# Part 2 - Optimization

1. Problem statement

2. Optimization of a Multi-Generation Energy System by integrating life cycle assessment

3. Optimization of a Micro-Grid by means of mixed-integer linear programming

# Problem statement

## Environmental impacts

**Europe**
**2020 strategy**

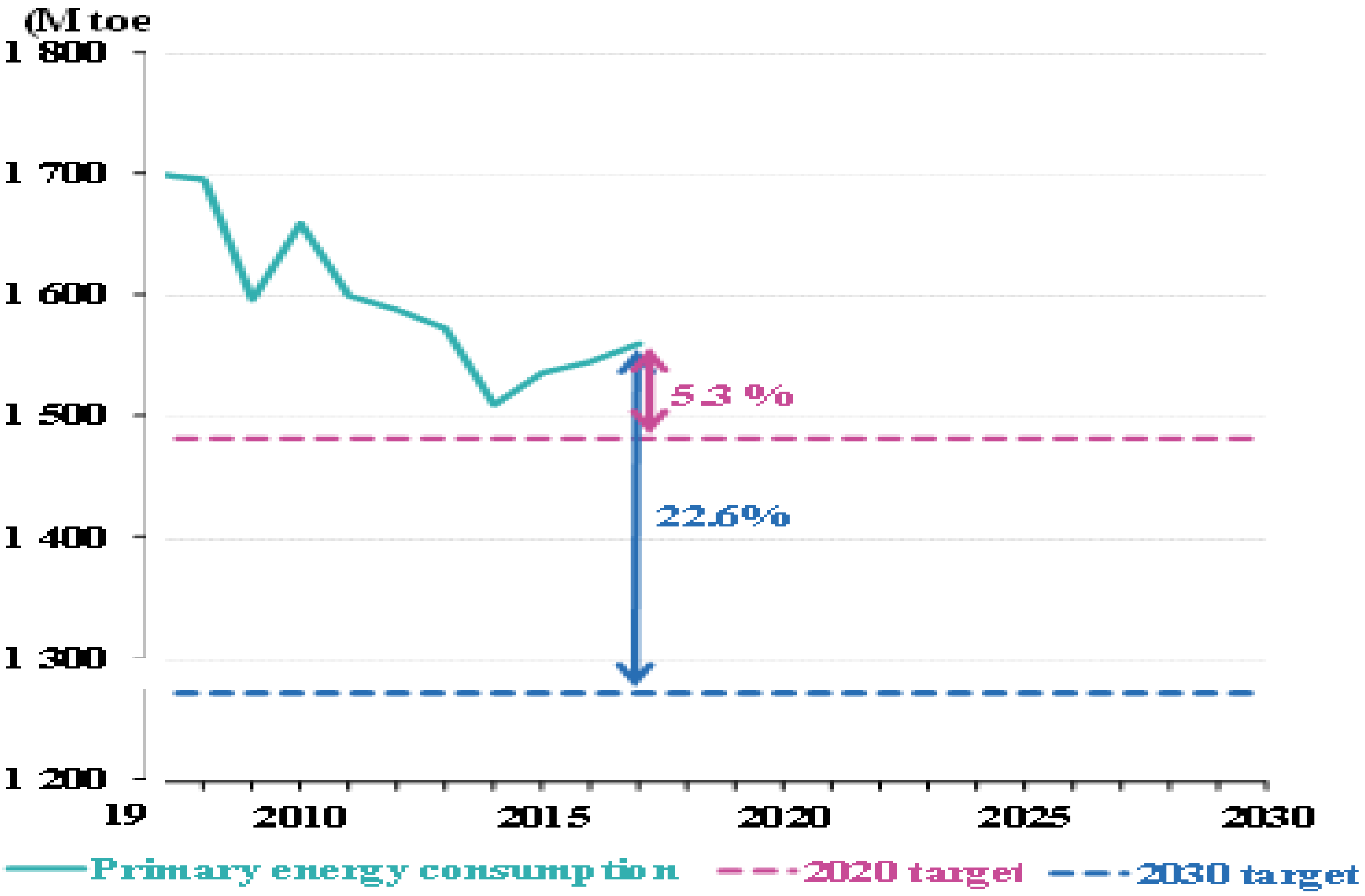
- A 20 % reduction in GHG emissions compared with 1990 levels;
- A 20 % share of renewable energy
- A 20 % improvement in energy efficiency

2014 →

**Europe**
**2030 strategy**

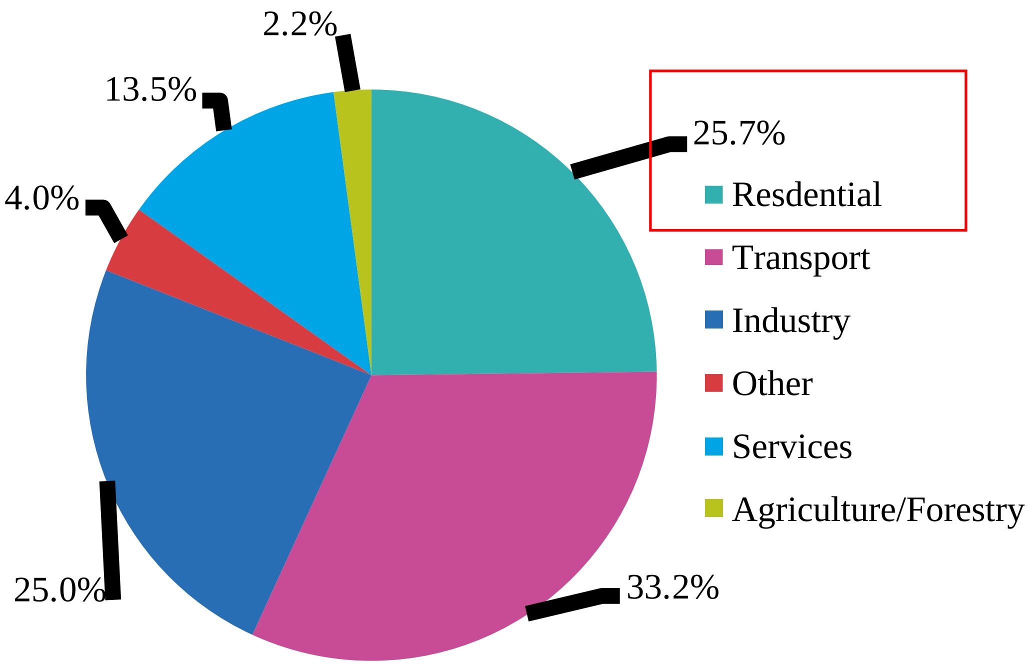
- At least a 40 % cut in GHG emissions (from 1990 levels)
- At least 32 % share for renewable energy
- At least a 32.5 % improvement in energy efficiency

# Primary energy consumption

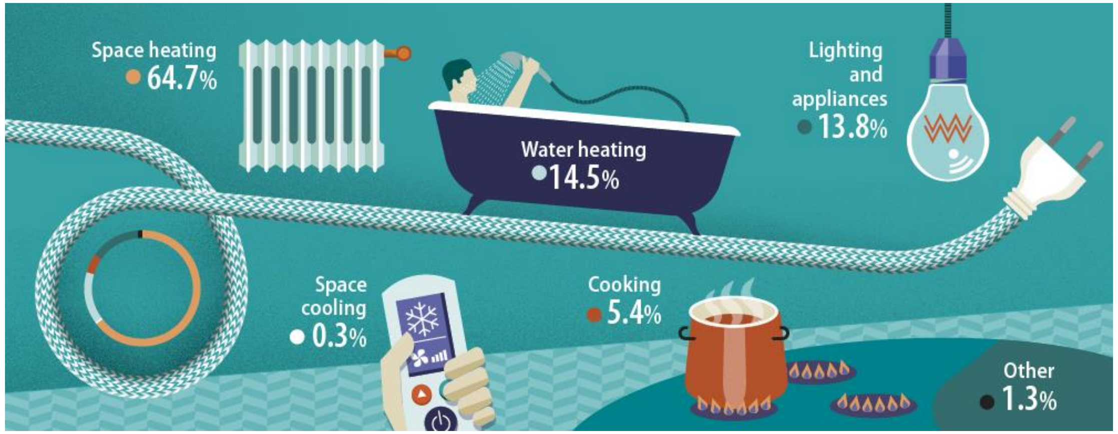



Source: Eurostat (online data code: nrg_ind_eff)

# Primary energy consumption



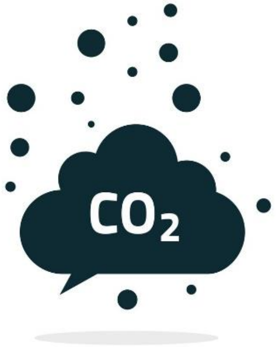

**Energy consumption by sector in the EU-28, 2016**




**Energy consumption in EU households (Source: Eurostat)**

# Transition toward sustainable energy

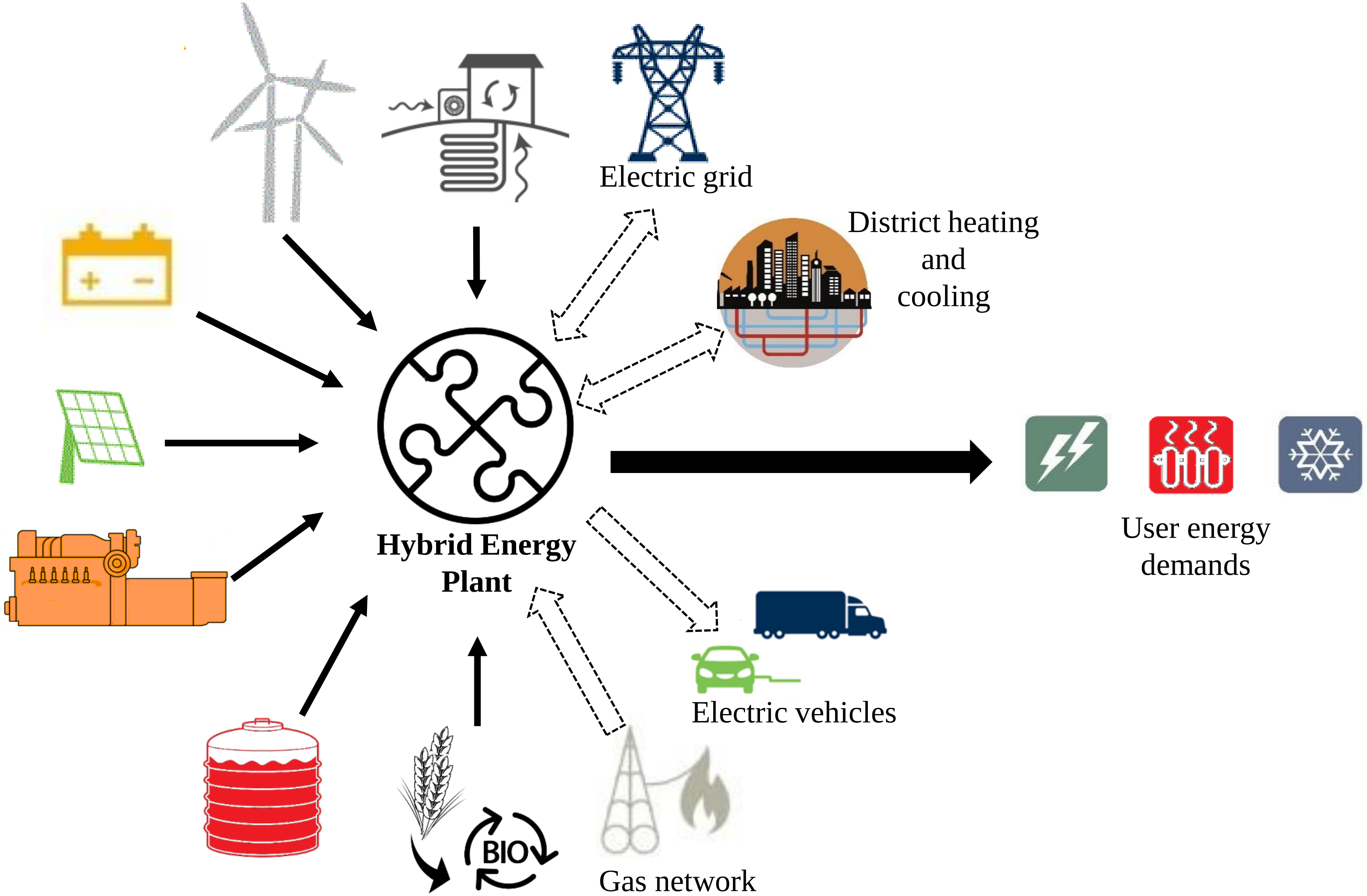
Moving from Fossil Fuel Dependence to a Clean-Energy Future



