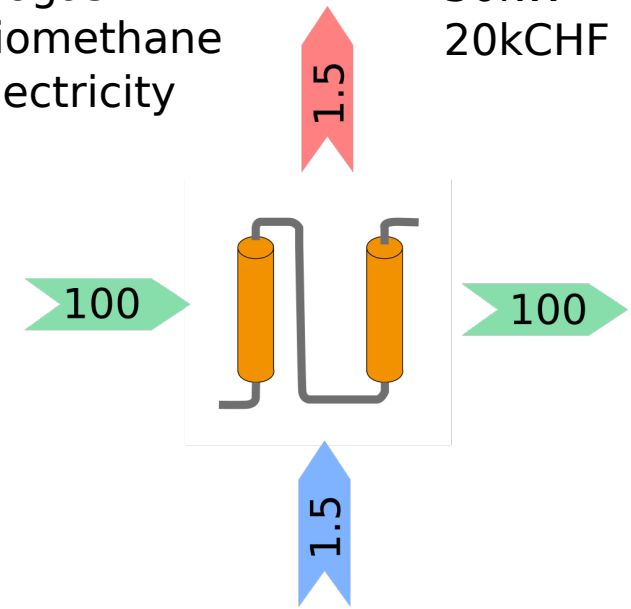
Model Description

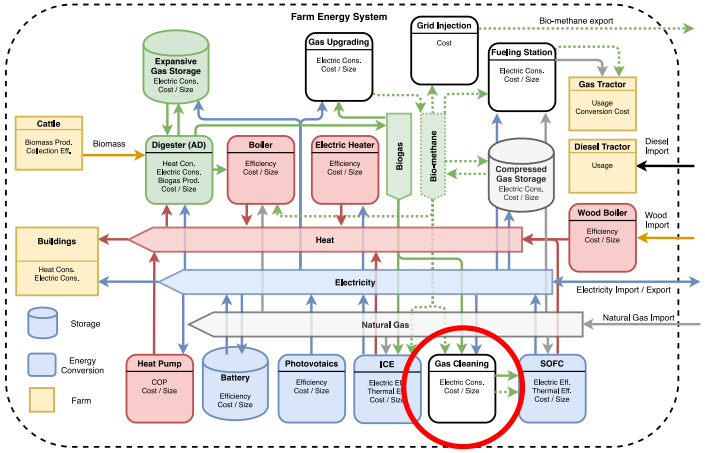
Storage: Gas Cleaning for SOFC

GCSOFC

<u>Inputs:</u>
Biogas
Biomethane
Electricity

<u>Typical size:</u>
30kW
20kCHF





Credit: Haruka Ogawa

Model Description

Storage: Gas Cleaning for SOFC

$$\dot{E}^{-r}_{u,d,h} = \dot{E}^{+r}_{u,d,h} \qquad [kW] \qquad (40)$$

$$\dot{E}^{+EL}_{u,d,h} = f_{u_{EL/BG}} \cdot (\dot{E}^{-BG}_{u,d,h} + x_{BG} \cdot \dot{E}^{-BM}_{u,d,h}) \qquad [kW] \qquad (41)$$

$$\dot{E}^{-BG}_{u,d,h} + x_{BG} \cdot \dot{E}^{-BM}_{u,d,h} \leq S_u \qquad [kW] \qquad (42)$$

Name	Symbol	Value	Units	Source
Electric consumption	$f_{GCSOFC_{EL/BG}}$	0.015	—	N. Ter-borch PdS
Biogas methane fraction	x_{BG}	0.6	—	J. Van Herle
Cost multiplier	c_u^{mult}	1	—	N. Ter-borch PdS
Specific investment cost	c_u^{size}	0.56	$kCHF/kW$	N. Ter-borch PdS
Fixed investment cost	c_u^{fixe}	2.8	$kCHF$	N. Ter-borch PdS
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life	n_u	10	*Years*	N. Ter-borch PdS
Maintenance	c_u^{maint}	0.185	—	N. Ter-borch PdS
Smallest size	S_u^{min}	1	kW	Setting
Reference size	S_u^{ref}	50	kW	N. Ter-borch PdS

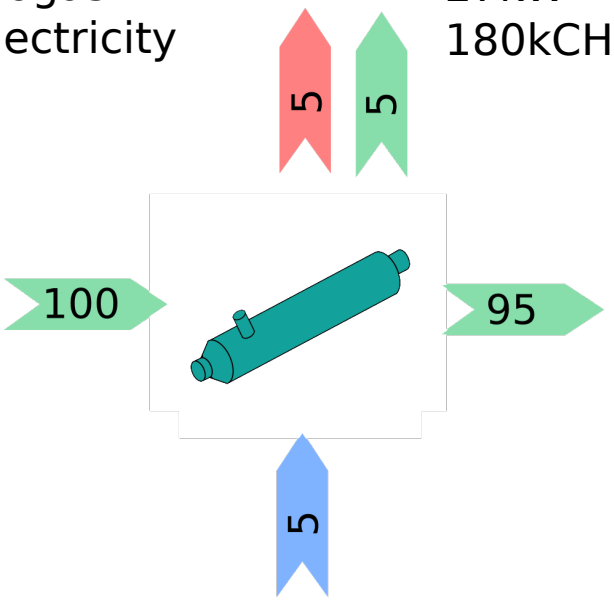
Model Description

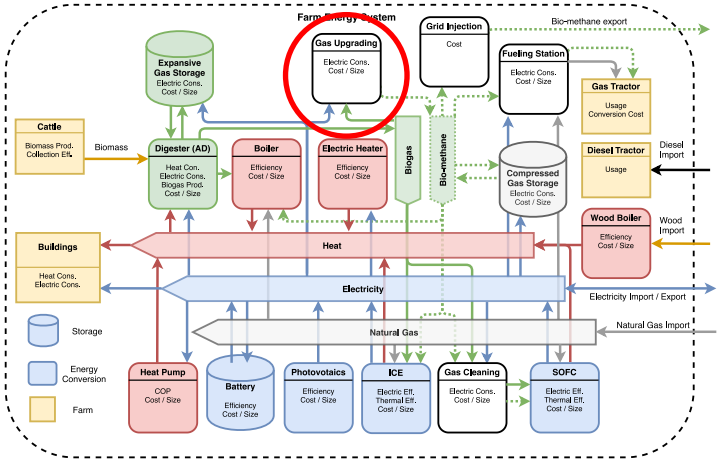
Utility: Biogas Upgrading

BU

<u>Inputs:</u>
Biogas
Electricity

<u>Typical size:</u>
27kW
180kCHF

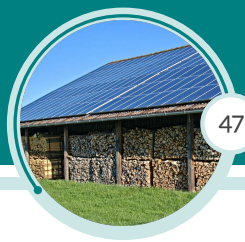




Credit: Haruka Ogawa

Model Description

Storage: Biogas Upgrading



$$\dot{E}^{-BM}_{BU,d,h} = \eta_{BU} \cdot \dot{E}^{+BG}_{BU,d,h} \qquad [kW] \qquad (43)$$

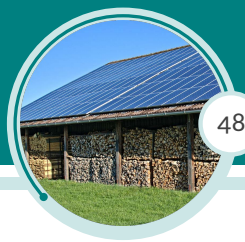
$$\dot{E}^{+EL}_{BU,d,h} = f_{u_{EL/BM}} \cdot \dot{E}^{-BM}_{u,d,h} \qquad [kW] \qquad (44)$$

$$\dot{E}^{-BM}_{BU,d,h} \leq S_{BU} \qquad [kW] \qquad (45)$$

Name	Symbol	Value	Units	Source
Efficiency	η_u	0.95	—	Chen 2015
Electric consumption	$f^{comp}_{u_{EL/BM}}$	0.045	—	Chen 2015
Cost multiplier	c^{mult}_u	5.1	—	Scaling
Specific investment cost	c^{size}_u	0.89	$kCHF/kW$	Chen 2015
Fixed investment cost	c^{fixe}_u	11.4	$kCHF$	Chen 2015
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life	n_u	15	*Years*	He 2018
Maintenance	c^{maint}_u	0.02	—	Chen 2015
Smallest size	S^{min}_u	10	kW	Setting
Reference size	S^{ref}_u	1000	kW	Chen 2015

