INDUSTRIAL ENERGY MANAGEMENT

COGENERATION - EXAMPLE

Davide Pivetta

AY 2024 – 2025

Energy analysis of a wine cellar

Objectives:

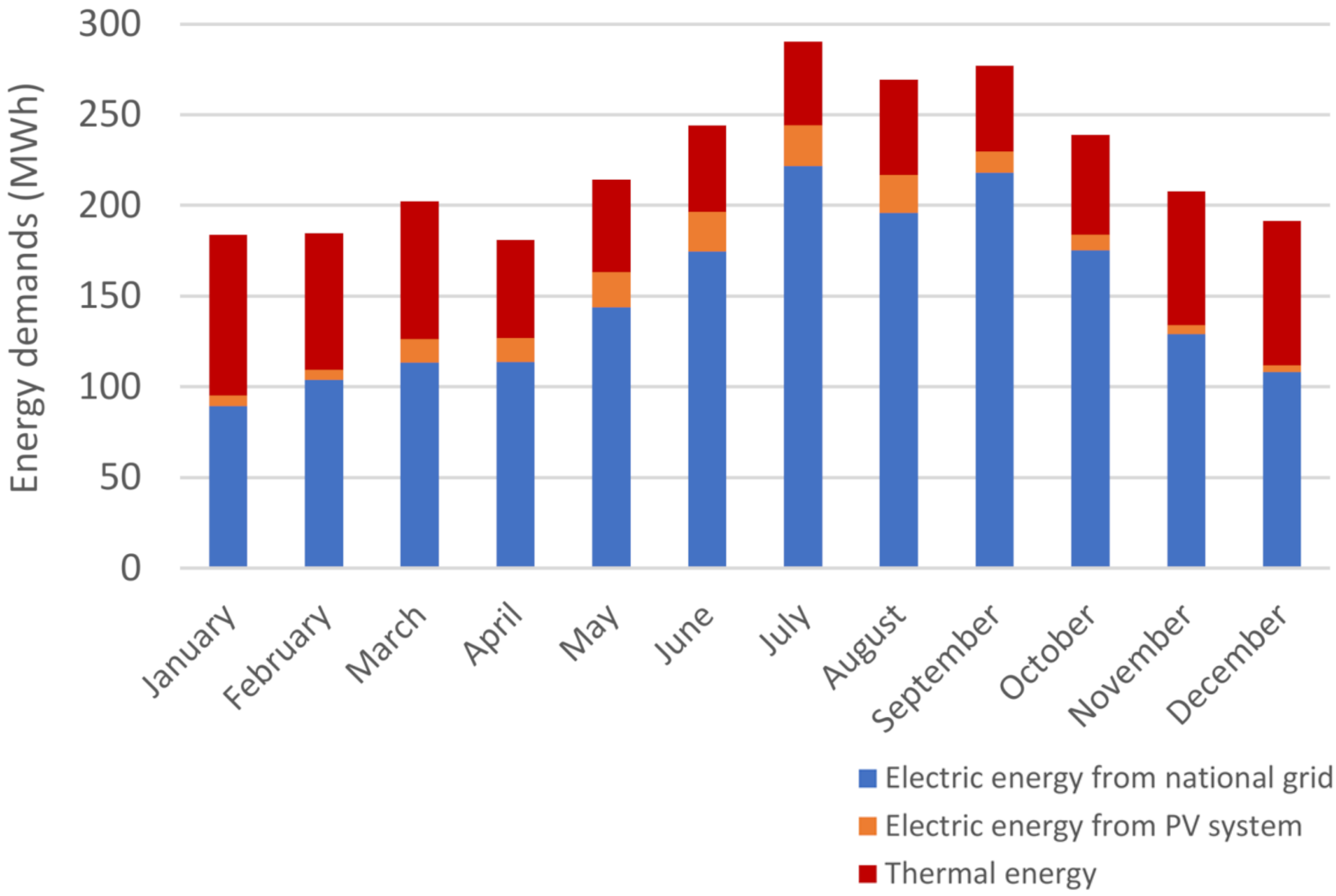
- Analysing the wine cellar energy demand
- Identify existing energy conversion and storage units
- Propose other energy system configurations
- Optimisation of the operation of the proposed configurations

Roncadelle (Treviso province)

Borgo Molino Vigne&Vini - http://www.borgomolino.it/

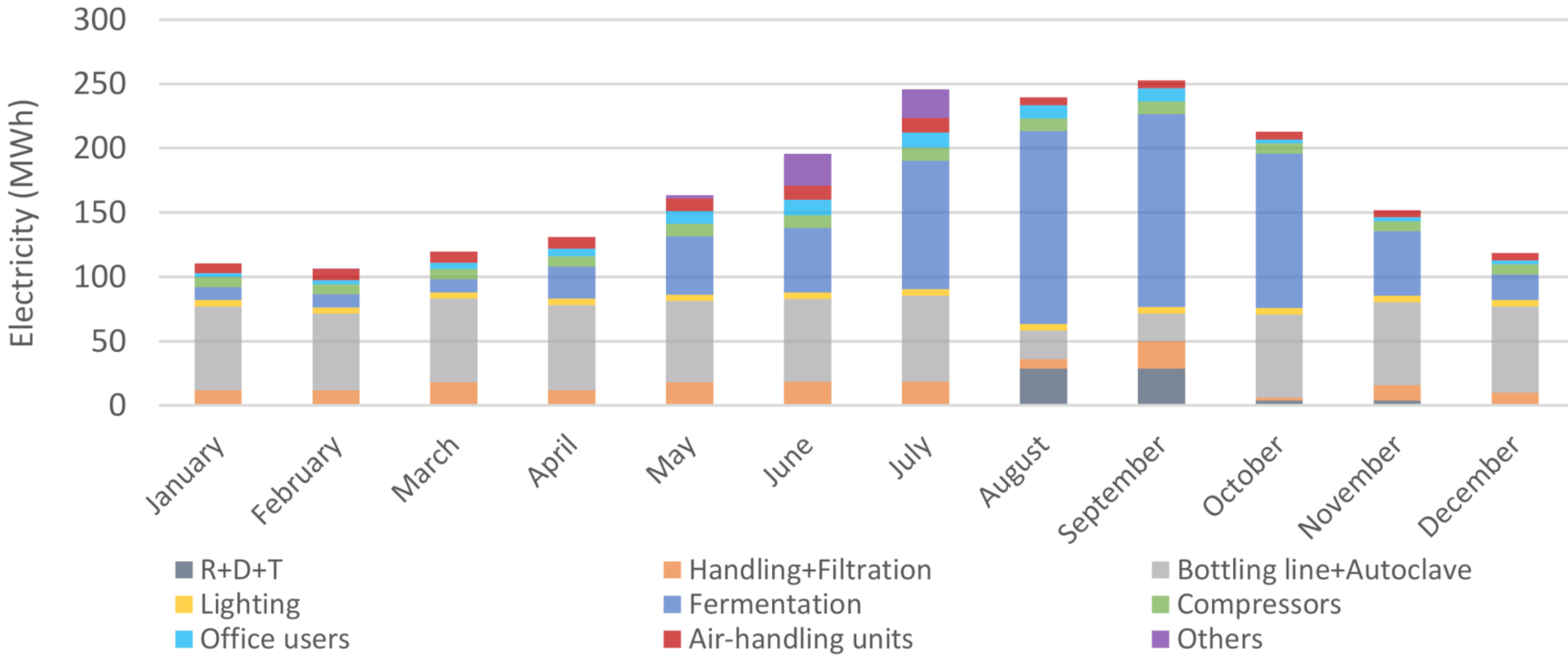
BORGO MOLINO
Vigne & Vini

Overall energy demand



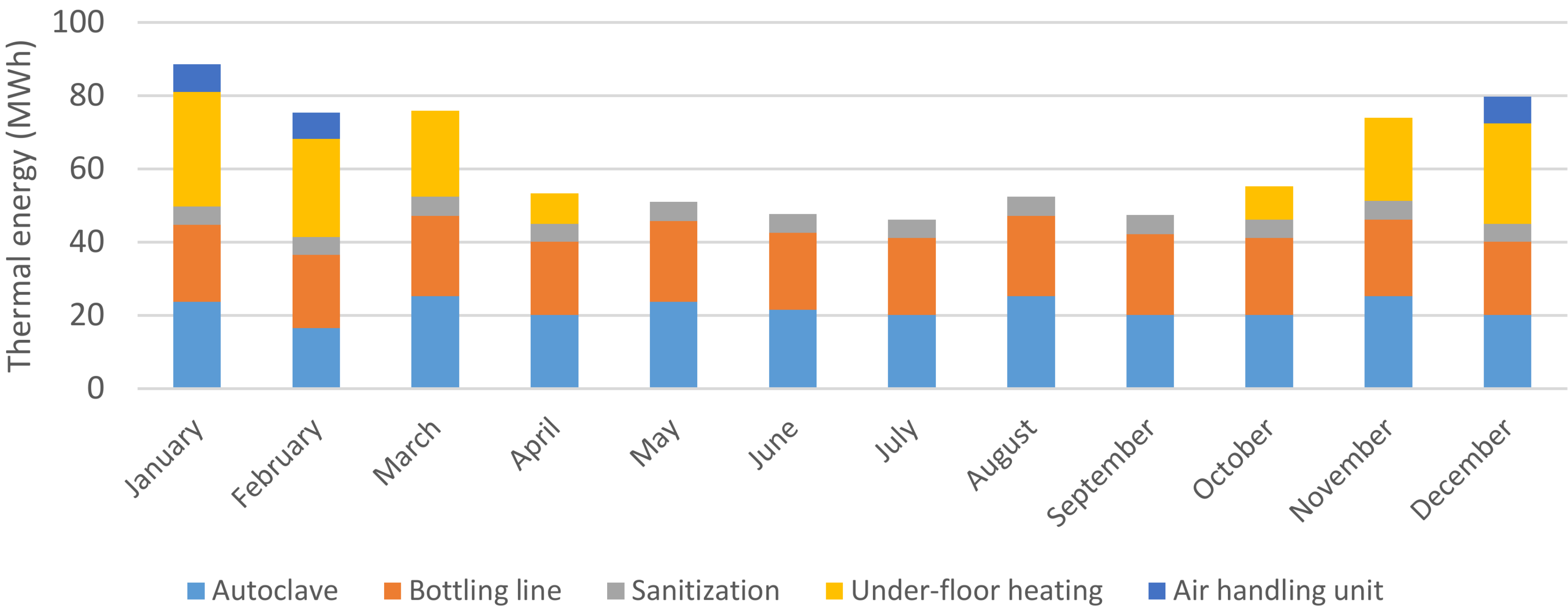
Source: Pivetta et al., Choice of the Optimal Design and Operation of Multi-Energy Conversion Systems in a Prosecco Wine Cellar. Energies 2020

Electricity energy demand



Source: Pivetta et al., Choice of the Optimal Design and Operation of Multi-Energy Conversion Systems in a Prosecco Wine Cellar. Energies 2020

Thermal energy demand

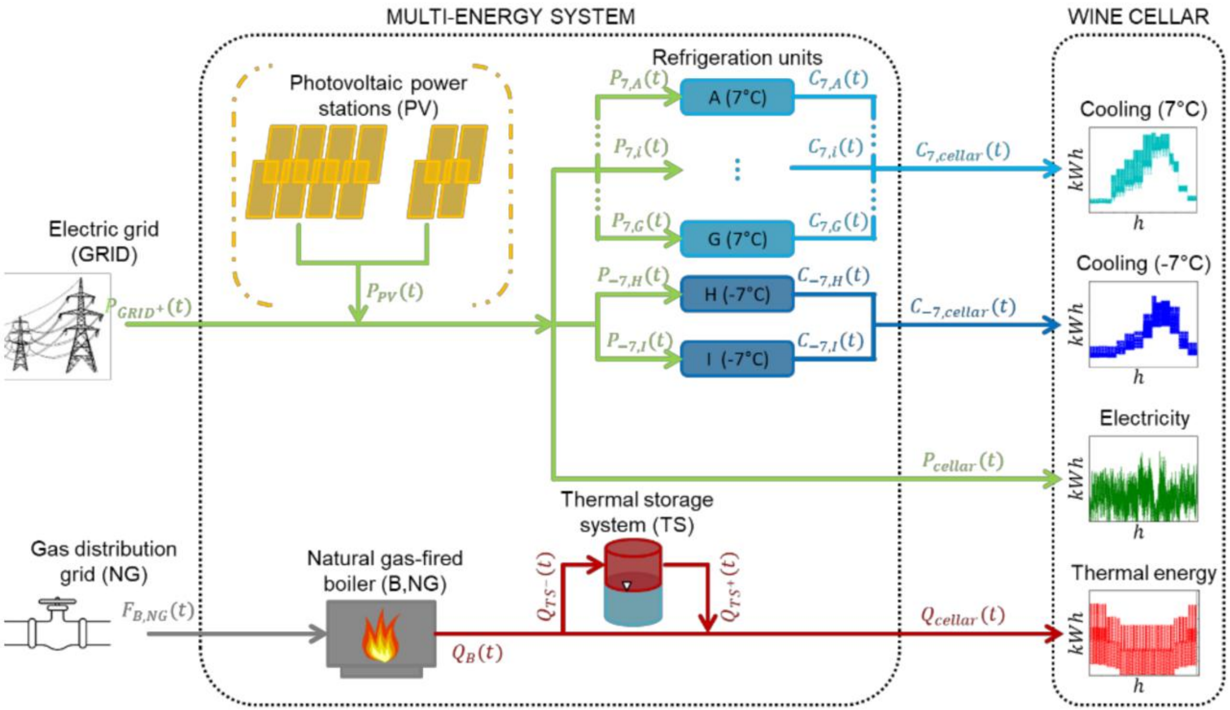


Source: Pivetta et al., Choice of the Optimal Design and Operation of Multi-Energy Conversion Systems in a Prosecco Wine Cellar. Energies 2020