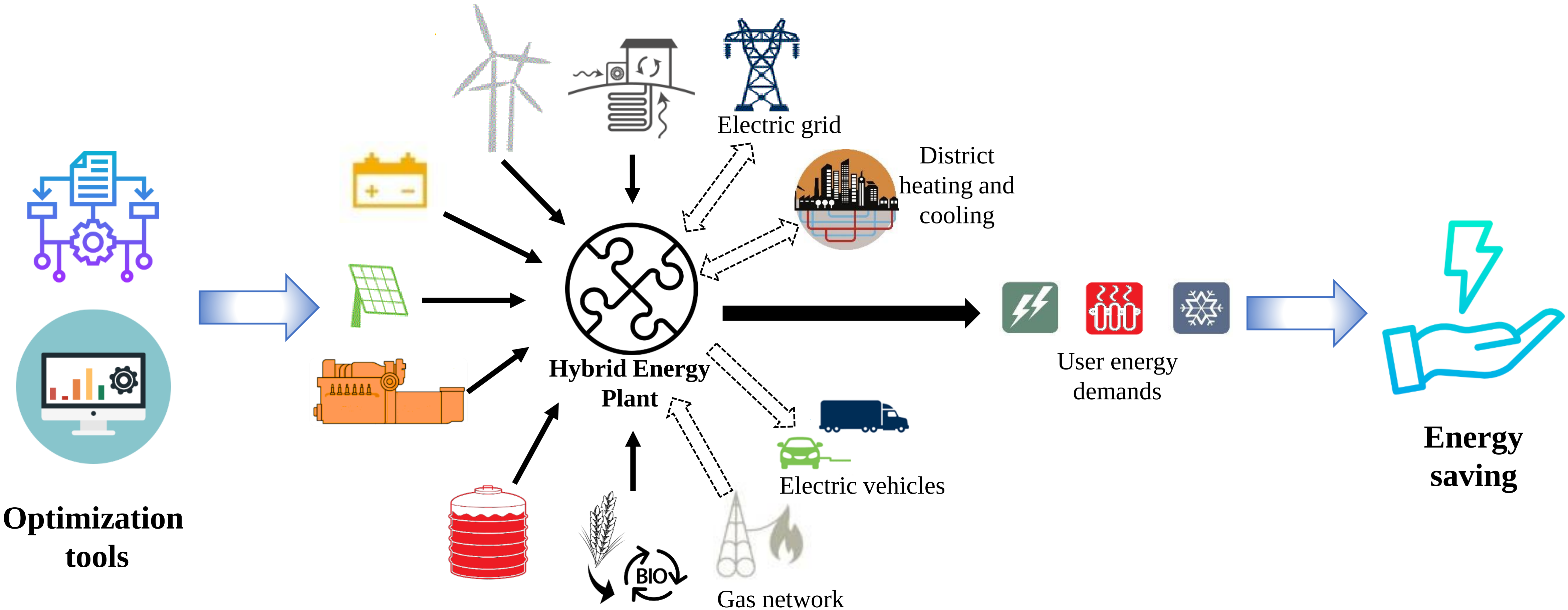

Environmental impacts

Intermittency

# Hybridization



# How to achieve as much as possible PE saving?



# Optimization of a Multi-Generation Energy System based on Life Cycle Assessment

# Methodology framework

## Input data

**Energy demands**
Heating, hot water, cooling, electricity, etc.

**Environmental data**
Ambient temperature, solar radiation, wind speed, etc.

**Technical data**
Systems' efficiencies, de-rating curves, start-up, etc.

**Economic & Emissions data**
Electricity and gas price, systems' costs, operational costs, operational emissions, etc.

## Energy plant model

**Energy systems models**
Photovoltaic, cogenerator, heat pump, gas boiler, etc.

**Storage technologies models**
Thermal energy storage, batteries, etc.

**Operation strategy**
Thermal demand following, electrical demand following, etc.

## Life cycle assessment

**Goal and scope definition:** Cradle-to gate LCA of energy systems in a range of sizes.

**Life cycle inventory:** Market analysis of energy systems, inventory compilation, inventory scaling.

**Life cycle impact assessment:** Impact categories definition, classification and characterization.

**Results:** Impacts curves vs. size, dominance analysis, sensitivity analysis.

## Design optimization

**Decision variables**
Energy systems' sizes

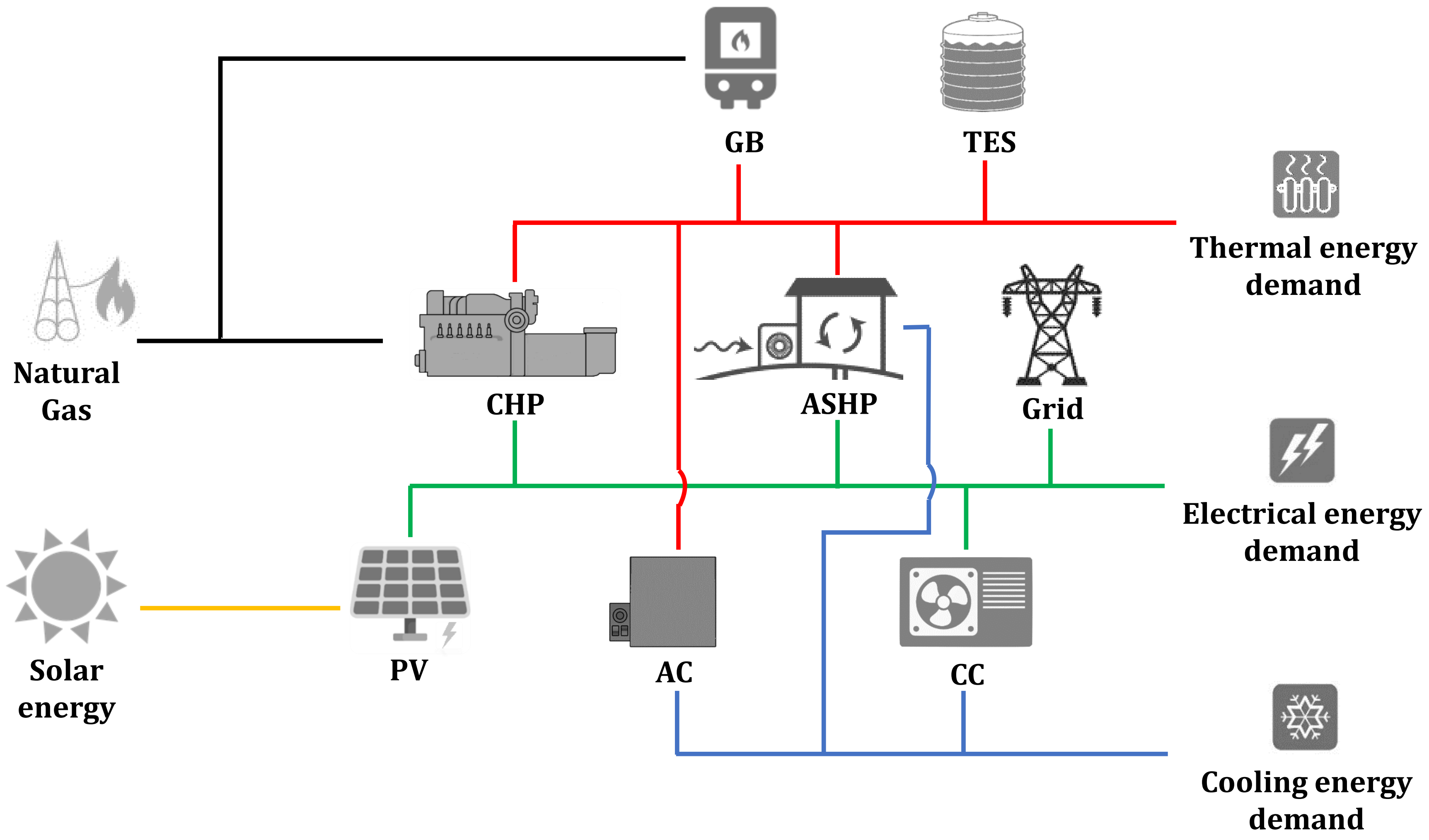
**Objective function**
life cycle costs,
Life cycle energy demand,
Life cycle emissions, etc.

**Constraints**
Energy balances,
net metering, operational constraints, etc.

**Optimization algorithm**
Genetic algorithm, particle swarm optimization, etc.

**Optimal design**

# Layout of the multi-generation energy system



# Energy balance

The thermal, cooling and electric energy demands are met by the HEP according to:

$$E_{\text{user,th,k}} = E_{\text{CHP,th}\rightarrow\text{user,k}} + E_{\text{GB,th}\rightarrow\text{user,k}} + E_{\text{ASHP,th,k}} + E_{\text{TES,th,out}\rightarrow\text{user,k}}$$

$$E_{\text{user,cool,k}} = E_{\text{ASHP,cool,k}} + E_{\text{CC,cool,k}} + E_{\text{AC,cool,k}}$$

$$E_{\text{user,el,k}} + E_{\text{ASHP,el,k}} + E_{\text{CC,el,k}} = E_{\text{PV,el,k}} + E_{\text{CHP,el,k}} + E_{\text{Grid,el,taken,k}}$$

# Objective function

The on-site PE is given by the fuel and electric energy used throughout the considered time frame (*i* is the time step):

$$PE_{\mathrm{op}} = \sum_{i=1}^{N} PE_{\mathrm{fuel,CHP}}(i) + PE_{\mathrm{fuel,AB}}(i) + PE_{\mathrm{E_{el,taken}}}(i) - PE_{\mathrm{E_{el,sent}}}(i)$$

The total CED is represented by the CED of the optimized technologies and the Italian grid:

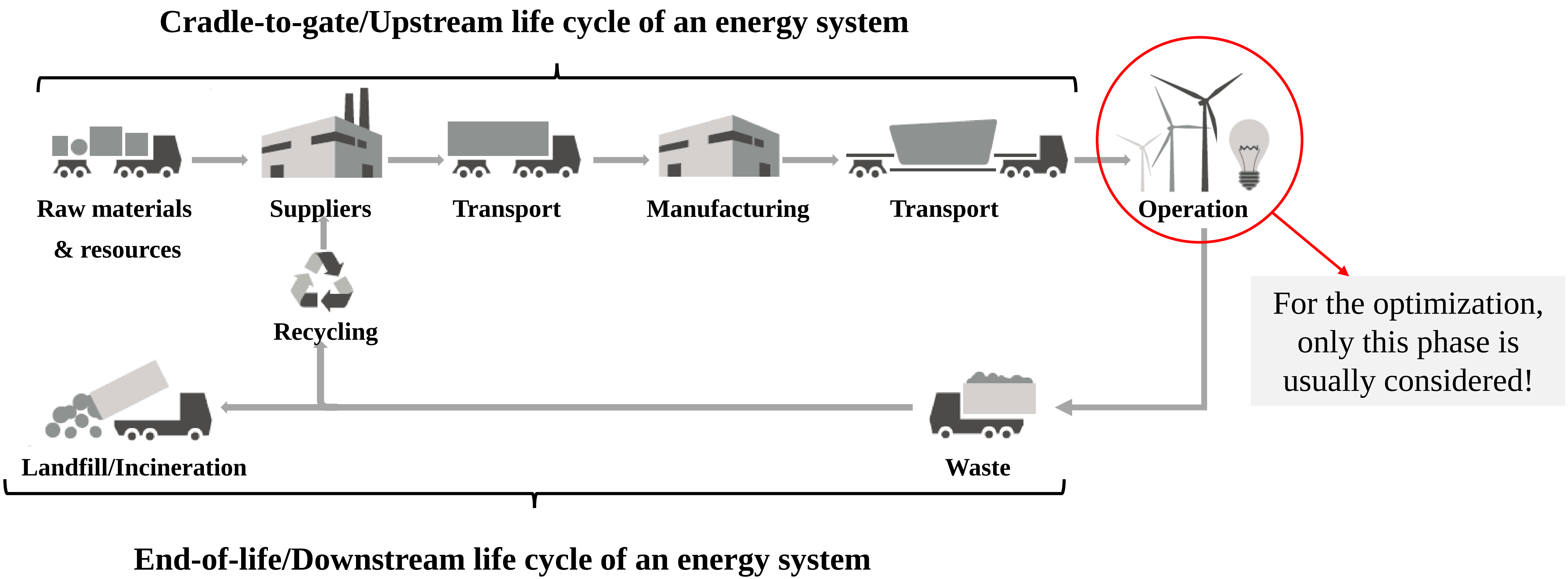
$$CED = \sum_{\mathrm{z}} \frac{CED_{\mathrm{z}}(P_{\mathrm{z}})}{lifetime(z)} + CED_{\mathrm{grid}}(El_{\mathrm{taken}}) + CED_{\mathrm{GN}}(V_{gas})$$

National grid

Gas network

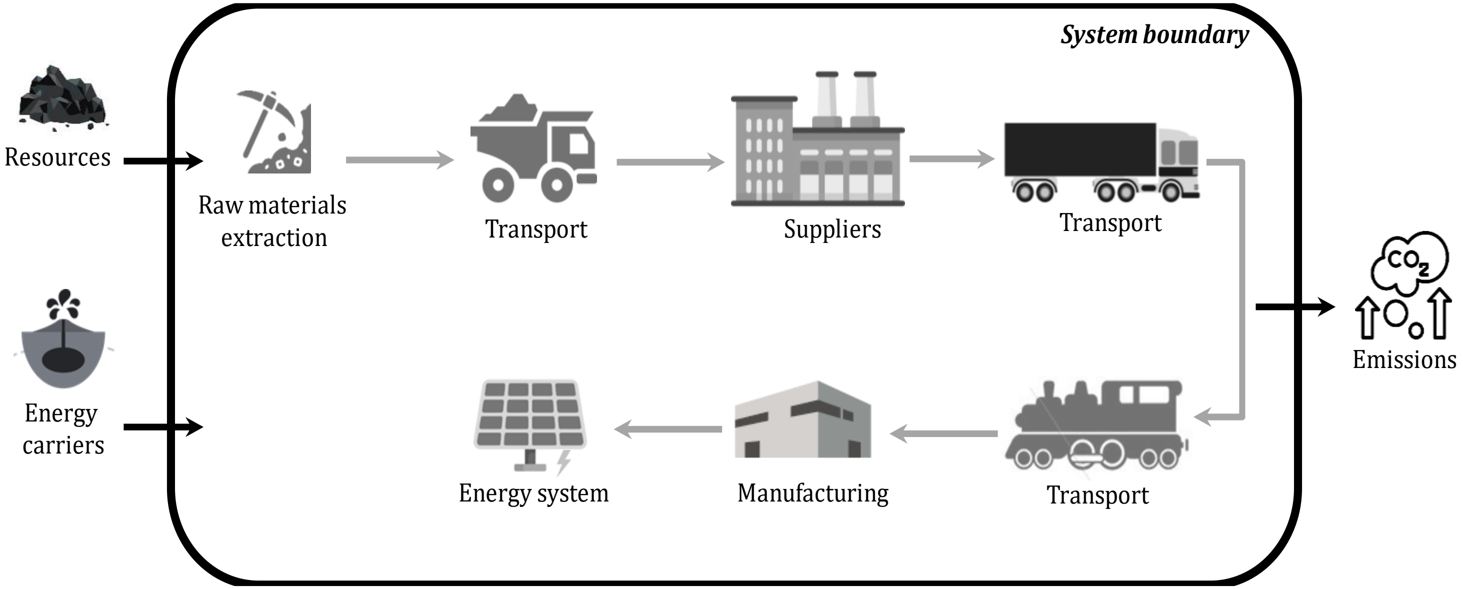
HEP components

# Why should we care about off-site PE consumption?



# Cradle-to-gate LCA

Off-site primary energy consumption are determined by carrying out a cradle-to-gate LCA




- Solar thermal collector (STC);
- Photovoltaic panel (PV);
- Combined heat and power (CHP);
- Ground source heat pump (GSHP);
- Air source heat pump (ASHP);
- Absorption chiller (ABS);
- Pellet boiler (PB);
- Hot water storage.

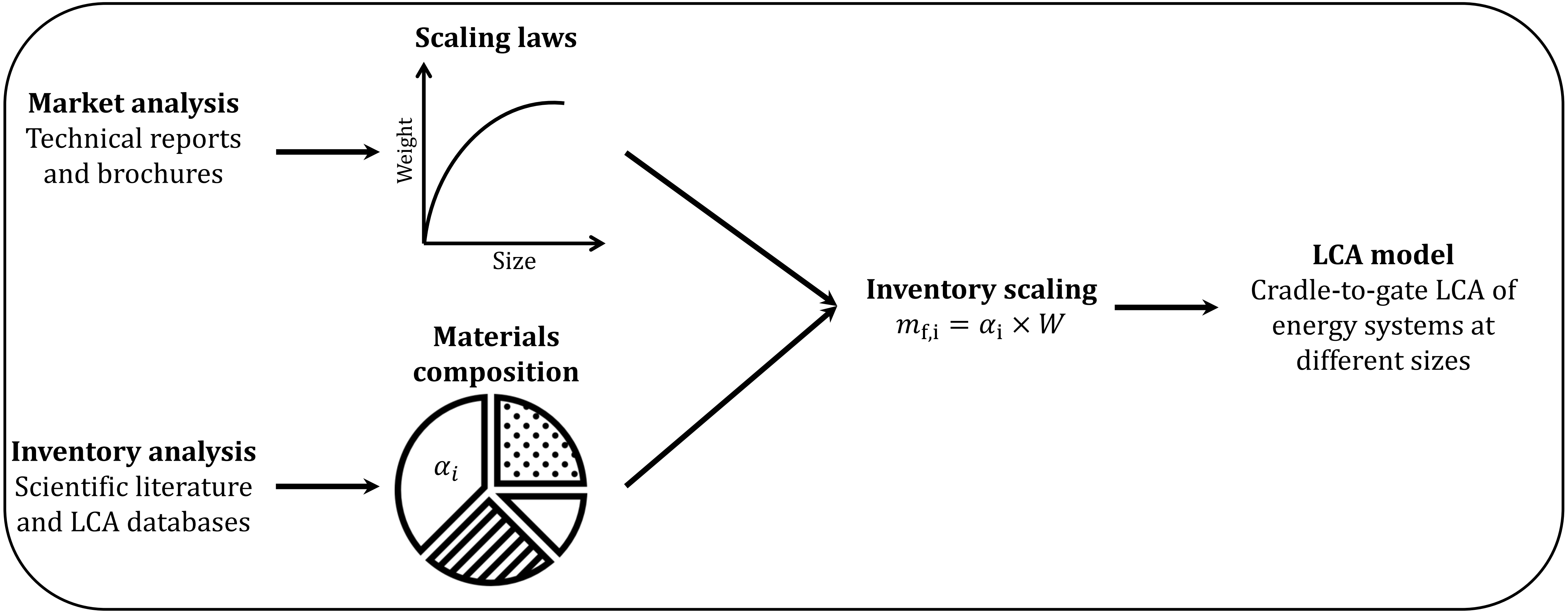
The primary energy consumed throughout the cradle-to-gate life cycle is represented by the Cumulative Energy Demand (CED)