Model Description

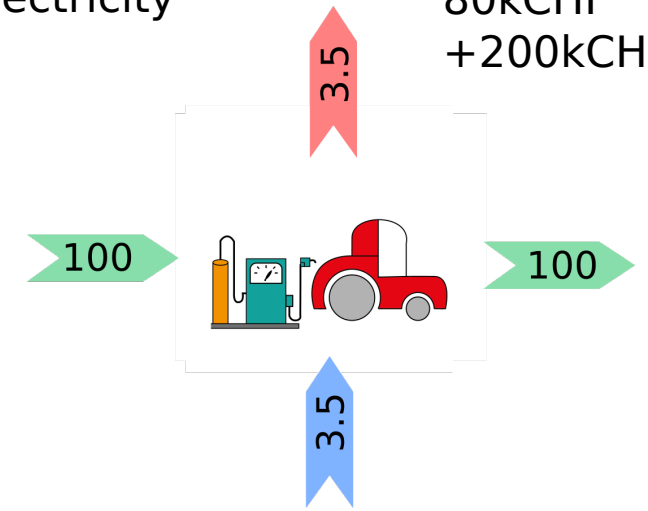
Utility: Gas Fueling Station

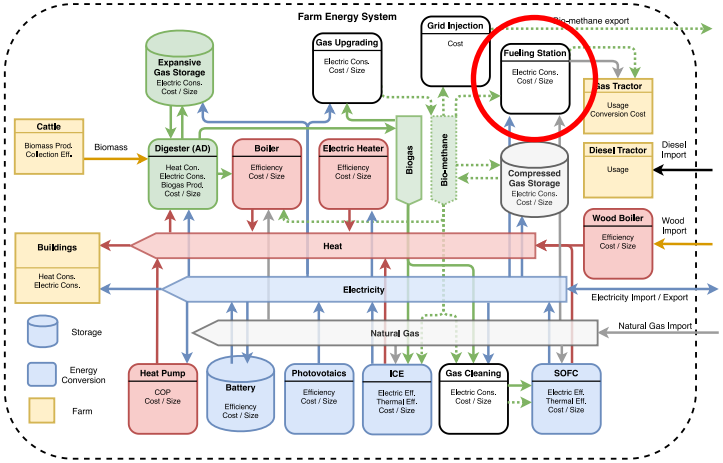


GFS

<u>Inputs:</u>
Biomethane
Electricity

<u>Typical size:</u>
30kW
80kCHF
+200kCHF

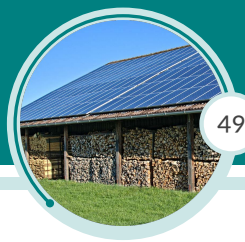




Credit: Haruka Ogawa

Model Description

Utility: Gas Fueling Station



$$\dot{E}^{-r}_{u,d,h} = \dot{E}^{+r}_{u,d,h} \qquad [kW] \qquad (46)$$

$$\dot{E}^{+EL}_{u,d,h} = (f^{comp}_{u_{EL/NG}} + f^{dry}_{u_{EL/BG}} \cdot x_{BG}) \sum_{r}^{(BM,NG)} \dot{E}^{+r}_{u,d,h} \qquad [kW] \qquad (47)$$

$$\sum_{r}^{(BM,NG)} \dot{E}^{-r}_{u,d,h} \leq S_u \qquad [kW] \qquad (48)$$

Model Description

Utility: Gas Fueling Station

Name	Symbol	Value	Units	Source
Typical size	S_u^{typ}	30	kW	Calc
Total cost at S^{typ}	c_u^{total}	41	$kCHF$	Calc
Conversion cost	$c_u^{convert}$	48	$kCHF/Tractor$	Clarke 2012
Electric consumption compressor	$f_{u_{EL/NG}}^{comp}$	0.03	—	Sinor 1991
Electric consumption dryer	$f_{u_{EL/BG}}^{dry}$	0.008	—	N. Ter-borch PdS
Fueling time	$t_{slow-fuel}$	10	h	Smith 2014
Minimum operating temperature	T_u^{oper}	5	$^{\circ}C$	Setting
Cost multiplier	c_u^{mult}	1.8	—	Default
Specific investment cost	c_u^{size}	1.03	$kCHF/kW$	Smith 2014, Ahman 2010
Fixed investment cost	c_u^{fixe}	12.3	$kCHF$	Smith 2014, Ahman 2010
LCA emissions	$m_{CO_2,u}^{LCA}$	0.02	tCO_2/kW	Default
Life	n_u	25	$Years$	Smith 2014
Maintenance	c_u^{maint}	0.02	—	Default
Smallest size	S_u^{min}	10	kW	Smith 2014
Reference size	S_u^{ref}	30	kW	Smith 2014

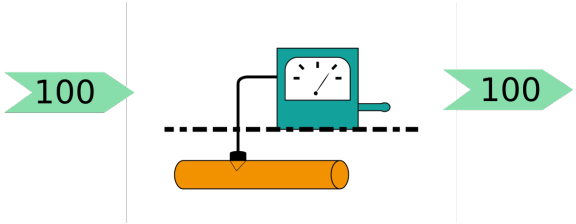
Model Description

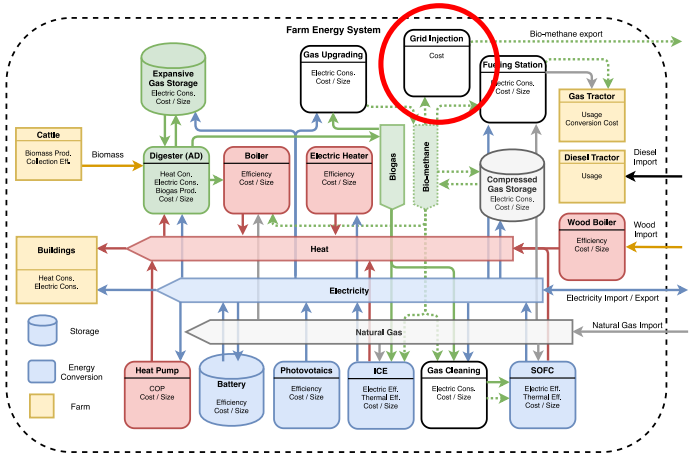
Utility: Grid Injection

GI

<u>Inputs:</u>
Biomethane

<u>Typical size:</u>
14kW
14kCHF

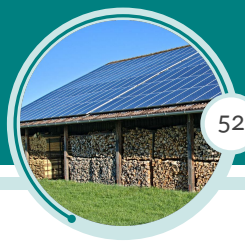




Credit: Haruka Ogawa

Model Description

Storage: Grid Injection



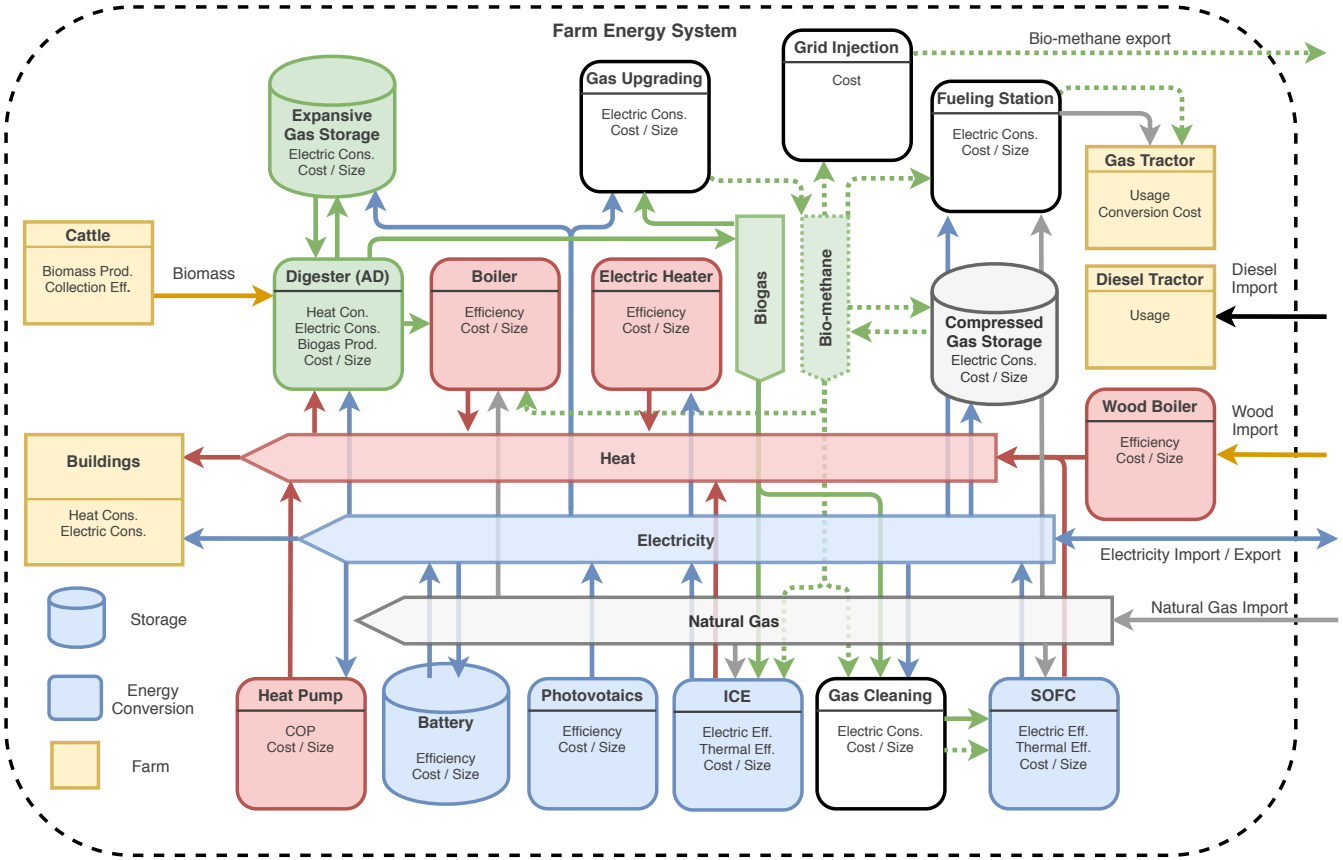
$$\dot{E}^{-BM}_{GI,d,h} = \dot{E}^{+BM}_{GI,d,h} \qquad [kW] \qquad (49)$$

