Grant Agreement Number: 101034060

Project Acronym: SMARTER

Project title: SteaM and gAs networks Revamping for the sTeElworks of the futuRe

Deliverable 6.2

Proceedings of the SMARTER workshop.

Summary

1 Project summary and purpose of the present document

The SMARTER project aims to develop methodologies and tools to optimize energy networks in integrated steel plants, with the objectives of increasing energy efficiency and reducing CO_2 emissions. It includes two specific industrial case studies:

- The first case study focuses on creating real-time control and decision-making tools for the ArcelorMittal Bremen (ABG) plant. It aims to optimise energy flows, in particular steam and process off-gases, within integrated steelworks using the blast furnace (BF)/ basic oxygen furnace (BOF) steelmaking route. This approach involves upgrading energy networks and implementing innovative methods to develop a Decision Support System (DSS) that assists operators in enhancing energy flow and synchronizing energy transformation and utilization.
- The second case study examines energy networks in a potential steel mill of the future, based on the voestalpine Stahl GmbH plant in Linz, Austria (VAS). Hypothetical future scenarios, including the adoption of hydrogen-based steelmaking, are defined and simulated to evaluate the impact on CO_2 emissions reduction, external energy demand, and internal energy usage.

After the official conclusion of the project, on February 17 2025, the SMARTER Consortium organised the Final Workshop of the project in the form of an online event which gathered 5 presentations followed by a panel discussion and Q&A session for an overall duration of 2 hours.

The program of the workshop is shown in Figure 1 and was spread through a LinkedIn post published on the LinkedIn account of the project and diffused by the partners, on the project website in the section of the events, and via email via the networks of the partners as well as via an email spread by the secretary of the European Steel Technology Platform (ESTEP).

Figure 1. Programme of the Final Workshop of SMARTER.

The Workshop gathered a total of 49 participants from different countries and entities. At the end of the Workshop, a short questionnaire was spread among participants to collect very basic information on the audience. Figure 2 shows the distribution of the participants among the different countries, while Figure 3 shows their distribution among the different types of company/institution.

The third and last question of the Survey concerned the level of appreciation of the Workshop on a Likert scale on 5 levels (expressed as "stars", with 5 stars corresponding to the maximum appreciations). Figure 4 shows the outcomes of such question, which was overall very satisfactory, with an average rating of 4.5/5.

The present document collects all the presentations discussed during the workshop.

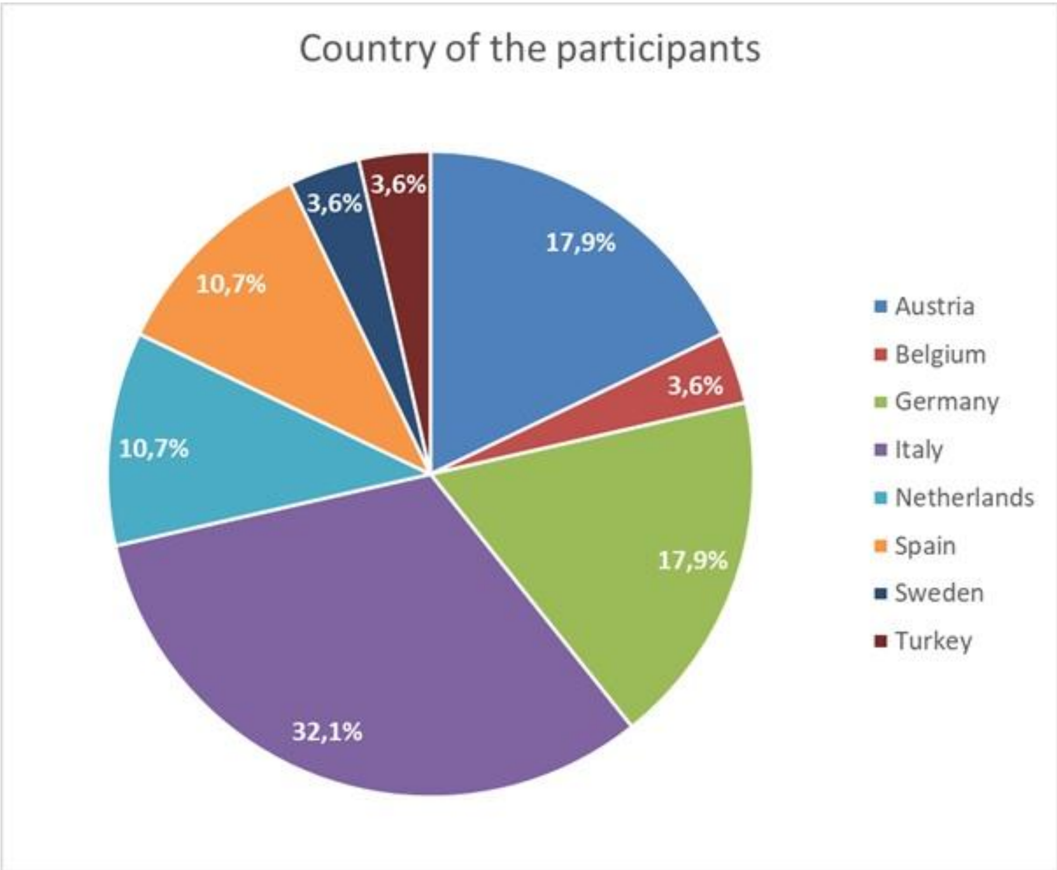

Figure 2. Distribution of the participants of the SMARTER Workshop among countries.

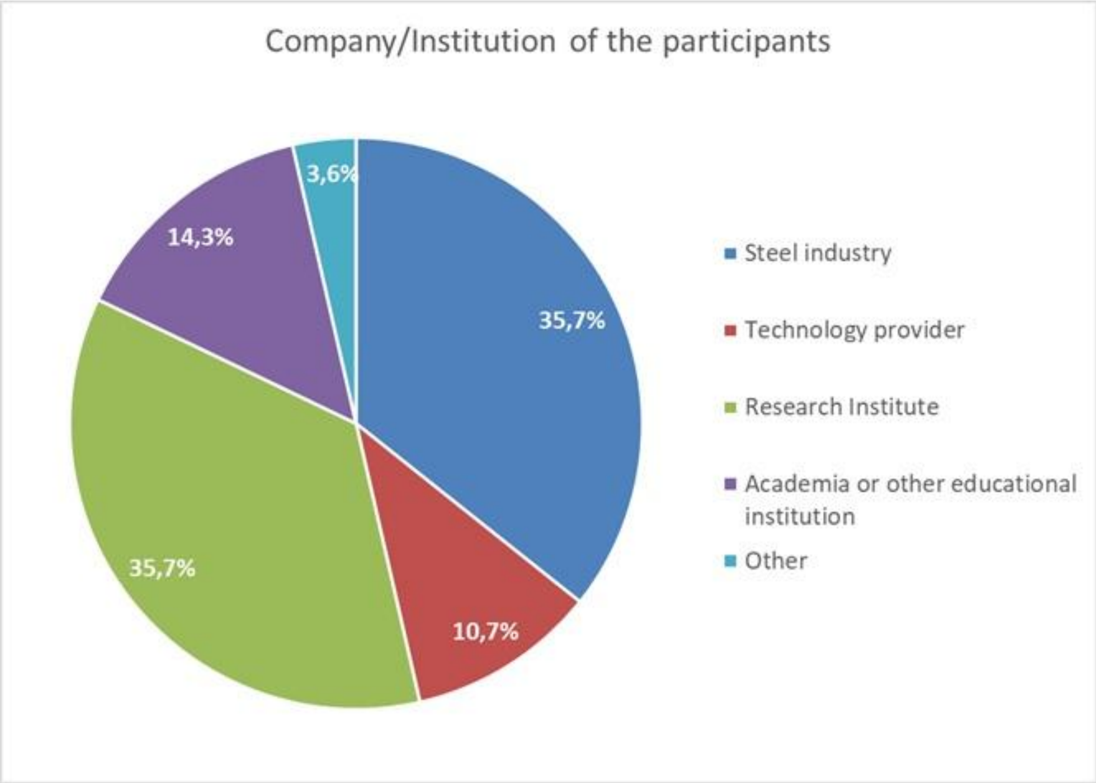

Figure 3. Distribution of the participants of the SMARTER Workshop among the different types of company/institution.

Figure 4. Rating of the Workshop as expressed by the participants.

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ArcelorMittal

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INTRODUCTION TO THE PROJECT "STEAM AND GAS NETWORKS REVAMPING FOR THE STEELWORKS OF THE FUTURE"

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Valentina Colla

ICT COISP

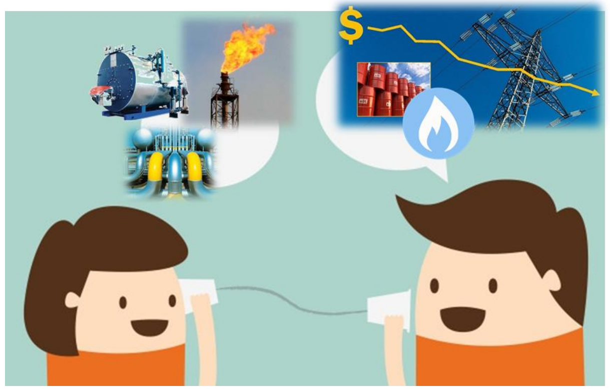
Information and Communication Technologies for Complex Industrial Systems and Processes

Final SMARTER Workshop, February 17, 2025.

Background and motivations

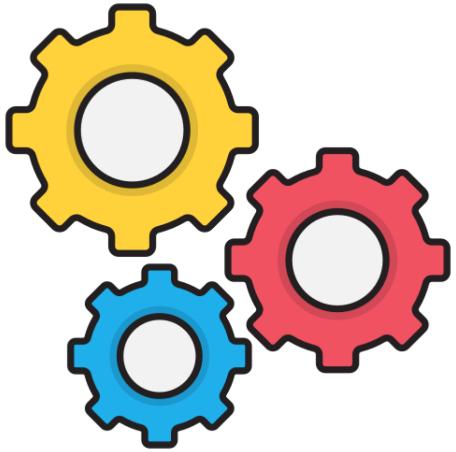
Strategic management of energy in a company to optimize energy efficiency, reduce costs, and minimize environmental impact**.**

Main goals: Reduce energy consumption, improve the efficiency of production processes, reduce CO_2 emissions, and comply with environmental regulations.



A **DSS** is needed for:

- **Energy consumption monitoring**
  - Detection and continuous monitoring of consumption in real time or periodically.
  - Data analysis to identify consumption trends and peak usage.
- **Energy cost optimization**
  - Identifying solutions to reduce costs
  - Scenario simulation and comparison of strategies to save energy and reduce CO_2 emissions.
- **Energy demand forecasting.**
  - Use of forecasting algorithms based on historical, weather and production data.
  - Real-time adaptation to respond to changes in demand.
- **Integration of renewable and/or byproduct sources**
  - Evaluation of the potential for integration of renewable energy
  - Resource planning based on variability of energy sources.
- **Predictive maintenance management, etc…**



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Background and motivations

Issues:

- **Complexity of integrating byproduct energy sources.**
  - Variations in energy production and problematic forecasting of source availability.
  - Need for solutions for energy balancing and peak generation management.
- **Cost and complexity of technology**
  - Lack of commercial software in the field
  - Implementation of advanced monitoring systems and sensors is expensive (through commercial libraries)
  - Stability and reliability of open-source libraries
  - Interoperability issues between legacy systems and new technologies.
- **Data quality and availability.**
  - Inconsistent, incomplete data or data collected in different formats can compromise analyses.
  - Difficulty in accessing data in real time and at a granular level for some consumption areas.
- **Data security and privacy**
  - Need to ensure security of collected data, especially in industrial settings.
  - Protection of sensitive information for compliance with privacy regulations.
- **System scalability and adaptability**
  - Adapting DSS to changes in business or industrial structures can be complex.
  - Scalability issues when integrating new components or energy sources.