Current energy system configuration

Energy conversion units:

- Natural gas-fired boiler (275 kW)
- Vapour compression chillers (COP≈3)
- Photovoltaic plant (150 kW_P)

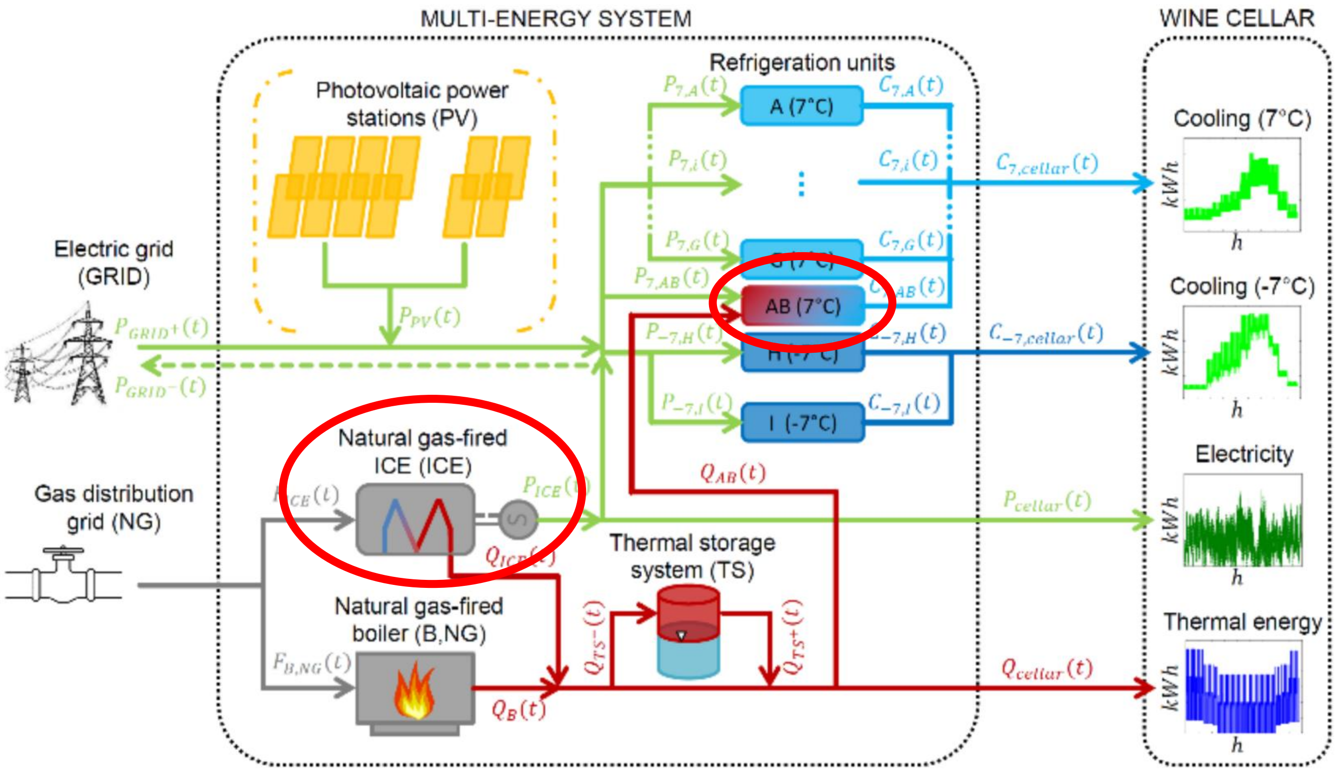


Source: Pivetta et al., Choice of the Optimal Design and Operation of Multi-Energy Conversion Systems in a Prosecco Wine Cellar. Energies 2020

Alternative energy system configuration

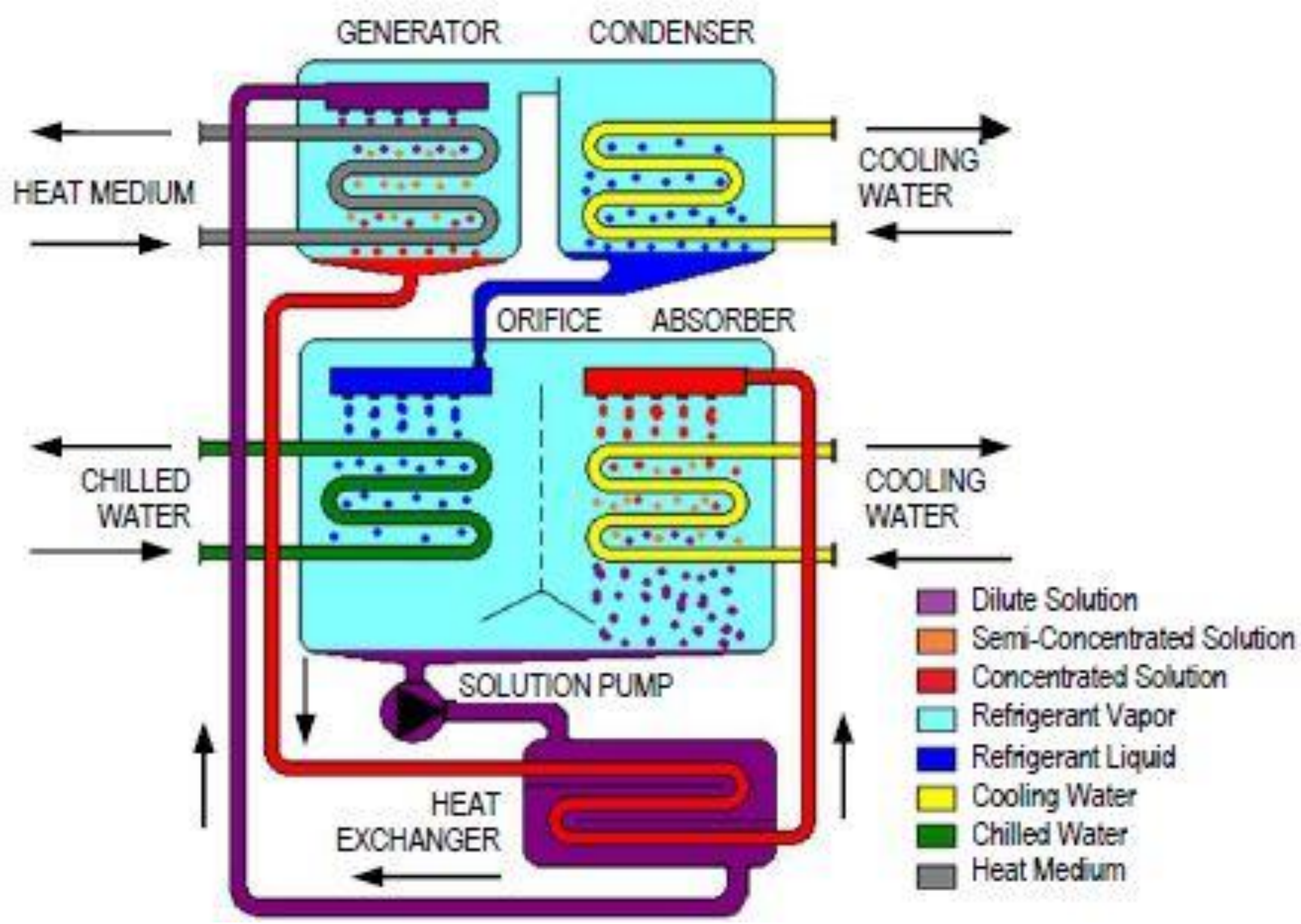
New energy unit:

- Cogeneration internal combustion engine powered by natural gas (200 kW electric)
- Absorption chiller (176 kW cooling)



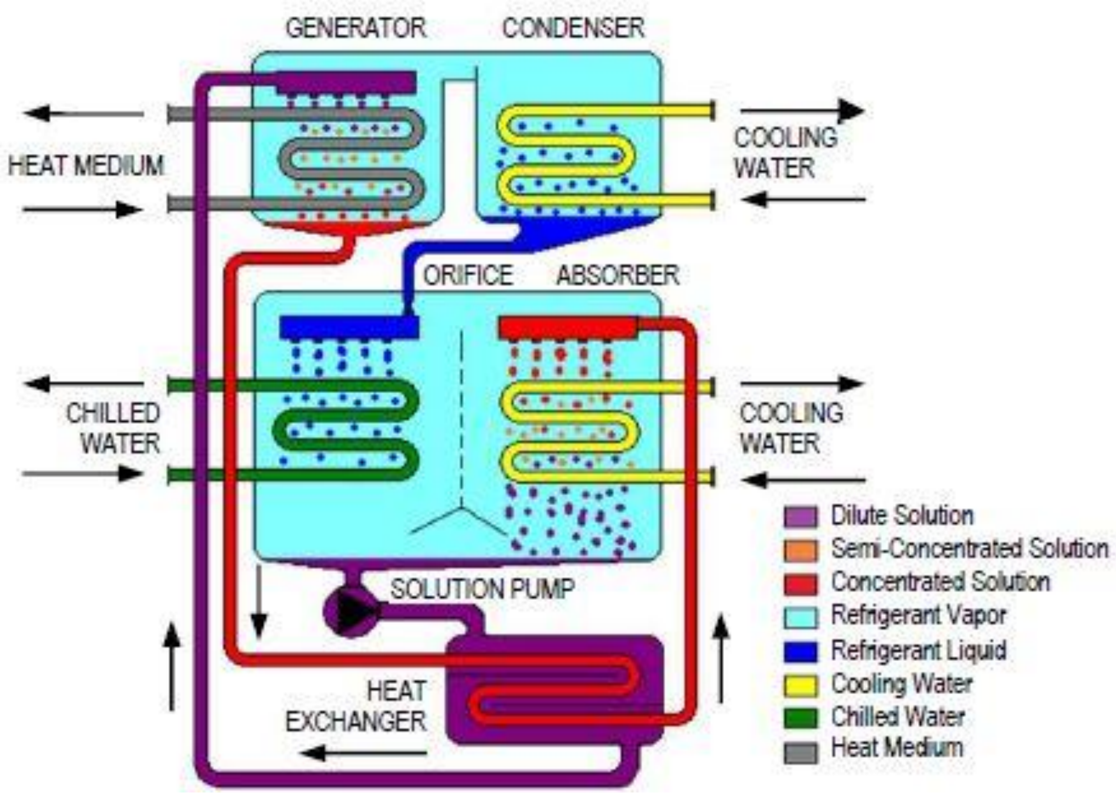
Source: Pivetta et al., Choice of the Optimal Design and Operation of Multi-Energy Conversion Systems in a Prosecco Wine Cellar. Energies 2020

Absorption chiller



Source: www.yazakienergy.com

Absorption chiller



100 kW heat → COP=0.7 → 70 kW cooling

Source: www.yazakienergy.com

Absorption chiller

Source: www.yazakienergy.com

Mixed-Integer Linear Programming (MILP) Optimization

The MILP problem for the optimization of the operation of each configuration is set as:

Find $\mathbf{x}*(t)$ and $\boldsymbol{\delta}*(t)$ (i.e., the optimum values of the continuous $\mathbf{x}$, and binary, $\boldsymbol{\delta}$, decision variables associated with the operation of the energy system) that maximize or minimize the objective function Z (Equation (1)) subject to the constraint relationships $\mathbf{g}(t)$ and $\mathbf{h}(t)$ (Equations (2) and (3)), which make up the model of the entire energy system of the cellar:

$$Z = f(x^*(t), \beta^*, \delta^*) \qquad (1)$$

$$g(x^*(t), \beta^*, \delta^*) = 0 \qquad (2)$$

$$h(x^*(t), \beta^*, \delta^*) \leq 0 \qquad (3)$$

Constraints

$$\varphi_{in,i}(t) = K1_i \cdot \varphi_{out,i}(t) + K2_i \cdot \delta_i(t)$$

$$\varphi_{out,i}(t) \leq \varphi_{out,i}^{MAX} \cdot \delta_i(t)$$

$$\varphi_{out,i}(t) \geq \varphi_{out,i}^{MIN} \cdot \delta_i(t)$$

General formulation of energy conversion units

Internal combustion engine

$$F_{ICE}(t) = K1_{ICE} * P_{ICE}(t) + K2_{ICE} * \delta_{ICE}(t)$$

$$QH_{ICE}(t) \leq K3_{ICE} * P_{ICE}(t) + K4_{ICE} * \delta_{ICE}(t)$$

$$P_{ICE,min} * \delta_{ICE}(t) \leq P_{ICE}(t) \leq P_{ICE,max} * \delta_{ICE}(t)$$