$$\dot{E}^{-BM}_{GI,d,h} \leq S_{GI} \qquad [kW] \qquad (50)$$

Name	Symbol	Value	Units	Source
Cost multiplier	c_u^{mult}	5.1	—	Default
Specific investment cost	c_u^{size}	0.11	$kCHF/kW$	Biollaz 2017
Fixed investment cost	c_u^{fixe}	1.4	$kCHF$	Biollaz 2017
LCA emissions	$m^{LCA}_{CO_2,u}$	0.02	tCO_2/kW	Default
Life	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	Biollaz 2017

Model Description

Energy balance



Model Description

Energy balance

Electricity

$$\dot{E}^{-EL}_{grid,d,h} + \sum_{u}^{Units} \dot{E}^{-EL}_{u,d,h} = \dot{E}^{+EL}_{grid,d,h} + \sum_{u}^{Units} \dot{E}^{+EL}_{u,d,h} + \dot{E}^{+EL}_{b,d,h} \qquad [kW] \qquad (51)$$

$$\dot{E}^{+EL}_{u,d,h} \leq \sum_{u}^{BAT \notin Units} \dot{E}^{-EL}_{u,d,h} \qquad [kW] \qquad (52)$$

$$Z^{\dot{E}^{+EL}}_{grid,d,h} + Z^{\dot{E}^{-EL}}_{grid,d,h} \leq 1 \qquad [-] \qquad (53)$$

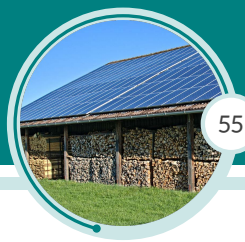
$$Z^{\dot{E}^{+EL}}_{grid,d,h} \cdot M \geq \dot{E}^{+EL}_{grid,d,h} \qquad [kW] \qquad (54)$$

$$Z^{\dot{E}^{-EL}}_{grid,d,h} \cdot M \geq \dot{E}^{-EL}_{grid,d,h} \qquad [kW] \qquad (55)$$

Biogas

$$\sum_{u}^{GCSOFC \notin Units} \dot{E}^{-BG}_{u,d,h} = \sum_{u}^{SOFC \notin Units} \dot{E}^{+BG}_{u,d,h} + \dot{E}^{+BG}_{waste,d,h} \qquad [kW] \qquad (56)$$

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



Biomethane

$$\dot{E}^{-BM}_{CGT,d,h} + \dot{E}^{-BM}_{BU,d,h} = \sum_{u}^{SOFC \notin Units} \dot{E}^{+BM}_{u,d,h} + \dot{E}^{+BM}_{waste,d,h} \qquad [kW] \qquad (58)$$

$$\dot{E}^{-BM}_{GI,d,h} = \dot{E}^{+EL}_{grid,d,h} \qquad [kW] \qquad (59)$$

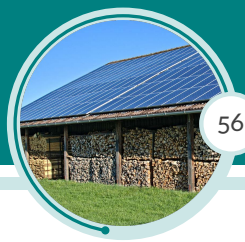
$$\dot{E}^{-BM}_{GFS,d,h} + \dot{E}^{-NG}_{GFS,d,h} = \dot{E}^{+Fuel}_{tractors,d,h} \cdot Z_{GFS} \qquad [kW] \qquad (60)$$

Heat

$$\sum_{u}^{Units} \dot{Q}^{-}_{u,d,h} = \dot{Q}^{+}_{b,d,h} + \dot{Q}^{+}_{AD,d,h} + \dot{Q}^{+}_{waste,d,h} \qquad [kW] \qquad (61)$$

Model Description

Energy balance



Biomass, Natural Gas, Wood and Diesel

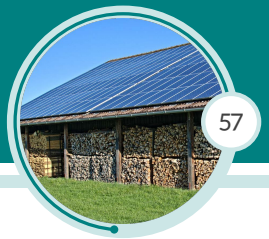
$$\dot{E}^{-Biomass}_{Farm,d,h} = \dot{E}^{+Biomass}_{AD,d,h} + \dot{E}^{+Biomass}_{waste,d,h} \quad [kW] \quad (62)$$

$$\dot{E}^{-NG}_{grid,d,h} = \sum_{u}^{Units} \dot{E}^{+NG}_{u,d,h} \quad [kW] \quad (63)$$

$$\dot{E}^{-Wood}_{grid,d,h} = \dot{E}^{+Wood}_{WBOI,d,h} \quad [kW] \quad (64)$$

$$\dot{E}^{-Diesel}_{grid,d,h} = \dot{E}^{+Fuel}_{tractors,d,h} \cdot (1 - Z_{GFS}) \quad [kW] \quad (65)$$

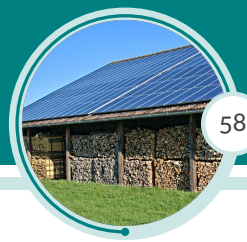
$$E^{\pm r}_{g} = 10^{-3} \sum_{d}^{Days} \left(\sum_{h}^{Hours} \dot{E}^{\pm r}_{g,d,h} \cdot f_d \right) \quad [MWh] \quad (66)$$



credit: https://www.vecteezy.com/members/sceneit

Model Description

Economic objective functions



$$Z_u \cdot M \leq S_u \qquad [kW] \qquad (67)$$

$$Z_u \cdot 10 \leq CAPEX_u \qquad [kW] \qquad (68)$$

$$S_u \leq S_u^{min} \cdot Z_u \qquad [kW] \qquad (69)$$

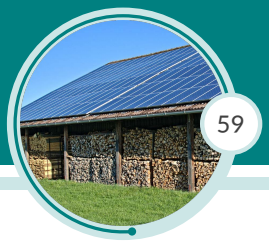
$$CAPEX_u = 10^{-3} \cdot c_u^{mult}(c_u^{size} \cdot S_u + c_u^{fixe} \cdot Z_u)\tau_u \qquad [MCHF/year] \qquad (70)$$

$$CAPEX = \sum_u^{Units} CAPEX_u \qquad [MCHF/year] \qquad (71)$$

$$OPEX = 10^{-3} \sum_r^{Resources} \left(c_r^{buy} \cdot E_{grid}^{-r} - c_r^{sell} \cdot E_{grid}^{+r}\right) + \sum_u^{Units} \left(c_u^{maint} \cdot \frac{CAPEX_u}{\tau_u}\right) \qquad [MCHF/year] \qquad (72)$$

$$TOTEX = OPEX + CAPEX \qquad [MCHF/year] \qquad (73)$$

$$\tau_u = \frac{i(1+i)^{n_u}}{(1+i)^{n_u} - 1} \qquad [-] \qquad (74)$$



Emissions in $[ktCO_2/year]$

$$ENVEX_{EL} = 10^{-6} \cdot \sum_{d}^{Days} \sum_{h}^{Hours} m^{buy}_{CO_2,EL,d,h} \cdot (\dot{E}^{-EL}_{grid,d,h} - f^{sell}_{CO_2} \cdot \dot{E}^{+EL}_{grid,d,h}) \cdot f_d \tag{75}$$

$$ENVEX_r = 10^{-3} \cdot m^{buy}_{CO_2,r} \cdot (E^{-r}_{grid} - f^{sell}_{CO_2} \cdot E^{+r}_{grid}) \tag{76}$$

$$ENVEX = \sum_{r}^{Resources} ENVEX_r + 10^{-3} \cdot \sum_{u}^{Units} \left(\frac{m^{LCA}_{CO_2,u}}{n_u} \cdot S_u \right) + (1 - f^{AD_{reduction}}_{CO_2} \cdot Z_{AD}) \cdot m_{CO_2,manure} \tag{77}$$