Project goals and main objectives

- Steelworks off-gases are valuable sources of energy and chemical compounds, their optimal valorization plays a key role for a sustainable steel production.
- Managing steam and gas networks is a very complex task due to numerous constraints deriving from their structures and variability in production and demands. Such complexity will increase with the transition to C-lean production processes.

Development of advanced methodologies and tools to support revamping and optimized management of steam and gas networks in integrated steelworks to improve energy efficiency and reduce CO_2 emissions, energy & management costs.

Two “scopes” in the project:

1. Traditional BF/BOF route
2. Implementation of innovative production and auxiliary units

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Scope1: Traditional BF/BOF route

Coke Oven Gas (COG)

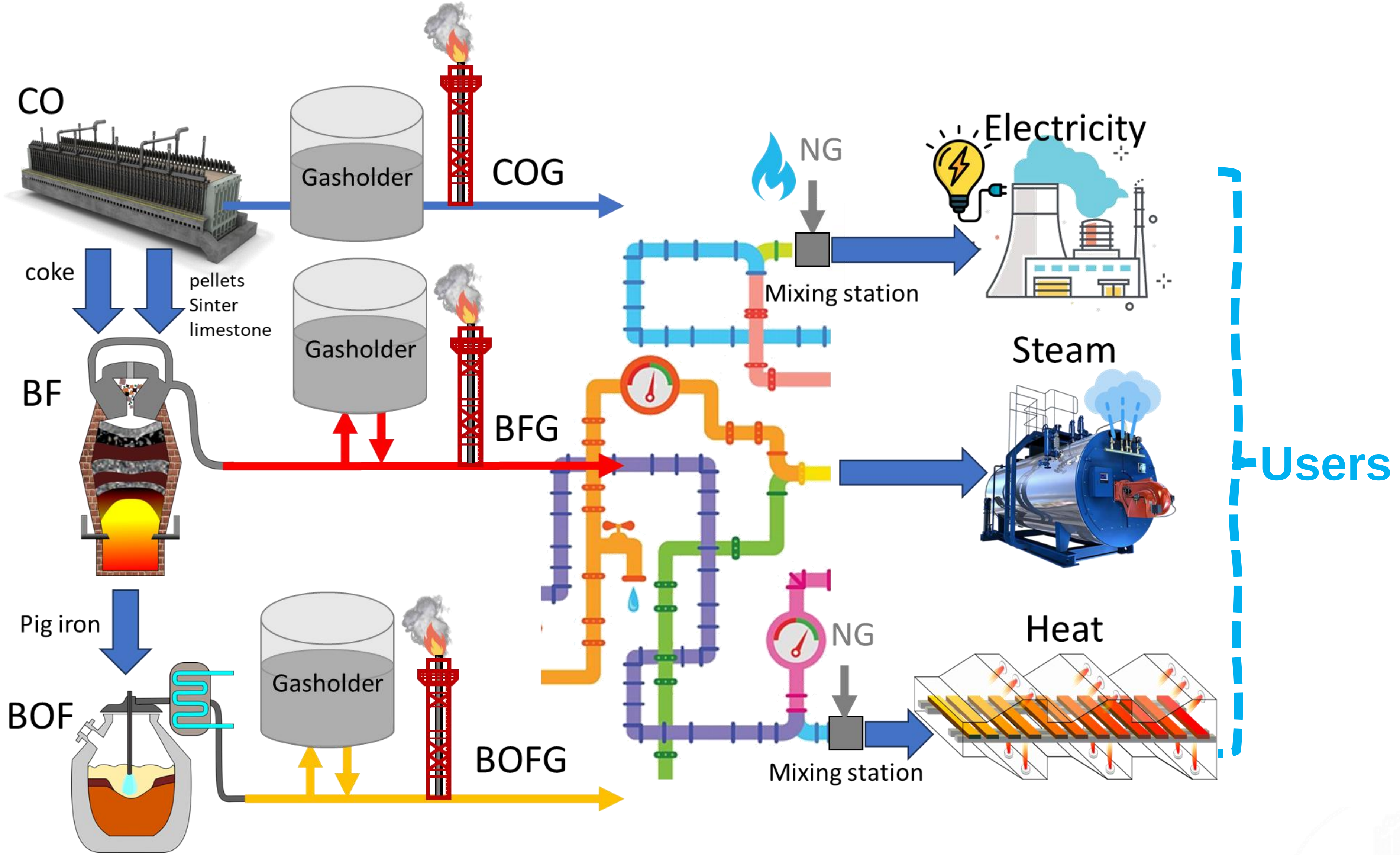
- Variable volume flow production and Net Calorific Value (NCV)
- The highest Net Calorific Value (NCV), ~ 50% of Natural Gas (NG)

Blast Furnace Gas (BFG)

- Slowly variable volume flow production and NCV
- The lowest NCV (~9% of NG NCV)

Basic Oxygen Furnace Gas (BOFG)

- Good NCV (~25% NG NCV)
- Discontinuous volume flow production and variable NCV



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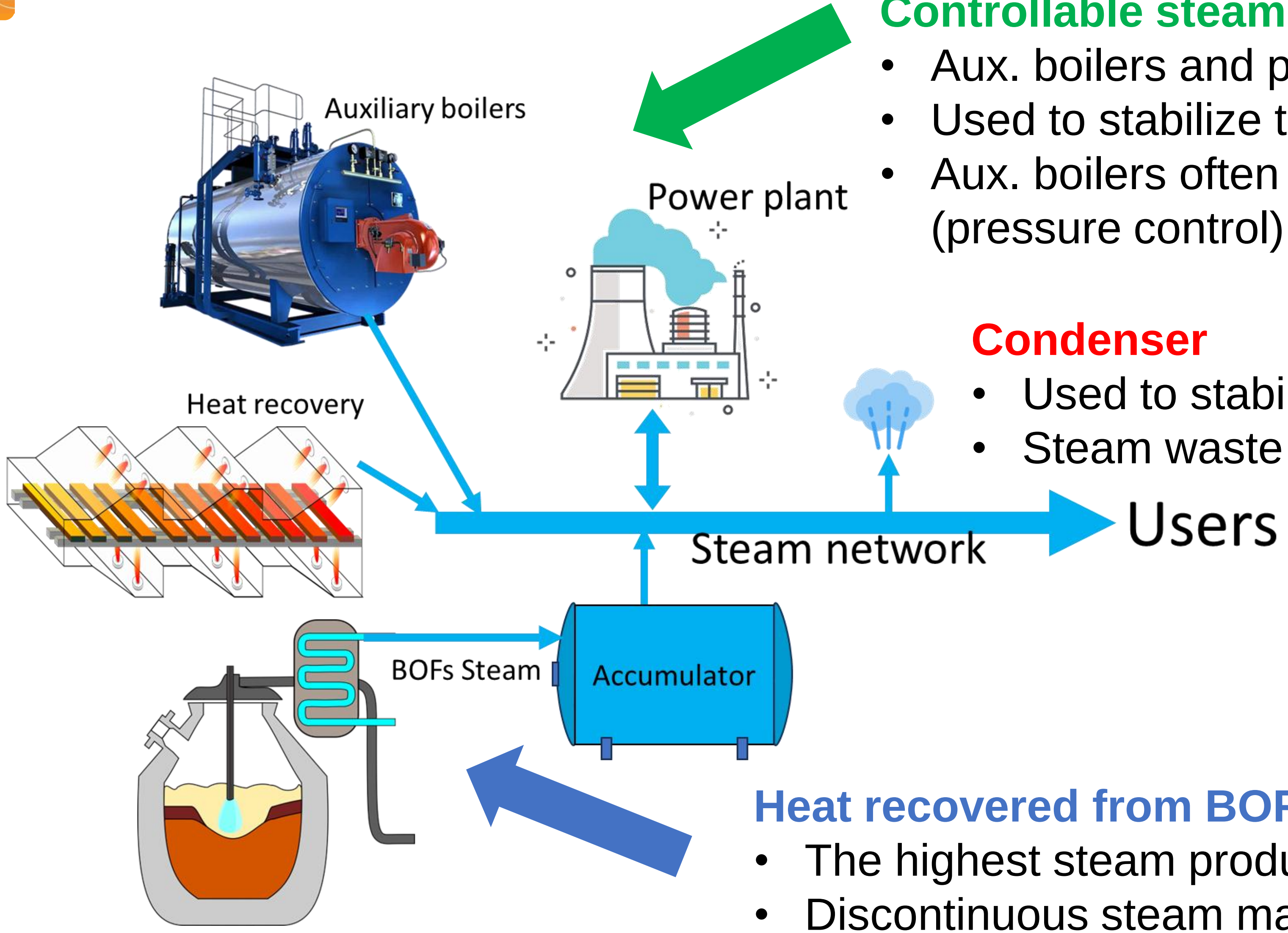
Scope1: Traditional BF/BOF route



Controllable steam production
- Aux. boilers and power plant
- Used to stabilize the pressure in the network
- Aux. boilers often used in switching mode (pressure control)

Condenser
- Used to stabilize the pressure in the network
- Steam waste

Heat recovered from BOFG or from furnaces
- The highest steam production
- Discontinuous steam mass flow