Absorption chiller

$$QH_{AB}(t) = K1_{AB} * Q7_{AB}(t) + K2_{AB} * \delta_{AB}(t)$$

$$P_{AB}(t) = K3_{AB} * Q7_{AB}(t) + K4_{AB} * \delta_{AB}(t)$$

$$Q7_{AB,min} * \delta_{AB}(t) \leq Q7_{AB}(t) \leq Q7_{AB,max} * \delta_{AB}(t)$$

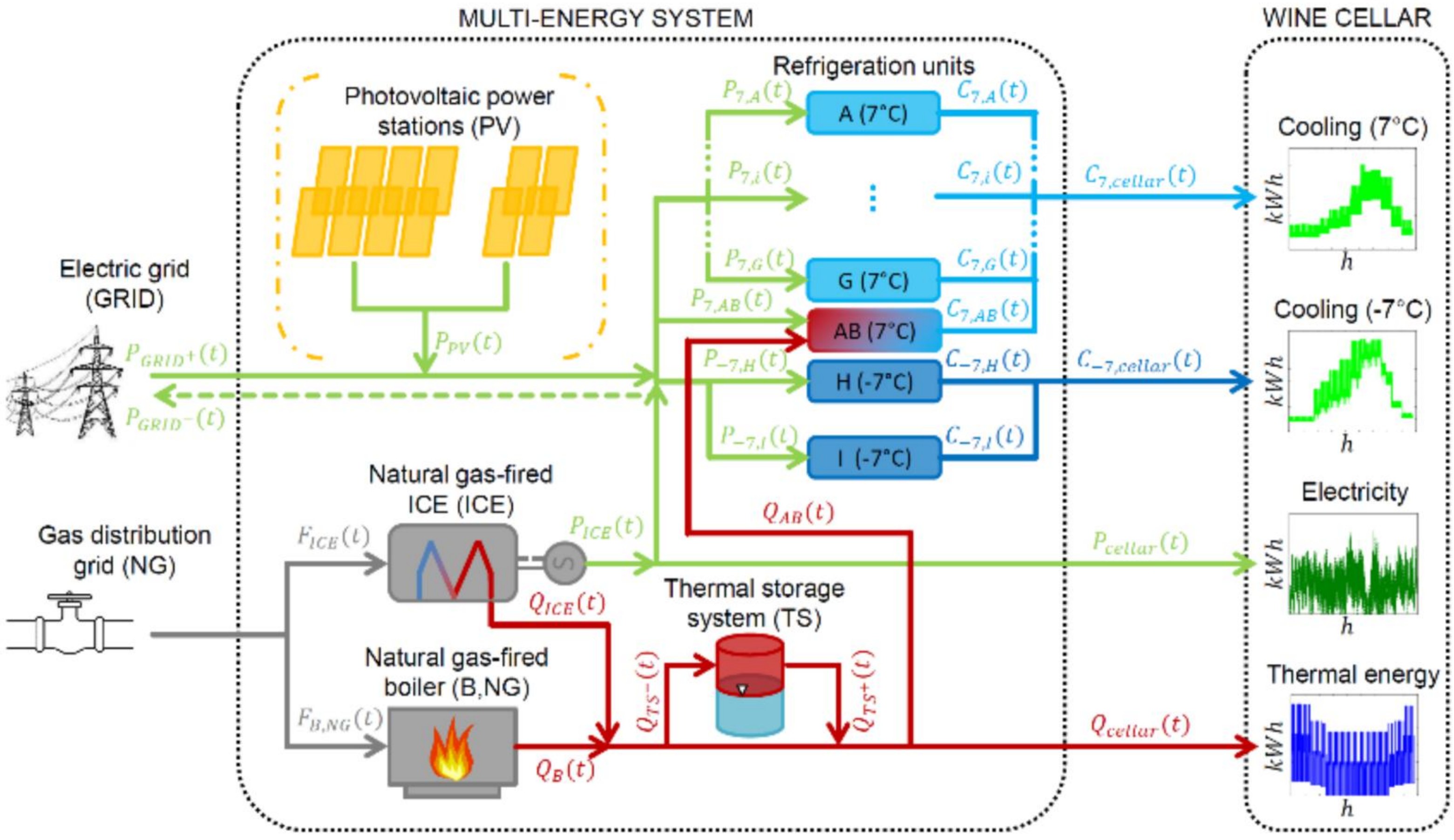
Constraints

Thermal energy storage

$$V_{TS}(t) = V_{TS}(t-1) + \left(\frac{1}{\rho_{TS} * c_{p,TS} * \left(\theta_{TS,hot} - \theta_{TS,cold}\right)}\right) * \left(\eta_H * F_{TS}(t) - \frac{1}{\eta_H} * QH_{TS}(t)\right) * dt$$

$$0.1 * V_{TS,max} \le V_{TS}(t) \le 0.9 * V_{TS,max}$$

Multi-energy system model



Objective functions

Minimization of cost

$$\sum F_{GN}(t) * c_{GN} + \sum P_{GR_{pos}}(t) * c_{GR_{pos}} - \sum P_{GR_{neg}}(t) * c_{GR_{neg}} + \sum F_{ICE}(t) * c_{ICE}$$

Minimization of primary energy consumption

$$\left(\sum F_{GN}(t) + F_{ICE}(t)\right) * e_{GN_t} + \left(\sum P_{GR_{pos}}(t) - \sum P_{GR_{neg}}(t)\right) * e_{GR_t}$$

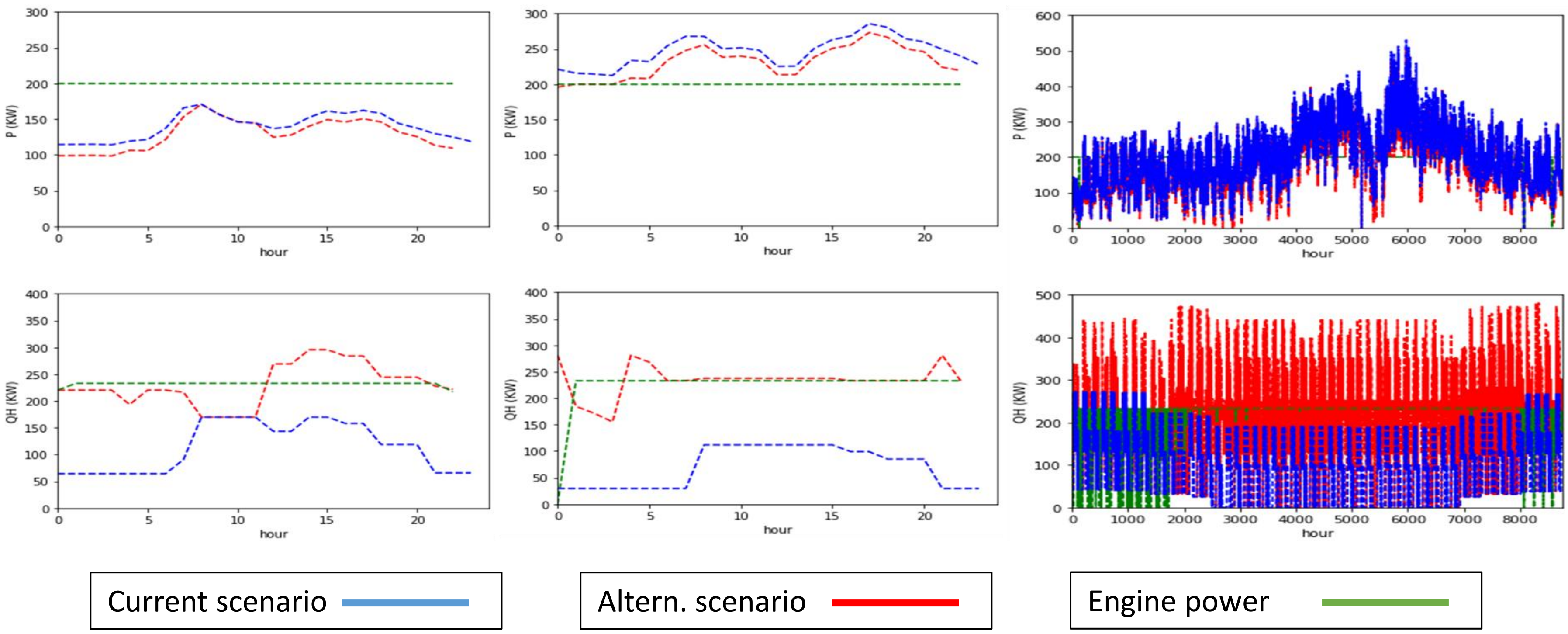
Minimization of primary energy consumption from fossil fuels

$$\left(\sum F_{GN}(t) + F_{ICE}(t)\right) * e_{GN} + \left(\sum P_{GR_{pos}}(t) - \sum P_{GR_{neg}}(t)\right) * e_{GR}$$

Optimization results

Minimization of operation costs

Winter | Summer | Yearly



Optimization results

Minimization of operation cost

	Operation cost (€/y)	Maintenance cost (€/y)	Total cost (€/y)	Revenues (€/y)	Payback time (y)	NPV* at 25 years (€)
1. Grid+boiler	288.509	0	288.509	0	/	/
2. ICE	160.360	35.000	195.360	93.149	3,8	962.832
3. ICE+Abchiller	**142.046**	**45.000**	**187.046**	**101.463**	**4,4**	**980.009**

*inflaction rate=5%

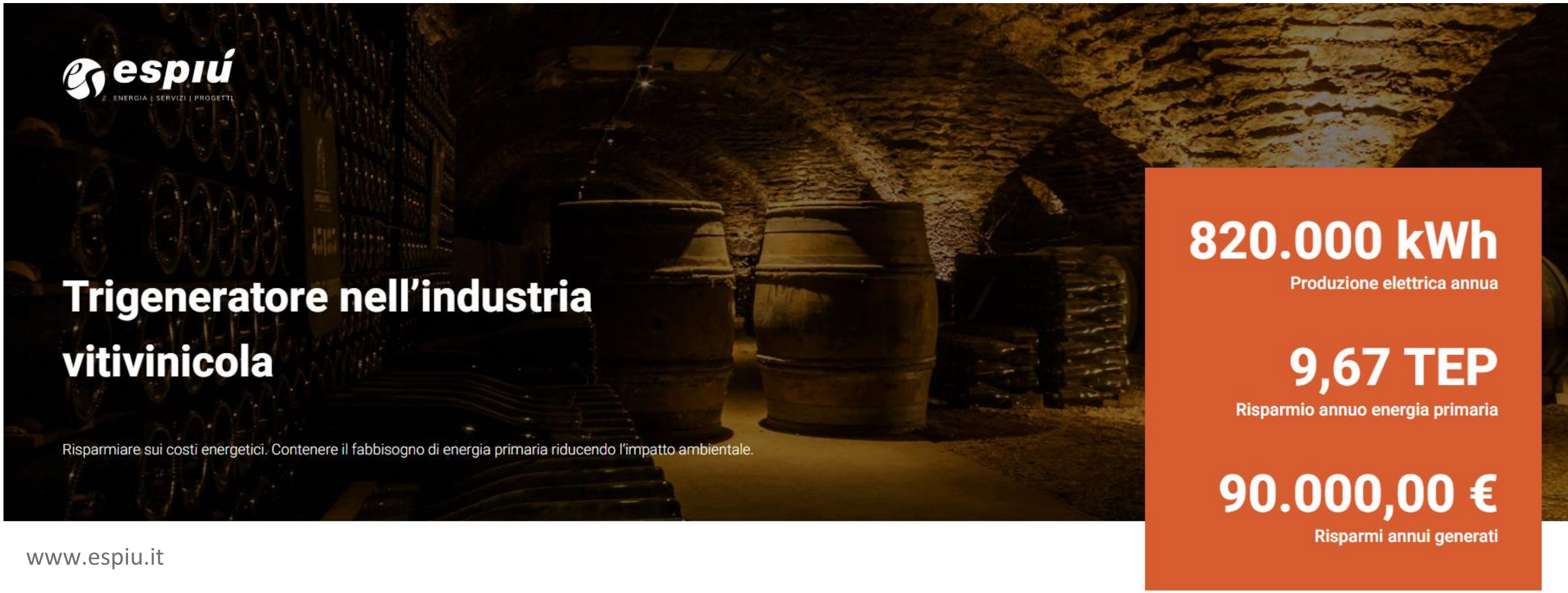
Minimization of primary energy

	Primary energy consumption (MWh)	Primary energy saved (MWh)
1. Grid+boiler	5201	/
2. ICE	4466	735
3. ICE+Abchiller	**4284**	**917**