# Modeling and data collection

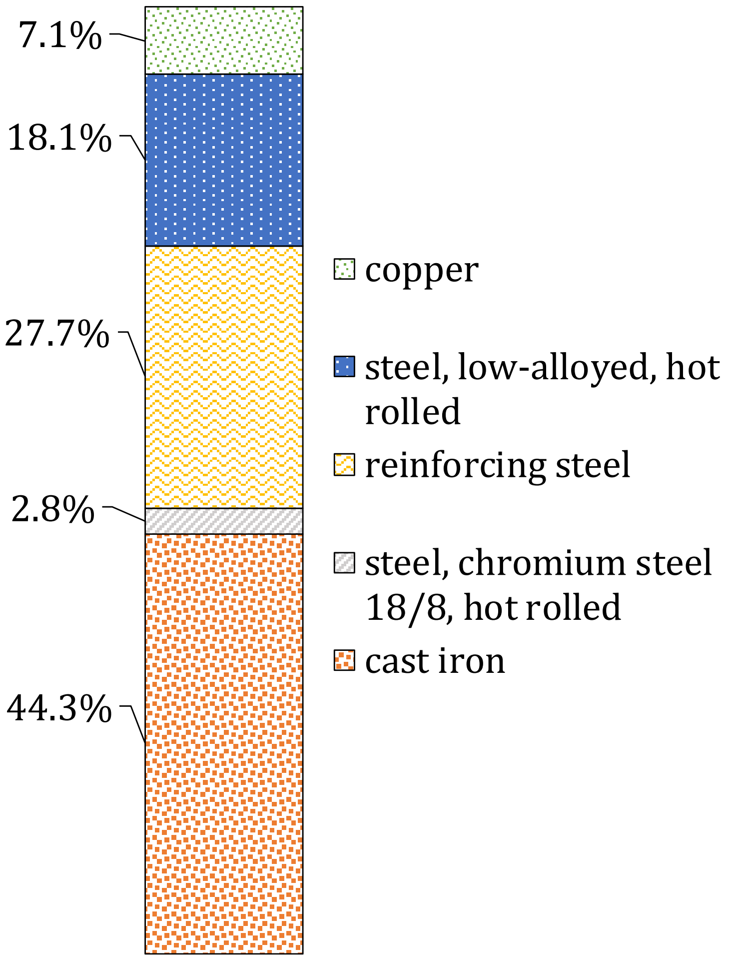
The LCI data were taken from the Ecoinvent® database considering a specific capacity with a focus on the European market.

A model for each system was constructed in openLCA®.

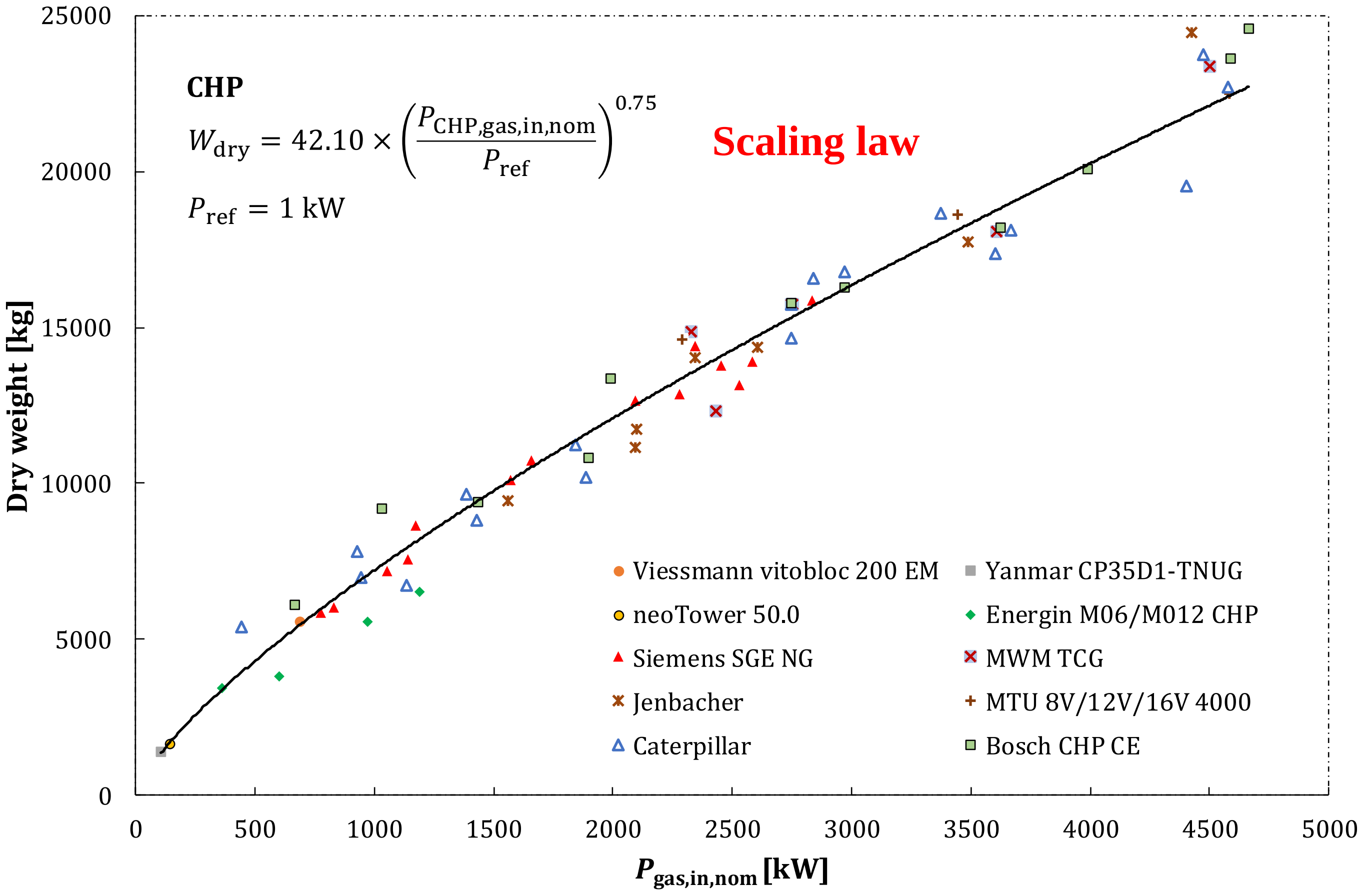
# Scaling of LCA



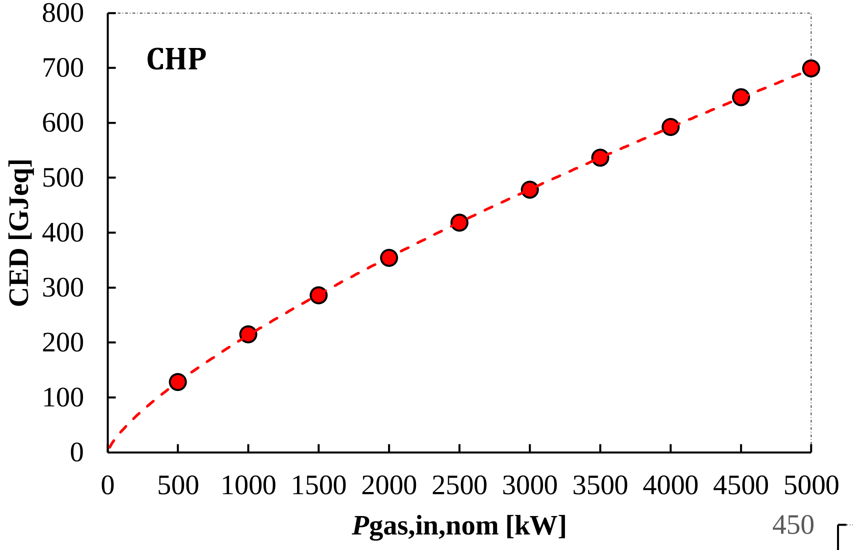
# Scaling of LCA

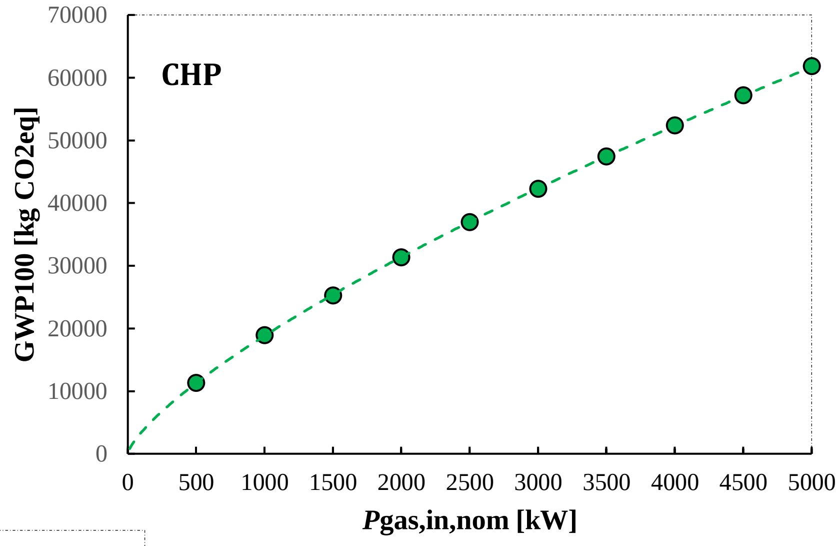


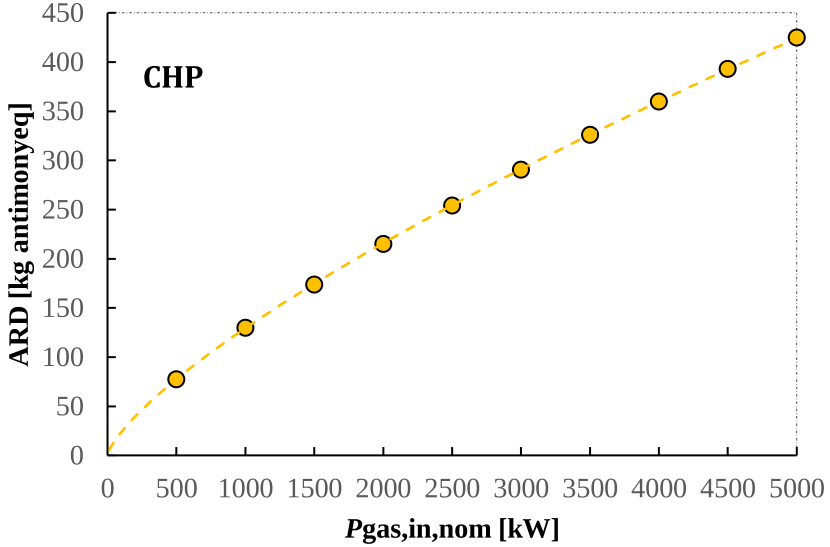

**Materials composition**



# CED impact curves vs. technology size



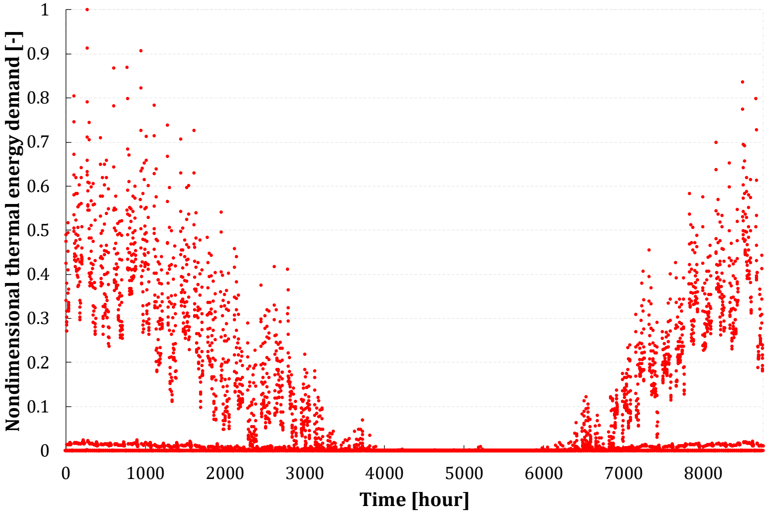



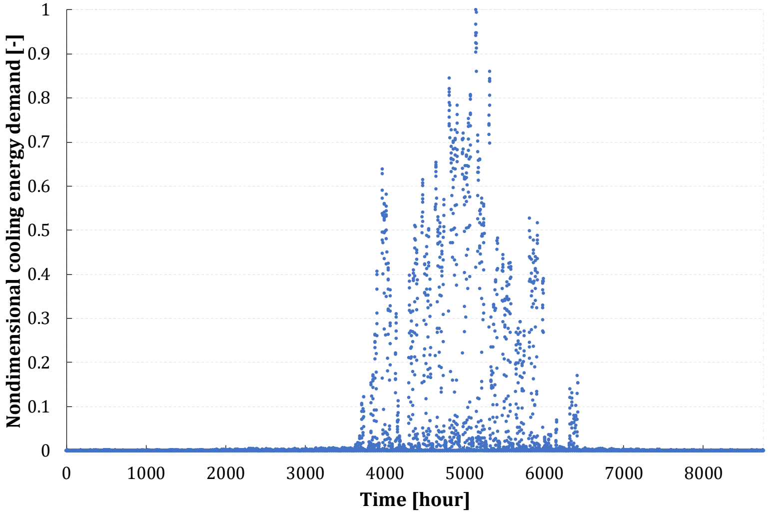



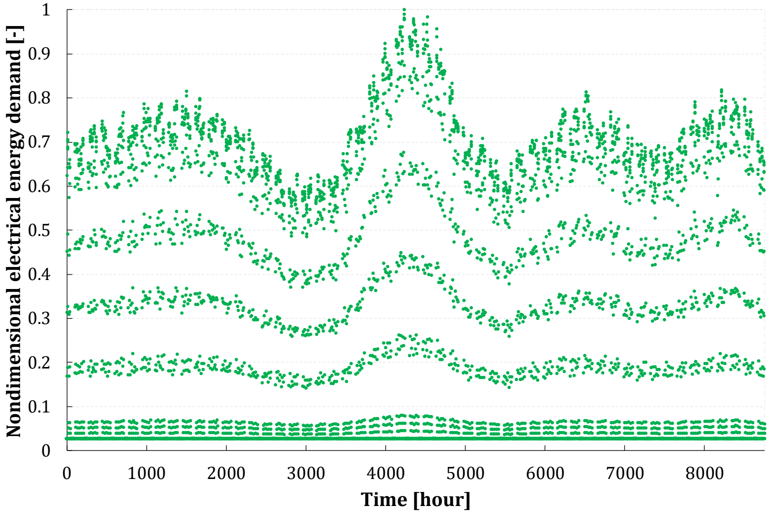

Department of Engineering Ferrara

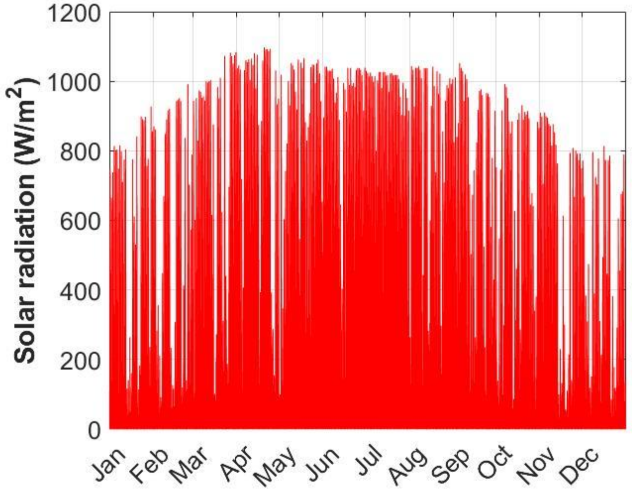
# Case study – University campus

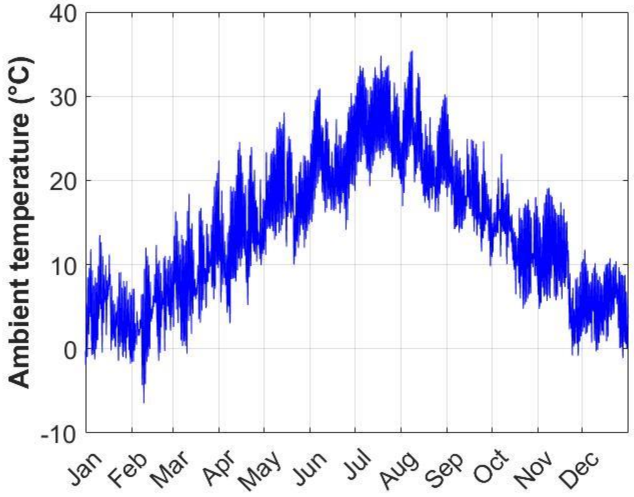
hourly heating, cooling and electric energy demands



