Exploring and Optimizing Process Off-Gas Management in Steelworks During Their Transitions Towards C-Lean Processes

SMARTER

Steam and gas networks revamping for the steelworks of the future

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Steel Production impact

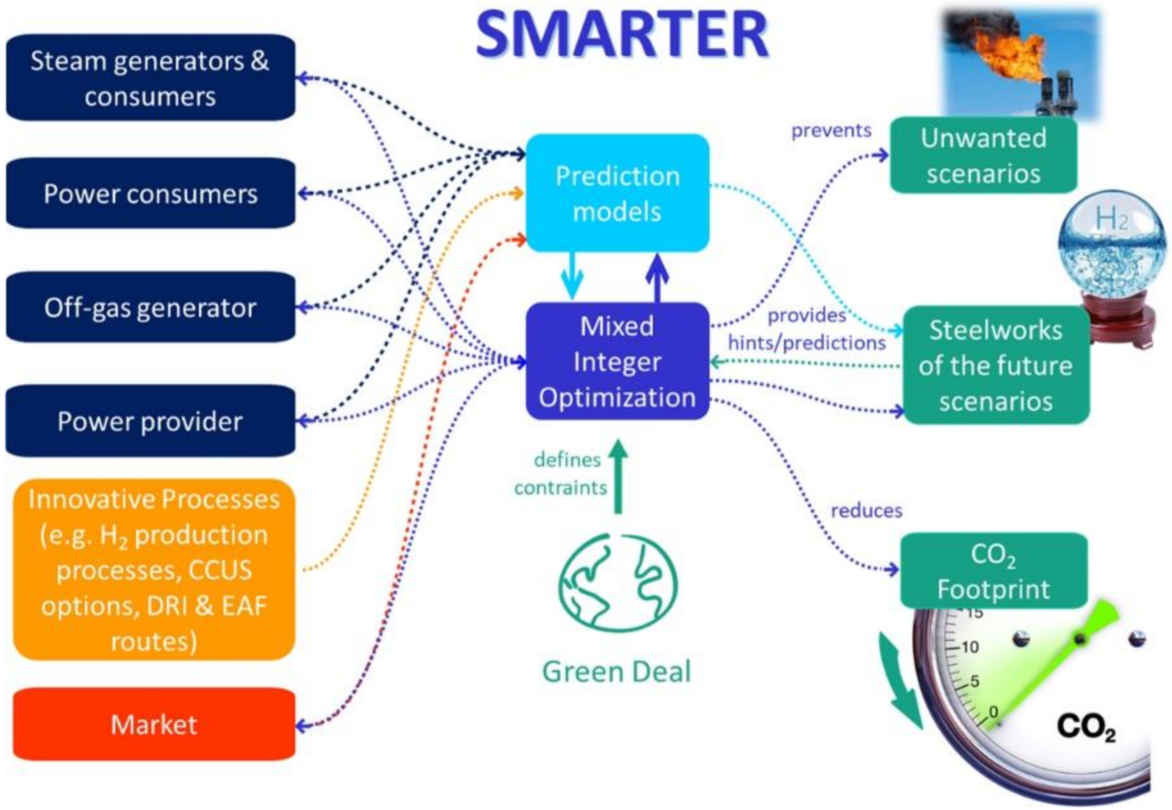
In 2023, around **126 million tons** of steel were produced in the EU.

1 ton of steel directly produces about **1.5 tons of CO_2**

about **6% of European CO_2 emissions** come from this sector

The Smarter Project

SMARTER develops advanced methodologies and tools to revamp and optimize gas and steam networks in steelworks, **enhancing energy efficiency, reducing CO2 emissions, and lowering energy and management costs.**



New scenarios

Simulation of **future** innovative scenarios:

- **Optimize** the management and the structure of the steam and gas networks inside integrated steelworks in the light of the future developments of the steel production