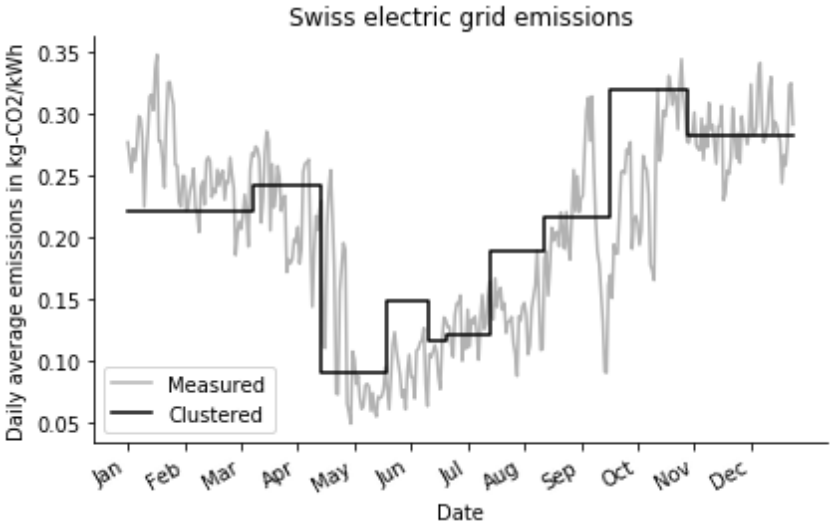
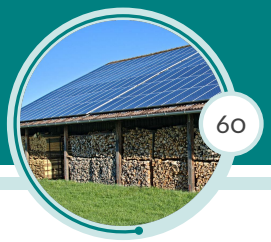


Figure: Emissions factor of the Swiss electric grid. Vuarnoz 2018

Part II : Results

Results
Current scenario



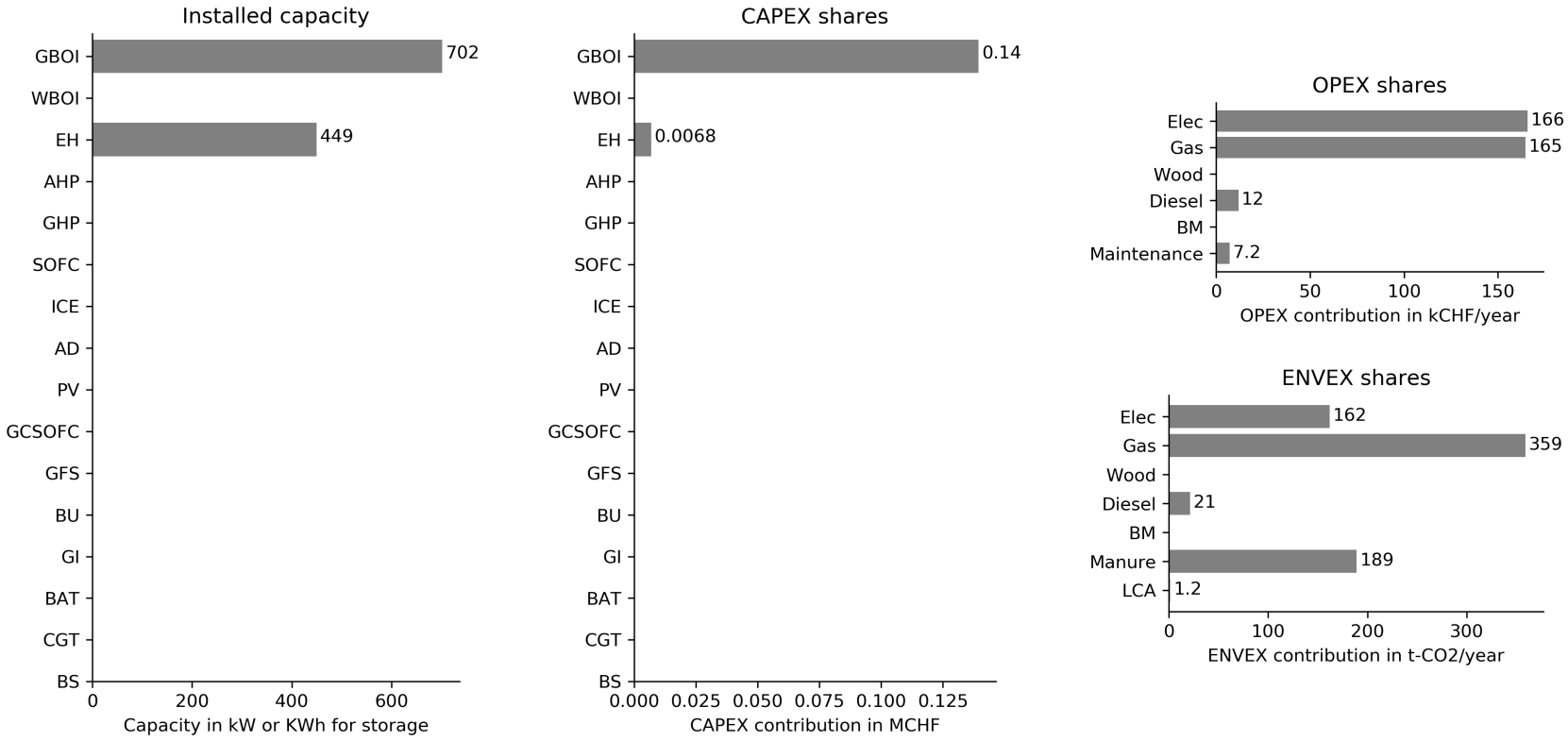
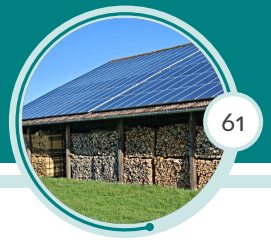
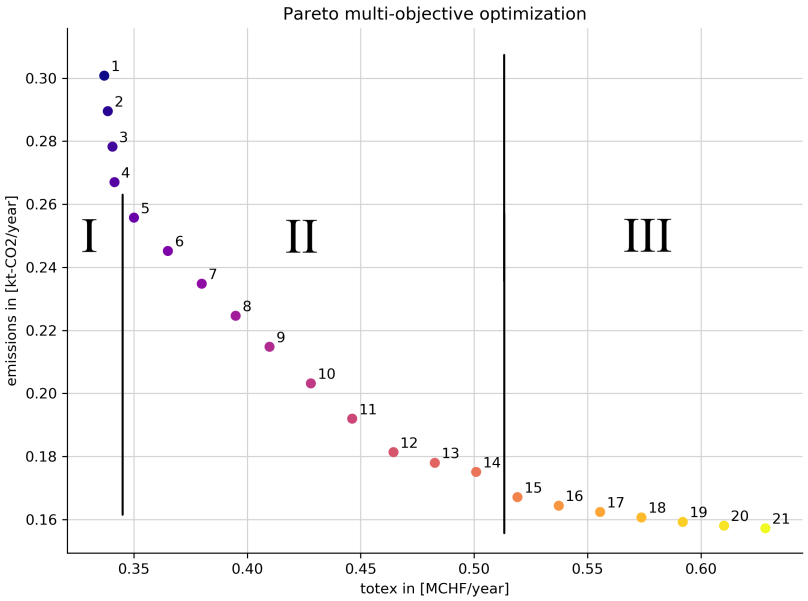


Figure: Scenario representing the current situation at SFF.