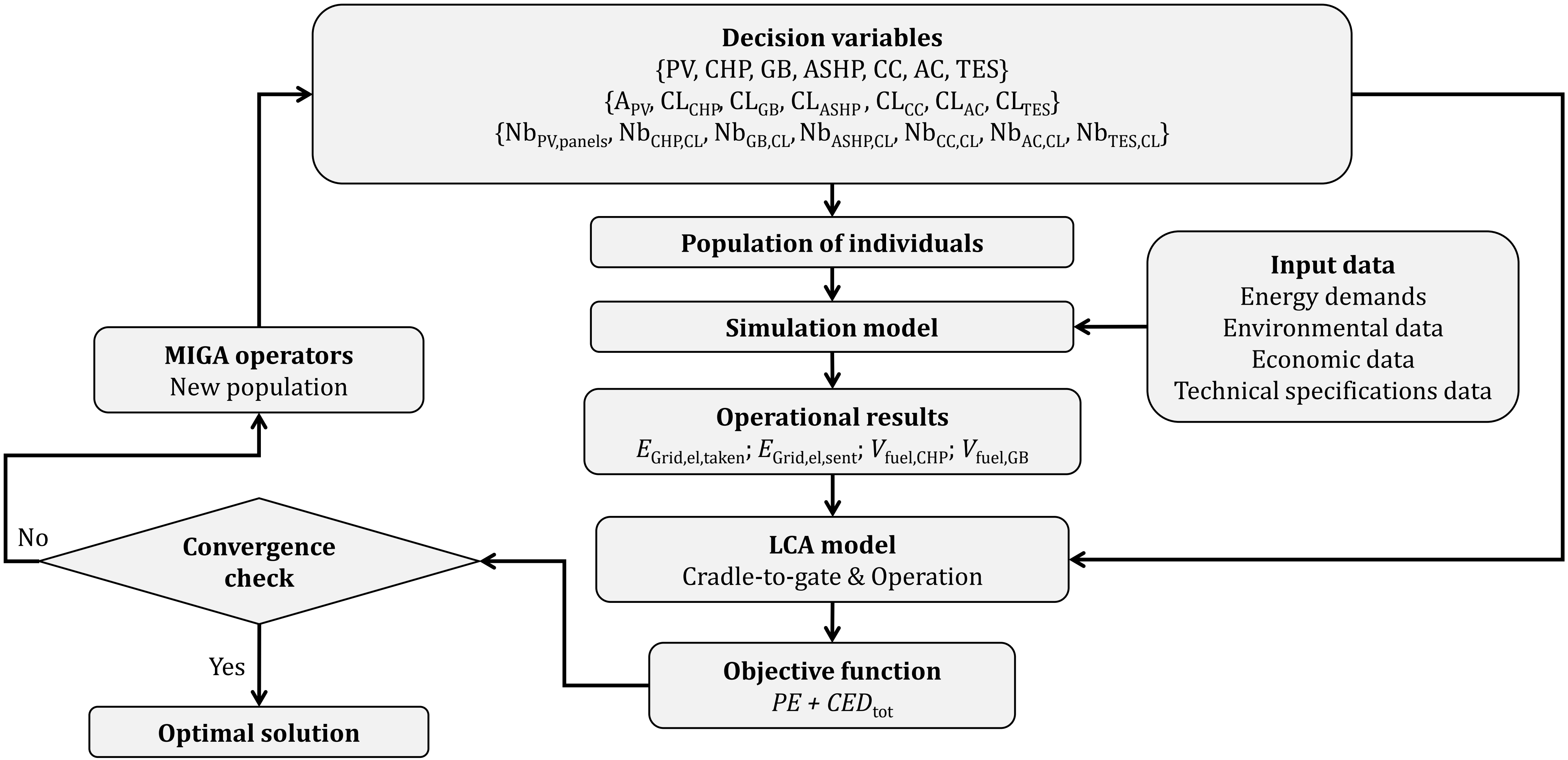



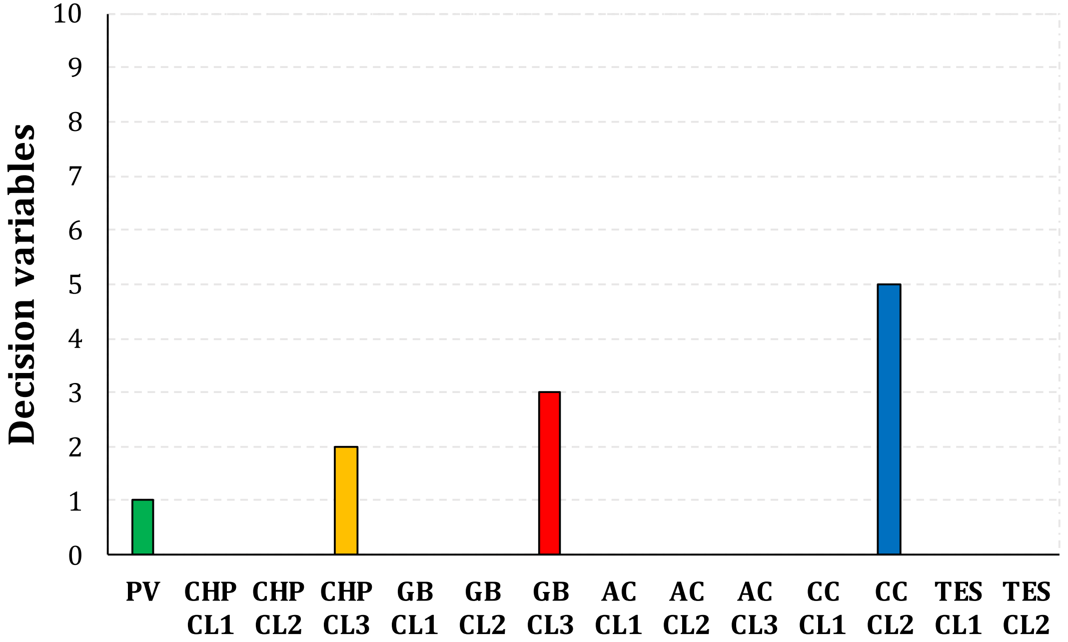



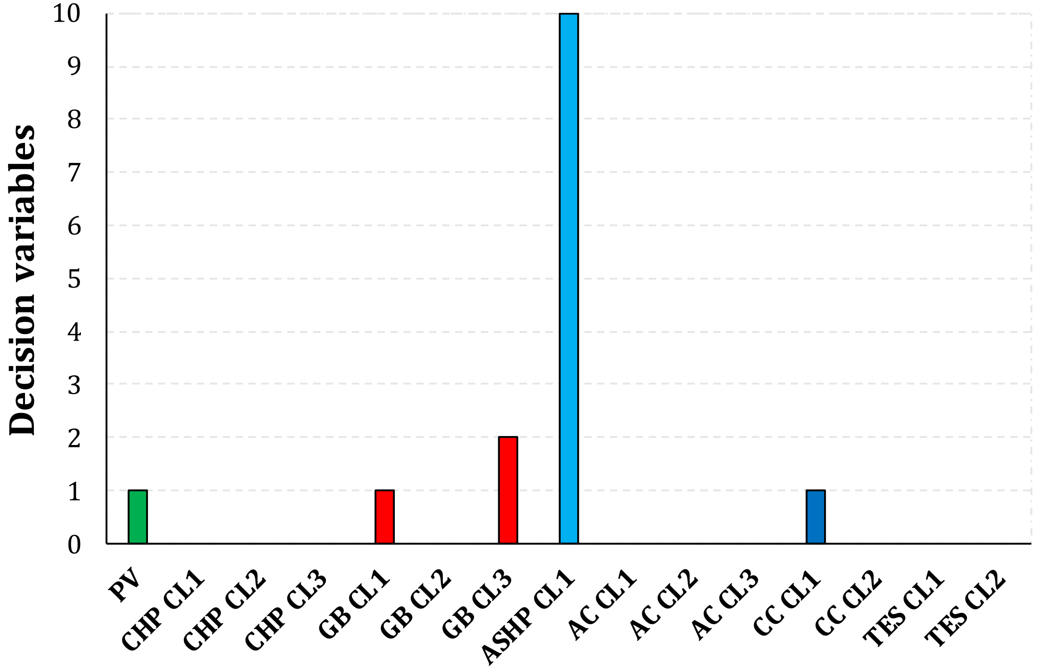



# Optimization – Genetic algorithm



# Optimization results (Sizes)

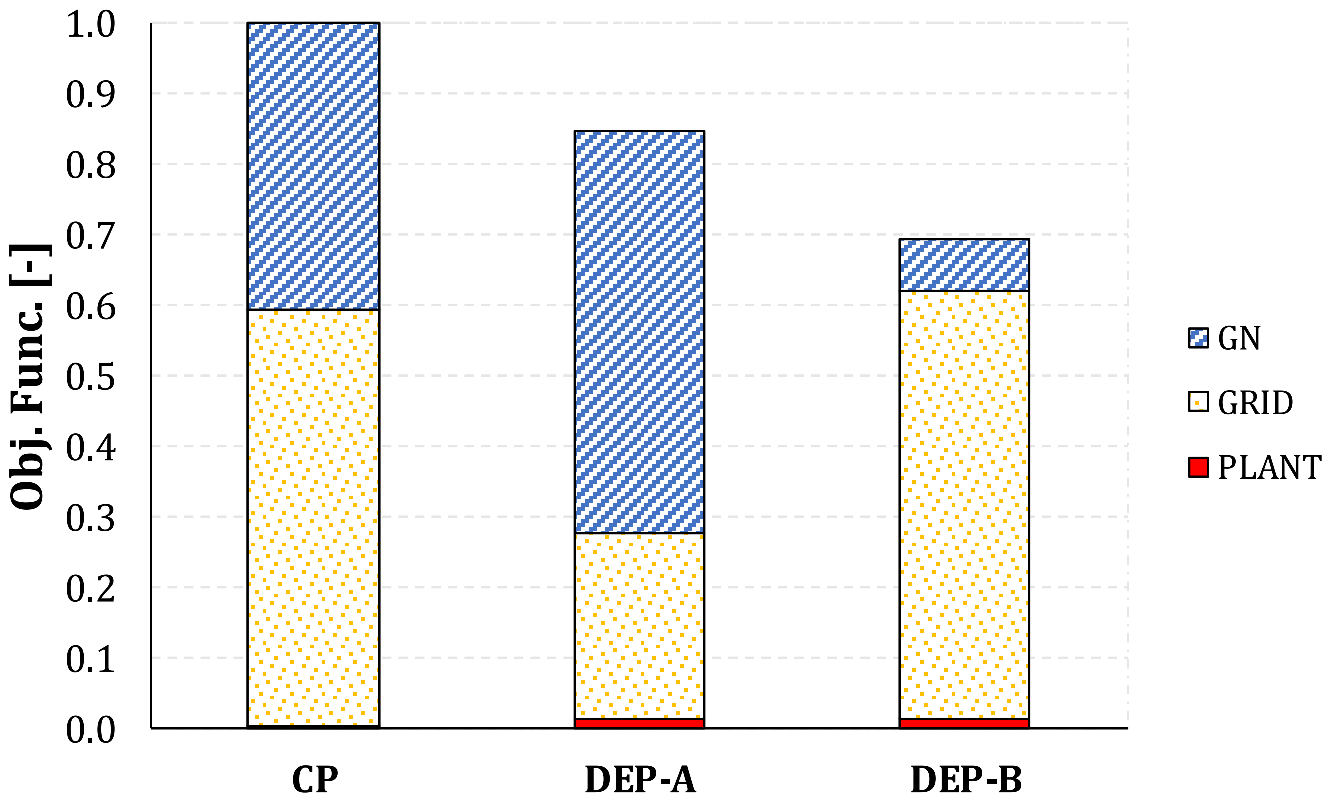


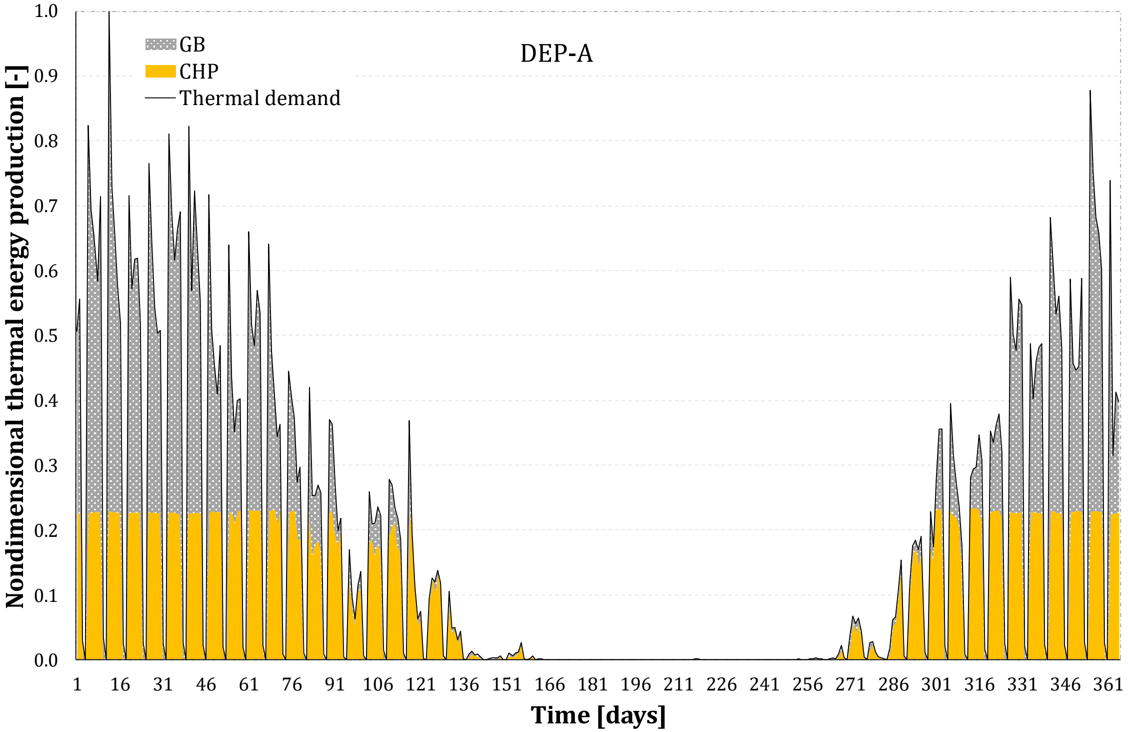

**Caso A:** i sistemi considerati sono fotovoltaico, cogeneratori, caldaie, frigoriferi ad assorbimento, frigoriferi a compressione e accumulo termico