Maximizing **profit**

Minimizing **environmental impact**

Minimizing **system stress**

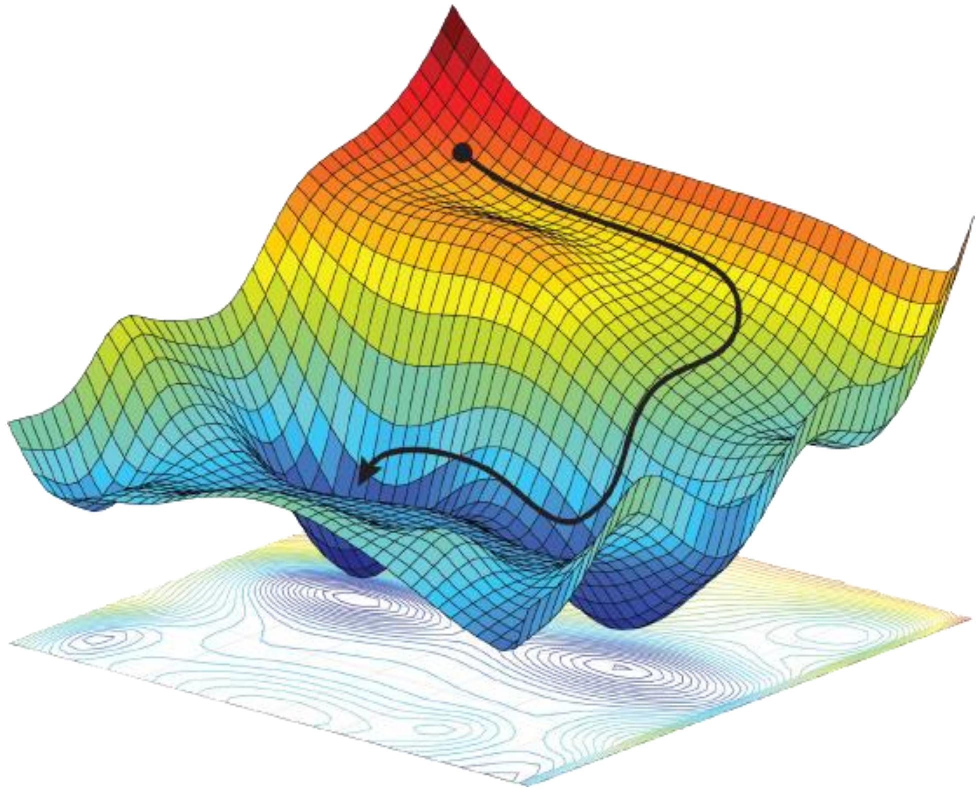
Problems

The POGs are produced intermittently

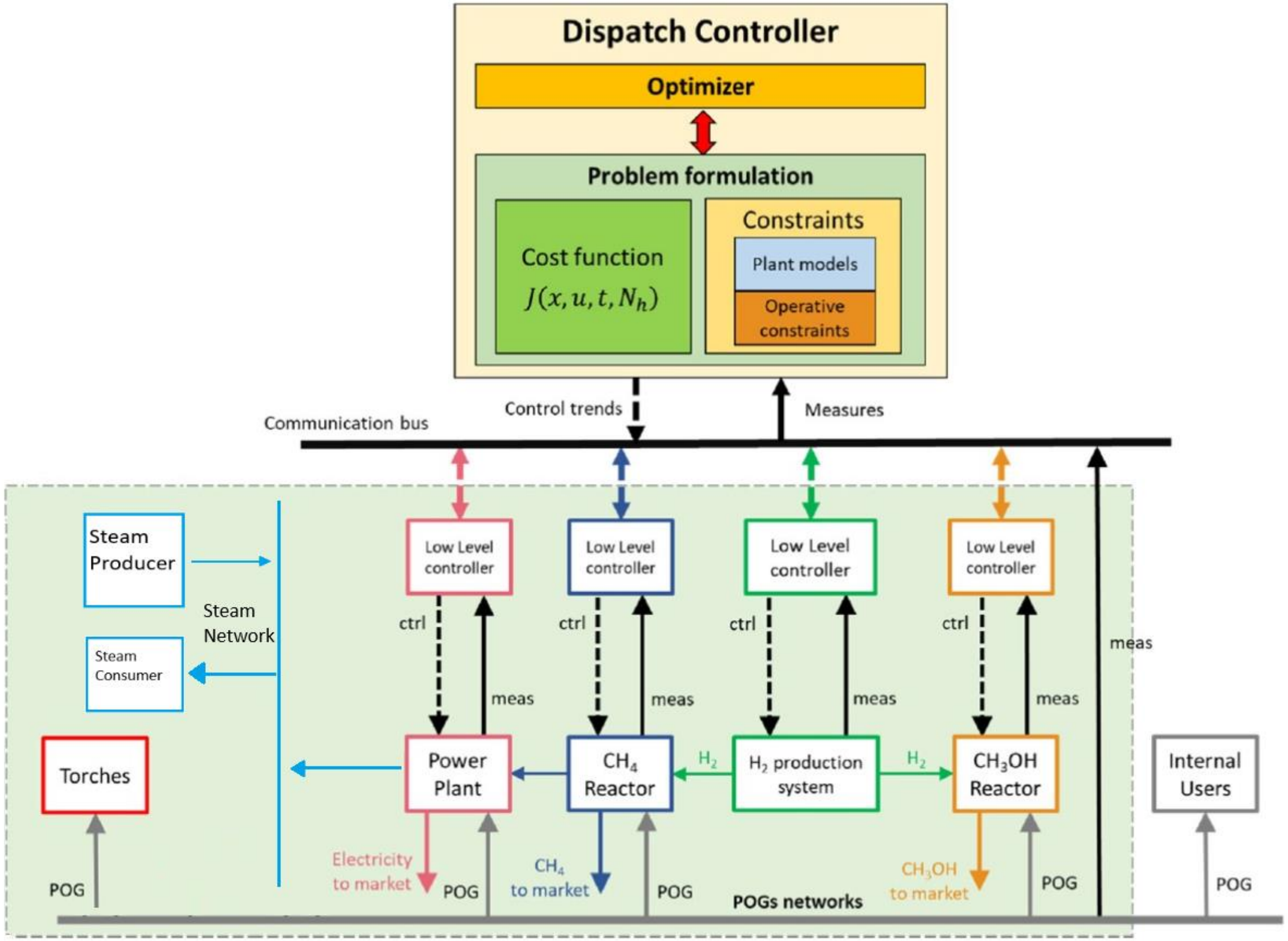
Solution

Data driven models

Optimization strategy



Control Scheme



Followed approach, Assumptions and New Ideas

- **Enhance** existing models, **developing** new units models, and **consider** the amount of carbon dioxide **captured** with CCSU solutions, e.g., for methane and/or methanol synthesis (as next slide), and **produced/consumed** by the system also in case of transitional scenarios (e.g., replacement of BF with EAF and DR process)

- **Test** forecast algorithms to predict physical quantities

- **Develop** Key Performance indicators that **directly** quantifies the control performances :

$$KPI_{€} = \beta \sum_{k=1}^{N_{\text{simulation}}} (q_{\text{sold}}(k) - q_{\text{purchased}}(k))$$

$$KPI_{\text{time}} = k_{\mu}\mu_{\text{time}} + k_{\sigma}\sigma_{\text{time}} + k_{\text{comp}}t_{\text{comp}}^{\text{max}}$$

$$KPI_{\Delta} = \sum_{k=1}^{N_{\text{simulation}-1}} (\sum_{i} c_i|q_i(k+1) - q_i(k)| + \sum_{r} c_r|\delta^r(k+1) - \delta^r(k)|)$$

$$KPI_{CO_2} = \alpha \sum_{k=1}^{N_{\text{simulation}}} q_{CO_2}^{s}(k) - q_{CO_2}^{p}(k)$$

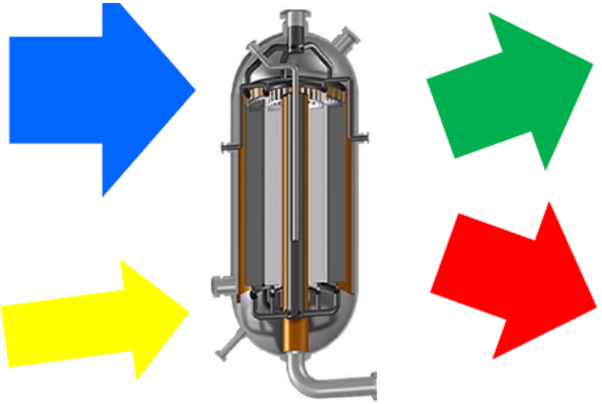
Followed approach, Assumptions and New Ideas

It is possible to valorize POG by converting them into chemicals that can be **stored** or **sold**

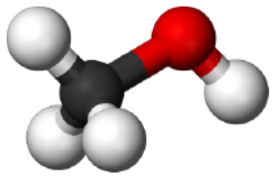
Hydrogen

POG:

- BFG
- BOFG
- COG

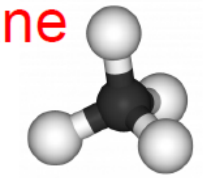


Methanol



$$CO + 2H_2 \rightarrow CH_3OH$$
$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

Methane



$$CO + 3H_2 \rightarrow CH_4 + H_2O$$
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$$KPI_{\mathrm{CO_2}} = \alpha \sum_{k=1}^{N_{\mathrm{simulation}}} q^{\mathrm{s}}_{\mathrm{CO_2}}(k) - q^{p}_{\mathrm{CO_2}}(k)$$

Followed approach, Assumptions and New Ideas

The **CO_2 produced** in the power plant can be calculated by using basic **chemical transformations** related to combustion process

$$C_\alpha H_\beta O_\gamma + \left(\alpha + \frac{\beta}{4} - \frac{\gamma}{2}\right)(O_2 + 3.77N_2) \rightarrow \alpha CO_2 + \frac{\beta}{2} H_2O + 3.77\left(\alpha + \frac{\beta}{4} - \frac{\gamma}{2}\right) N_2$$

$$KPI_{CO_2} = \alpha \sum_{k=1}^{N_{\text{simulation}}} q^{s}_{CO_2}(k) - q^{p}_{CO_2}(k)$$

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Followed approach, Assumptions and New Ideas

$$\min \quad J$$
$$\text{s.t.} \quad \mathbf{x}(k+1) = A\mathbf{x}(k) + B_u\mathbf{u}(k) + B_\delta\boldsymbol{\delta}(k)$$
$$\mathbf{y}(k) = C\mathbf{x}(k) + D_u\mathbf{u}(k) + D_\delta\boldsymbol{\delta}(k)$$
$$H_u\mathbf{u}(k) + H_x\mathbf{x}(k) + \mathbf{h}(k) \leq H_\delta\boldsymbol{\delta}(k)$$
$$\mathbf{x}(0) = \mathbf{x}_0$$
$$\boldsymbol{\delta}(0) = \boldsymbol{\delta}_0$$
$$\boldsymbol{\delta} \in \mathrm{Z}^d$$
$$k \in \{0, 1, \ldots, N_p - 1\}$$

$$J = \sum_{k=0}^{N_p-1} \gamma^k (l_{\text{eco}}(k) + l_{\text{env}}(k) + l_{\text{op}}(k))$$

- $l_{eco}(k) = \mathbf{c}_p^T \mathbf{E}_p(k) - \mathbf{c}_s^T \mathbf{E}_s(k)$
- $l_{env}(k) = -q^s_{CO_2}(k) + q^p_{CO_2}(k)$
- $l_{op}(k) = +C_{rs}(k) + C_{\Delta v_r}(k) + C_{\Delta PEM}(k) + C_{LGH}(k) + \mathbf{c_s}^T \mathbf{s}(k)$

Simulated Scenarios

- Standard Route
- Standard Route + Methane Reactor
- Standard Route + Methanol Reactor
- Replacement of 1 BF with EAF and externally purchased DRI
- Replacement of 1 BF with EAF and internally produced DRI, and Methane Reactor is considered
- Replacement of 1 BF with EAF and Green energy is considered