Minimization of primary fossil-based energy

	Primary energy from F.F. consumption (MWh)	Primary energy from F.F. saved (MWh)
1. Grid+boiler	4361	/
2. ICE	3935	426
3. ICE+Abchiller	3935	426

Real plant operation

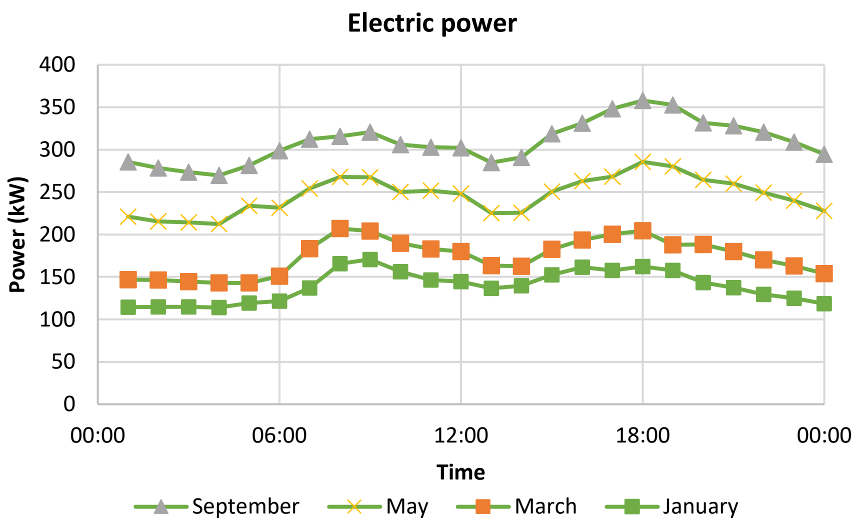


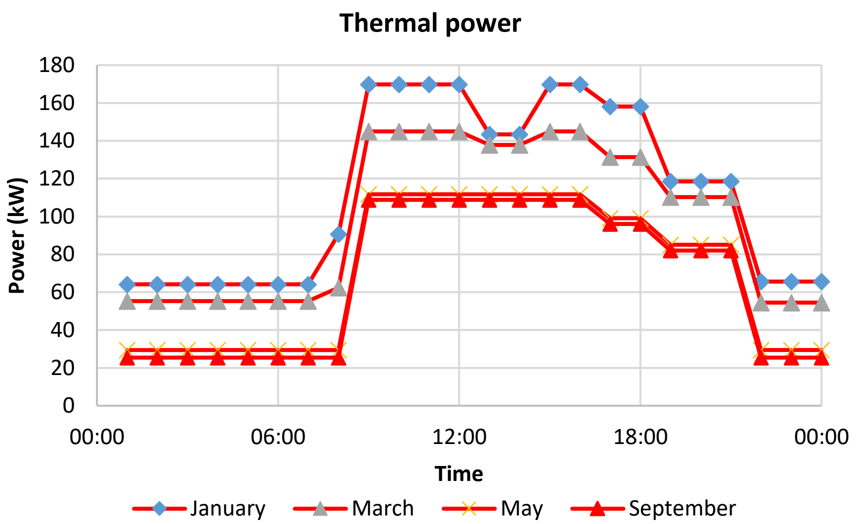
www.espiu.it

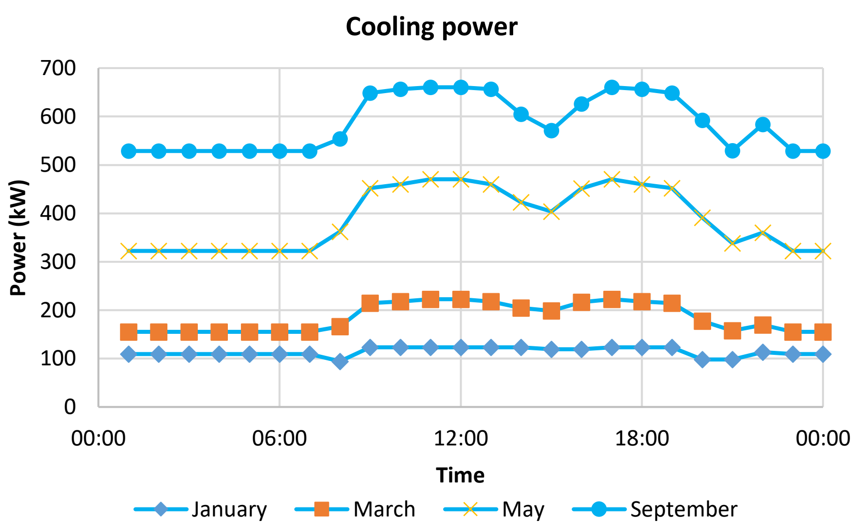
Exercise

Energy demand

Electrical, thermal and cooling power defined for 4 characteristic days (hourly data)





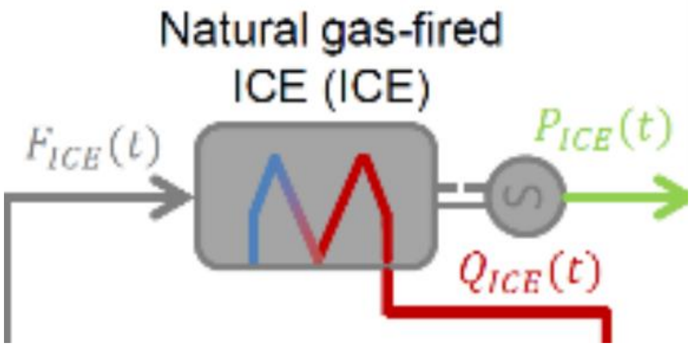


Internal combustion engine

$$F_{ICE}(t) = K1_{ICE} * P_{ICE}(t) + K2_{ICE} * \delta_{ICE}(t)$$

$$QH_{ICE}(t) \leq K3_{ICE} * P_{ICE}(t) + K4_{ICE} * \delta_{ICE}(t)$$

$$P_{ICE,min} * \delta_{ICE}(t) \leq P_{ICE}(t) \leq P_{ICE,max} * \delta_{ICE}(t)$$



Binary variable identifying ICE on-off status (1 o 0)

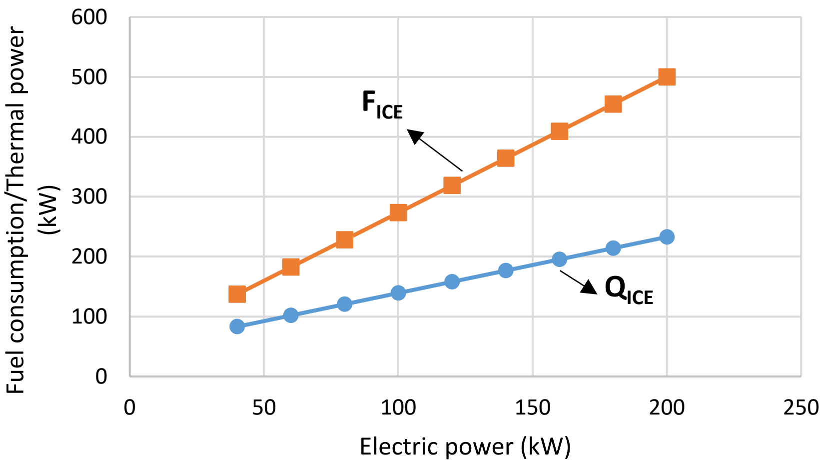
Continuous variable taken as reference for ICE operation

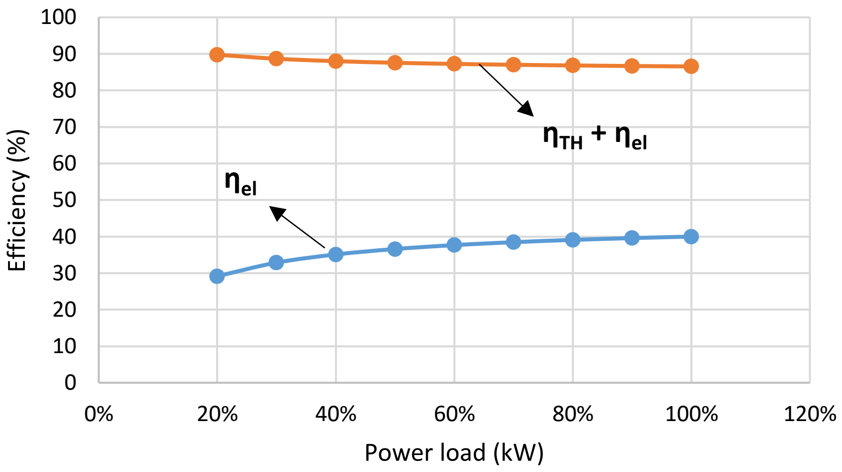
Internal combustion engine

$$F_{ICE}(t) = K1_{ICE} * P_{ICE}(t) + K2_{ICE} * \delta_{ICE}(t)$$

$$QH_{ICE}(t) \leq K3_{ICE} * P_{ICE}(t) + K4_{ICE} * \delta_{ICE}(t)$$

$$P_{ICE,min} * \delta_{ICE}(t) \leq P_{ICE}(t) \leq P_{ICE,max} * \delta_{ICE}(t)$$



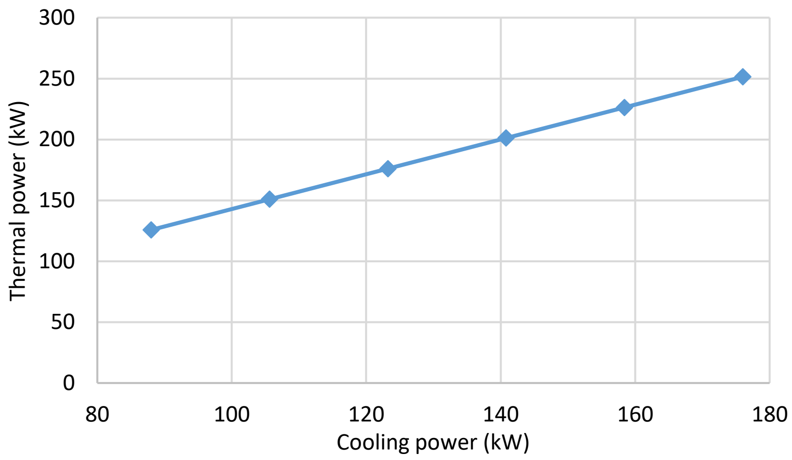


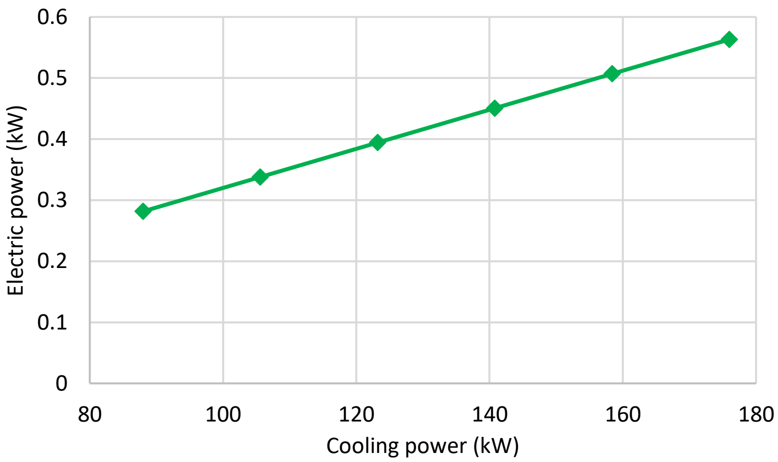
Absorption chiller

$$QH_{AB}(t) = K1_{AB} * Q7_{AB}(t) + K2_{AB} * \delta_{AB}(t)$$

$$P_{AB}(t) = K3_{AB} * Q7_{AB}(t) + K4_{AB} * \delta_{AB}(t)$$

$$Q7_{AB,min} * \delta_{AB}(t) \le Q7_{AB}(t) \le Q7_{AB,max} * \delta_{AB}(t)$$



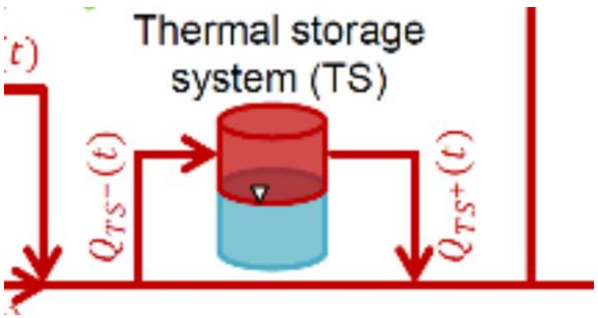


Thermal energy storage

$$V_{TS}(t) = V_{TS}(t-1) + \left(\frac{1}{\rho_{TS} * c_{p,TS} * \left(\theta_{TS,hot} - \theta_{TS,cold}\right)}\right) * \left(\eta_H * F_{TS}(t) - \frac{1}{\eta_H} * QH_{TS}(t)\right) * dt$$