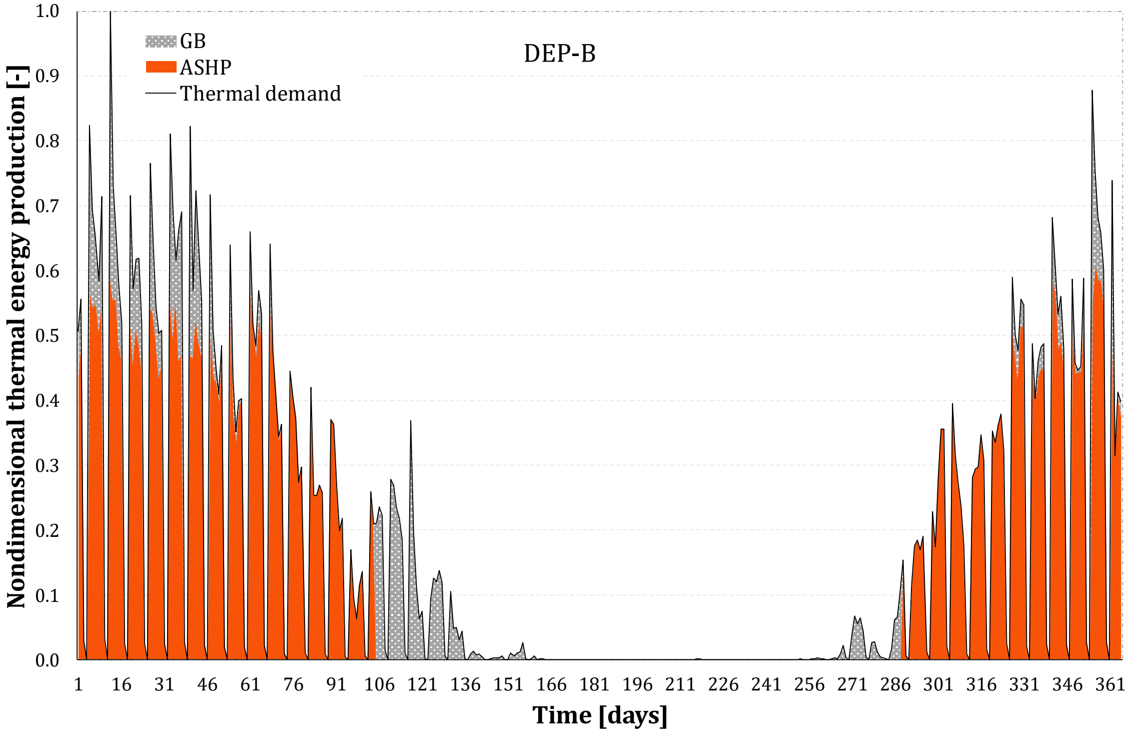
**Caso B:** rispetto al caso A, in questo caso c'è anche la possibilità di integrare delle pompe di calore

# Optimization results (Objective function)

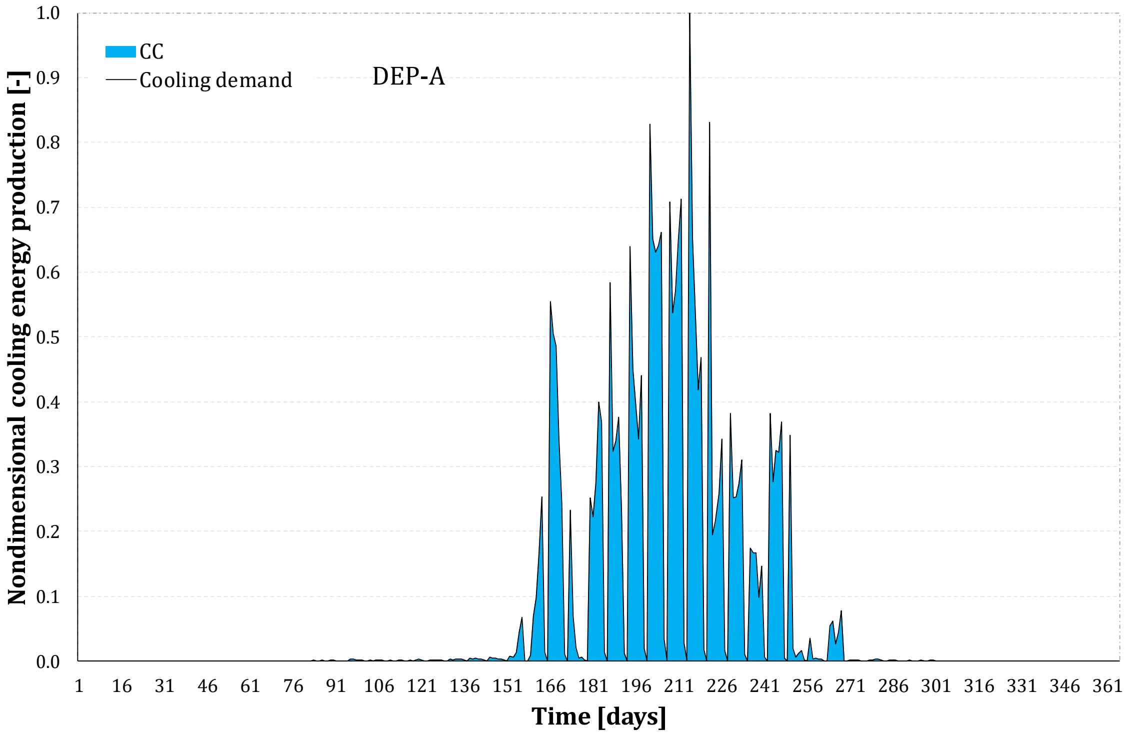


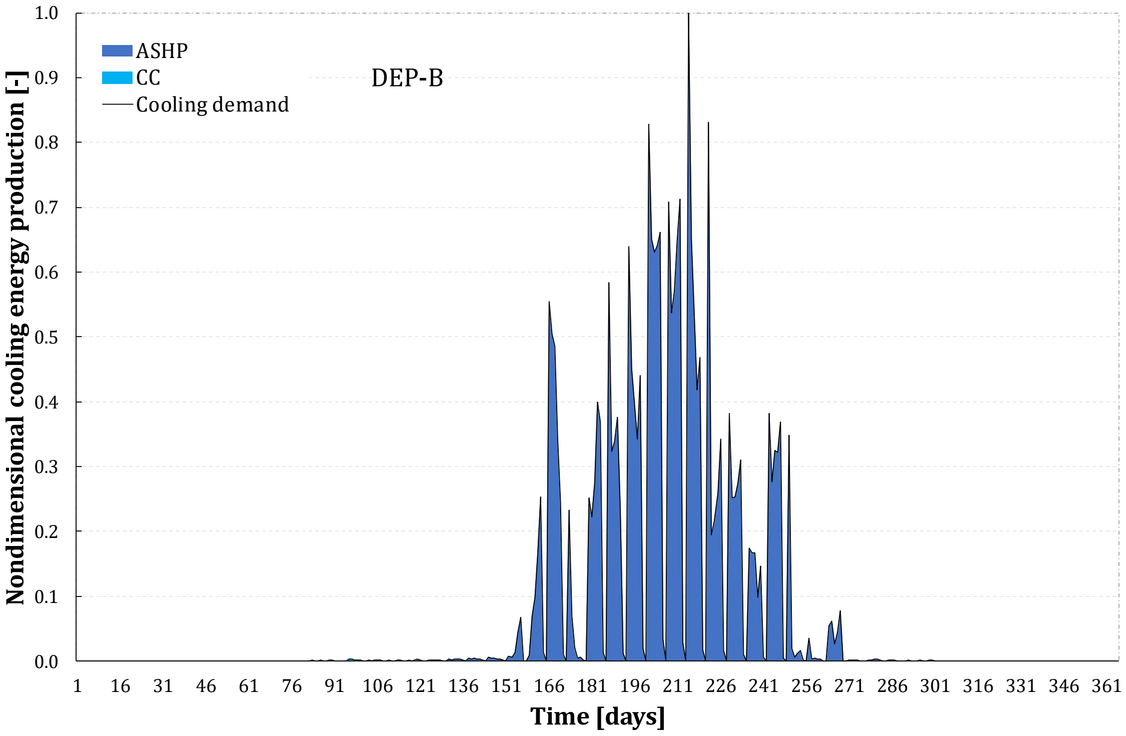
# Optimization results (Thermal energy production)



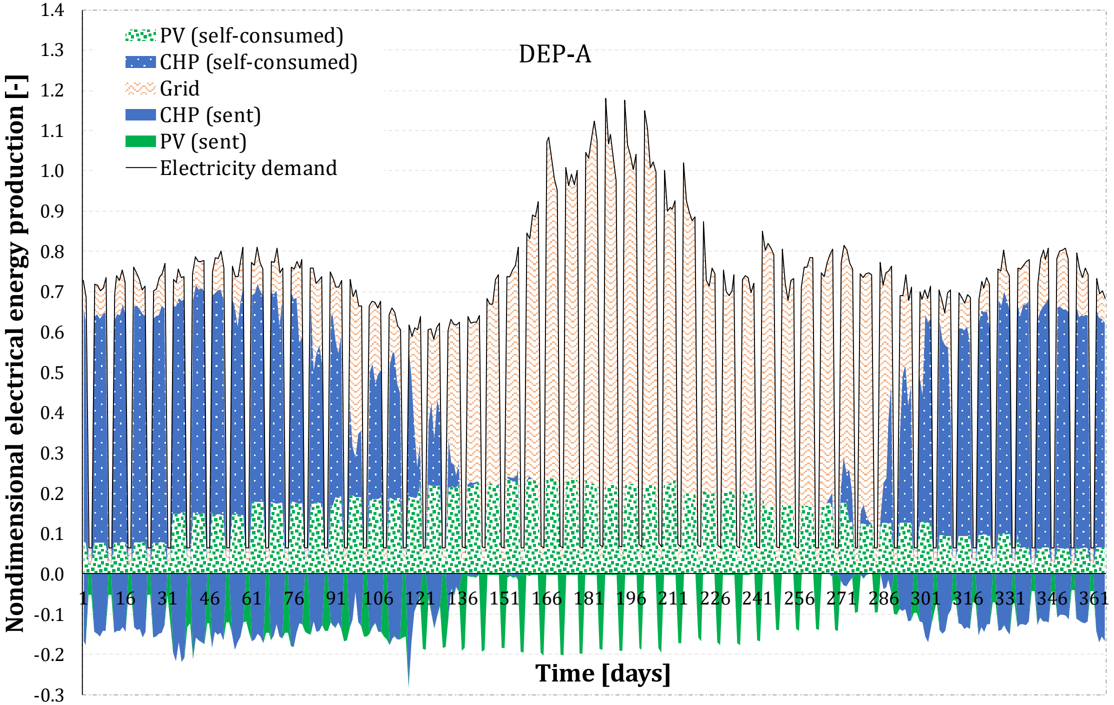



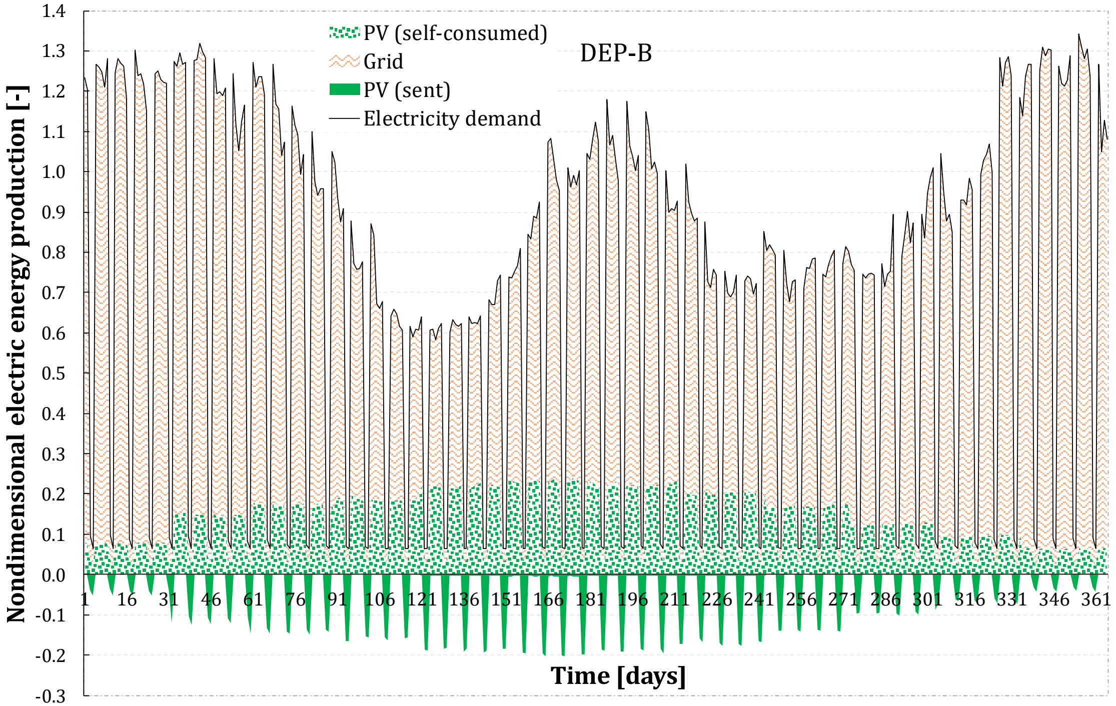
# Optimization results (Cooling energy production)



# Optimization results  (Electrical energy production)

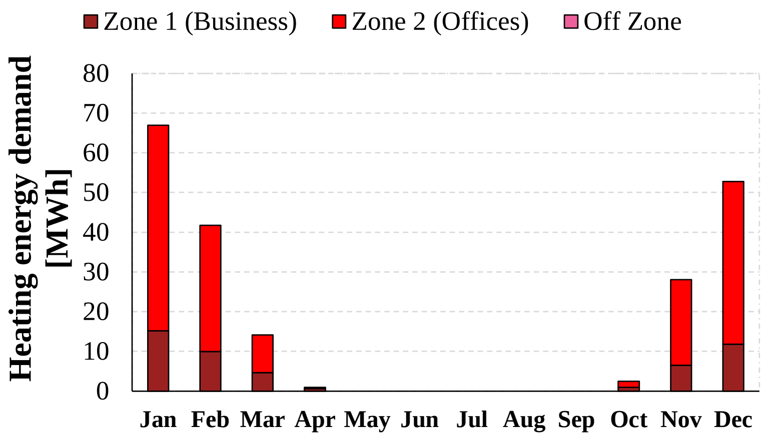


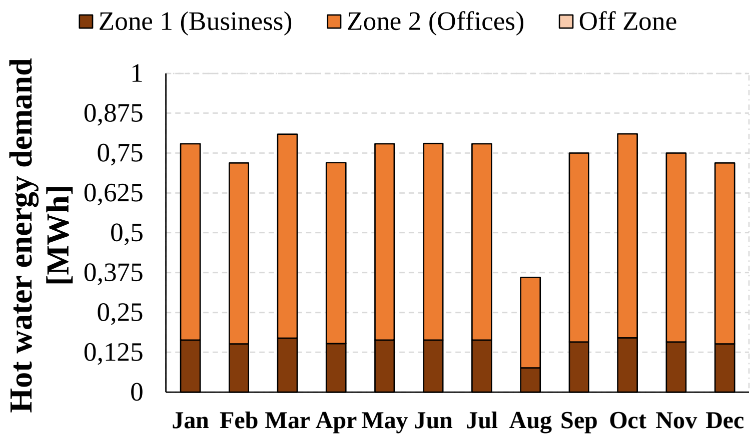



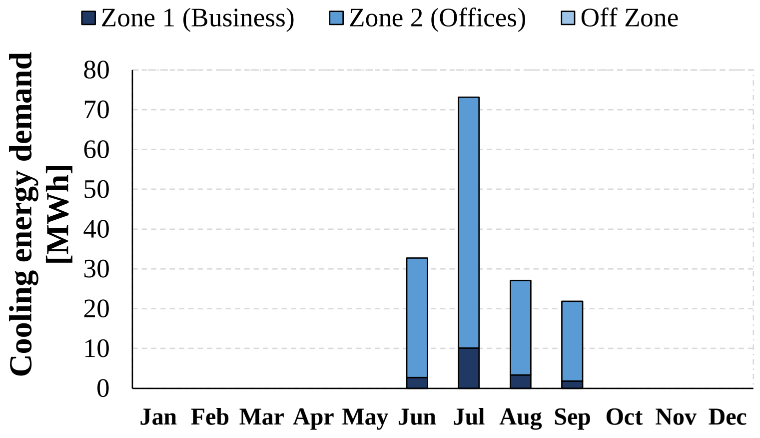
# Why should we consider LCA in the optimization process?