Results
Multi-objective





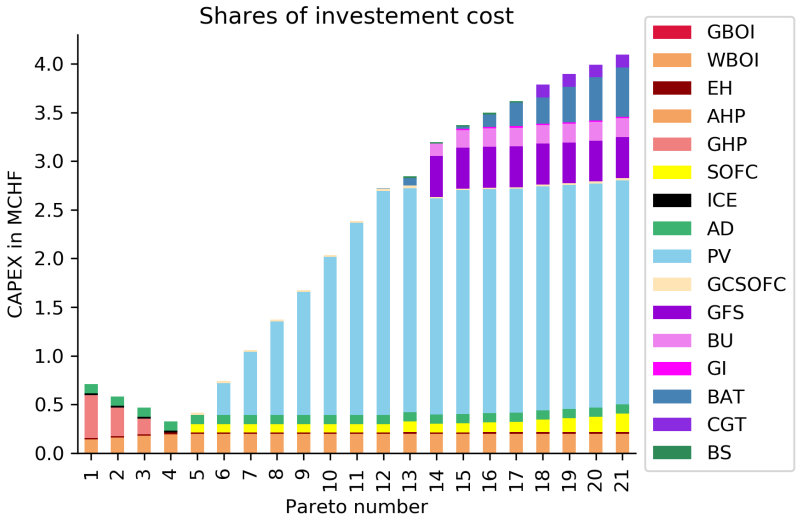
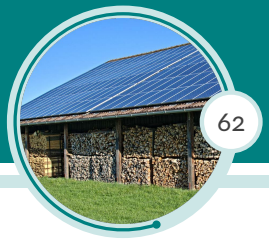
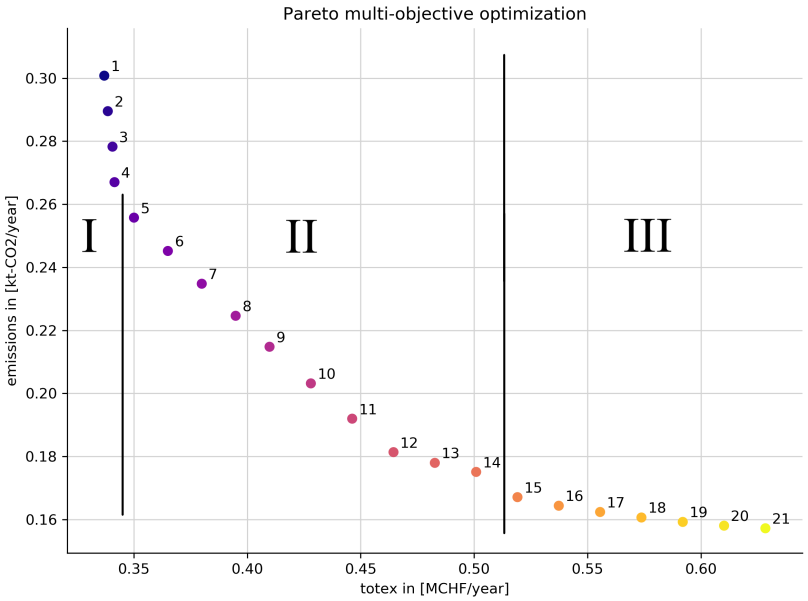


Figure: ENVEX-TOTEX multi-objective optimization

Results
Multi-objective





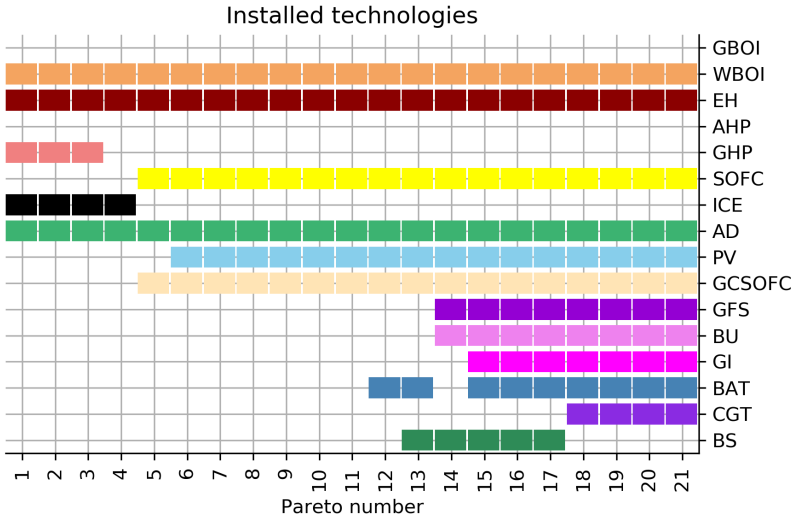
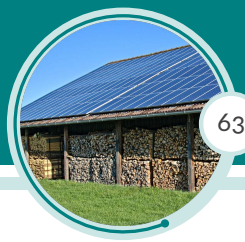


Figure: ENVEX-TOTEX multi-objective optimization

Results

Cheapest technologies to mitigate emissions

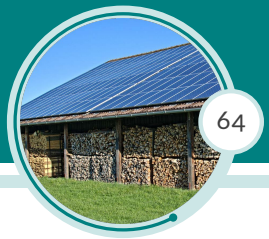


From the cheapest to the most expensive technology to mitigate emissions

1. Anaerobic Digestion with Internal Combustion Engine
2. Anaerobic Digestion with Solid Oxide Fuel Cell and Gas Cleaning
3. Photovoltaic panels
4. Small sized Battery
5. Raw Biogas Storage
6. Biogas Upgrading with Gas Fueling Station and converted CNG tractors
7. Grid Injection
8. Large scale Battery
9. Compressed Gas Tank

Results

Reducing costs without increasing emissions



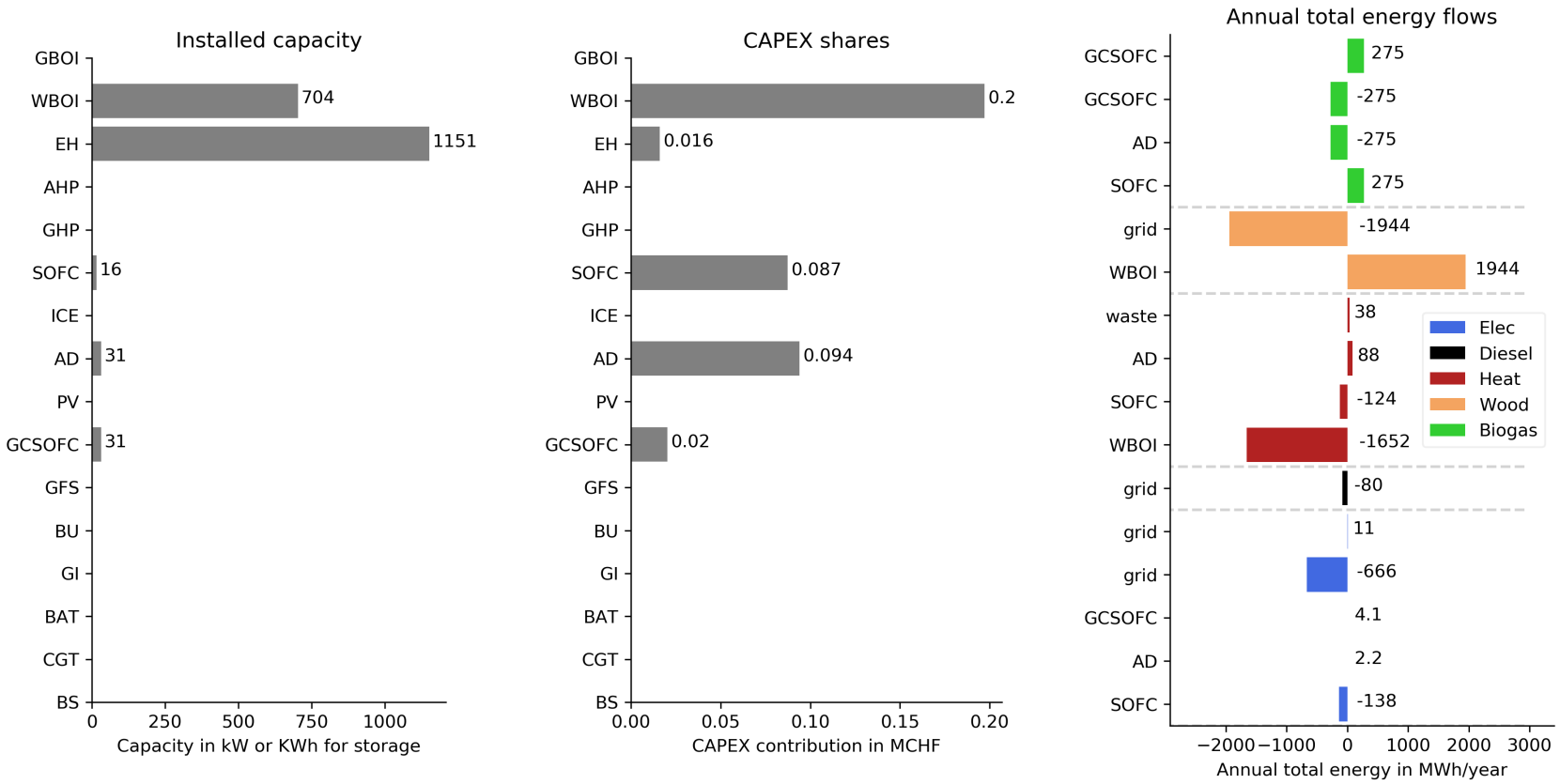
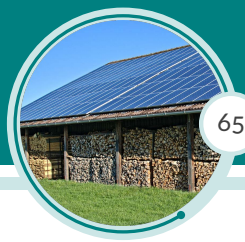