Reference Scenario

Standard Route including 1 coke plant, 1 big BF, 2 small BFs and 3 converters

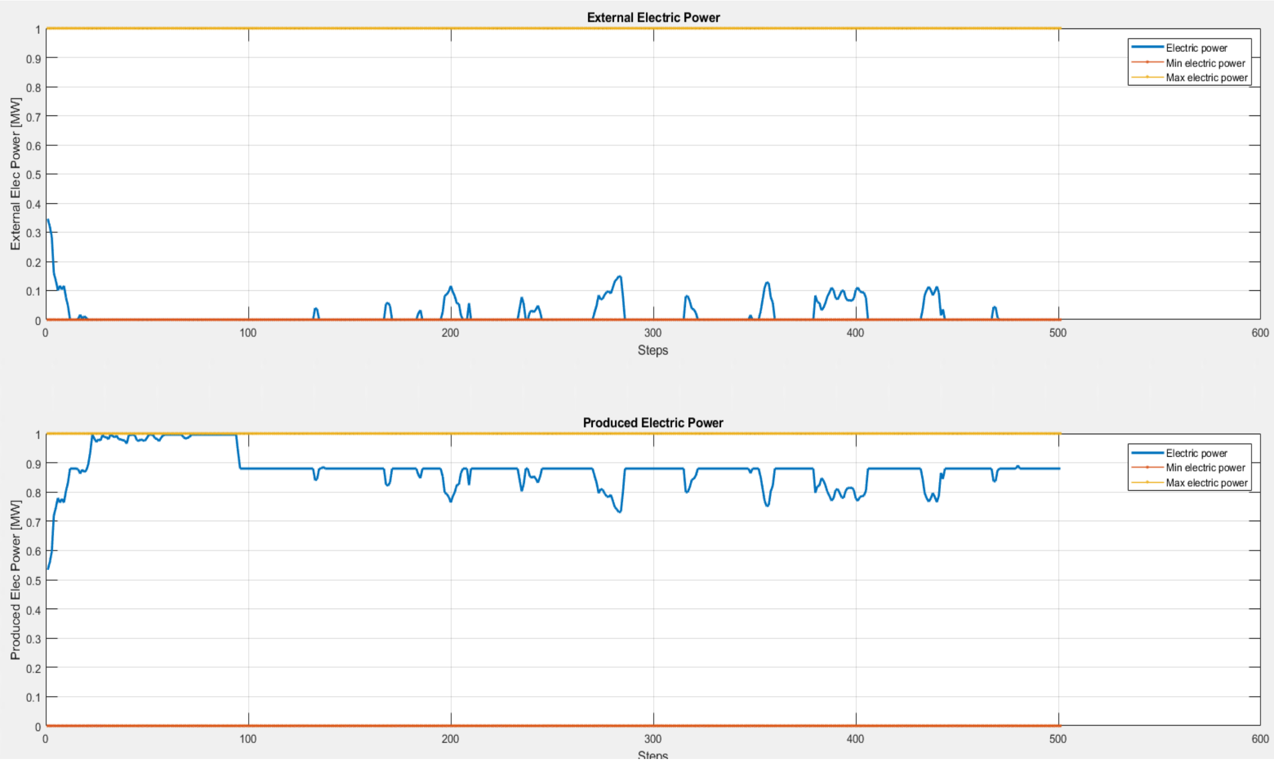
Historical energy prices

Internal energy (heat, electricity, steam) demands is always satisfied

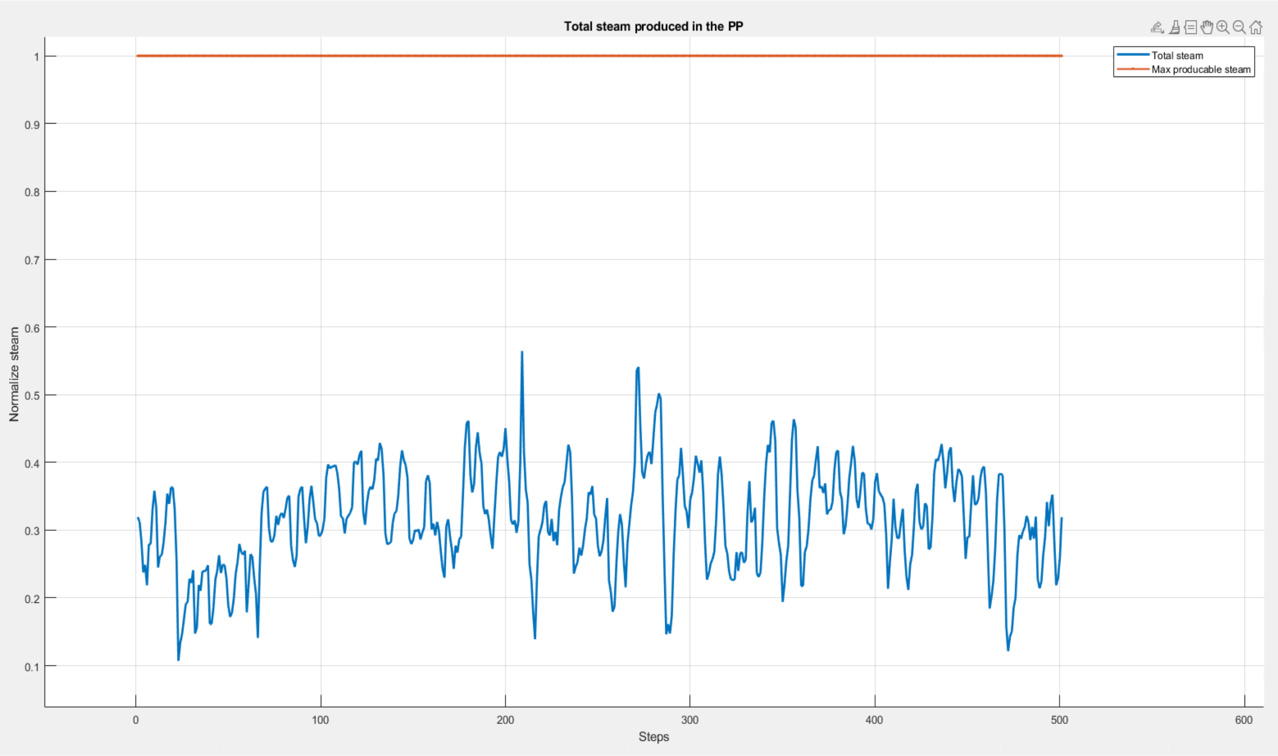
POGs excess can only be rerouted to PP and torches

Time changing production and consumption

Reference Scenario Results



Electrical power



Steam production

New Scenarios

Standard Route

POGs excess can only be rerouted to PP and torches

Novel Route

POGs excess can be rerouted to PP, torches and methane reactor

Remark:

- Physical constraints are always considered
- Internal energy demands are always satisfied
- Used H_2 is considered green