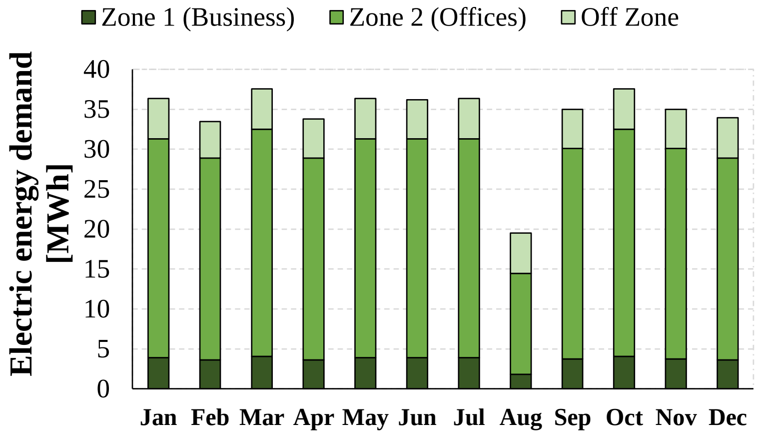
# Case study – Office building

Monthly heating, hot water, cooling and electric energy demands

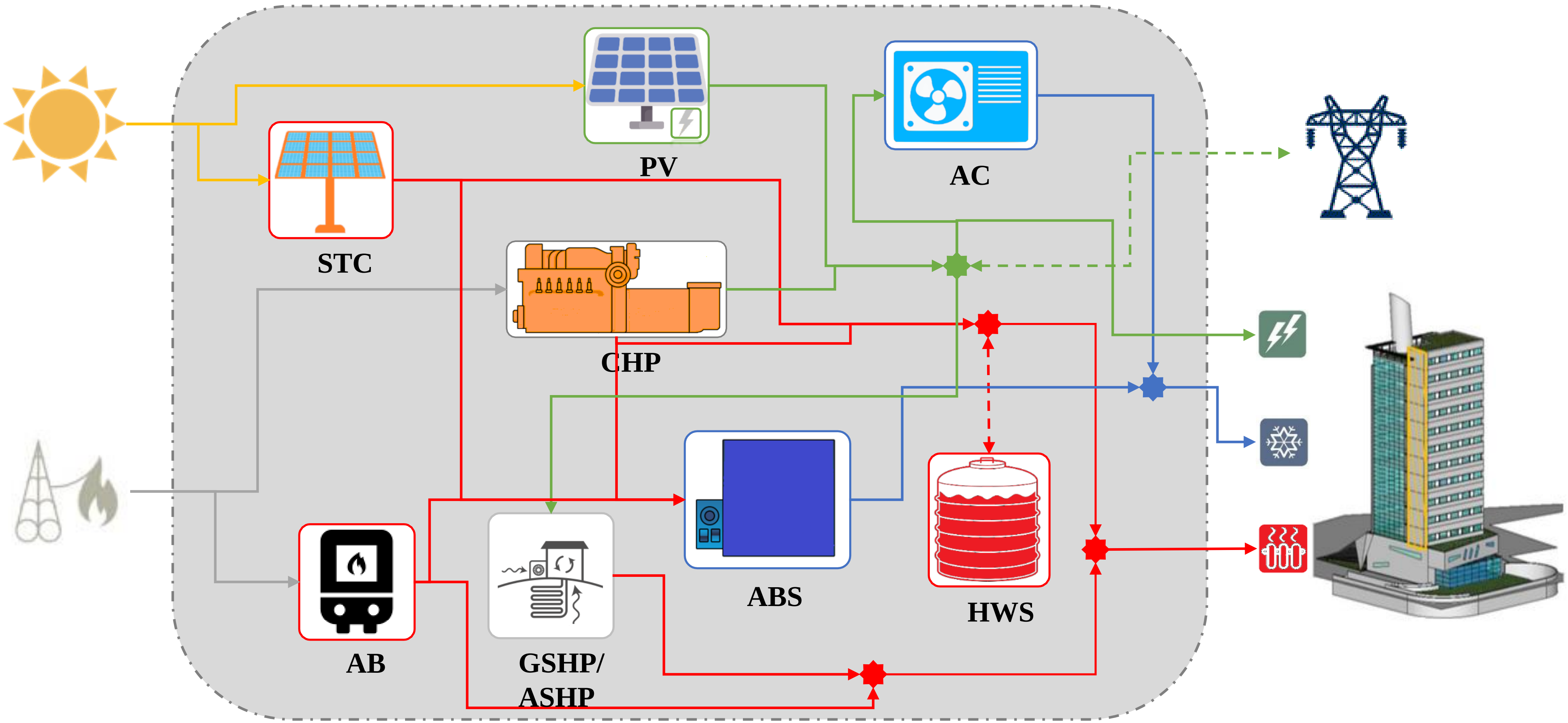



# Multi-Generation Energy System



# Energy balance

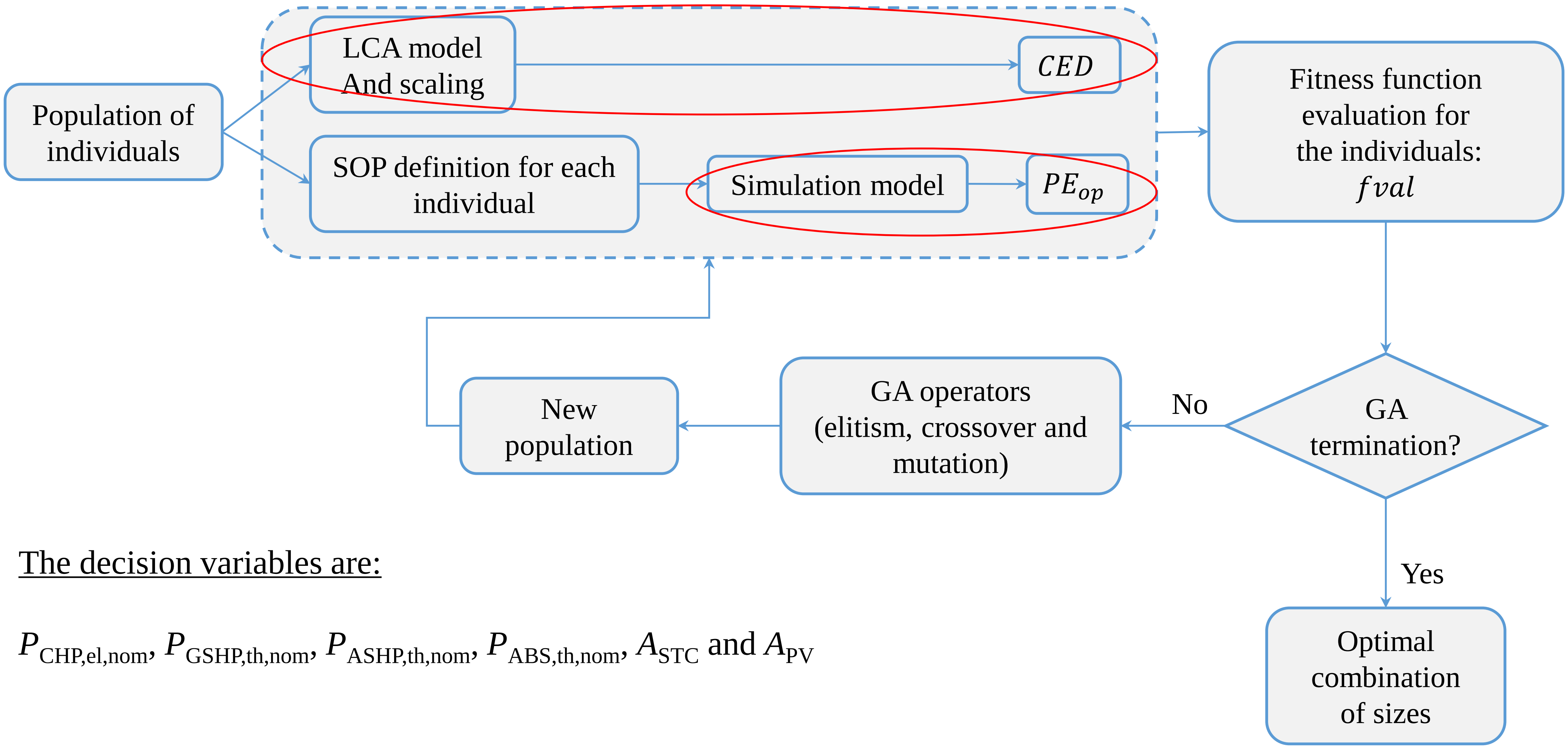
The thermal, cooling and electric energy demands are met by the HEP according to:

$$E_{\mathrm{th}}(i) = E_{\mathrm{STC,th}}(i) + E_{\mathrm{CHP,th}}(i) + E_{\mathrm{GSHP,th}}(i) + E_{\mathrm{ASHP,th}}(i) + E_{\mathrm{storage,th}}(i) + E_{\mathrm{AB,th}}(i)$$

$$E_{\mathrm{cool}}(i) = E_{\mathrm{GSHP,cool}}(i) + E_{\mathrm{ASHP,cool}}(i) + E_{\mathrm{ABS,cool}}(i) + E_{\mathrm{AC,cool}}(i)$$

$$E_{\mathrm{el}}(i) + E_{\mathrm{GSHP,el}}(i) + E_{\mathrm{ASHP,el}}(i) + E_{\mathrm{AC,el}}(i) = E_{\mathrm{PV,el}}(i) + E_{\mathrm{CHP,el}}(i) + E_{\mathrm{grid,el}}(i)$$

# Optimization




<u>The decision variables are:</u>

$P_{\mathrm{CHP,el,nom}}$, $P_{\mathrm{GSHP,th,nom}}$, $P_{\mathrm{ASHP,th,nom}}$, $P_{\mathrm{ABS,th,nom}}$, $A_{\mathrm{STC}}$ and $A_{\mathrm{PV}}$

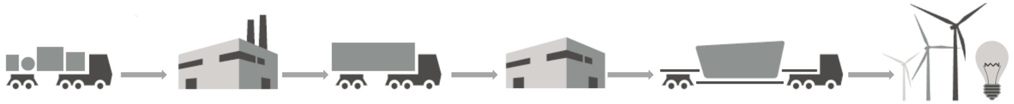
# “LCA not integrated” vs. “LCA integrated”

**Two approaches are considered**

## “LCA not integrated” approach


The primary energy consumption is minimized throughout the operation phase

## “LCA integrated” approach




<u>The objective function is represented by:</u>

$$fval = PE_{op}$$

<u>The objective function is represented by:</u>

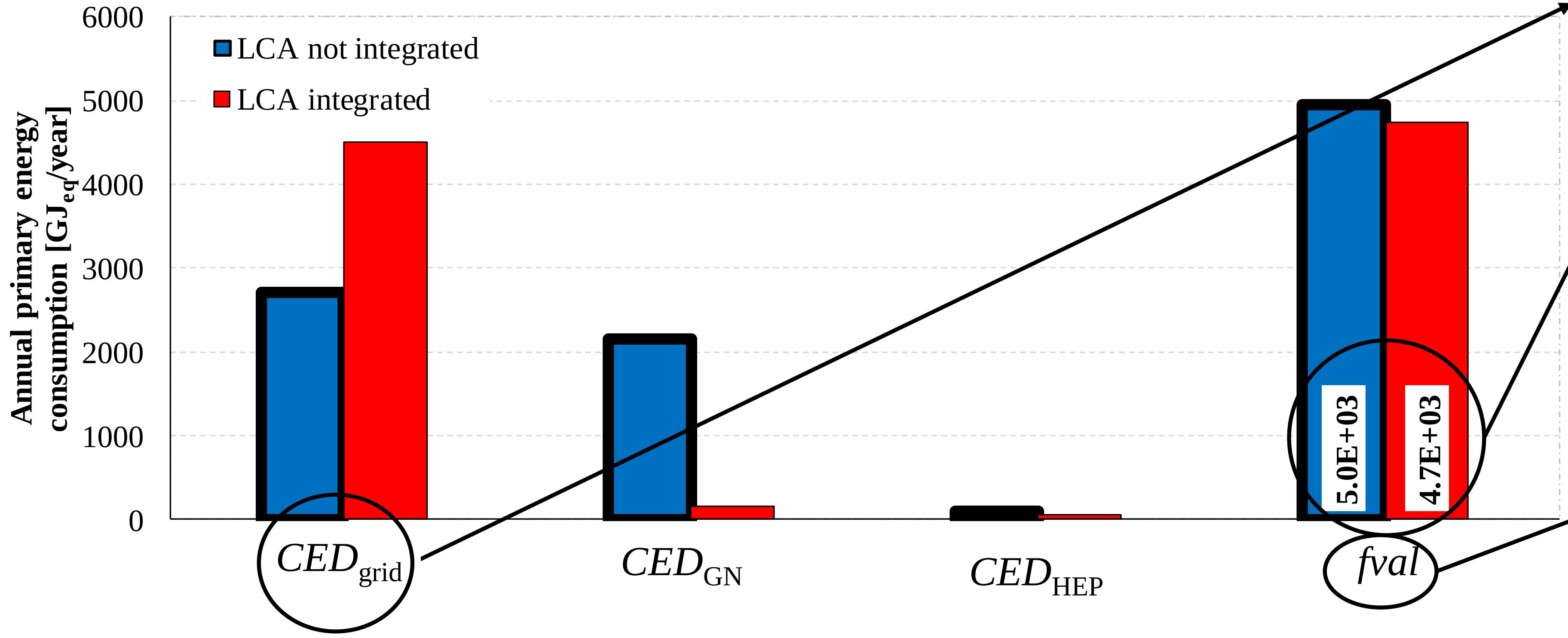
$$fval = PE_{op} + CED$$

# Optimization results

| Decision variables | LCA not integrated | LCA integrated |
|---|---|---|
| $A_{STC}$ [$m^2$] | 40.2 | 77.5 |
| $A_{PV}$ [$m^2$] | 287.8 | 249.9 |
| $P_{CHP,el,nom}$ [$kW_e$] | 93 | 0 |
| $P_{GSHP,th,nom}$ [$kW_{th}$] | 300 | 243 |
| $P_{ASHP,th,nom}$ [$kW_{th}$] | 65 | 92 |
| $P_{ABS,th,nom}$ [$kW_{th}$] | 156.1 | 0 |
| $V_{storage}$ [l] | 892.6 | 248.1 |

The two approaches ("LCA not integrated" and "LCA integrated") provide two different combinations of sizes.