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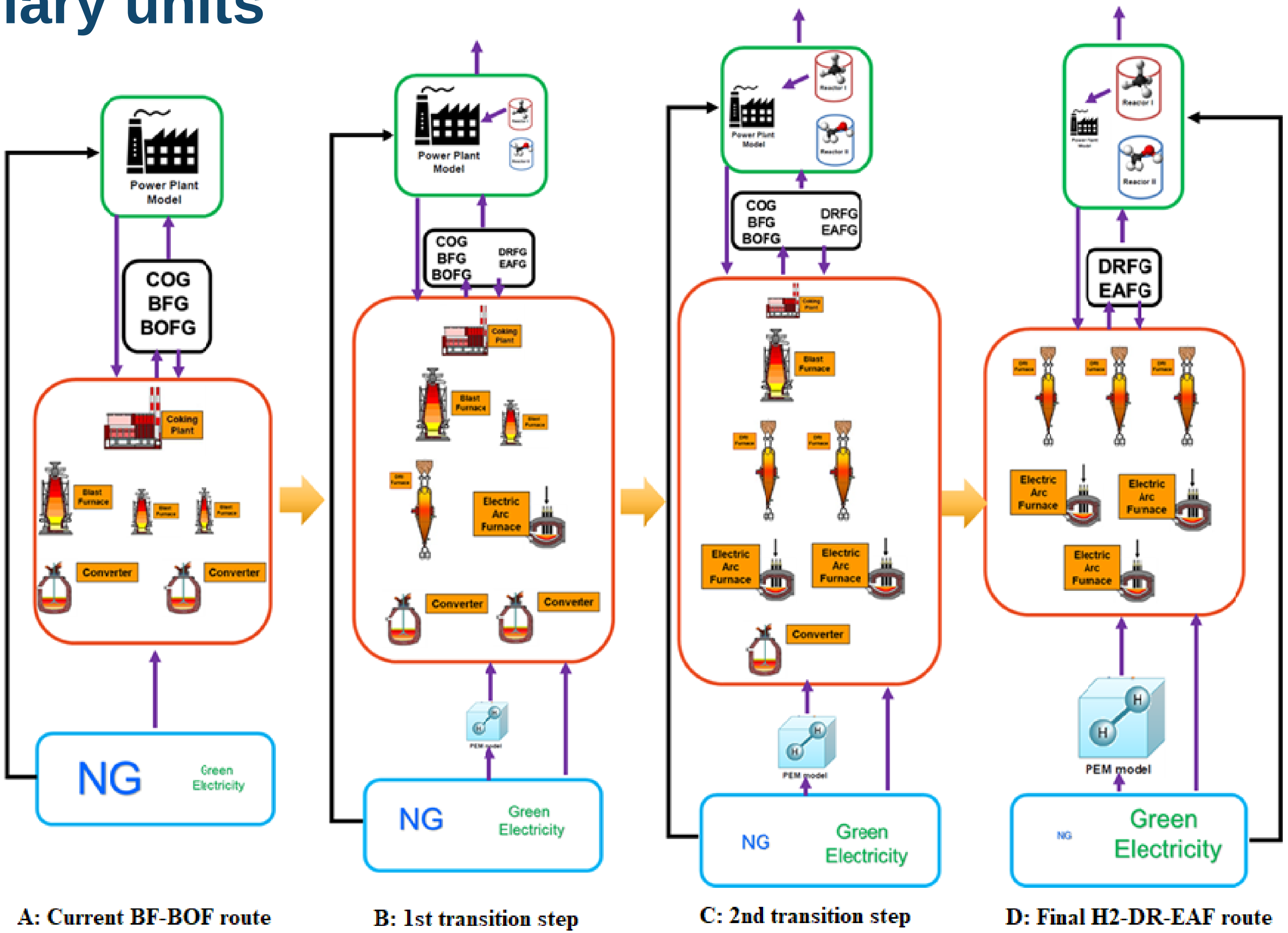
Scope 2: implementation of innovative production and auxiliary units



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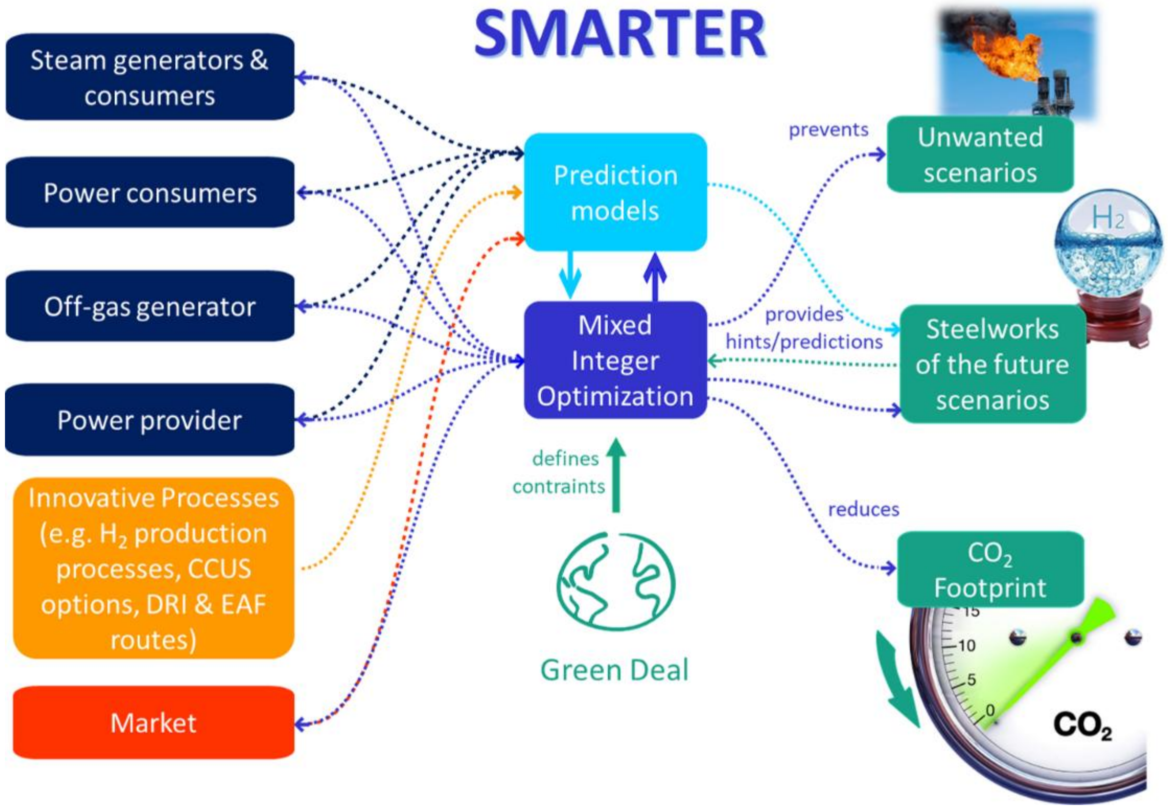
Methodology

- Development and adaptation of models forecasting gas, steam and power production and demands in involved processes.
- Analysis and revamping of gas and steam networks structure for more effective energy distribution and optimization
- Implementation of an advanced energy optimization approach
- Development of scenario analyses to assess how the implementation of innovative process steps in integrated steelmaking chain can affect the networks behavior and the overall energy management of the steelworks.
- Implementation and field tests of the optimization concept and management tools on a distributed calculation platform.
- Evaluation of environmental and economic impacts of optimized gas networks including innovative process units



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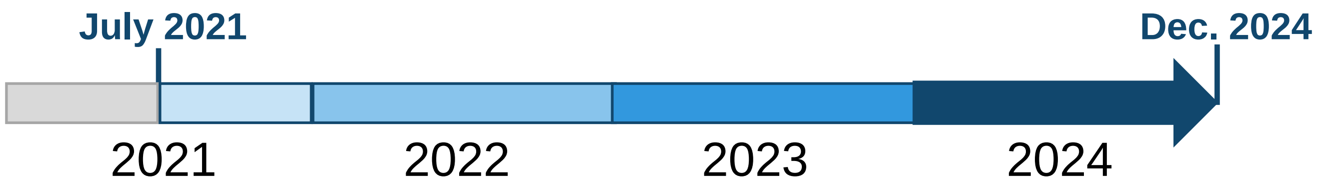
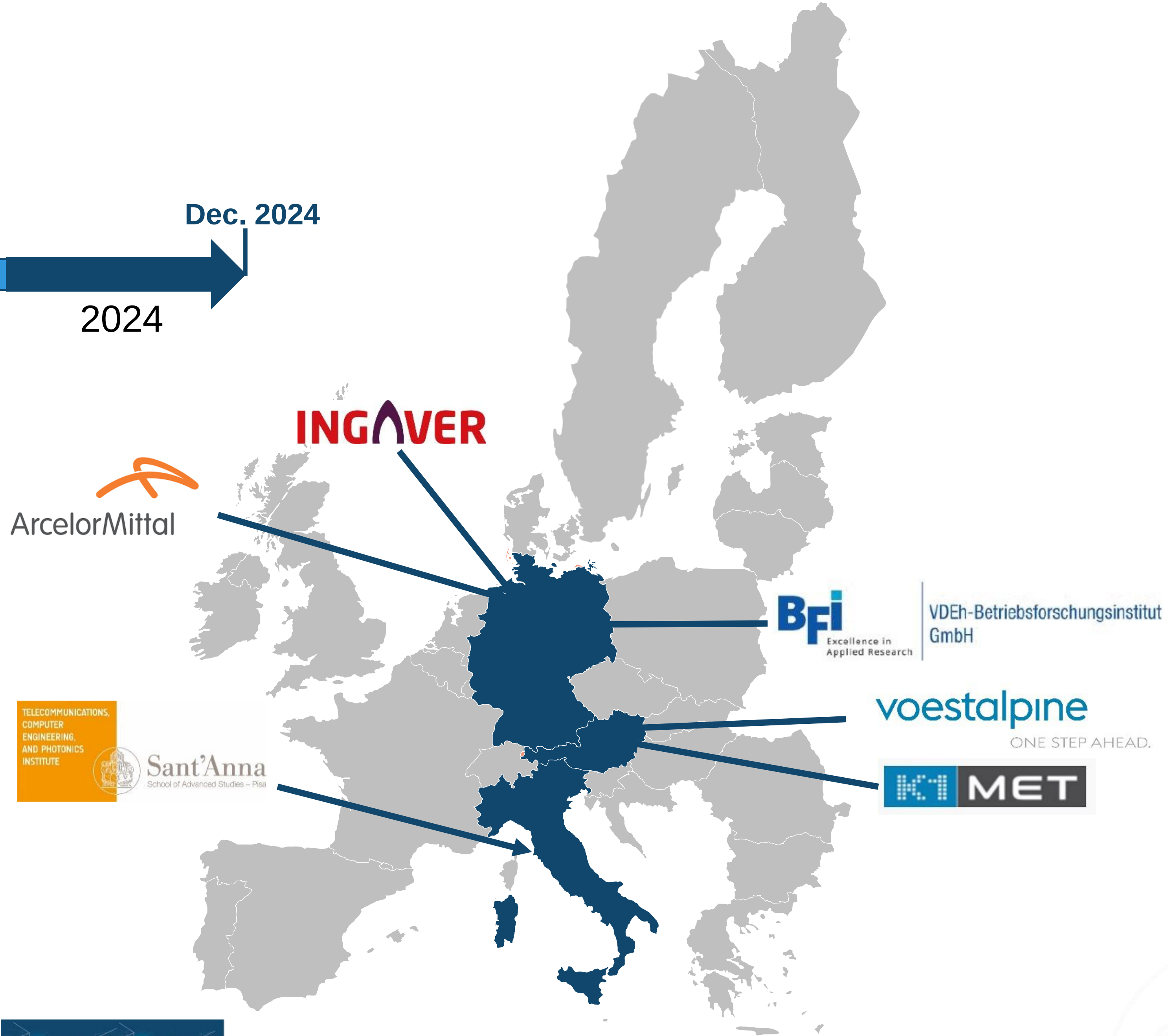
Consortium





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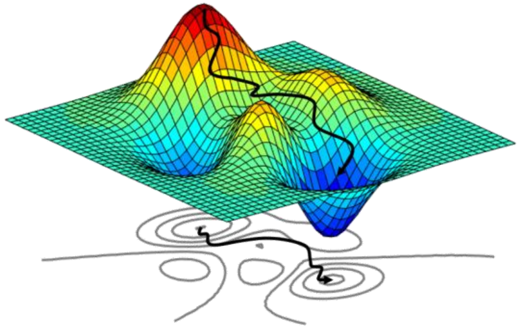
A long jouney….