KPI	Value
Money KPI %	$\approx +37.1\%$
Total KPI CO_2 %	$\approx -9.1\%$

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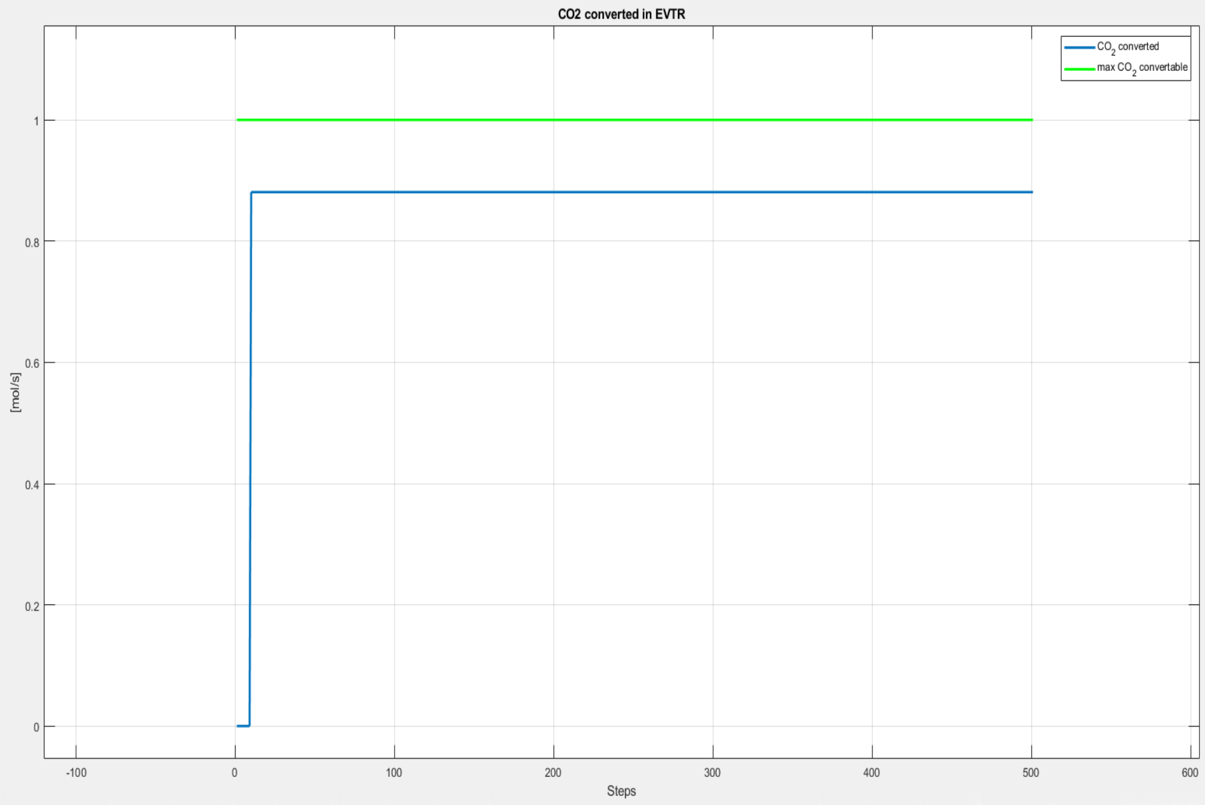
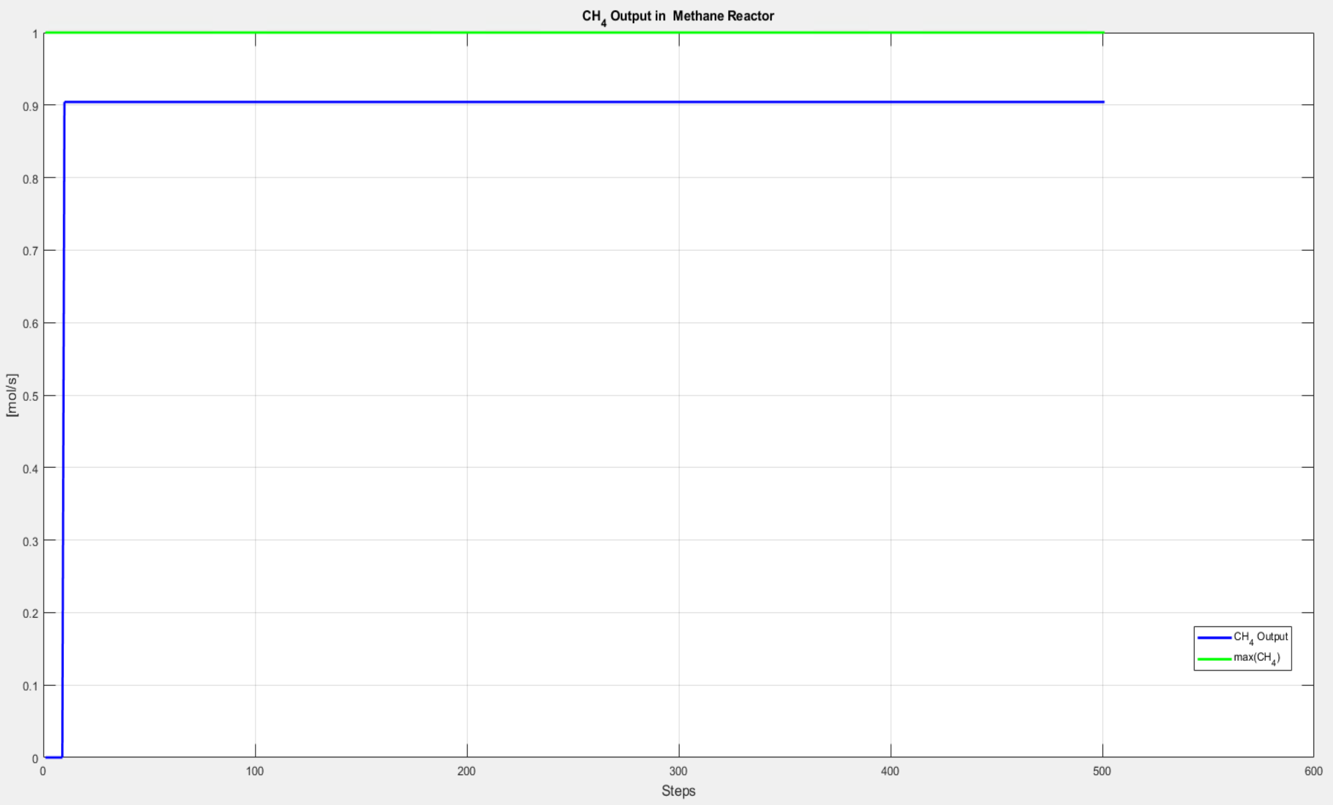
Results





CO_2 converted

CH_4 output

ICT COISP

New Scenarios

Standard Route

POGs can only be rerouted to PP and torches

Novel Route

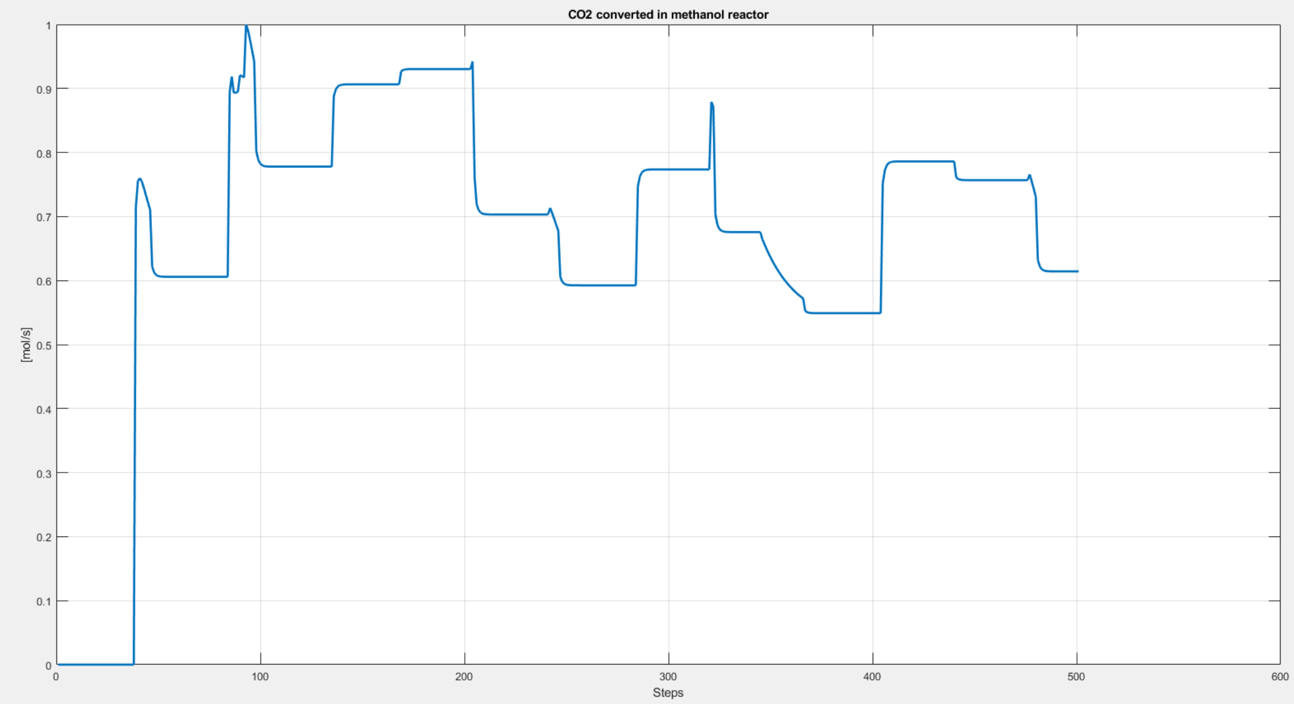
POGs can be rerouted to PP, torches and methanol reactor