$$0.1 * V_{TS,max} \leq V_{TS}(t) \leq 0.9 * V_{TS,max}$$

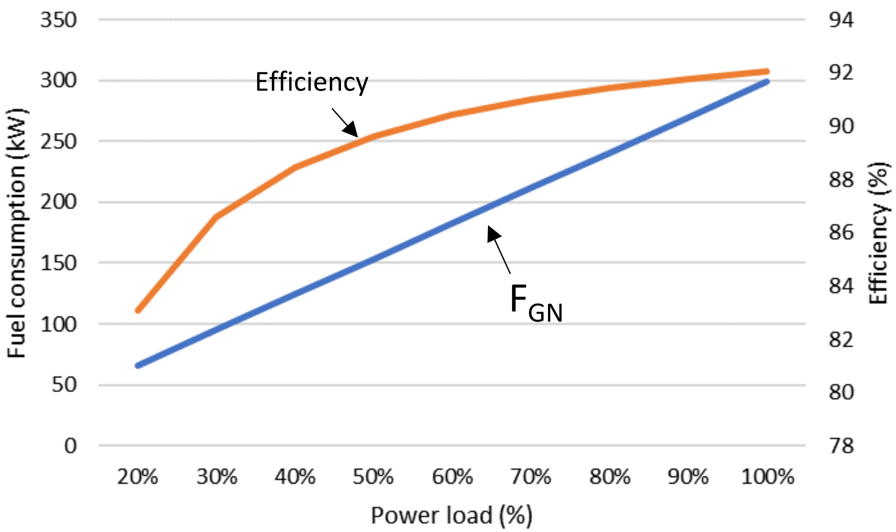
	Value	Unit
$V_{TS_{MAX}}$	10.0	m^3
ρ_{TS}	1000	kg/m^3
cp_{TS}	4.186	kJ/kgK
$\theta_{TS_{hot}}$	90	$°C$
$\theta_{TS_{hot}}$	50	$°C$



Boiler

$$F_{GN}(t) = (k1_{GN} * QH_{GN}(t) + k2_{GN}) * \delta_{GN}(t)$$

$$\delta_{GN}(t) * QH_{GN_{min}} \leq QH_{GN}(t) \leq QH_{GN_{max}} * \delta_{GN}(t)$$



Vapor compression chillers

$$QC_x(t) = COP_x * P_x(t)$$

Electric grid

$$if\ P_{GR_{pos}} > 0 \rightarrow P_{GR_{neg}} = 0$$
$$if\ P_{GR_{neg}} > 0 \rightarrow P_{GR_{pos}} = 0$$

Power balances

Electric power

$$P_{GR_{pos}}(t) * \delta_{GR}(t) - P_{GR_{neg}}(t) * \left(1 - \delta_{GR}(t)\right) + P_{ICE}(t) * \delta_{ICE}(t) = P_{el}(t) + P_{x}(t) + P_{AB}(t) * \delta_{AB}(t)$$

Thermal power

$$QH_{ICE}(t) * \delta_{ICE}(t) + Q_{TS}(t) + QH_{GN}(t) * \delta_{GN}(t) = P_{th}(t) + QH_{AB}(t) * \delta_{AB}(t) + F_{TS}(t)$$

Cooling power

$$QC_{AB}(t) * \delta_{AB}(t) + QC_{x}(t) = P_{cool}(t)$$

Data

	Purchase cost (€/kWh)	Sale cost (€/kWh)	Primary energy coef. (-)	Primary energy F.F. coef. (-)
Electricity from grid	0.140	0.075	2.42	1.95

	ICE cost (€/kWh)	Boiler cost (€/kWh)	Primary energy coef. (-)	Primary energy F.F. coef. (-)
Natural gas	0.0311	0.0374	1.05	1.05

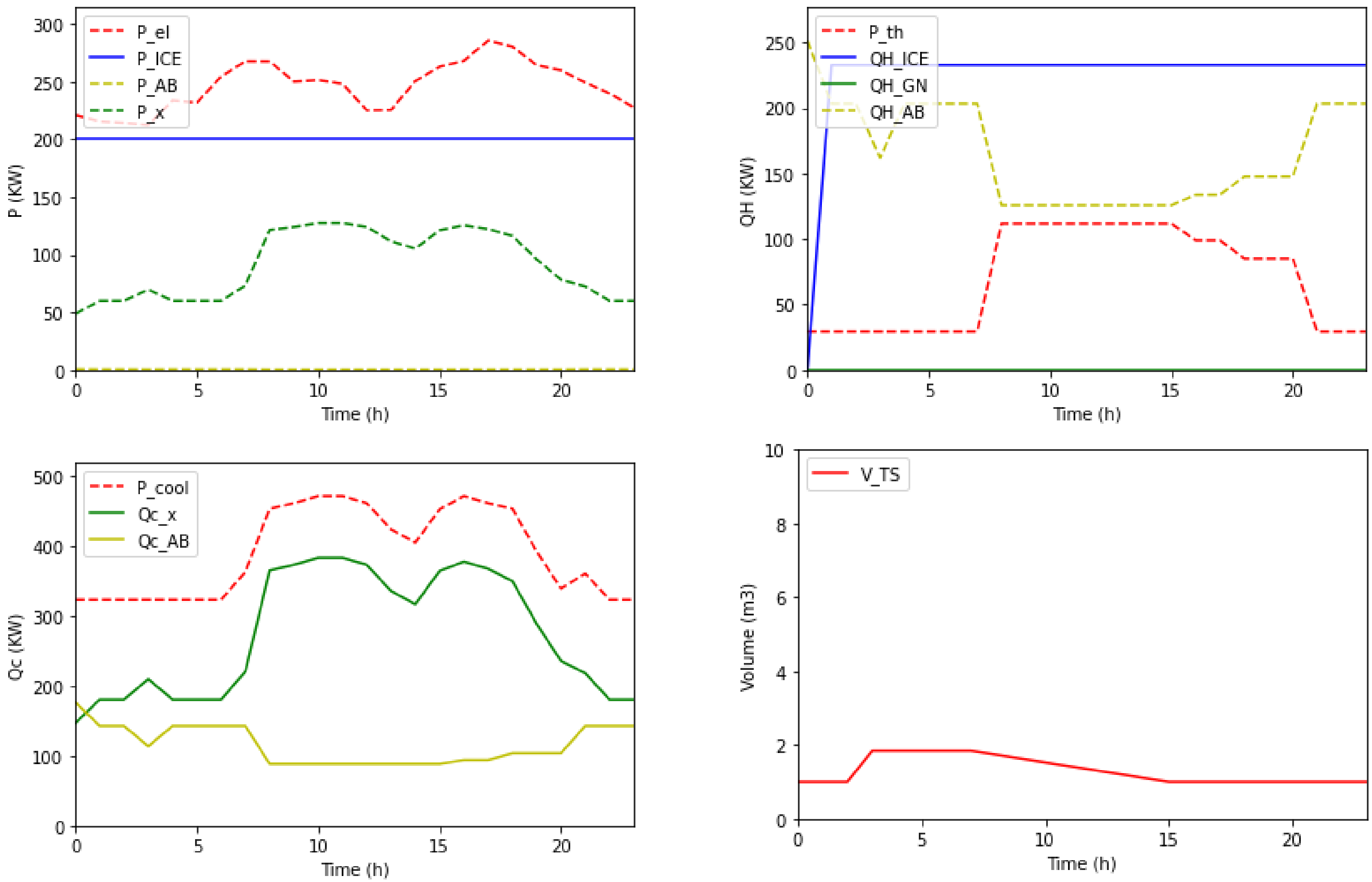
$$PES = \left(1 - \frac{E_{fuel}}{\frac{E_{el}}{\eta_{el,ref} \times p} + \frac{Q_{rec}}{\eta_{th,ref}}}\right) \times 100$$

Primary energy saving

Reference values	
Electrical efficiency ($\eta_{el,ref}$)	0.525
Thermal efficiency ($\eta_{th,ref}$)	0.90
Grid distrib. efficiency (p)	0.925

Optimization results

Ex. Cost minimization with ICE + AB: case study **May**



Optimization results

Ex. Cost minimization with ICE + AB: case study **May**

> Objective function value is = 835

> Cost = 835.38 euro

> Primary energy consumption = 20589 kWh

> Primary energy consumption from fossil fuels = 19038 kWh

> ICE utilization factor = 100.0 %

> Absorption chiller utilization factor = 65.6 %

> Boiler utilization factor = 0.0 %

$$u.f._i = \frac{\int_0^{24} \varphi_i(t)dt}{24 * \varphi_{i,max}} * 100$$

> Average efficiency = 51.91 %

> Average efficiency (baseline) = 45.34 %

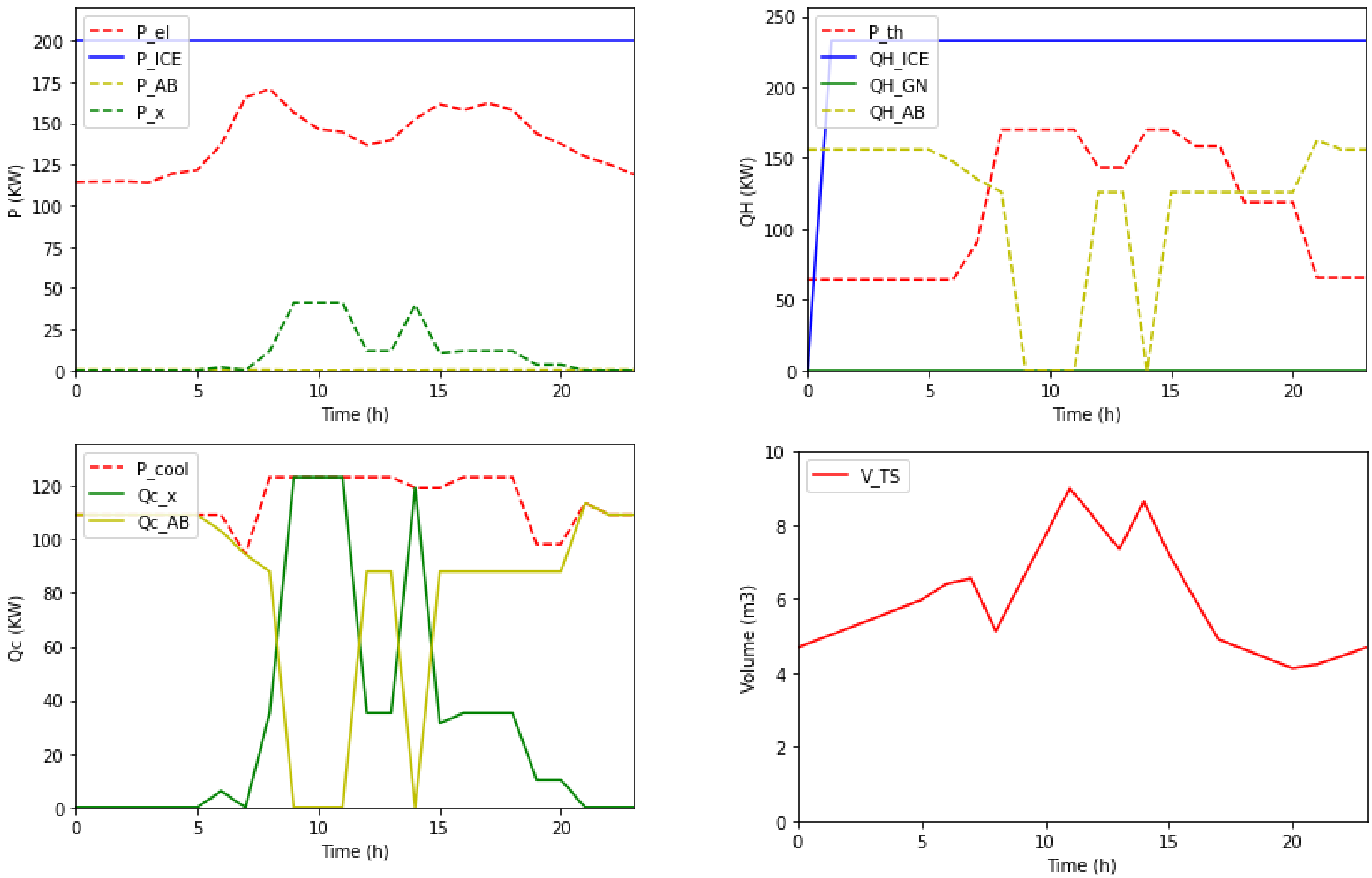
$$\eta = \frac{\int_0^{24} \left(P_{el}(t) + P_{th}(t) + \frac{P_{cool}(t)}{COP_x}\right) dt}{PEC} * 100$$