ENCOP
GASNET
i3Upgrade
SMARTER

Management optimization of the off-gas networks within integrated steelworks



Methodologies for control systems, optimization and modelling, and DSS for process operators

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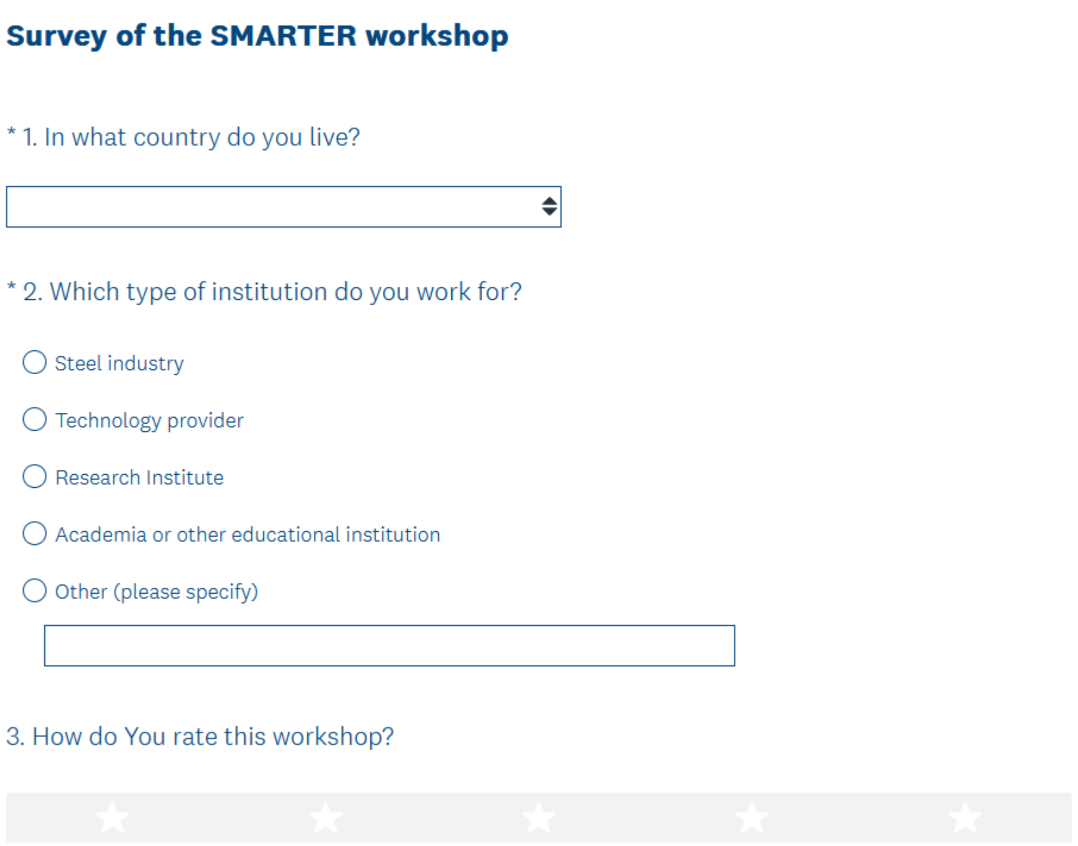
….still ongoing

AgiFlex

A small favor

Please fill out our small survey!

https://www.surveymonkey.com/r/NSLPZDJ


Survey of the SMARTER workshop

* 1. In what country do you live?

* 2. Which type of institution do you work for?

- Steel industry
- Technology provider
- Research Institute
- Academia or other educational institution
- Other (please specify)

3. How do You rate this workshop?

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Thank you!

e-mail: valentina.colla@santannapisa.it

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A DECISION SUPPORT SYSTEM FOR ENERGY MANAGEMENT IN INTEGRATED STEELWORKS

S. Dettori (***Scuola Superiore Sant'Anna***)

SMARTER Final Workshop
17 February 2025, Online

Contents

- Introduction
- Architecture
- Methodologies
- Technologies
- Offline tests
- Discussion and conclusions

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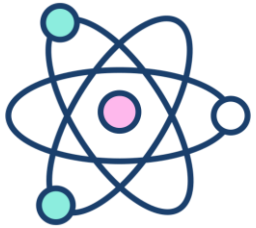
Introduction

Issues:

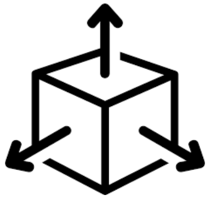
- **Cost and complexity of technology**
  - Lack of commercial software in the field.
  - Implementation of advanced monitoring systems and sensors is expensive (through commercial libraries).
  - Stability and reliability of open-source libraries.
  - Interoperability issues between legacy systems and new technologies.

- **Methodologies Vs Computational burden**
  - Modelling: accuracy of the model and **explainability** **Vs** computational time.
  - Control: complete formulation of the control strategy **Vs** computational time.



- **Data quality and availability**
  - Inconsistent, incomplete data or data collected in different formats can compromise analyses and development of data-driven methodologies.
  - Difficulty in accessing data in real time and at a granular level for some consumption areas.

- **System scalability and adaptability**
  - Adapting DSS to changes in business or industrial structures can be complex.
  - Scalability issues when integrating new components or energy sources.



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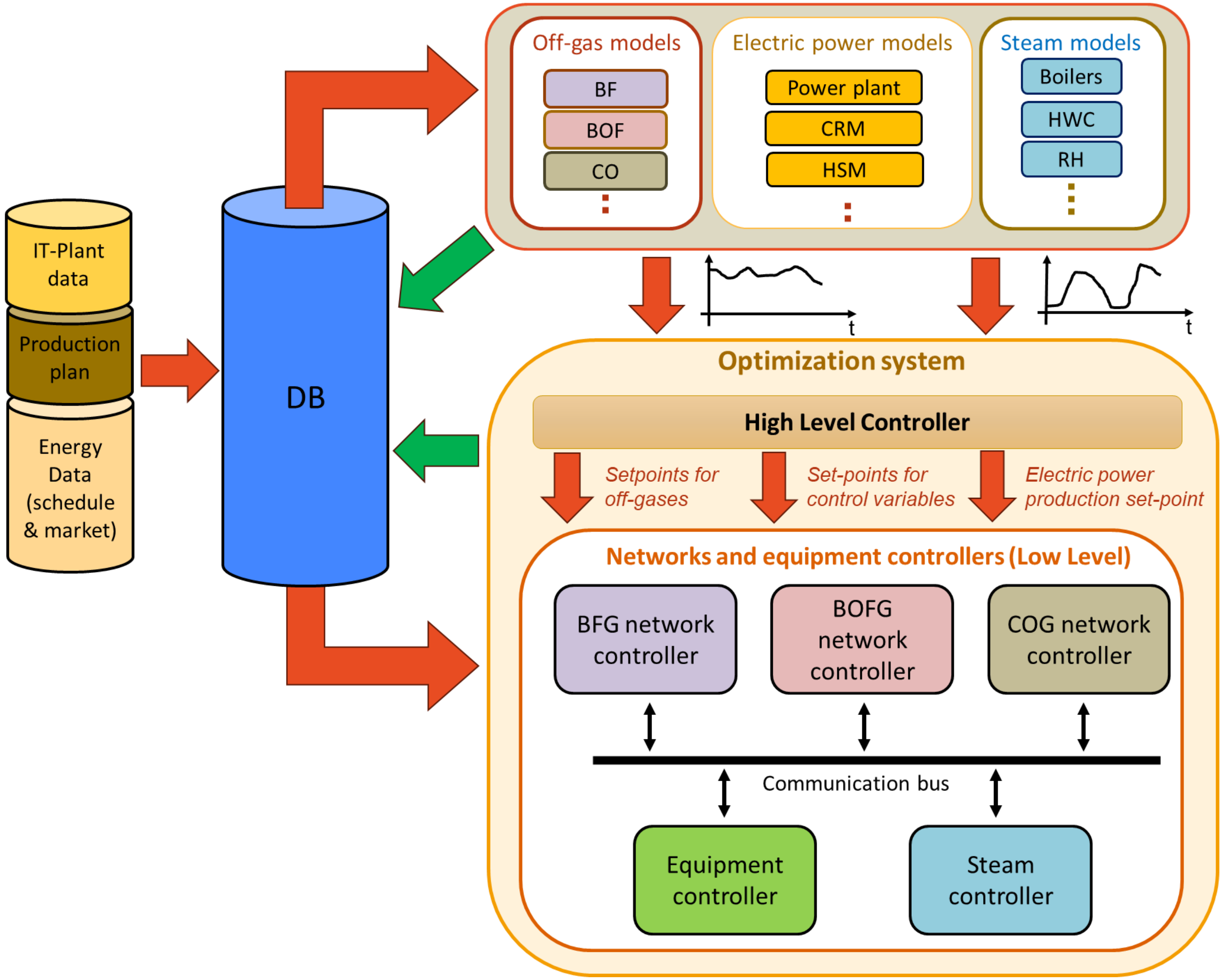
Architecture

A **database** for collecting data from different sources

- Scheduling of the production
- Current and past measures

And a **communication system** based on webservices



A Digital Twin

- Describes the current and future behavior of the integrated steelworks:
  - POGs
  - Electricity
  - Steam
  - Heating
- Modelled and validated through field data + **continual learning**

The optimization system

- Optimizes in real-time the control strategy
- Shows KPIs and control strategies to process operators through HMI

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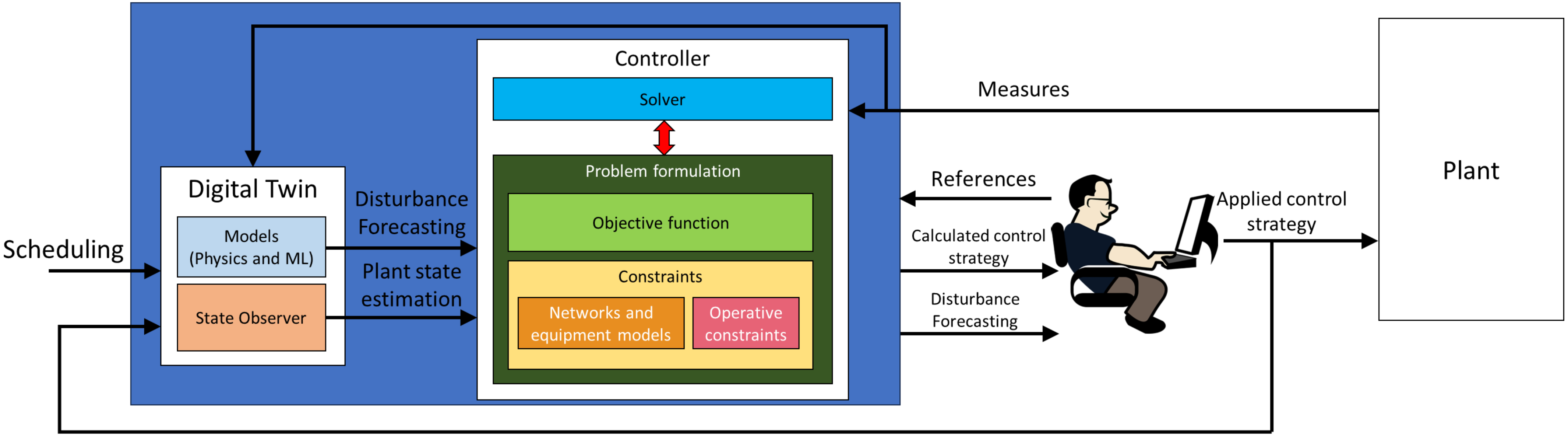
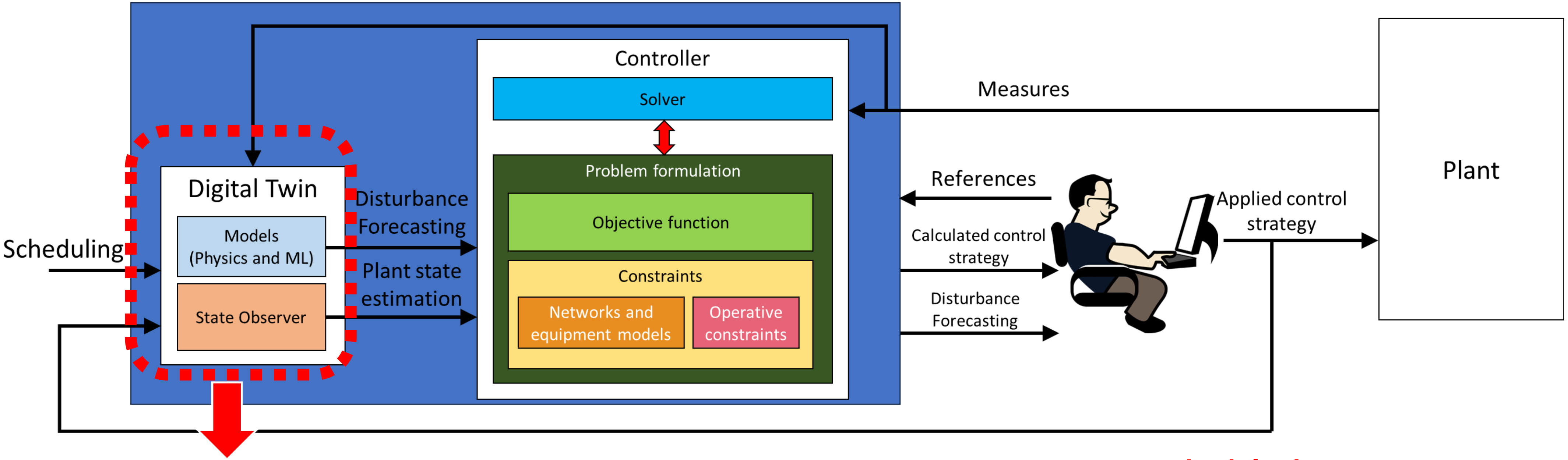
Methodologies