Figure: Solution 5 on the Pareto graph

Results

Reducing costs without increasing emissions



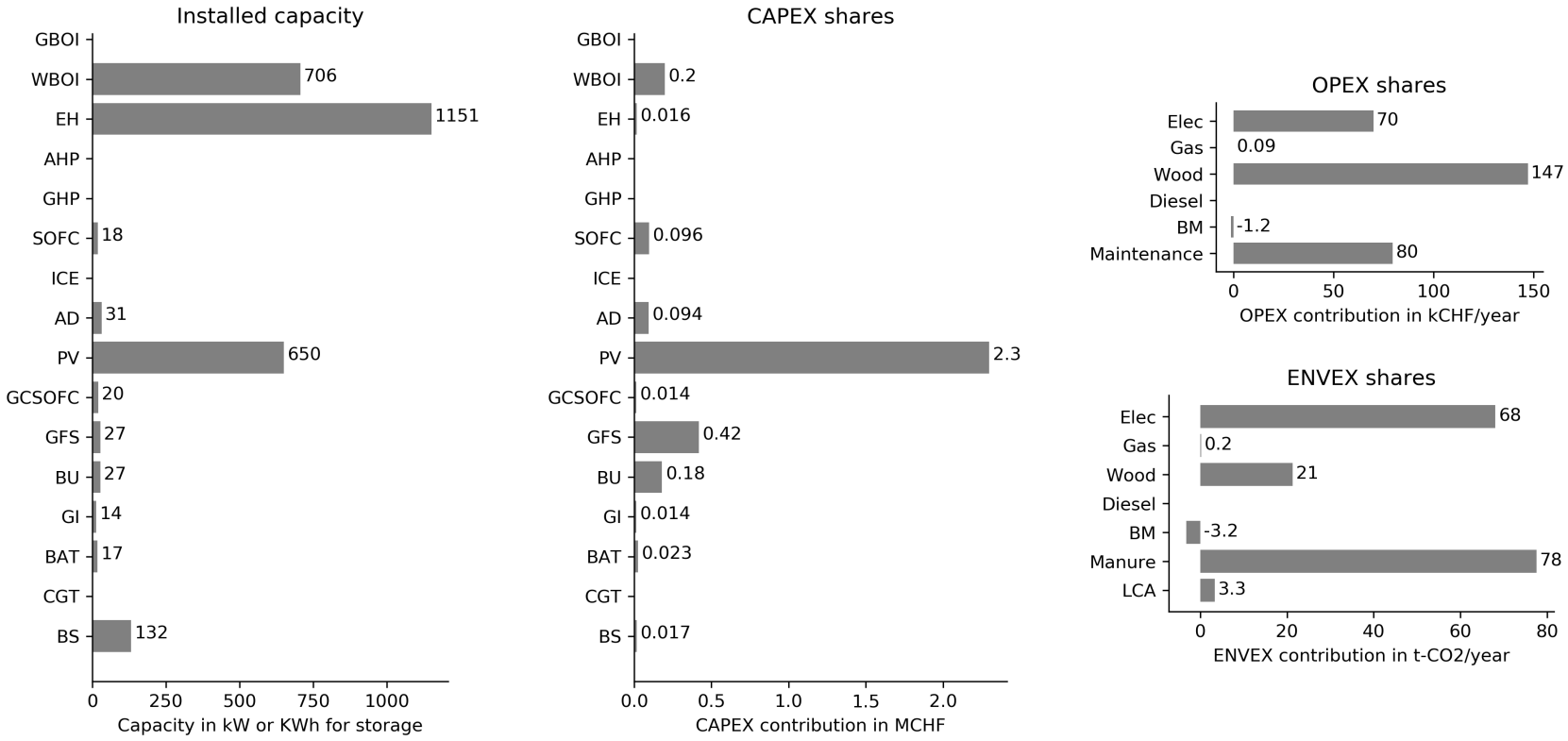
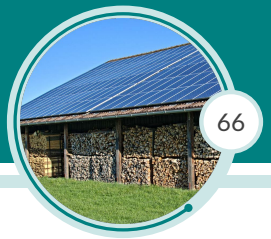
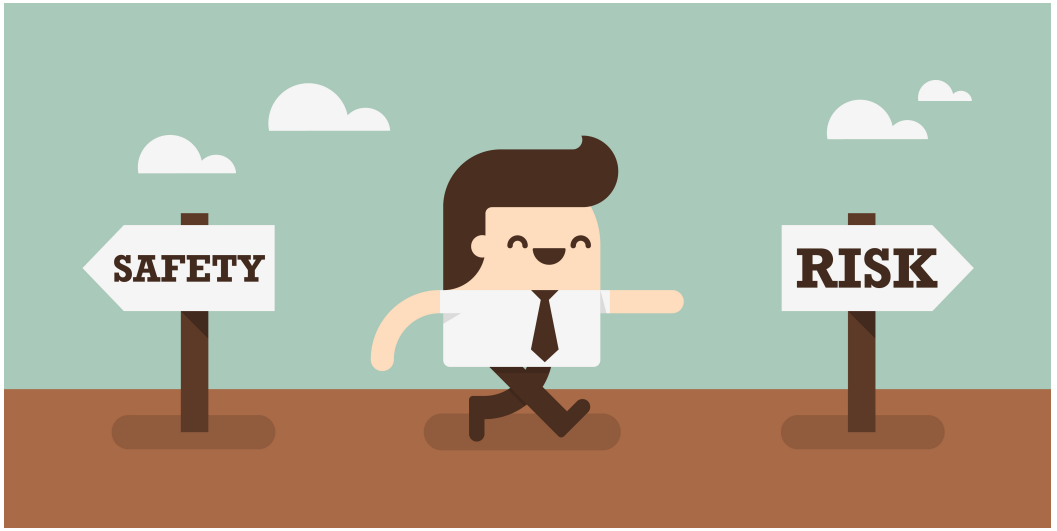


Figure: Solution 15 on the Pareto graph

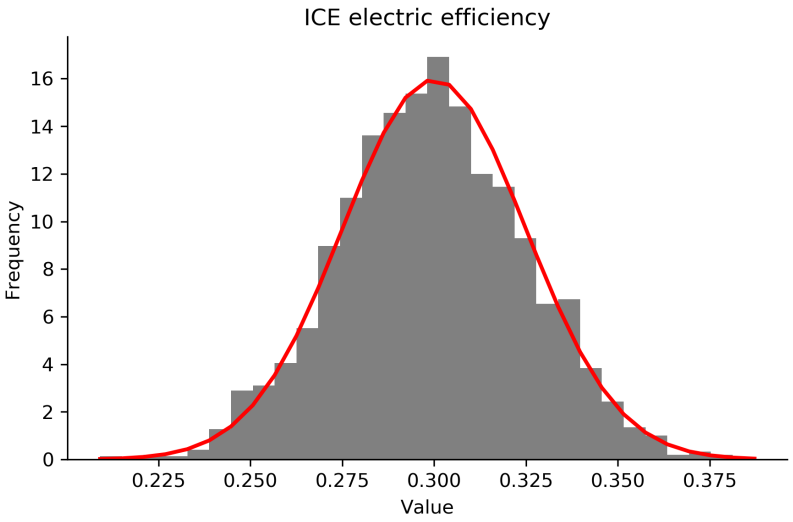




credit: https://www.vecteezy.com/members/doodervector

Results

Uncertainty: Monte Carlo analysis



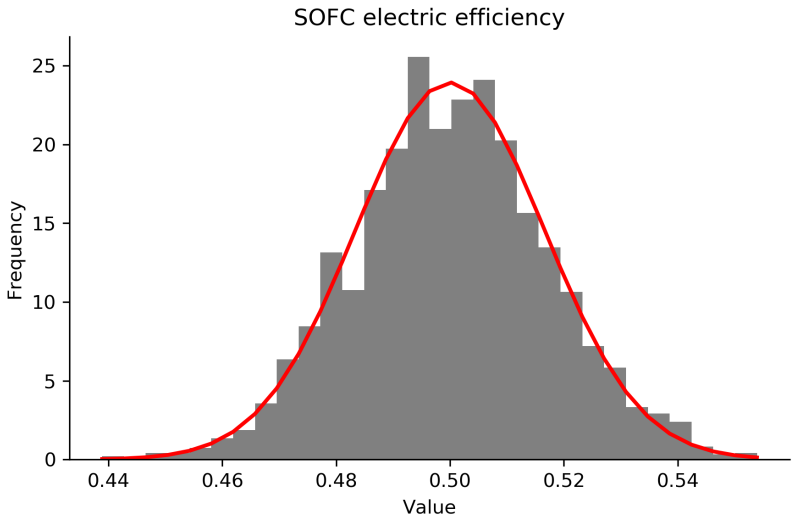
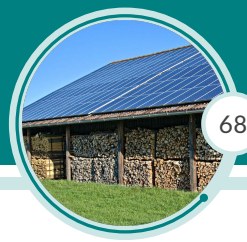