> Primary Energy Saving (PES) = 24.21 %

PEC: Primary Energy Consumption

Optimization results

Ex. Cost minimization with ICE + AB: case study **January**



Pag. 31

Optimization results

Ex. Cost minimization with ICE + AB: case study **January**

> Objective function value is = 283

> Cost = 283.20 euro

> Primary energy consumption = 9696 kWh

> Primary energy consumption from fossil fuels = 10260 kWh

> ICE utilization factor = 100.0 %

> Absorption chiller utilization factor = 46.8 %

-18 % f.u. assorbitore

> Boiler utilization factor = 0.0 %

> Average efficiency = 71.85 %

> Average efficiency (baseline) = 53.02 %

+19 % efficienza complessiva

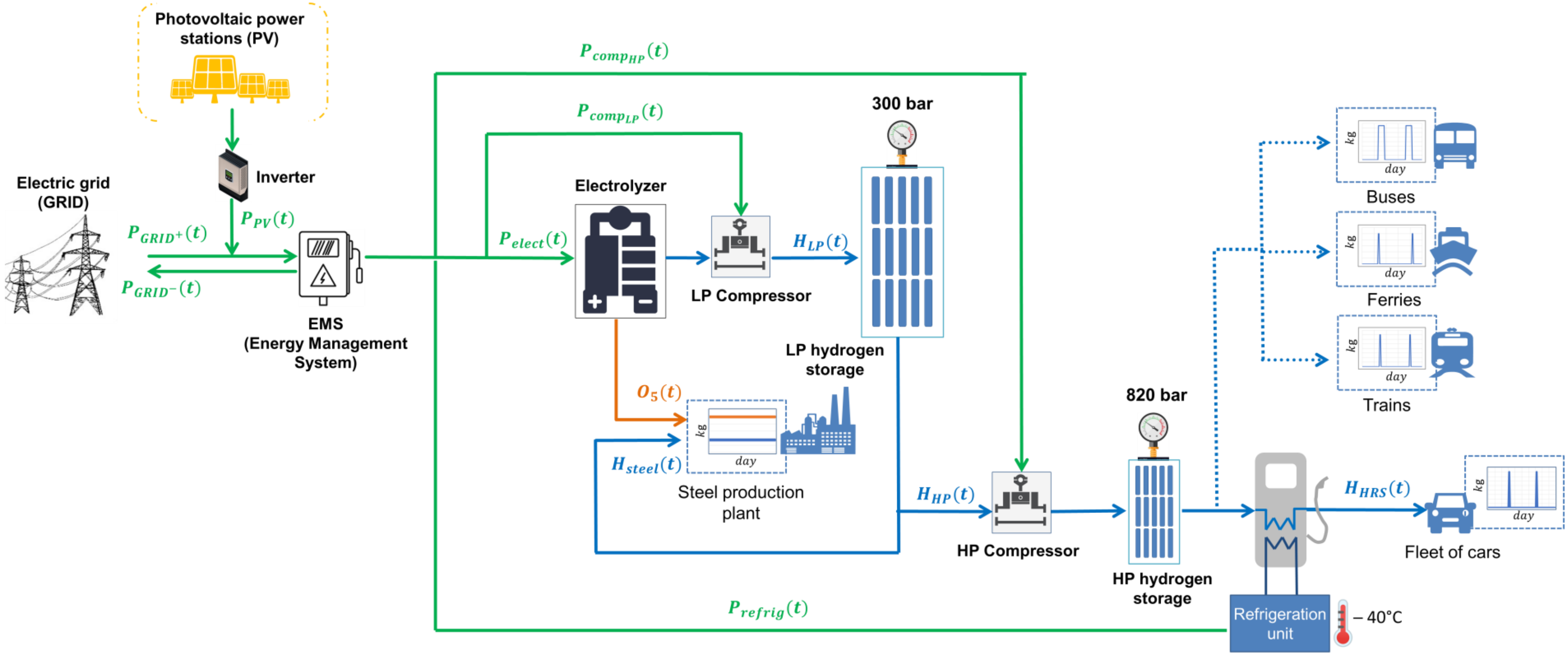
> Primary Energy Saving (PES) = 24.21 %

Exercise

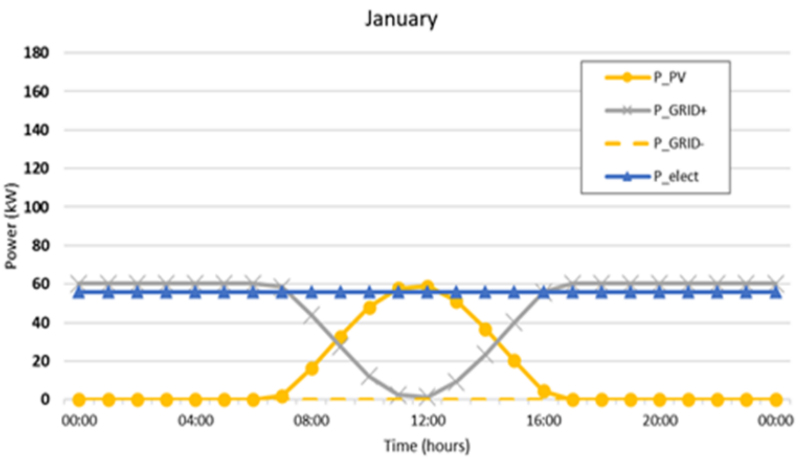
1. Optimize the energy system with and without absorption chiller for all three set objective functions
2. Calculate annual values of cost, primary energy, and primary energy from fossil source (average value multiplied x 365 days) and average PES value, utilization factor of motor and absorption chiller
3. Comment on results obtained

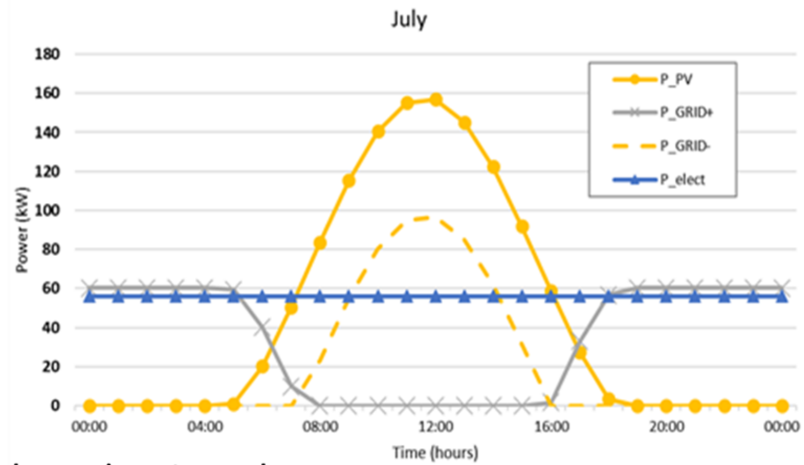
ENESYS Lab activities

Green hydrogen production, storage and distribution systems

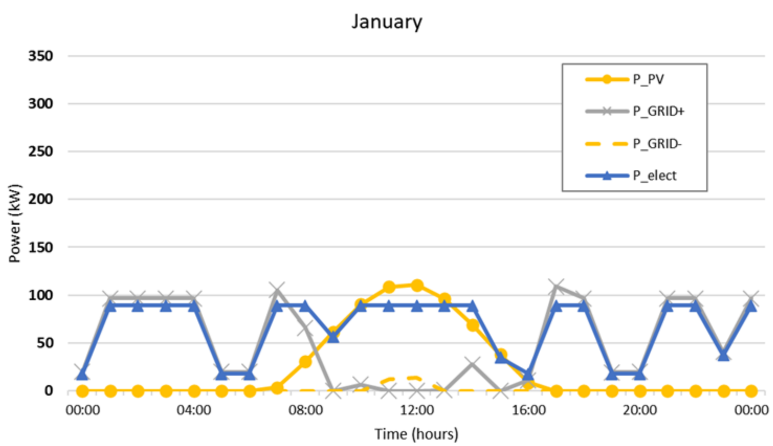


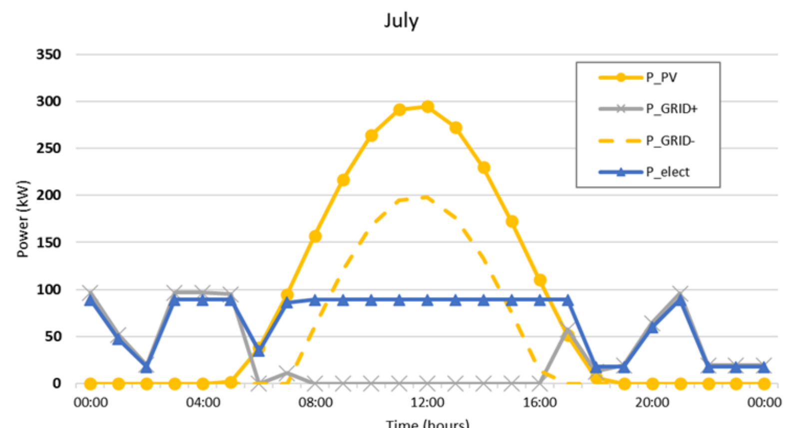
Green hydrogen production, storage and distribution systems





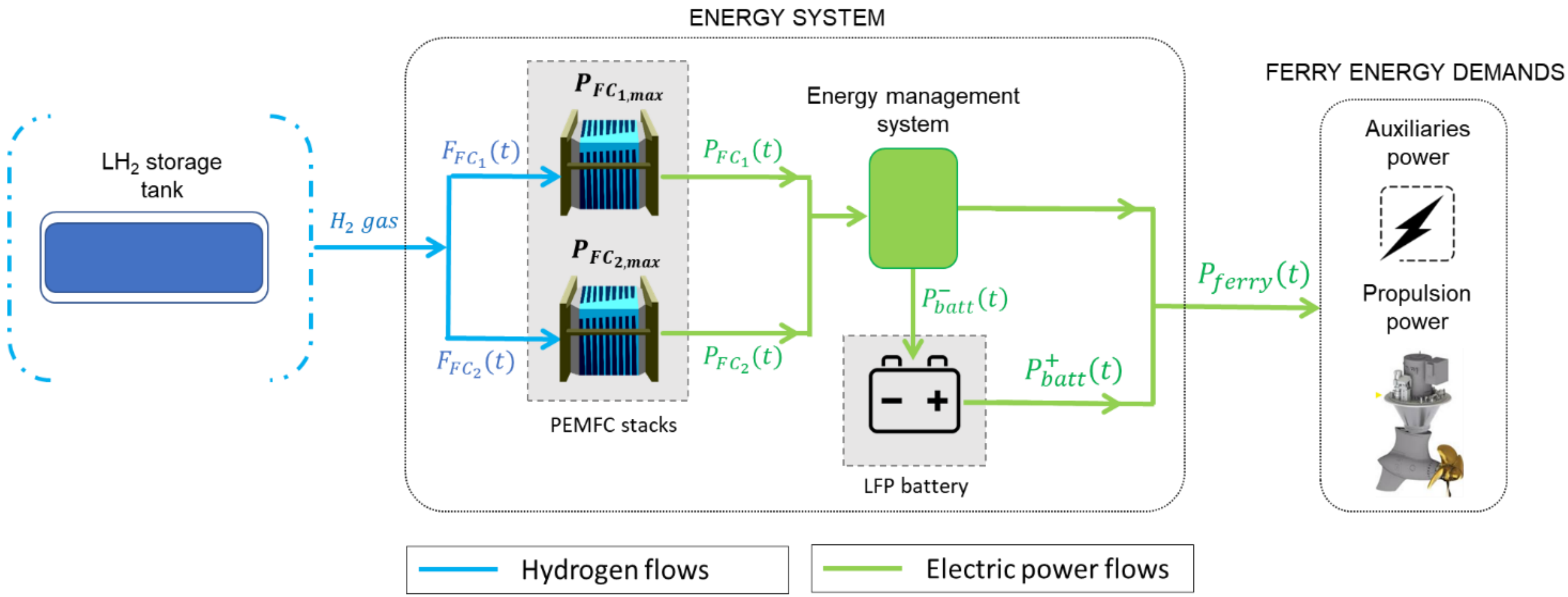
Hydrogen for the steel production plant





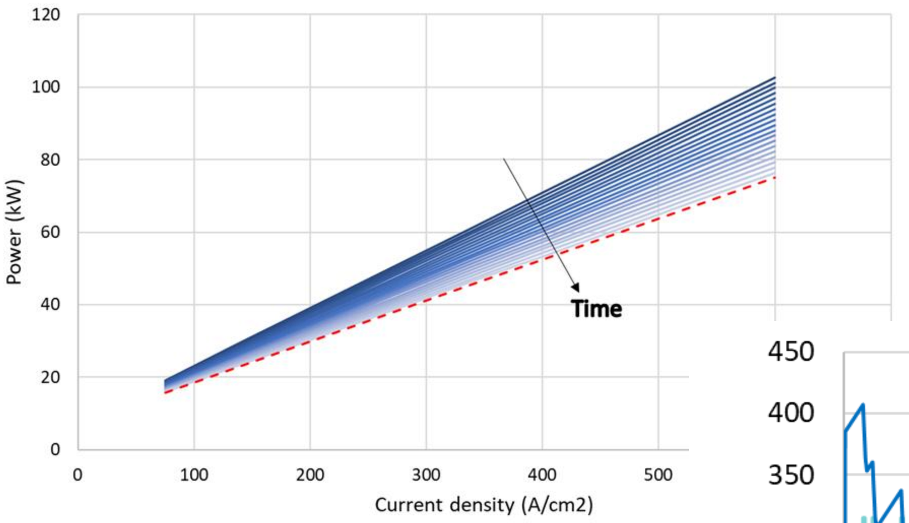
Hydrogen for the steel production plant and the hydrogen refueling station