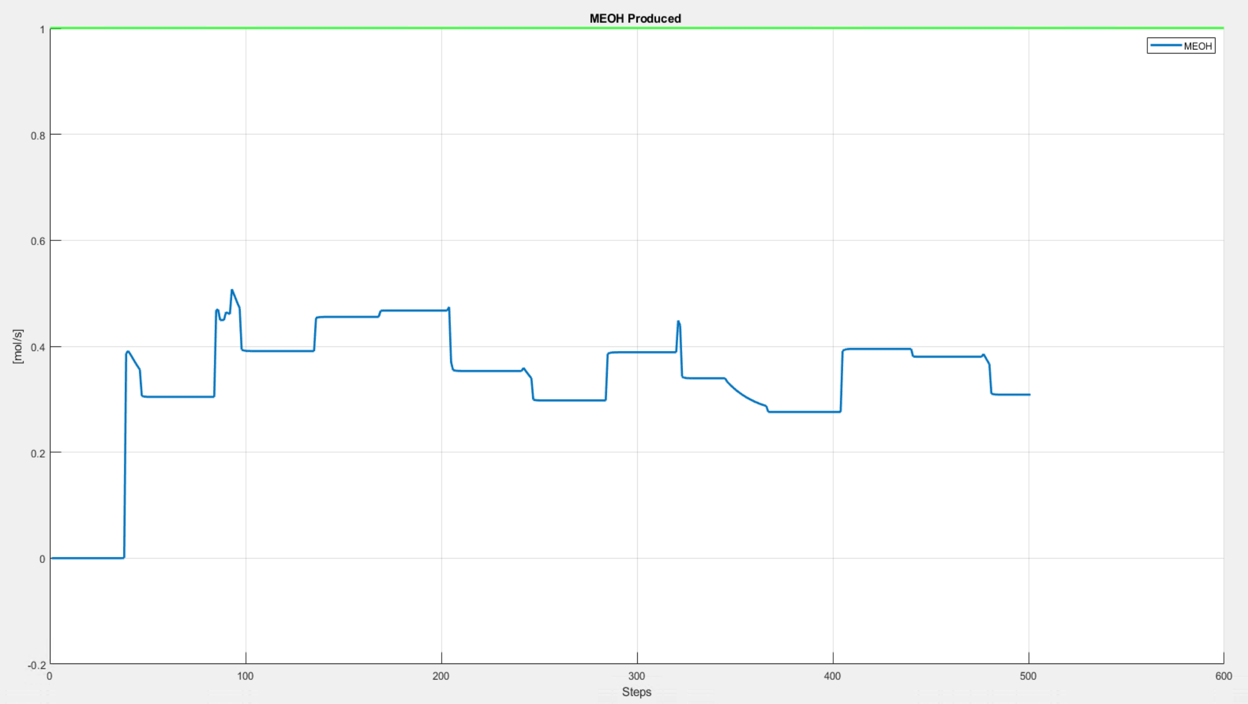
Remark:

- Physical constraints are always considered
- Internal energy demands are always satisfied
- Used H_2 is considered green

KPI	Value
Money KPI %	$\approx +50,3\%$
Total KPI CO_2 %	$\approx -4,6\%$

Results



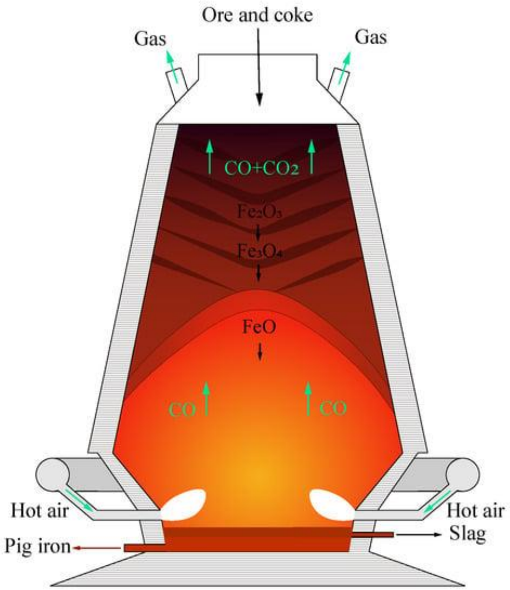


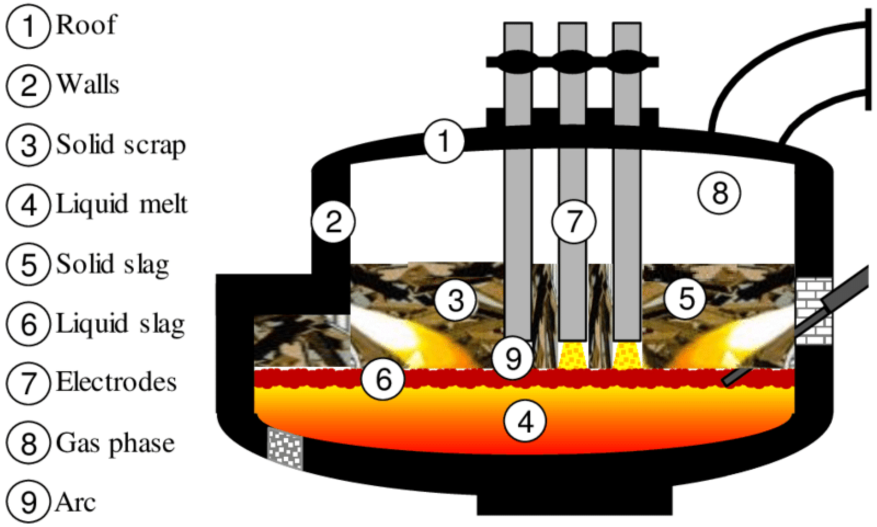
CO_2 converted

MeOH produced

New Scenarios

Replace 1 small BF with **EAF** fed by scrap and **externally purchased DRI**





Considerations and KPIs results

We have replaced 1 small blast furnace; we have used historical data and physical models to calculate the **energy** requirements

$$E_{\mathrm{EAF}} = \frac{2.344}{\eta_{\mathrm{DRI}}} \times \left(\frac{M_{\mathrm{DRI}}}{M_{\mathrm{TM}}}\right) + 371.874 \quad [\mathrm{kWh/ton}]$$

and **CO_2 emissions (direct and indirect)** for the Electric Arc Furnace (EAF)