Figure: Example probability distribution of parameter values

Results

Uncertainty: Monte Carlo analysis



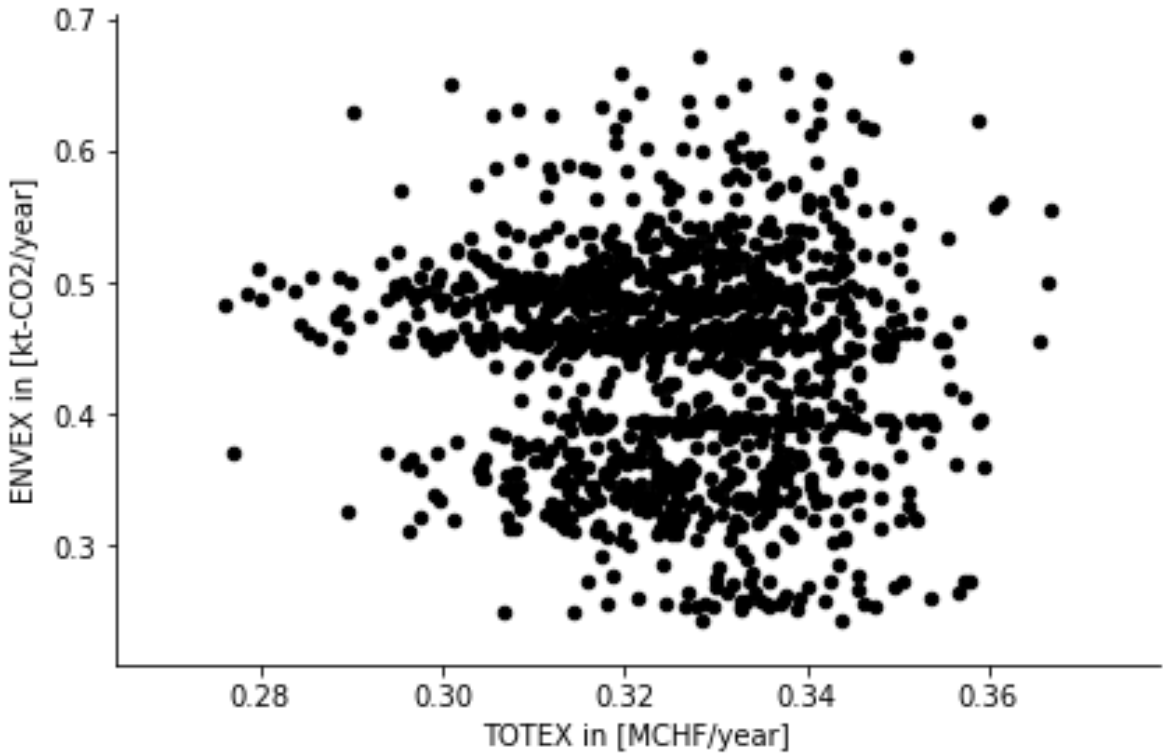


Figure: Uncertainty on ENVEX and TOTEX

Results

Uncertainty: Monte Carlo analysis

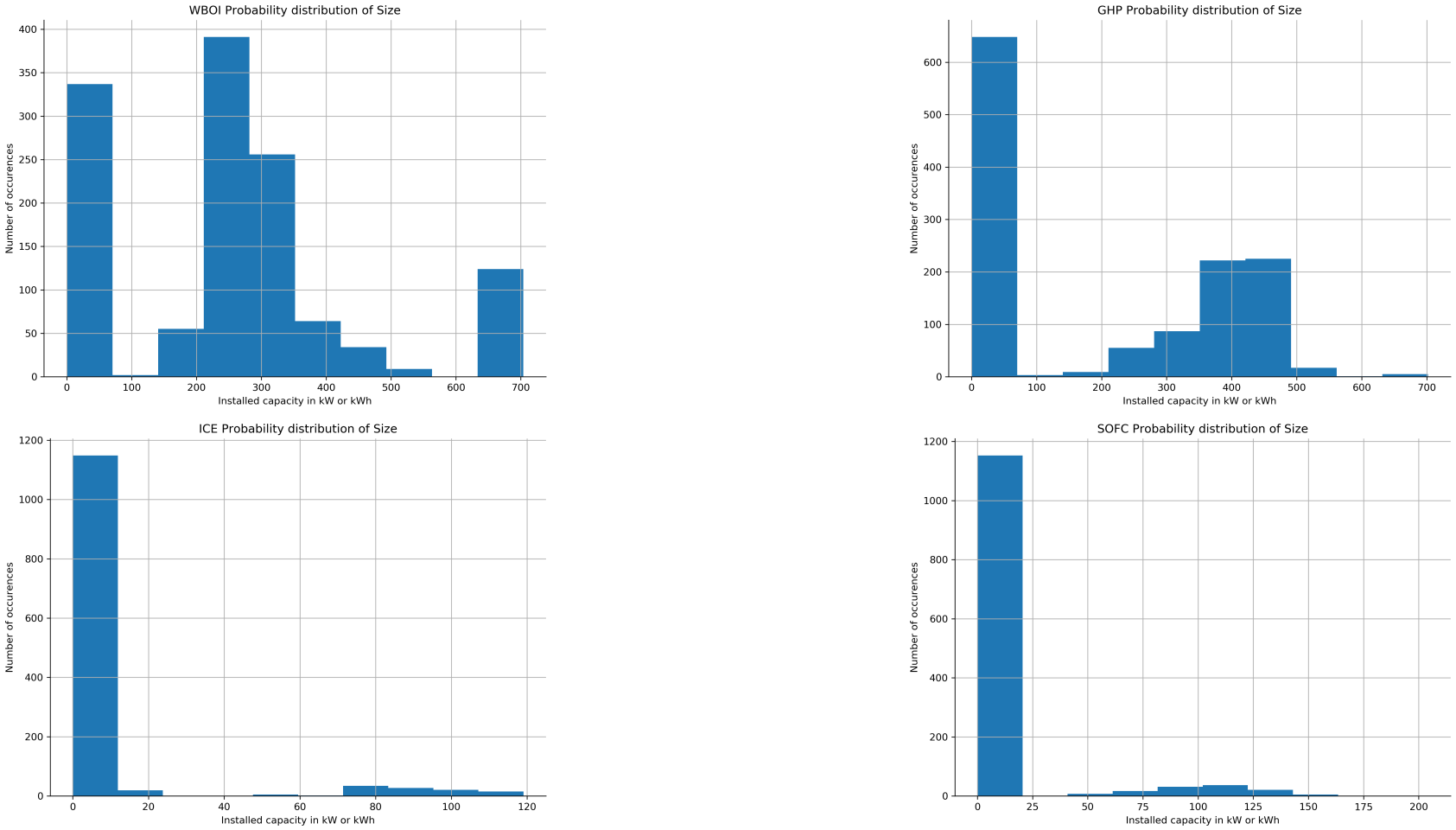
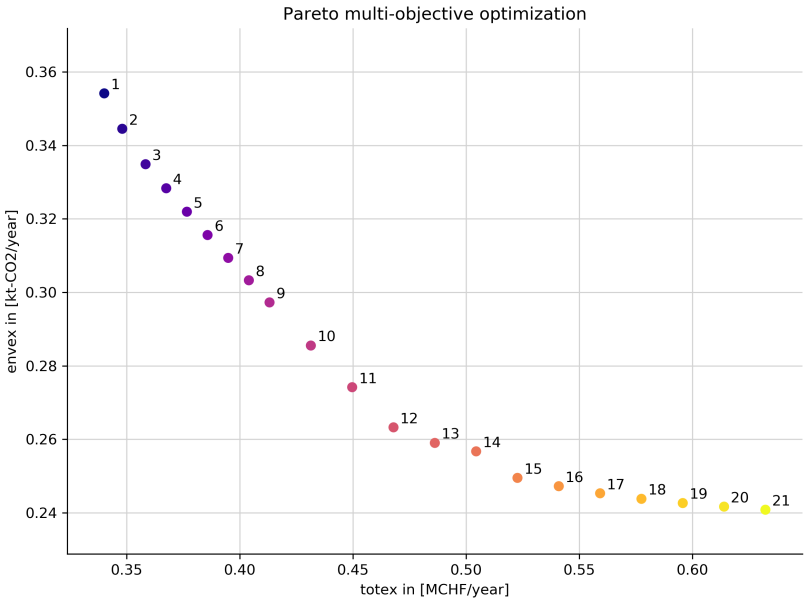