Key points:

- A **digital twin** for describing the plant from the energy **distribution** point of view
- A set of control tools for formulating and solving control/optimization problems
- **Human in the loop**: the DSS shows forecasts and proposes control solutions to operators

Methodologies



A digital twin is a **virtual representation** of a physical object, process, or system, updated with real-time data to simulate, predict, and optimize performance.

Key Components:

- **Physical Entity**: The actual object or system being modeled.
- **Digital Model**: The virtual counterpart that mirrors the physical entity.
- **Data Connection**: Real-time data flow between the physical and digital versions.

Modelling and forecasting objectives:

- POGs production and consumption
- Electricity consumption and production
- Steam production and consumption
- Equipment: power plant, gasholders, boilers, etc.

Methodologies:

- Energy forecasting
  - Deep Echo State Networks and Feed forward neural networks
  - Nonlinear ARMAX models
  - Gaussian regression models
  - Moving average models (for slowly changing energy streams)
  - Custom models
- Networks and equipment models:
  - Linear correlations and state space models

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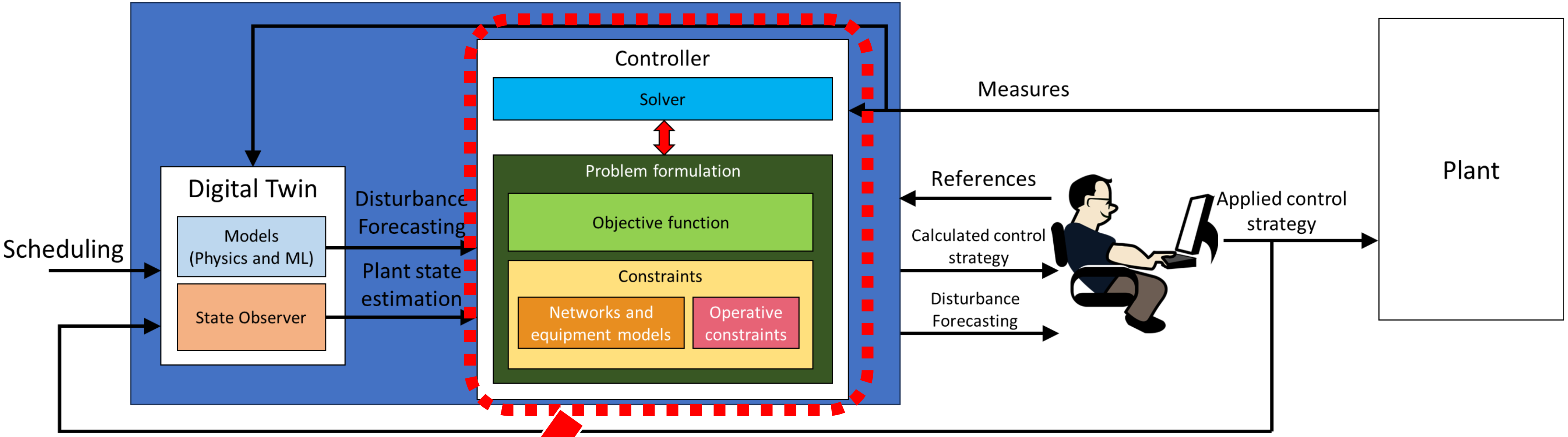
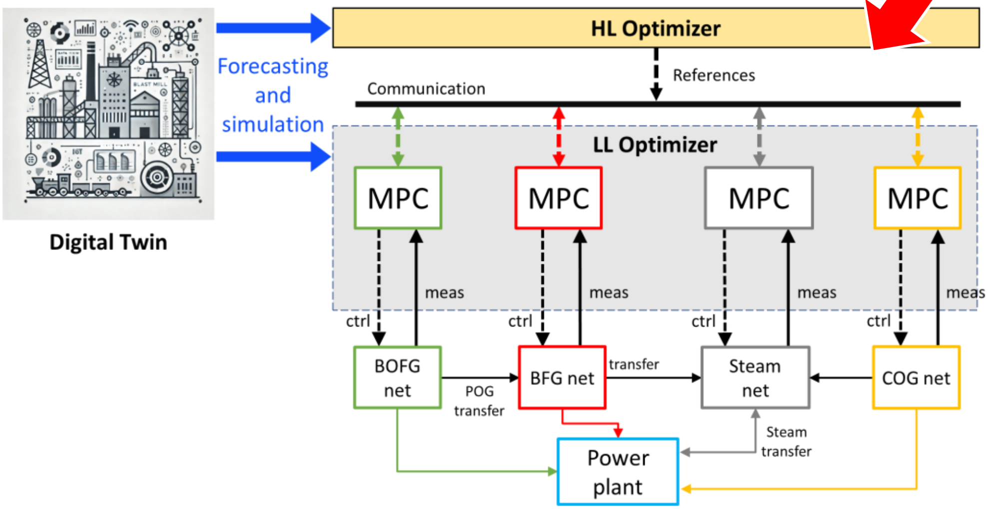
Methodologies





A set of tools for formulating control/optimization strategies:

- Hierarchical control
  - High level controllers
  - Low level controllers
- Linear Programming (**LP**)
- Mixed Integer Linear Programming (**MILP**)
- Nonlinear Programming

The HL Optimizer solves a LP

- **Costs**: minimization of overall Economic balance and energy wastes
- **Constraints**: main constraints on equipment and power plant

The LL Optimizer solves MILP

- **Costs**: economic costs and environmental impact of each energy network
- **Constraints**: detailed list of constraints

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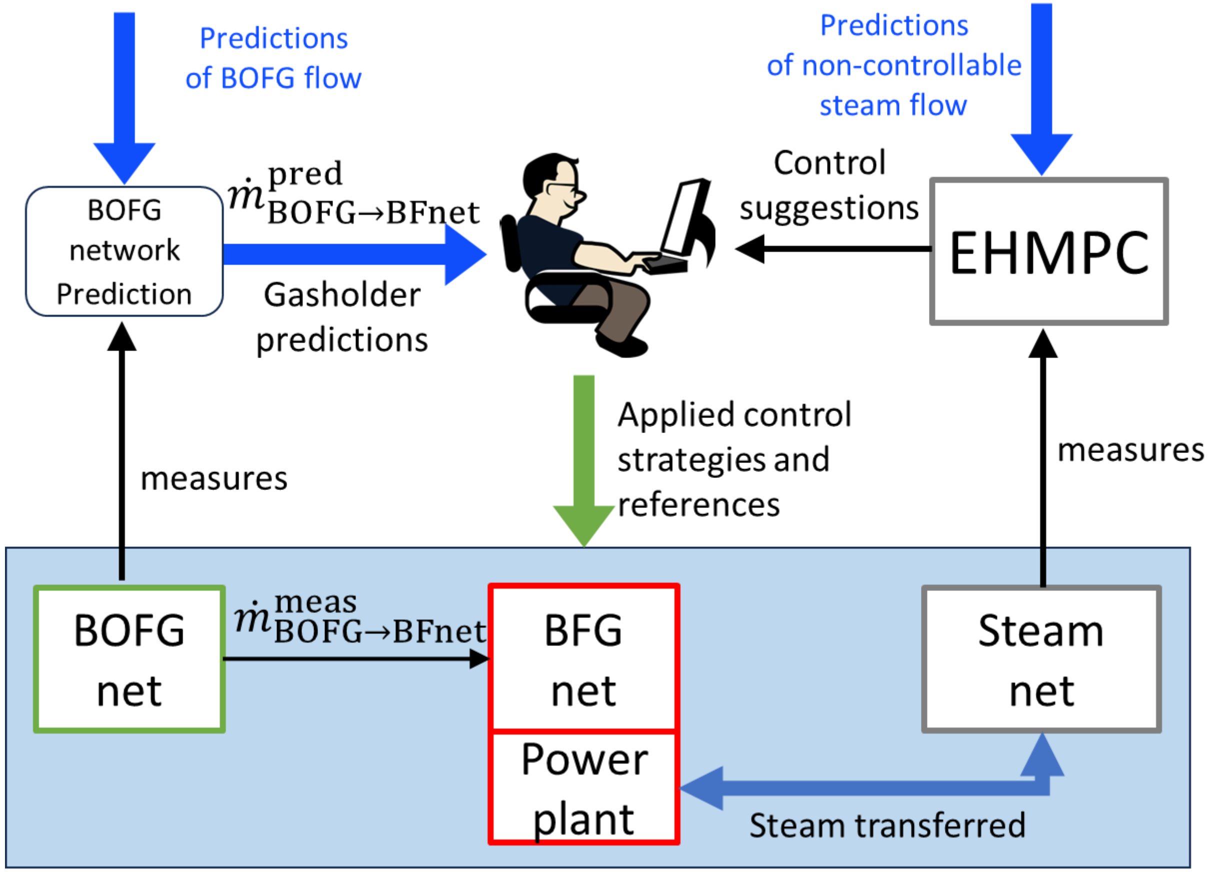
Methodologies

DSS architecture developed for AMB:



Constraints and technical difficulties:

- **BFG Network:**
  - In nominal conditions the power plant cannot sell electricity to the external grid.
  - This operation can be done during planned interruptions (maintenance, etc.) or unforeseeable causes and failures
- **BOFG Network:**
  - Low accuracy of models for forecasting energy consumption in WBFs

Main decision variables and supervision possibilities:

- Steam transfer between PP and steam network through a steam pendulum line
- Monitoring of BOFG gasholder level through forecasting models
  - Transfer of BOFG to BFG network