# Optimization results



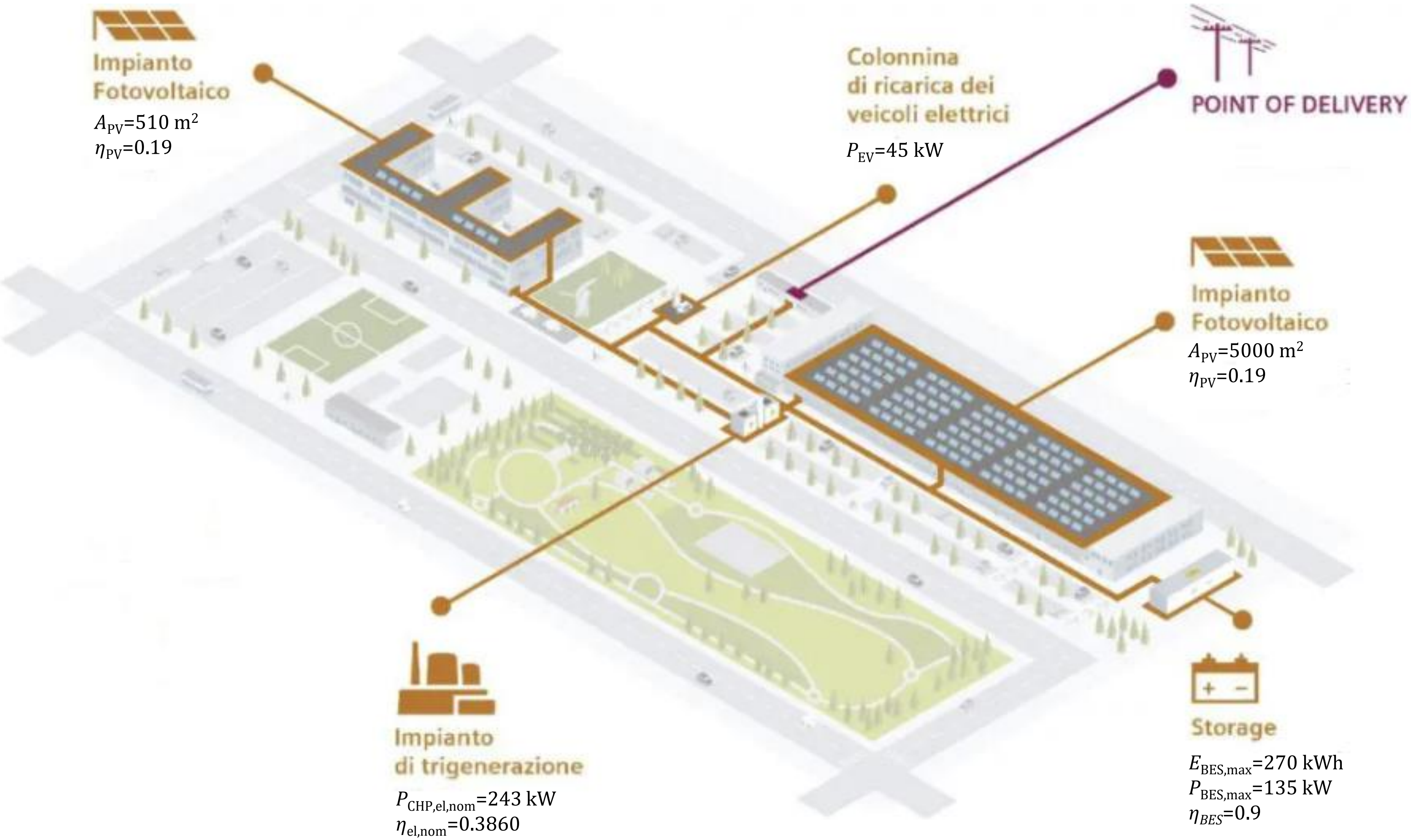

The contribution of the grid represented by $CED_{grid}$ has the largest effect on the optimization results.

The integration of LCA may lead to a higher primary energy saving (about 4.4 %)

The total primary energy consumption

# Optimization of the operation of a micro-grid

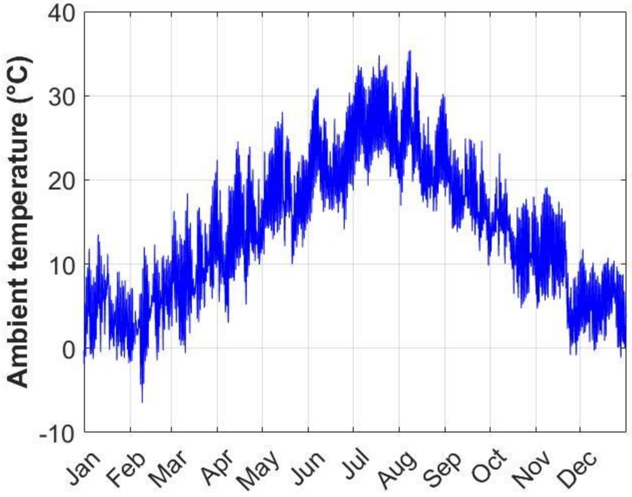
# Micro-grid



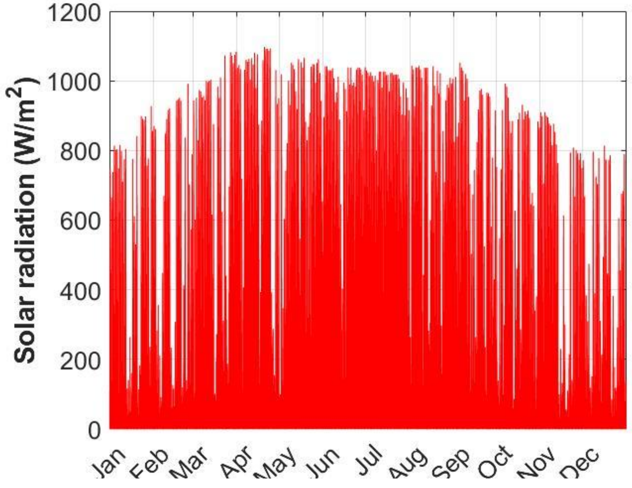
Impianto
Fotovoltaico
$A_{PV}$=510 m$^2$
$\eta_{PV}$=0.19
Colonnina
di ricarica dei
veicoli elettrici
$P_{EV}$=45 kW
POINT OF DELIVERY
Impianto
Fotovoltaico
$A_{PV}$=5000 m$^2$
$\eta_{PV}$=0.19
Impianto
di trigenerazione
$P_{CHP,el,nom}$=243 kW
$\eta_{el,nom}$=0.3860
Storage
$E_{BES,max}$=270 kWh
$P_{BES,max}$=135 kW
$\eta_{BES}$=0.9

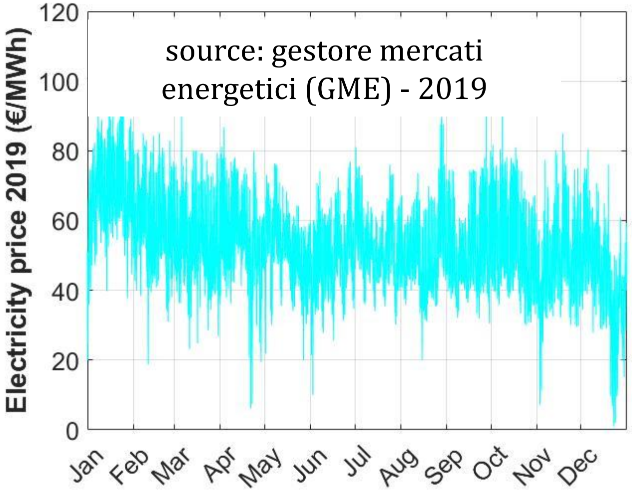
# Environmental and economic data

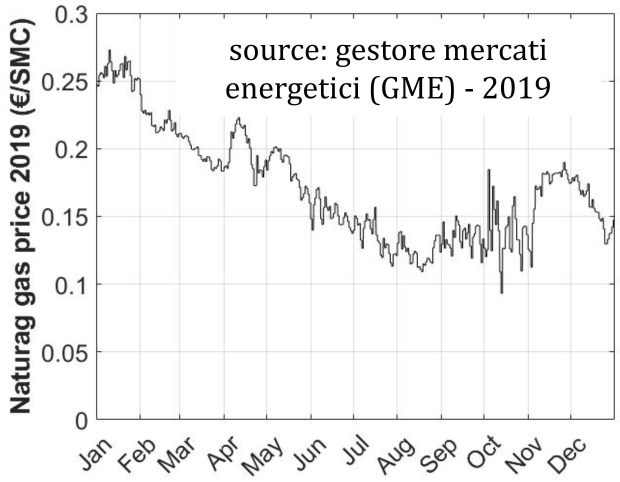
Ambient temperature for Milan-Italy
(source: https://ec.europa.eu/jrc/en/pvgis)




Solar radiation for Milan-Italy
(source: https://ec.europa.eu/jrc/en/pvgis)

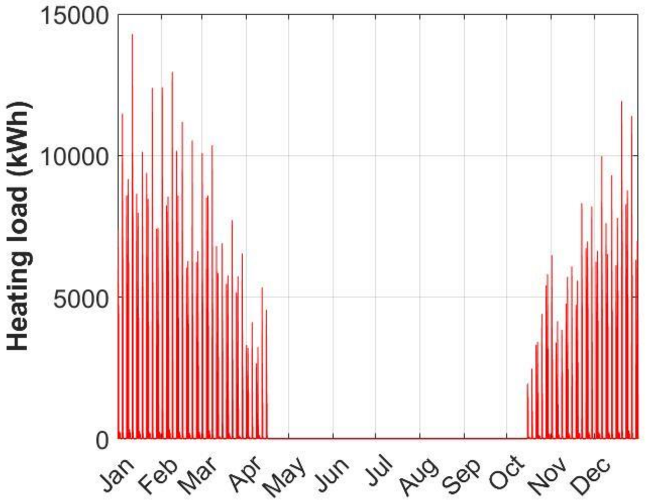


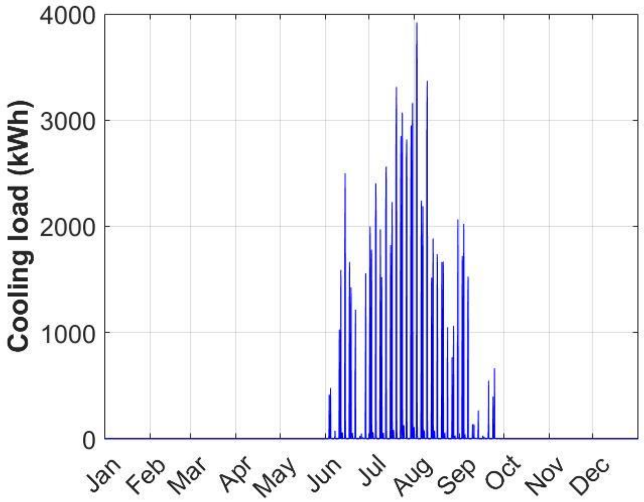



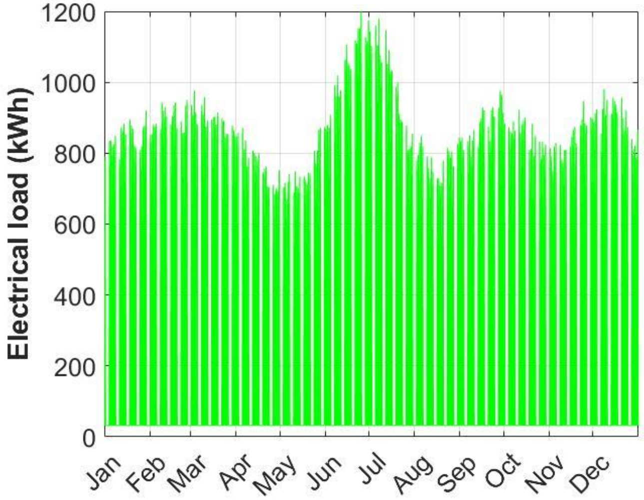



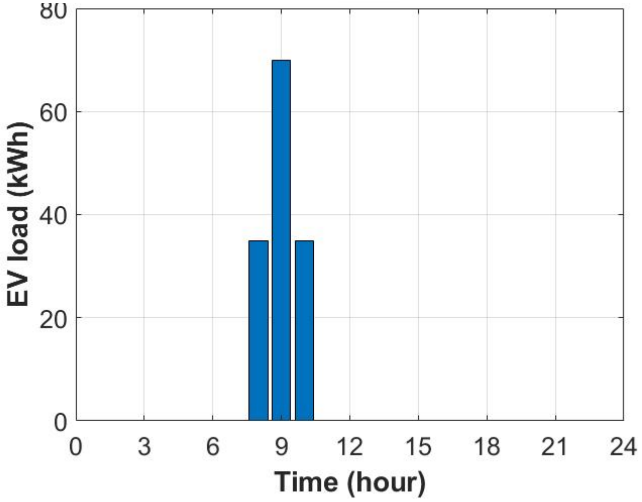
# Energy loads

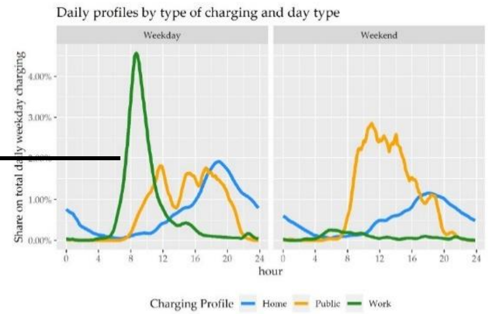
The heating, cooling and electric loads of the case study



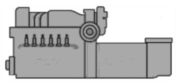



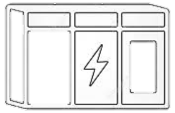

**source:** Noussan et al. (2020), *energies*, 13, 2527

# Decision variables

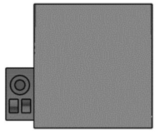
$$\begin{cases} P_{el,PV\to load,t} & continuous \\ P_{el,PV\to BES,t} & continuous \\ P_{el,PV\to grid,t} & continuous \end{cases}$$



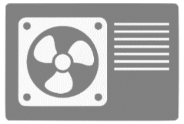
$$\begin{cases} P_{el,CHP,t} & continuous \\ P_{th,CHP\to load,t} & continuous \\ P_{th,CHP\to AC,t} & continuous \\ P_{th,CHP\to TES,t} & continuous \\ isON_t & integer \\ start_t & integer \end{cases}$$



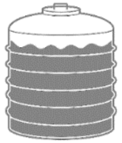
$$\begin{cases} SoC_{BES,t} & continuous \\ P_{el,BES\to EV,t} & continuous \\ P_{el,BES\to load} & continuous \end{cases}$$



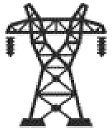
$P_{cool,AC,t}$ $\quad$ *continuous*



$$\begin{cases} P_{cool,ASHP,t} & continuous \\ P_{th,ASHP,t} & continuous \end{cases}$$



$$\begin{cases} SoC_{TES,t} & continuous \\ P_{th,TES\to load} & continuous \\ P_{th,TES\to AC} & continuous \end{cases}$$



$$\begin{cases} P_{el,grid\to load,t} & continuous \\ P_{el,grid\to EV,t} & continuous \end{cases}$$

- The problem has 18 continuous variables and 2 integer variables.
- The operational variables must be optimized over one year (8760 hours).
- The total number of variables is (18+2)×8760 =175200.
- Since continuous and integer variables are present, the problem can be formulated as a Mixed-Integer Linear Programming (MILP).
- The objective function and problem constraints must be linear!
- In this project, the scheduling problem has been solved in Matlab.