Figure: Probability distribution of installed capacities

Results
Without wood boiler



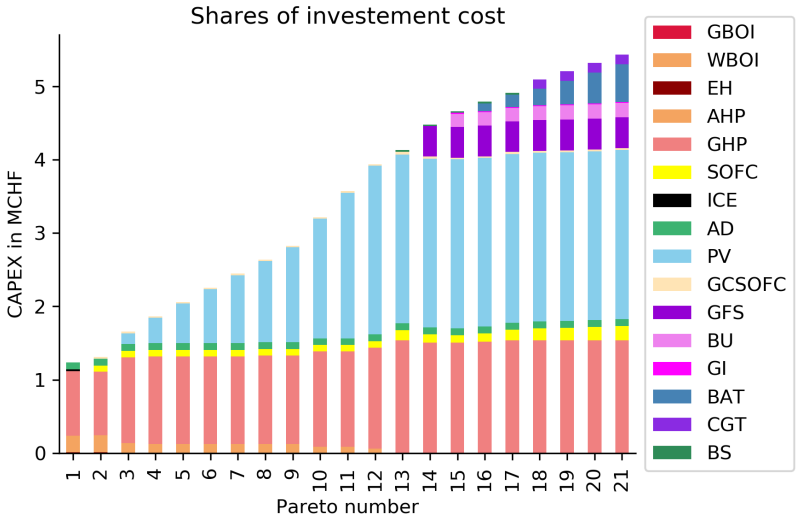


Figure: Without the Wood Boiler: ENVEX-TOTEX multi-objective optimization

Results
Without wood boiler

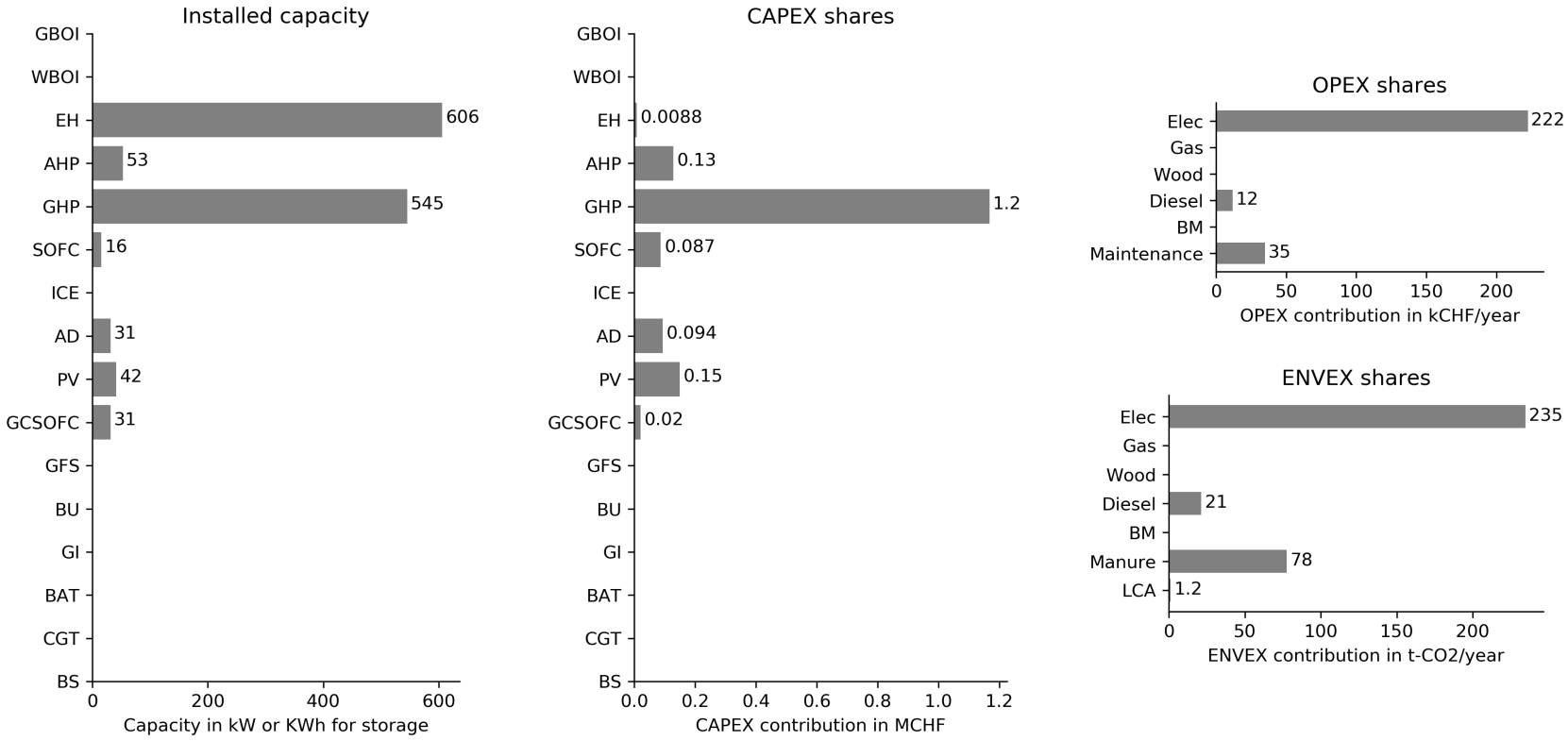
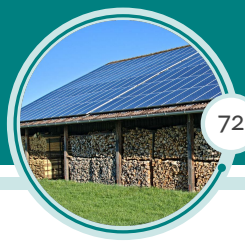


Figure: Solution 3 on the "No wood boiler" Pareto graph

Results
Comparison



Objective	Scenario	ENVEX	TOTEX	OPEX	CAPEX
		[tCO_2/ year]	[kCHF/ year]	[kCHF/ year]	[kCHF/ year]
TOTEX	Current scenario	733	359	350	0.15
ENVEX-TOTEX (4)	AD + ICE	267 -64%	341 -5%	319 -10%	0.33 X 2
ENVEX-TOTEX (5)	AD + SOFC	256 -65%	350	316 -10%	0.41 X 3
ENVEX-TOTEX (15)	All technologies	167 -77%	519 +45%	296 -15%	3.4 X 23
ENVEX-TOTEX (3)	No wood boiler	335 -54%	358	269 -23%	1.7 X 11

Discussion
Recommendations

Recommendations to reduce emissions by half without increasing total costs

- **Heating** Geothermal Heat Pump > Wood Boiler
- **Cogeneration** SOFC > Internal Combustion Engine
- **Production** Anaerobic Digester > PV

Discussion
Recommendations

Recommendations to reduce emissions further

- **Biogas upgrading** - biomethane fueled tractors
- **Short term storage** - raw biogas storage
- **Long term storage** - not a favorable solution

Discussion
Limitations

The Farm Energy System is meant to compare **many** options. It is fast, simple but lack precision. It indicates which energy pathway is or is not worth further investigations.

- **Thermodynamics** - bad for heat pumps
- **Load profiles** - essential
- **Economics** - compared to an existing installation

Discussion
Future research

The Swiss Future Farm is a special case, with high energy consumption and low biomass potential.

- **Typical small scale farm** - extrapolate for Switzerland
- **Power to Gas** - reaching carbon neutrality
- **Projections** - carbon tax and energy prices

Conclusion

I hope this analysis promotes the smart use of renewables, to reduce emissions of the Swiss Future Farm.

I hope this model can be used in future research project.

Thank you all for your attention and your support throughout this project