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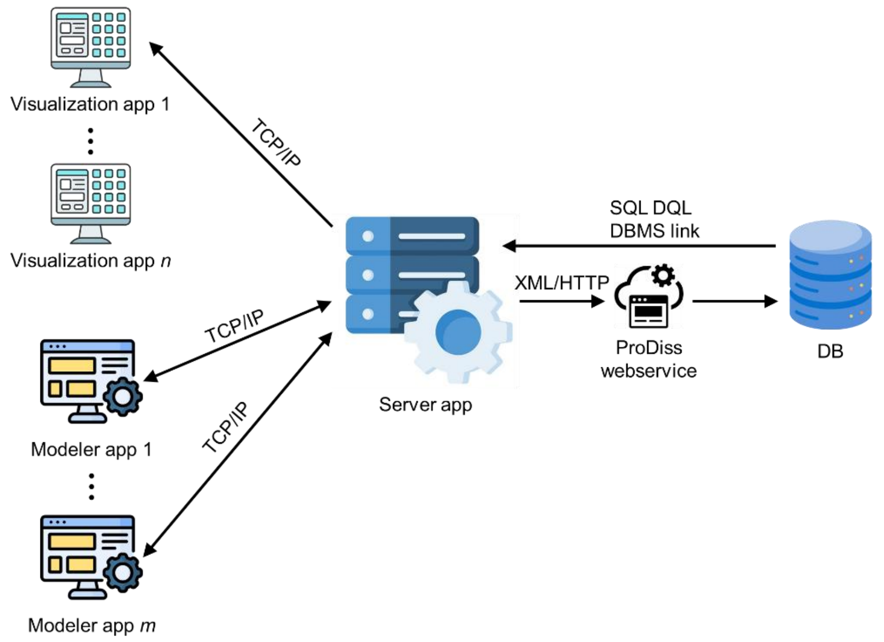
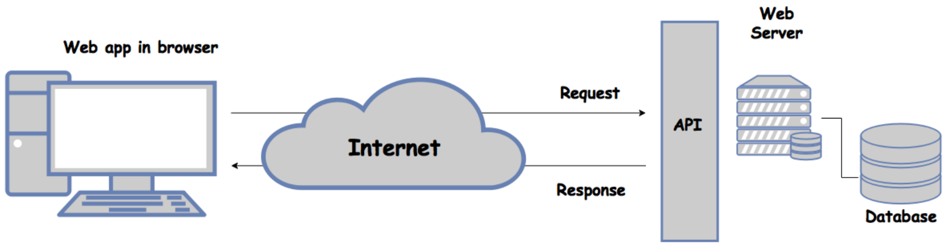
Technologies

Two versions of the software:

- A standalone based client-server paradigm for prototyping the concept: Three main applications:
  - A server application
  - A viewer application
  - A digital twin application



- A production software based on RESTful web-services that runs on a server and can be called through a web API



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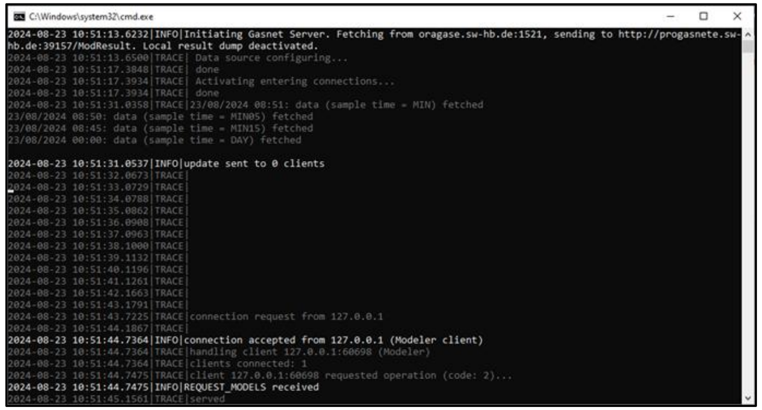
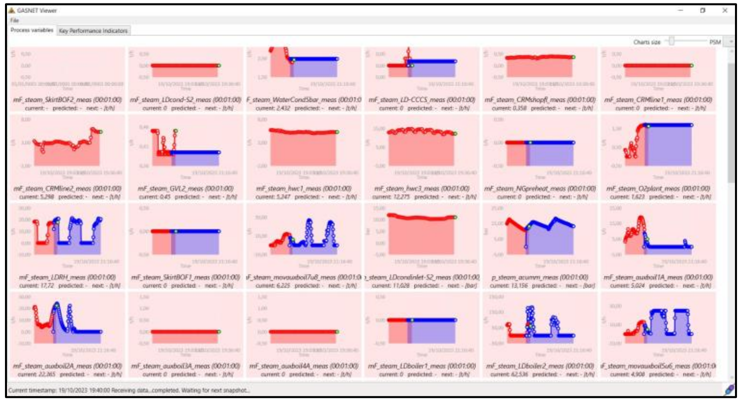
Technologies

Server app



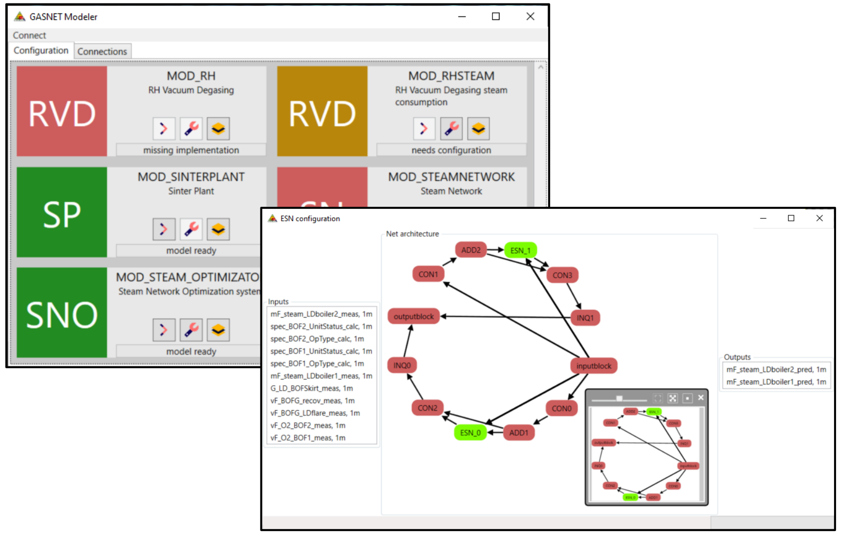
- Fetches data from the DB and distributes it to clients
- Sends digital twin calculations to the DB and process operators' HMIs
- Logging functions

Viewer app



- GUI for visualizing measures, KPIs, and forecasting of the digital twin
- Organizes the data visualization in function of the plant/system/energy media

Modeler app (digital twin)



- For configuring, training and simulating the models included in the digital twin
- Several methodologies for system modelling

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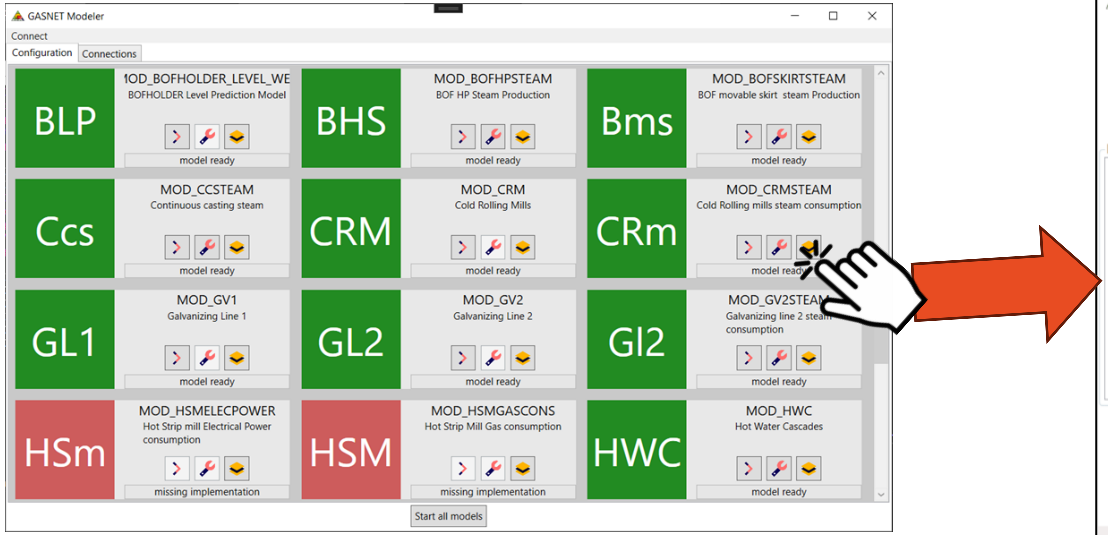
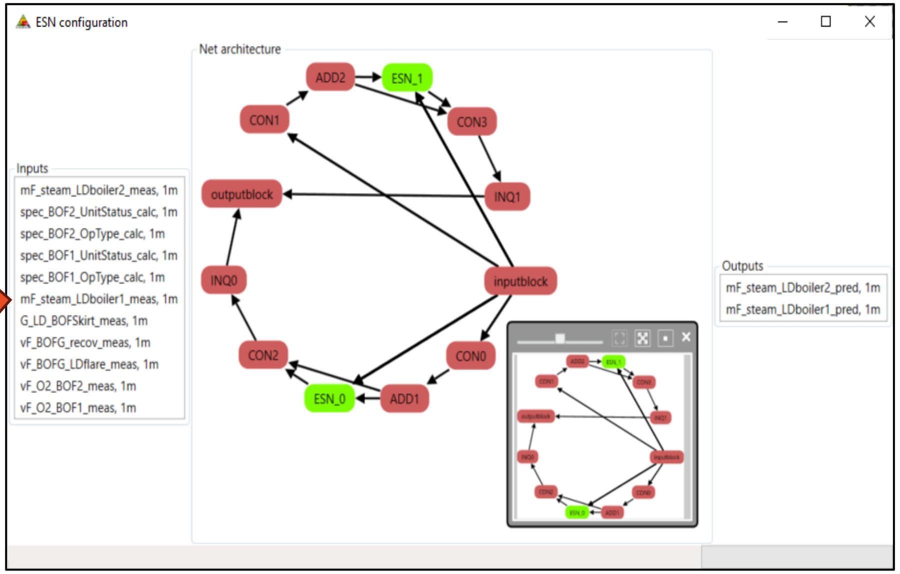
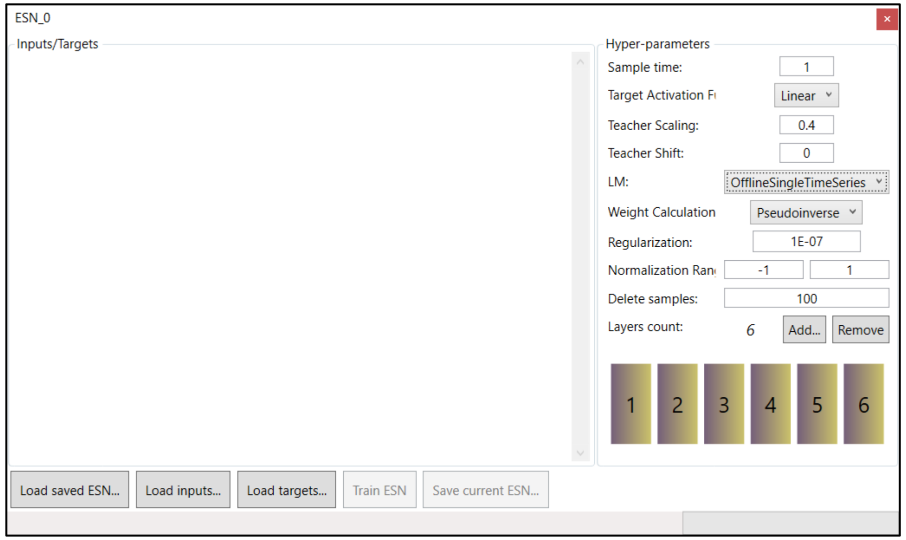
Technologies