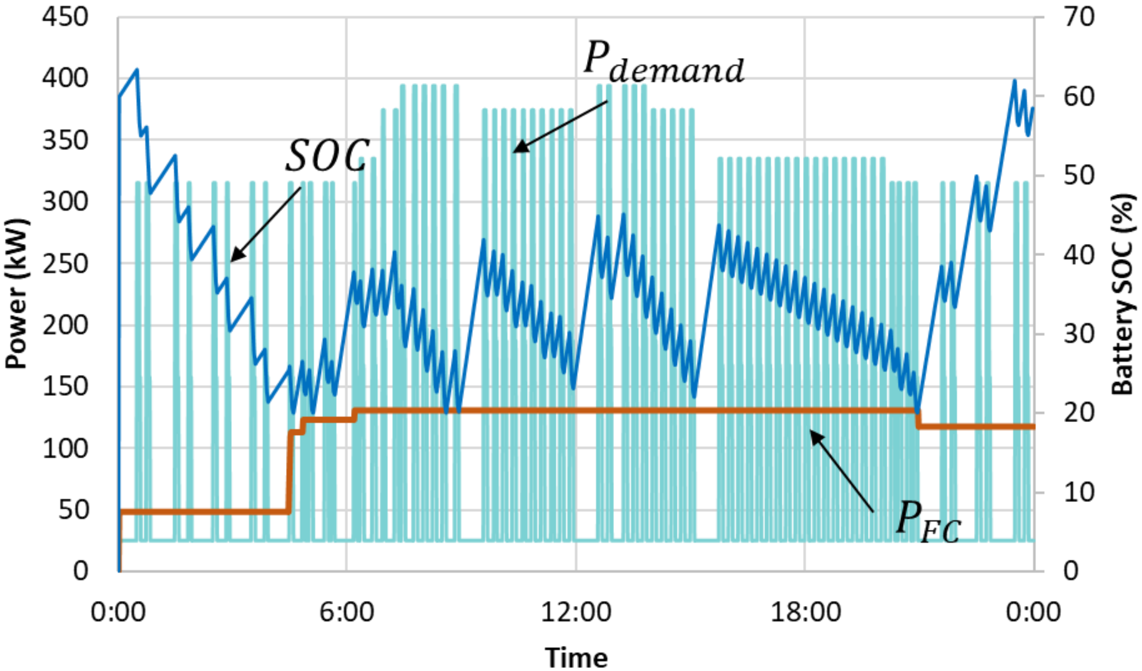
Hybrid propulsion systems (PEMFC + Li-ion battery) for ships



D. Pivetta, C. Dall'Armi, R. Taccani, Multi-objective optimization of hybrid PEMFC/Li-ion battery propulsion systems for small and medium size ferries, International Journal of Hydrogen Energy, 2021, https://doi.org/10.1016/j.ijhydene.2021.02.124.

Hybrid propulsion systems (PEMFC + Li-ion battery) for ships





Thank you for your attention!

Davide Pivetta

e-mail: davide.pivetta@phd.units.it

Excercises for the exam

Exercise: group 1

Exercise for group 1

Evaluate the impact in terms of reducing emissions and operating costs with a Proton-Exchange Membrane Fuel Cells (PEMFC) operating at high temperature (150-180°C), fueled with pure hydrogen. Set the cell size equal to 200 electric kW and consider the possibility of heat recovery. The equations describing the operation of the PEMFC are:

$$F_{FC}(t) = (k1_{FC} * P_{FC}(t) + k2_{FC}) * \delta_{FC}(t)$$

$$QH_{FC}(t) = (k3_{FC} * P_{FC}(t) + k4_{FC}) * \delta_{FC}(t)$$

$$\delta_{FC}(t) * P_{FC_{min}} \leq P_{FC}(t) \leq P_{FC_{max}} * \delta_{FC}(t)$$

	Value	Unit
$k1_{FC}$	0.078	kg/(kWh)
$k2_{FC}$	2.3	kg/h
$k3_{FC}$	0.780	-
$k4_{FC}$	22.0	kW
$P_{FC_{min}}$	80	kW
$P_{FC_{max}}$	200	kW

Exercise for group 1

Set a new objective function that goes to simultaneously minimize system operating costs and emissions. Define an emissions objective function for evaluating $CO_{2,eq}$ emissions.

$$f_{emis} = \left(\sum P_{GR_{pos}}(t) - \sum P_{GR_{neg}}(t)\right) * E_{GR} + \left(\sum F_{ICE}(t) + \sum F_{GN}(t)\right) * E_{GN} + \sum F_{FC}(t) * E_{H_2}$$

Define a carbon tax to evaluate in cost terms the emission of CO2,eq. The multi-objective function that will be minimized is equal to the linear combination of the two objective functions:

$$f_{MO} = f_{cost} + carbon_{tax} * f_{emis}$$

Note: The costs of purchasing hydrogen for the fuel cell are $\sum F_{FC}(t) * c_{H_2}$.

Exercise for group 1

Problem data:

	Value	Unit
cH2	7	€/kg_{H2}
Carbon tax	0 - 5,000	€/$tCO_{2,eq}$

	Emission factors	Unit
Electricity from grid	0.35	kg_{CO2}/kWh
Natural gas	2.8	kg_{CO2}/kg_{NG}
Hydrogen	3.0	kg_{CO2}/kg_{H2}

Exercise for group 1

1. Optimize the energy system in the two configurations: i) motor + absorption chiller and ii) fuel cell + battery
2. Calculate results on an annual basis (average value multiplied x 365 days) of cost and emissions. Comment on the results obtained.
3. Evaluate with which carbon tax would be cost-effective to use the fuel cell solution compared to the engine solution.

Technical report to be submitted:

- Description of the energy conversion and storage units
- Applied methodology (MILP approach) with reference to equations describing energy units and objective functions
- Comparison of the results obtained with configuration ICE + Absorption chiller
- Conclusions and proposed future development of the activity

Exercise: group 2

Exercise for group 2

Evaluate the impact in terms of reducing emissions and operating costs by installing a heat pump to cover the heat energy demand of the wine cellar. The heat pump can be powered by a new 150 kW_P PV plant.

The equation describing the operation of the HP is:

$$QH_{HP}(t) = COP_{HP} * P_{HP}(t)$$

Assume a COP_{HP} equal to 4.

Use the model of PVGIS to calculate the PV producibility, assuming solar irradiance of 2024.

Exercise for group 2

Set a new objective function that goes to simultaneously minimize system operating costs and emissions. Define an emissions objective function for evaluating $CO_{2,eq}$ emissions.

$$f_{emis} = \left(\sum P_{GR_{pos}}(t) - \sum P_{GR_{neg}}(t) \right) * E_{GR}$$

Define a carbon tax to evaluate in cost terms the emission of CO2,eq. The multi-objective function that will be minimized is equal to the linear combination of the two objective functions:

$$f_{MO} = f_{cost} + carbon_{tax} * f_{emis}$$

Use the same assumptions of exercise group 1.

Exercise for group 2

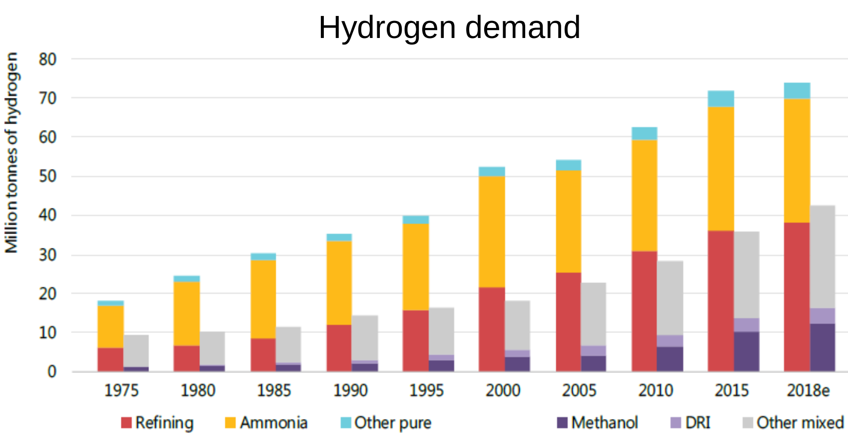
1. Optimize the energy system in the two configurations: i) motor + absorption chiller and ii) PV + HP
2. Calculate results on an annual basis (average value multiplied x 365 days) of cost and emissions. Comment on the results obtained.
3. Evaluate with which carbon tax would be cost-effective to use the HP solution compared to the engine solution.

Technical report to be submitted:

- Description of the energy conversion and storage units
- Applied methodology (MILP approach) with reference to equations describing energy units and objective functions
- Comparison of the results obtained with configuration ICE + Absorption chiller
- Conclusions and proposed future development of the activity

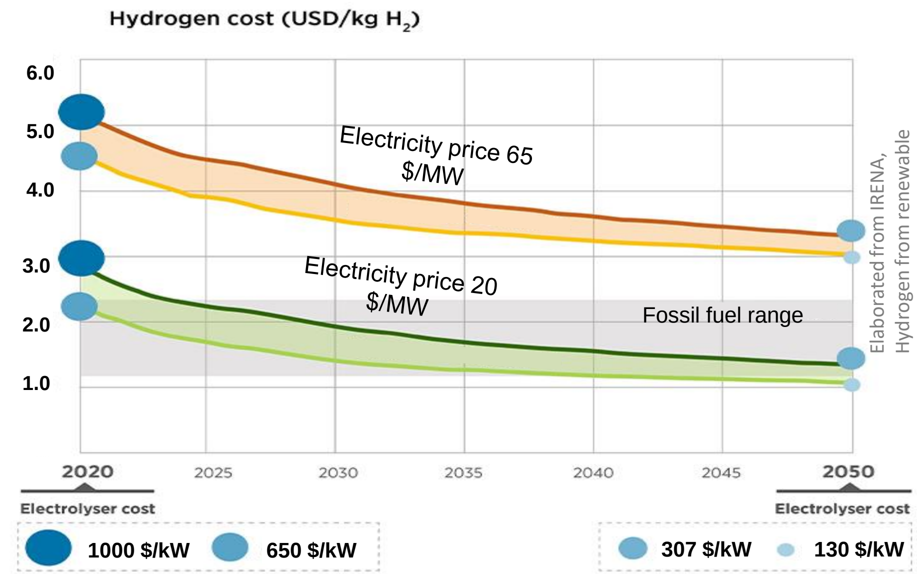
Exercise: group 3

Exercise for group 3



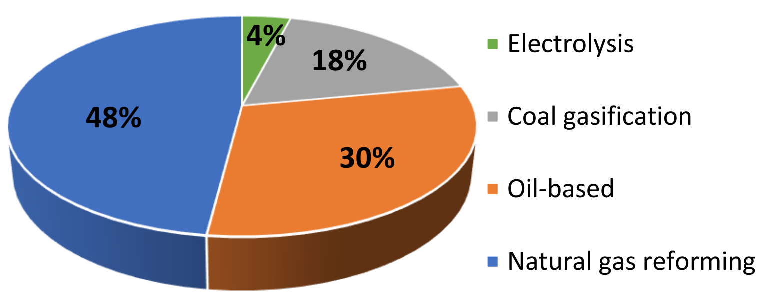
DRI = direct reduced iron steel production