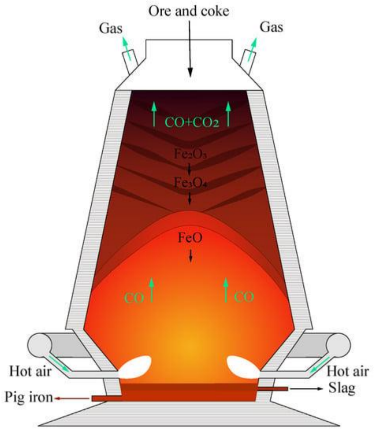
$$\mathrm{CO}_2^{\mathrm{EAF}} = 9.002 \times \left(\frac{M_{\mathrm{DRI}}}{M_{\mathrm{scrap}} + M_{\mathrm{DRI}}}\right) + 327.109 \quad [\mathrm{kgCO_2/ton}]$$

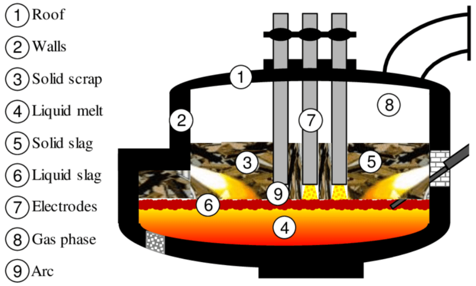
KPIs Results

KPI	Value
Money KPI %	$\approx -58.54\%$
Total KPI CO_2 %	$\approx -17.52\%$

New Scenarios

Replace 1 small BF with **EAF** fed by scrap and **DRI internally produced + methane reactor**

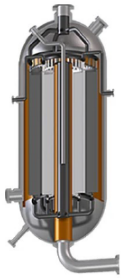




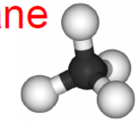
Hydrogen

POG:

- BFG
- BOFG
- COG



Methane



$$CO + 3H_2 \rightarrow CH_4 + H_2O$$
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Considerations and KPIs results

We can calculate the **CH_4 demand** in $\frac{Nm^3}{tDRI}$ by the shaft furnace

$$M_{CH_4} = \begin{cases} -300.220R_{H_2}^3 + 175.677R_{H_2}^2 - 130.886R_{H_2} + 259.521, & 0 \le R_{H_2} < 1 \end{cases}$$

CO_2 equivalent output from the whole DRI process in $kg/tDRI$.

$$q_{\mathrm{CO_2}}^{\mathrm{DRI}} = \begin{cases} -474.224R_H^2 + 39.721R_H + 438.519, & 0 \le R_H < 1 \end{cases}$$

And **energy consumed** in $kWh/tDRI$. $E^{\mathrm{DRI}} = 112.5$

Remark:

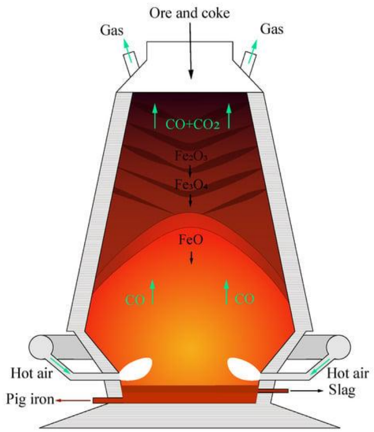
- Physical constraints are always considered
- Internal energy demands are always satisfied
- Used H_2 is considered green

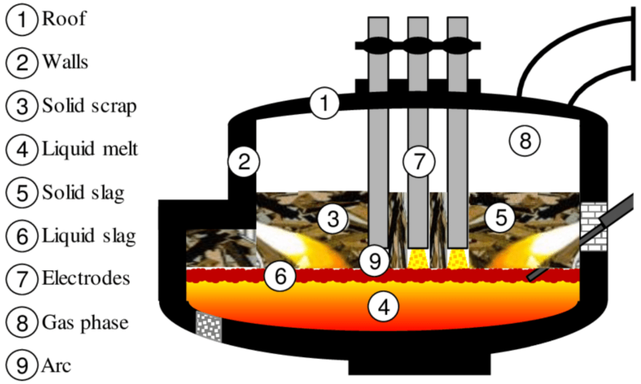
KPIs Results

KPI	Value
Money KPI %	$\approx -31.6\%$
Total KPI CO_2 %	$\approx -28.1\%$

New Scenario

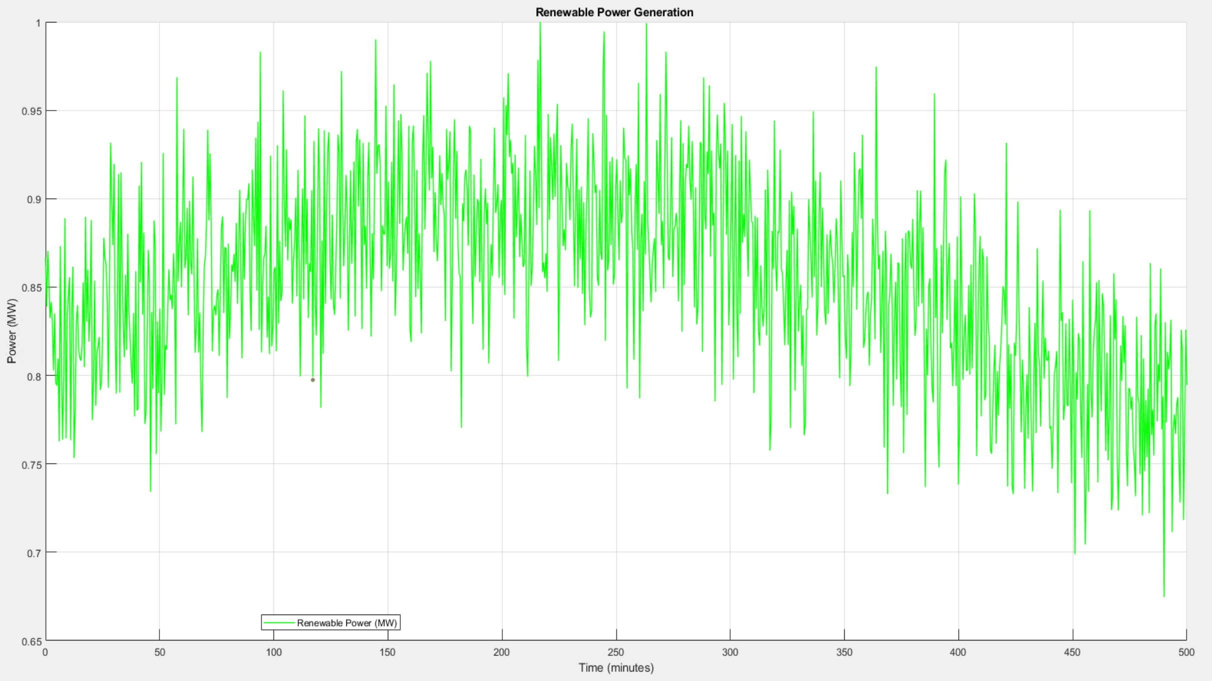
Replace 1 small BF with **EAF** and **renewable energy is considered**