Model configuration (Simulink like)



Configure model' parameters

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Technologies

	Digital Twin	Optimization system
Prototype	MATLAB python	MATLAB YALMIP GUROBI OPTIMIZATION
Production	C# Microsoft .NET ASP.NET python Keras Flask FastAPI	C# Microsoft .NET Google OR-Tools

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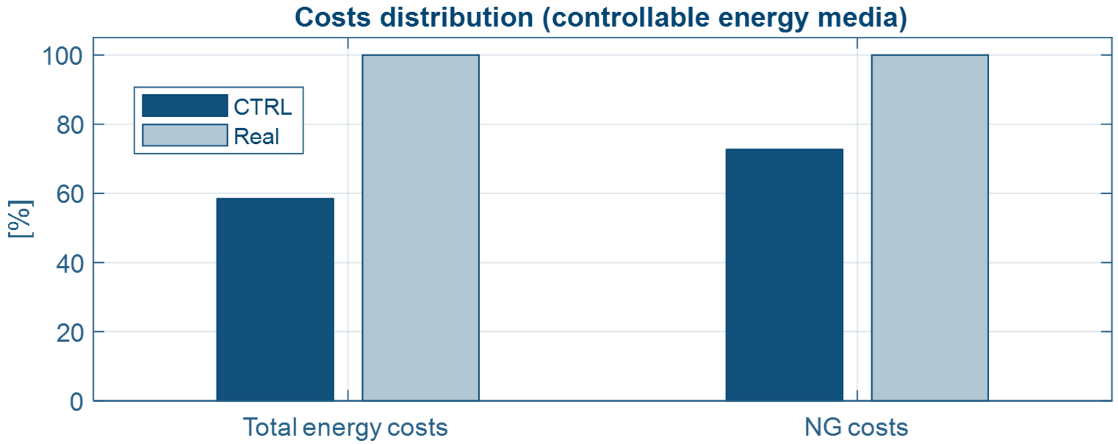
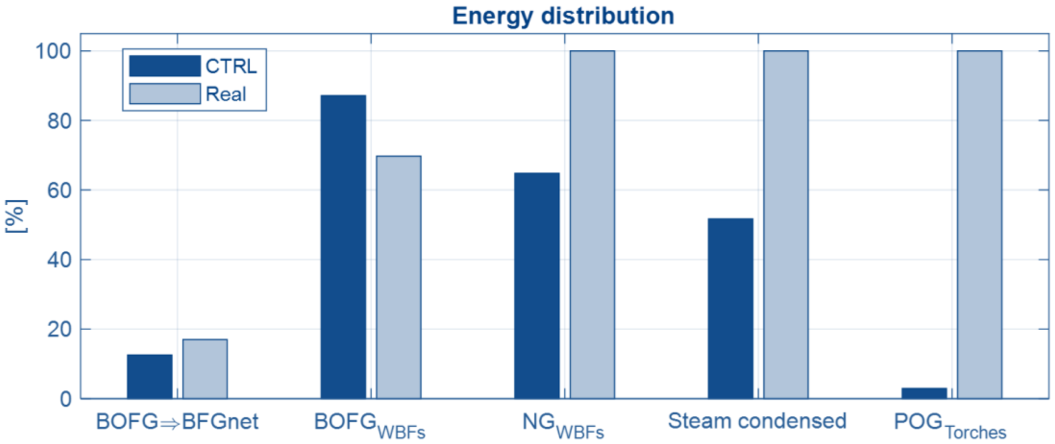
From off-line to online test

- Simulation campaign for offline testing the digital twin and control strategy.
  - Several scenarios have been simulated for different periods of steel production and unexpected disturbances and faults (including maintenance periods)
- Tests for steam network controller @ ArcelorMittal Bremen





$KPI_{torches\%}$ [%]	$KPI_{€\%}$ [%]	$KPI_{NG\%}$ [%]
-96.9	-41.56	-27.49

Discussion and summary

PROS


ML is effective for forecasting energy flows


Easy prototyping (Matlab / Python)


Real-time plantwide control


Solutions and ideas accepted by process operators

CONS


Long and complex industrialization through open-source libraries (Google Or-tools, Tensor flow, etc.)


Non-Open-source optimization libraries are expensive (CPLEX, Gurobi, etc.)


Complex and long tuning procedures


DSS + operators vs **Automatic control**: control action must be applied ASAP

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Thank you!

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Assessment of decarbonization pathways for the steel industry through energy network simulation

SMARTER Final Workshop, online, 17th of February 2025

Christa Mühlegger, O. Maier, A. Sasiain, I. Kofler,
A. Haider, A. Spanlang, B. Rummer

Coordinated by
FFG Tirol UAR Innovation Network SFG

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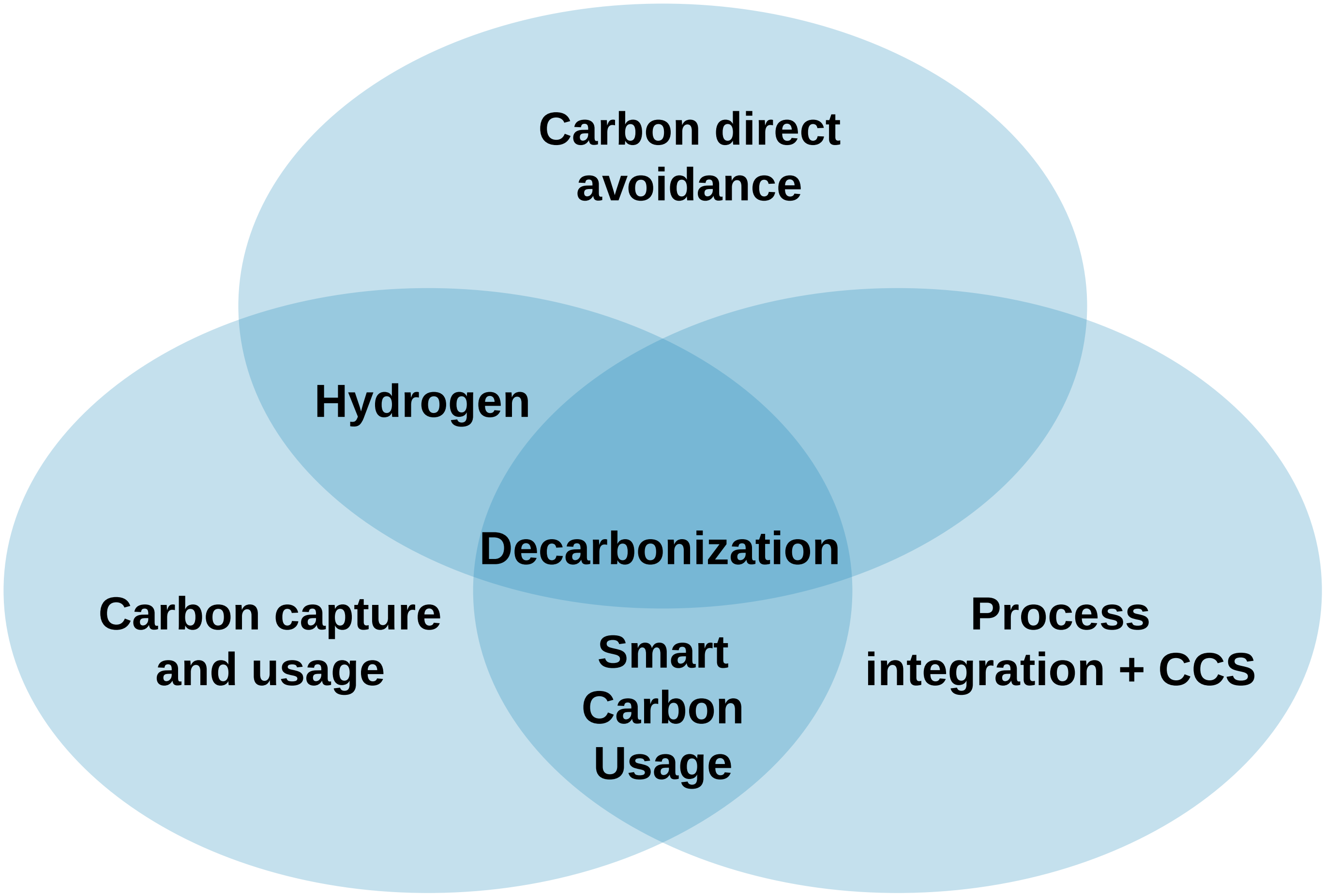
Federal Ministry Republic of Austria Labour and Economy
Federal Ministry Republic of Austria Climate Action, Environment, Energy, Mobility, Innovation and Technology
upper austria, Das Land Steiermark, Land Tirol

Wir sind ein familienfreundlicher Arbeitgeber!

Approaches for decarbonizing the steel industry

- **Carbon Direct Avoidance (CDA)** must be the favoured path to decarbonize the steel sector
  - Utilisation of renewable H_2 and/ or renewable energy to produce steel (e.g., electric arc furnace, direct reduction)

- **Smart Carbon Usage (SCU)**
  - **Unavoidable CO_2 emissions** from raw materials (e.g., limestone, iron ore)
  - Close the carbon cycle with **Carbon capture and utilisation technologies (CCU)**
  - Conversion of CO_2 and renewable H_2 into valuable products (e.g., methane, methanol)

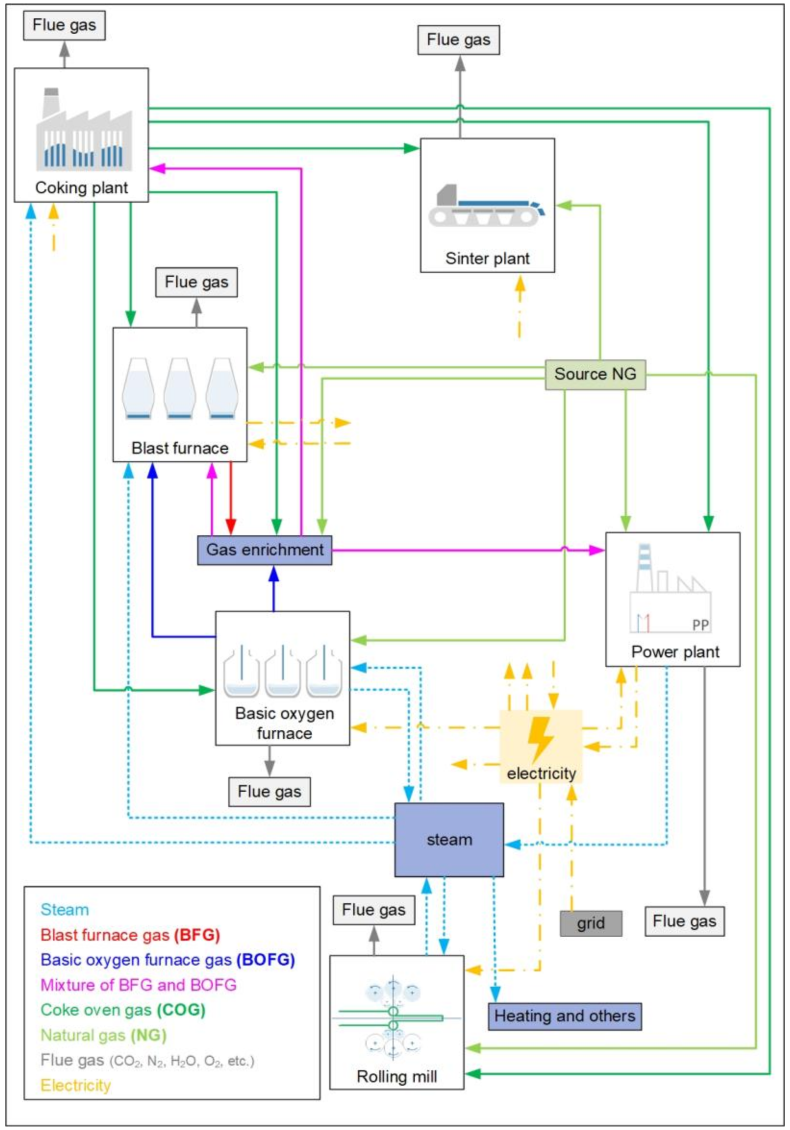


EUROFER. Low carbon roadmap. Pathways to a CO2-neutral European steel industry. 2019