International Energy Agency, The future of Hydrogen, 2019

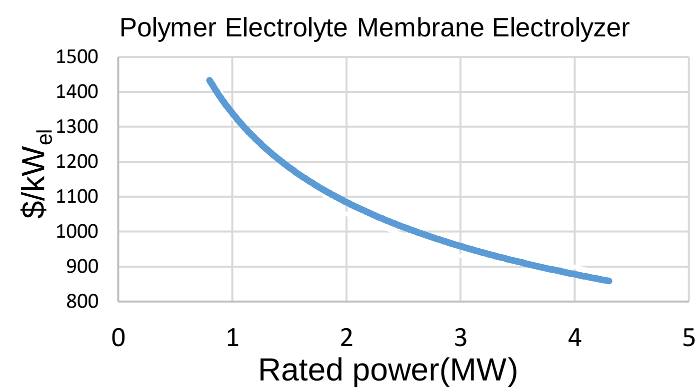


Elaborated from IRENA, Hydrogen from renewable power, 2018

Hydrogen production

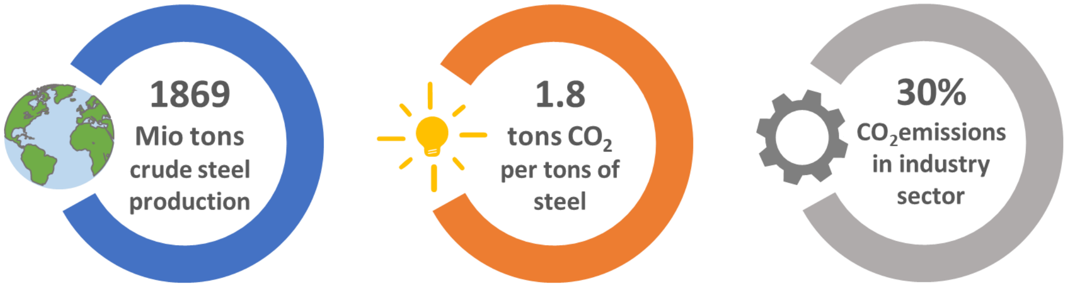


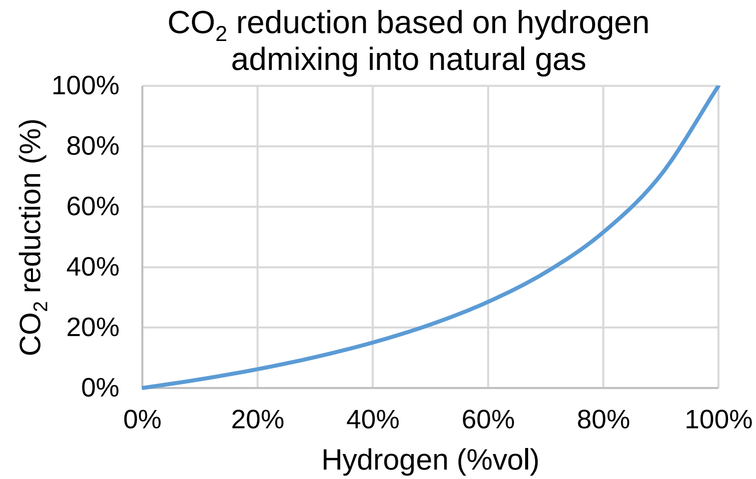
Extracted from International Renewable Energy Agency, Hydrogen from renewable power, 2018



Elaborated from IEA, The future of Hydrogen, 2019

Exercise for group 3

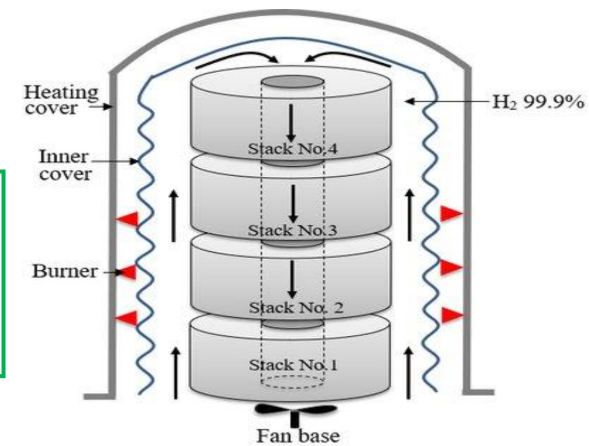




Hydrogen in steel industry

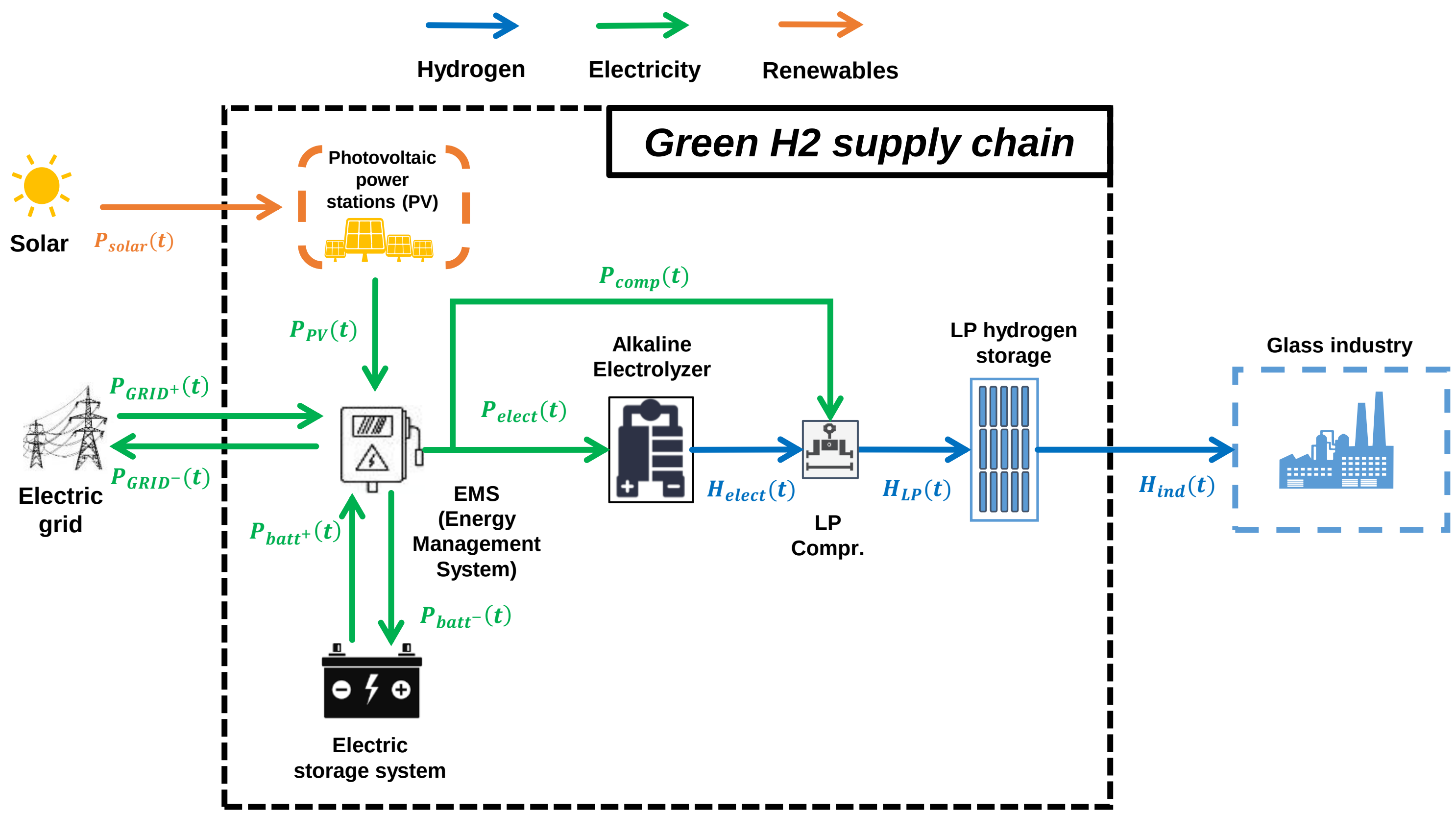
Hydrogen could **substitute** totally or partially the **natural gas**, usually used in several processes to provide heat (e.g. in **Electric Arc Furnaces** and **rolling mill**)

Hydrogen is used as a **technical gas**, for example in **batch annealing furnace** or **continuous annealing**. The substitution of grey hydrogen with green hydrogen could avoid the emission of about **10 kg_{CO2}/kg_{H2}**



Wichienrak R. et al., Factors affecting the mechanical properties variation after annealing of cold rolled steel sheet, E3S Web Conf., 2019, https://doi.org/10.1051/e3sconf/20199504003

Exercise for group 3



Exercise for group 3

1. Analyze the energy system configuration proposed to produce hydrogen for a steel industry.
2. Equations and characteristics of the energy conversion and storage units are reported in the code.

Technical report to be submitted:

- Description of the energy conversion and storage units
- Applied methodology (MILP approach) with reference to equations describing energy units and objective functions
- Evaluate the ratio between the optimal PV nominal power and the electrolyzer nominal power.
- Compare the H_2 production cost and emissions in Trieste respect to the case of Morocco.
- Conclusions and proposed future development of the activity

Exercise for group 3

Mixed-Integer Linear Programming – Simultaneously optimization of Levelized Cost of H_2 and CO_2 emissions

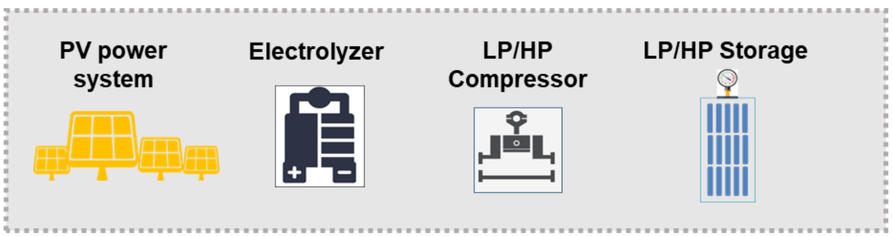
$$minimize\ (w_1 f_1 + w_2 f_2) \rightarrow \min(LCOH^*)$$

$$f_1 = LCOH = \frac{\sum D_{i,j}\left(C_{inv,a_{i,j}} + C_{rep,a_{i,j}} + C_{O\&M_{i,j}}\right) + c^{+}_{GRID}\sum P^{+}_{GRID}(t) - c^{-}_{GRID}\sum P^{-}_{GRID}(t)}{H_{2,demand}}$$

$$f_2 = CO_{2,eq} = CO_{2,GRID}\sum\left(P^{+}_{GRID}(t) - P^{-}_{GRID}(t)\right)$$

$$CO_{2,GRID} = 350\ t_{CO_2}/MWh$$
$$w_2 = 50\ €/t_{CO_2}$$

Optimal **design** and **operation** of the hydrogen system components:



For the *i-th* and *j-th* energy conversion and storage units:

$D_{i,j}$: design parameters

$C_{inv,a_{i,j}}$: annualized capital cost

$C_{rep,a_{i,j}}$: replacement cost

$C_{O\&M_{i,j}}$: yearly operation and maintenance cost

$H_{2,demand}$: yearly hydrogen demand

$Co_{2,GRID}$: average carbon footprint Italian grid

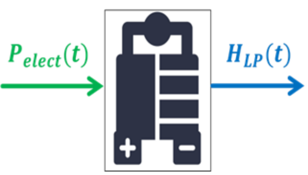
Exercise for group 3

Energy **conversion** units:

$$\varphi_{in,i}(t) = k_{1,i}\varphi_{out,i}(t) + k_{2,i}\delta_i(t)$$
$$k_{3,i}\varphi_{out,i_{max}}\delta_i(t) \le \varphi_{out,i}(t) \le k_{4,i}\varphi_{out,i_{max}}\delta_i(t)$$

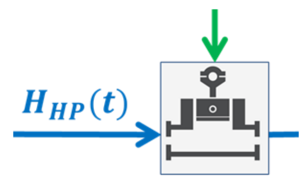
Energy **storage** units:

$$\varepsilon_j(t) = \varepsilon_j(t-1) + k_{1,j}\varphi_{in,j}(t) - k_{2,j}\varphi_{out,j}(t)$$
$$k_{3,j}\varepsilon_{j_{max}} \le \varepsilon_j(t) \le k_{4,j}\varepsilon_{j_{max}}$$



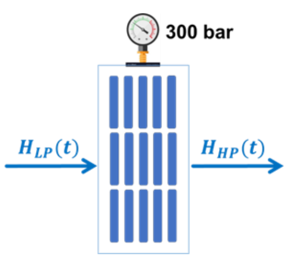
Electrolyzer model:

$$P_{elect}(t) = k_{1,el}H_{LP}(t) + k_{2,el}\delta_{el}(t)$$
$$k_{3,el}D_{elect}\delta_{el}(t) \le H_{LP}(t) \le k_{4,el}D_{elect}\delta_{el}(t)$$



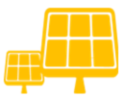
Compressor model:

$$P_{comp,HP}(t) = \frac{L_{comp,id}}{\eta_{mech} * \eta_{is} * \eta_{el}} * H_{HP}(t)$$
$$L_{comp,id} = \frac{\gamma}{\gamma - 1} RT_1 \left[\left(\frac{p_2}{p_1}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1 \right]$$



Low-pressure hydrogen storage model:

$$HS_{LP}(t) = HS_{LP}(t-1) + k_{1,LP}H_{LP}(t) - k_{2,LP}H_{HP}(t)$$
$$k_{3,LP}D_{HS_{LP}} \le HS_{LP}(t) \le k_{4,LP}D_{HS_{LP}}$$



PV plant model:

$$P_{PV}(t) = \eta_{PV} * \eta_{inverter} * D_{PV} * P_{solar}(t)$$
$$D_{PV} = k_{PV} * Area_{PV}$$

Thank you for your attention!

Davide Pivetta

e-mail: davide.pivetta@phd.units.it