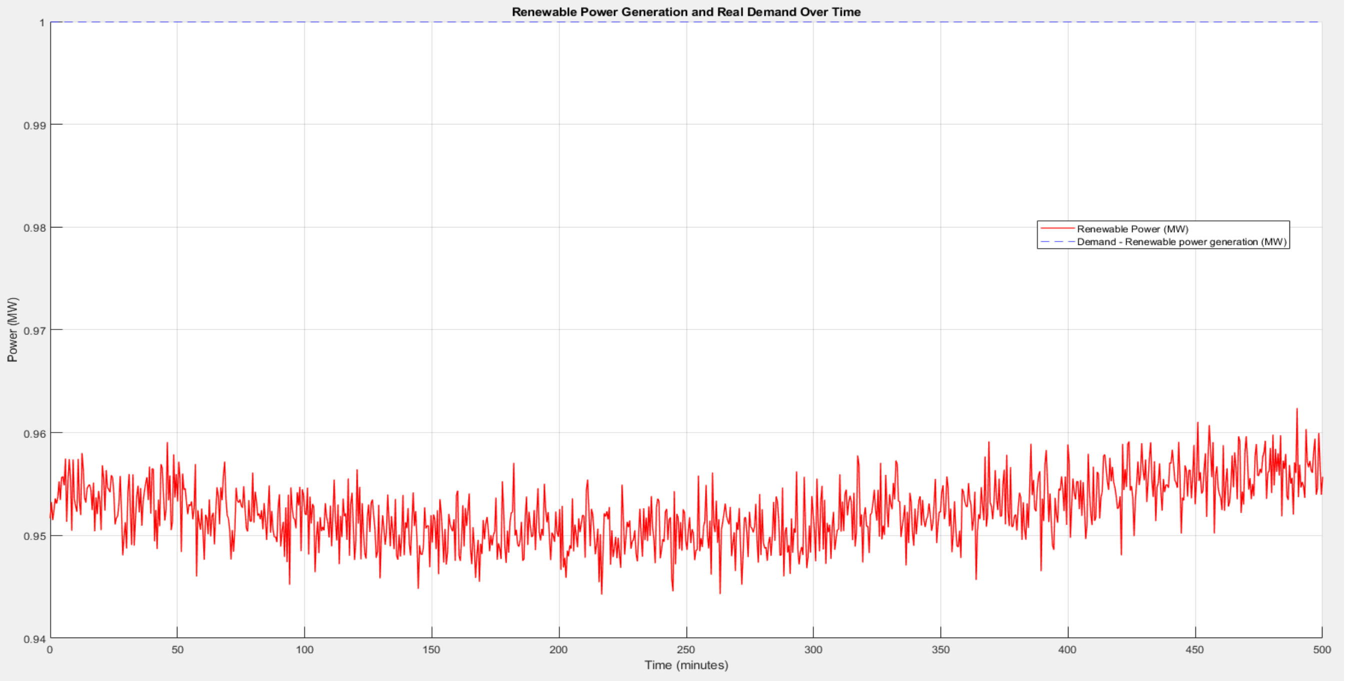




$$P_{\text{renewable}}(t) = P_{\text{avg\_ren}} + A\sin(\omega t + \phi) + \epsilon$$

Considerations and KPIs results





Renewable Power

Internal Demand

KPIs Results

KPI	Value
Money KPI %	$\approx -50.81\%$
Total KPI CO_2 %	$\approx -19.52\%$

ICT COISP

Final scenario KPIs comparison

KPI	Value
Money KPI %	≈ +37.1%
Total KPI CO_2 %	≈ −9.1%

Standard route + Methane Reactor

KPI	Value
Money KPI %	≈ +50, 3%
Total KPI CO_2 %	≈ −4.6%

Standard route + Methanol Reactor

KPI	Value
Money KPI %	≈ −58.54%
Total KPI CO_2 %	≈ −17.52%

1 small BF replaced with EAF and externally purchased DRI

BF partially replace with EAF+ Renewable energy

KPI	Value
Money KPI %	≈ −50.81%
Total KPI CO_2 %	≈ −19.52%

KPI	Value
Money KPI %	≈ −31.6%
Total KPI CO_2 %	≈ −28.1%

1 small BF replaced with EAF and internally produced DRI + Methane Reactor

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Conclusions and future works

We can clearly see an **environmental and an economic improvement when syntheses reactors are used** but It’s crucial to remark economic feasibility heavily depends on the **hydrogen production cost [2].**
It's important to recognize that, due to the complexity of the optimization system, it is highly sensitive to changes. Variations in production, consumption, and price can result in significantly different outcomes.

These studies are still in progress, and further considerations needs to be done.

Nevertheless, they certainly offer valuable insights for guiding steelworks transitions towards C-lean processes

Many additional scenarios can still be analyzed and compared with the baseline case, including dynamic price fluctuations, disturbances in the production, introduction of storage possibilities for chemicals produced by the reactors and introduction of Mixed-Integer Quadratic Programming techniques.

[2] Matino, I., Dettori, S., Zaccara, A., Petrucciani, A., Iannino, V., Colla,..& Rompalski, P. (2021). **Hydrogenrolein the valorizationof integrated steelworks process off-gases through methane and methanol syntheses**. *Matériaux& Techniques*,

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Thank you

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