# Problem constraints

$P_{el,PV\rightarrow load,t} + P_{el,CHP\rightarrow load,t} + P_{el,BES\rightarrow load,t} + P_{el,grid\rightarrow load,t} = P_{el,load,t} + P_{el,DRP,t} \quad \forall\, t \in T$ ← **Electrical load balance**

$P_{th,CHP\rightarrow load,t} + P_{el,TES\rightarrow load,t} + P_{th,ASHP,t} = P_{th,load,t} \quad \forall\, t \in T$ ← **Thermal load balance**

$P_{cool,AC,t} + P_{cool,ASHP,t} = P_{cool,load,t} \quad \forall\, t \in T$ ← **Cooling load balance**

$P_{el,BES\rightarrow EV,t} + P_{el,grid\rightarrow EV,t} = P_{el,EV,t}$ ← **EV load balance**

$-DRP_{max} \times P_{el,load,peak,day} \leq P_{el,DRP,t} \leq DRP_{max} \times P_{el,load,peak,day}$ ← **The increase/decrease should be less than a % of the daily peak load (*DRP*$_{max}$=10%; 20%; 30%)**

$\sum_{t=1}^{day} P_{el,DRP,t} = 0$ ← **The overall load over a certain time (day=24 h) remains fixed**

# Problem constraints

$P_{el,PV\rightarrow load,t} + P_{el,PV\rightarrow BES,t} + P_{el,PV\rightarrow grid,t} \leq P_{el,EV,t}$ ⟵ **Balance of PV production**

$P_{el,CHP,t} \leq isON_t \times P_{el,CHP,max,t}$ ⟵ **Maximum CHP production**

$P_{el,CHP,t} \geq isON_t \times P_{el,CHP,min,t}$ ⟵ **Minimum CHP production**

$isON_t - isON_{t-1} \leq start_{\,t}$ ⟵ **CHP startup**

$P_{el,PV\rightarrow grid,t} \leq P_{el,PV,tot,t}$ ⟵ **Maximum power sent to the grid**

$P_{th,CHP,t} = k_1 \times isON_t + k_2 \times P_{el,CHP,t}$ ⟵ **CHP thermal power as function of power de-rating**

$P_{fuel,CHP,t} = k_3 \times isON_t + k_4 \times P_{el,CHP,t} + start_t \times P_{fuel,CHP,startup}$ ⟵ **CHP fuel consumption as function of power de-rating and startup**

$SoC_{TES,t} = SoC_{TES,t-1} + P_{th,CHP\rightarrow TES,t-1} \times \Delta t - \left(P_{th,TES\rightarrow load,t-1} + P_{th,TES\rightarrow AC,t-1}\right) \times \Delta t$ ⟵ **State of charge of the thermal storage**

$SoC_{BES,t} = SoC_{BES,t-1} + P_{el,PV\rightarrow BES,t-1} \times \eta_{BES} \times \Delta t - \left(\left(P_{el,BES\rightarrow load,t-1} + P_{el,BES\rightarrow EV,t-1}\right) / \eta_{BES}\right) \times \Delta t$ ⟵ **State of charge of the batteries**

$P_{el,BES\rightarrow load,t} + P_{el,BES\rightarrow EV,t} \leq P_{el,BES,max}$ ⟵ **Maximum discharging power of the batteries**

$P_{el,PV\rightarrow BES,t} \times \Delta t \leq Capacity_{el,BES,max}$ ⟵ **Maximum charging power of the batteries**

$P_{el,grid\rightarrow load,t} + P_{el,grid\rightarrow EV,t} \leq \left(P_{el,load,t} + P_{el,EV,t}\right)$ ⟵ **Maximum power taken from the grid**

# Objective function

$$Op.costs = \sum_{t=1}^{T=8760} C_{CHP,t} + C_{O\&M,ASHP+AC,t} + C_{el,grid,taken,t} - C_{el,grid,sent,t}$$

← Operational costs over one year of operation

$$C_{CHP,t} = C_{fuel,t}(P_{CHP,el,t}) + C_{startup,t}(P_{CHP,el,t}) + C_{emis,t}(P_{CHP,el,t}) + C_{O\&M,t}(P_{CHP,el,t})$$

← Operational costs of the CHP

$$C_{el,grid,taken,t} = (PUN_t + \Delta PUN) \times P_{el,grid \rightarrow load} \times \Delta t$$

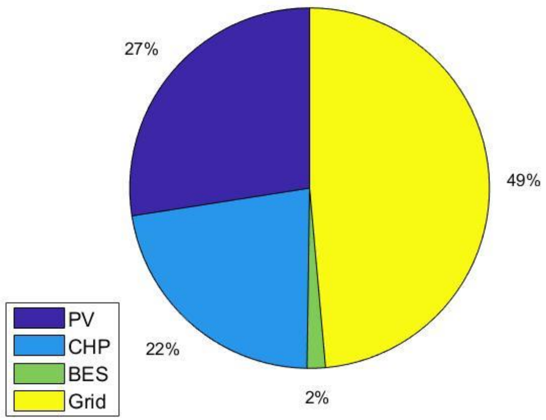
← Cost of the electricity taken from the grid in case of shortage

$$C_{el,grid,sent,t} = PUN_t \times P_{el,PV \rightarrow grid} \times \Delta t$$

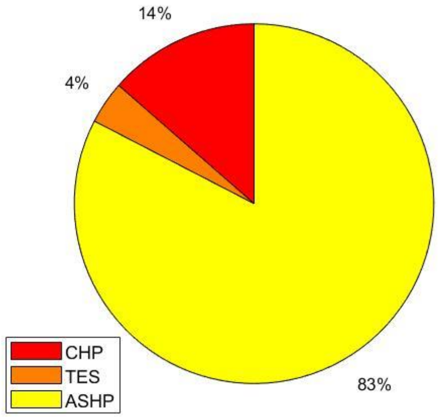
← Cost of the electricity sent to the grid in case of surplus production

# Results – Energy analysis

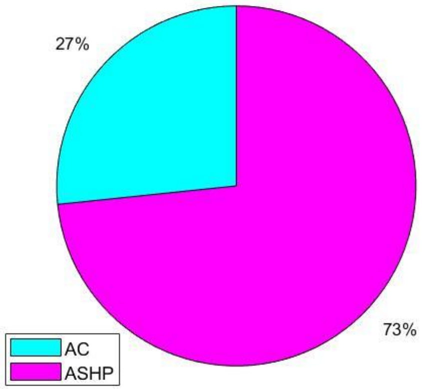
## Electricity production



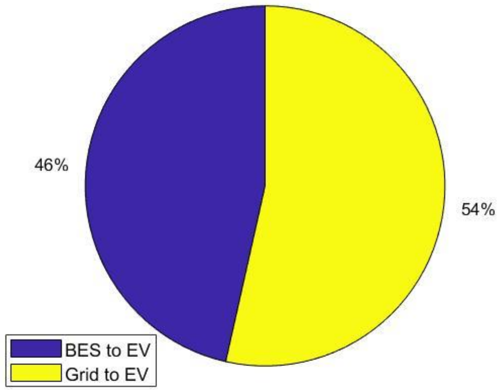

## Heating production



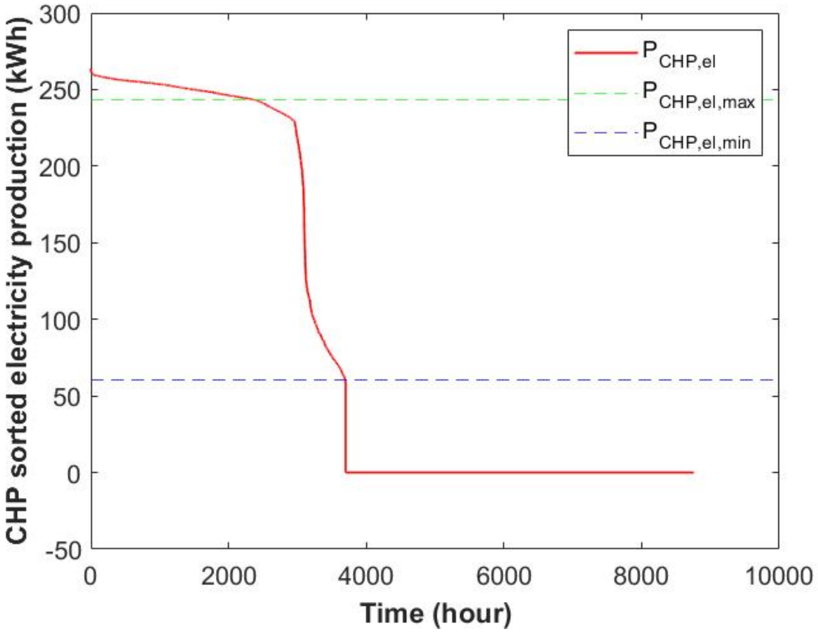

## Cooling production

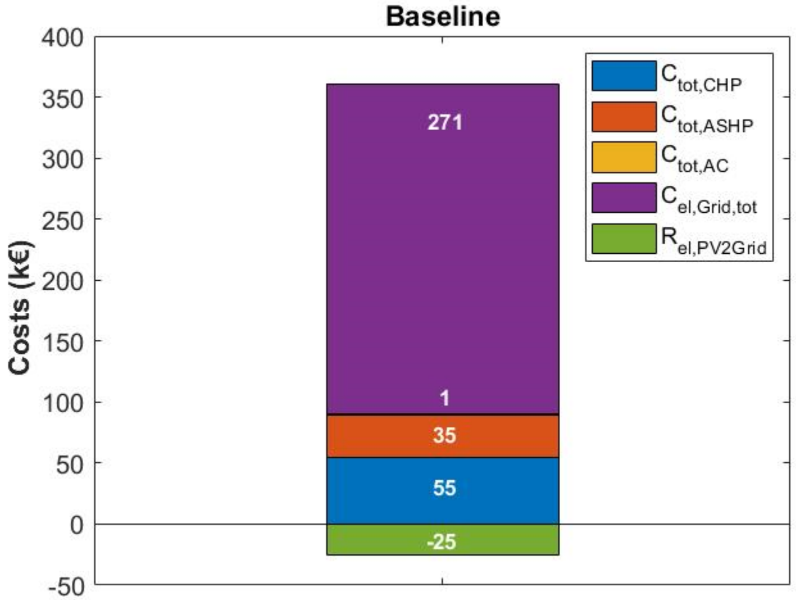



## Electric vehicles charging



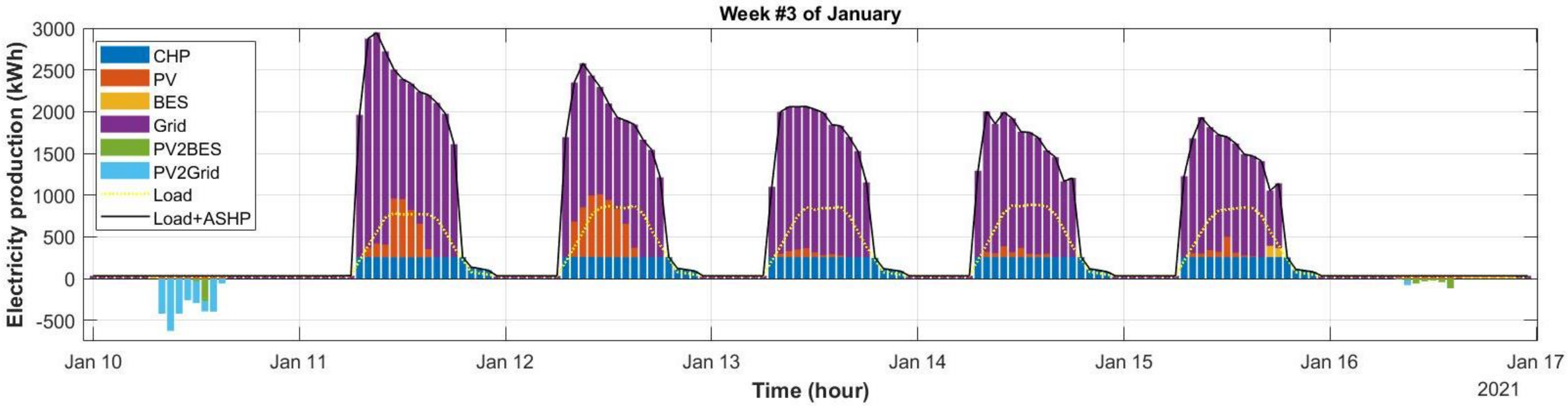
# Results – Energy analysis



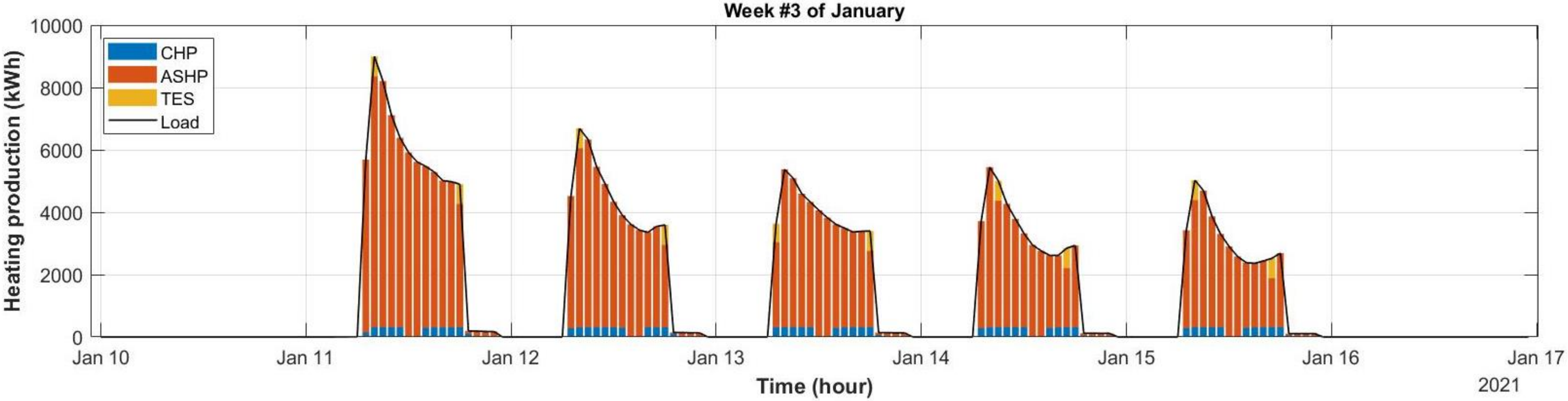




- The CHP runs for 3700 hours a year.
- The  total number of startups is 279.
- The average electrical efficiency is around 39%.
- The average electrical efficiency is around 38.6%.

# Results – Optimal scheduling



# Results – Optimal scheduling



# Results – Optimal scheduling