Overall model of the steel mill Linz in gPROMS

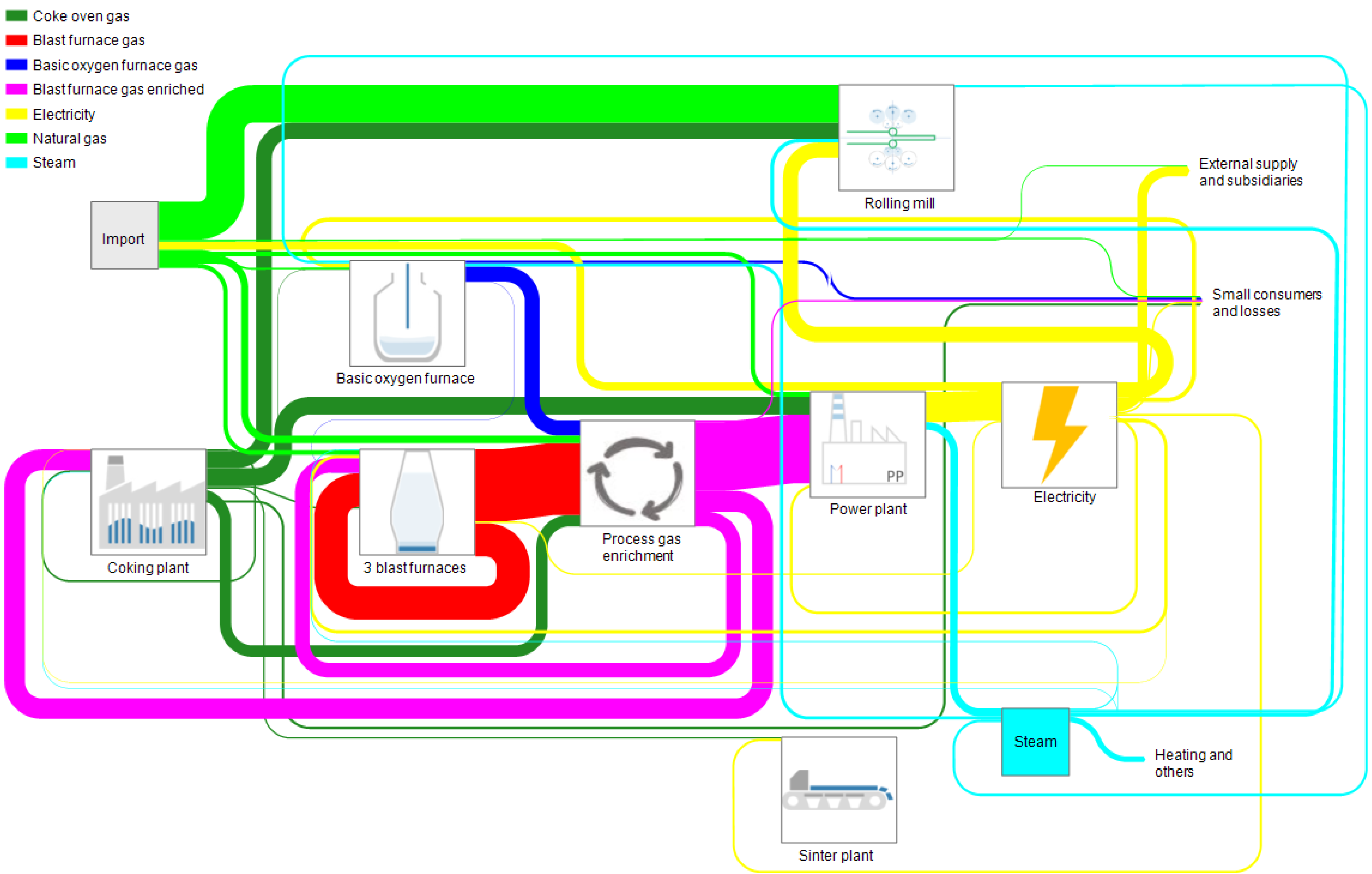
metallurgical competence center

- **gPROMS** = general PROcess Modeling System
  - Unified equation-oriented simulation environment for custom modelling and process simulation
  - Flexible steady-state & dynamic **flowsheet simulation**
- Mass, energy- and CO_2-balance in one comprehensive model
- **Stationary high fidelity digital twins** of the metallurgical units available in gPROMS
  - Metallurgical model library developed by Primetals, voestalpine, K1-MET, TU Wien
- **Measurement data** of voestalpine Linz of the year 2019 was utilized to set up a “Base Case” scenario
- Adaption of the model to **more sustainable future scenarios** → changes in the **gas** and **energy network**



Base case 2019

Energy streams



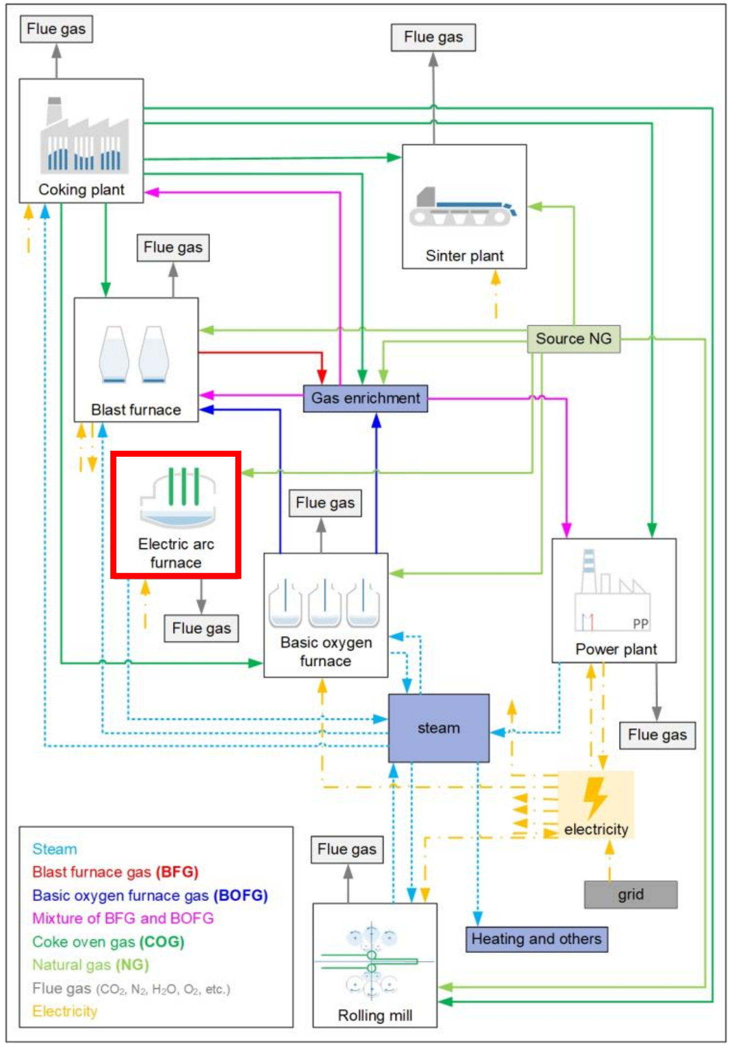
- Process gas enrichment
- External supply:
  - Electricity
  - Natural gas
- Steam produced by:
  - Waste heat recovery
  - Power plant
- Power plant:
  - Steam
  - Electricity

Steam network: represantative values winter

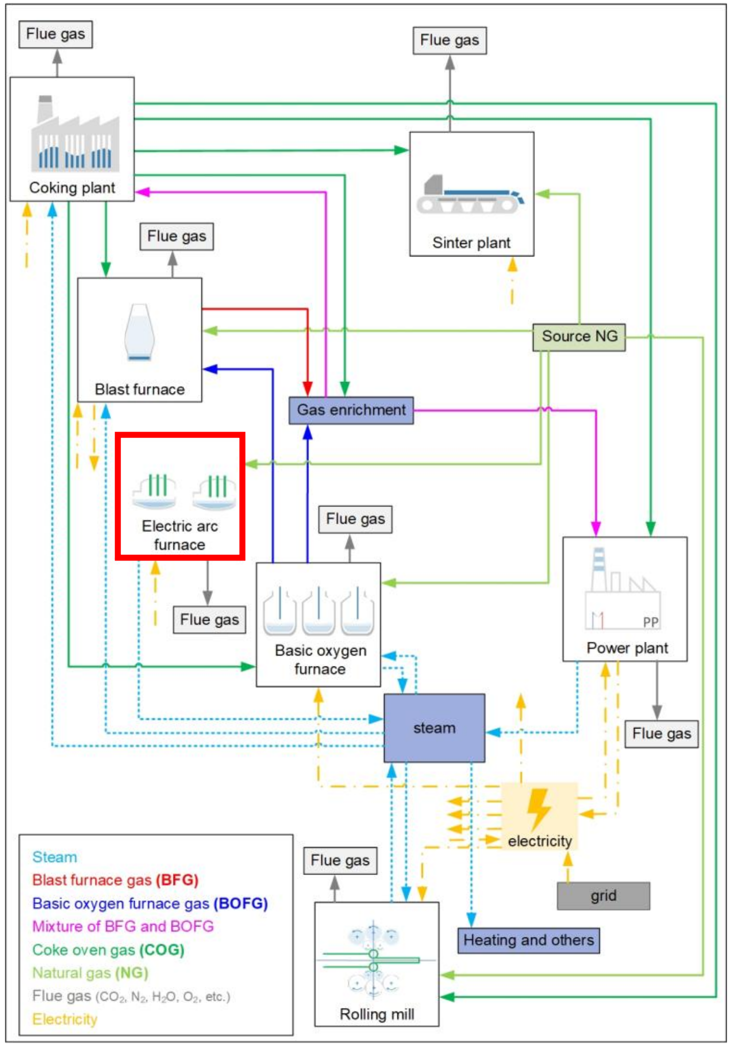
Simulation of possible decarbonization scenarios

Carbon direct avoidance

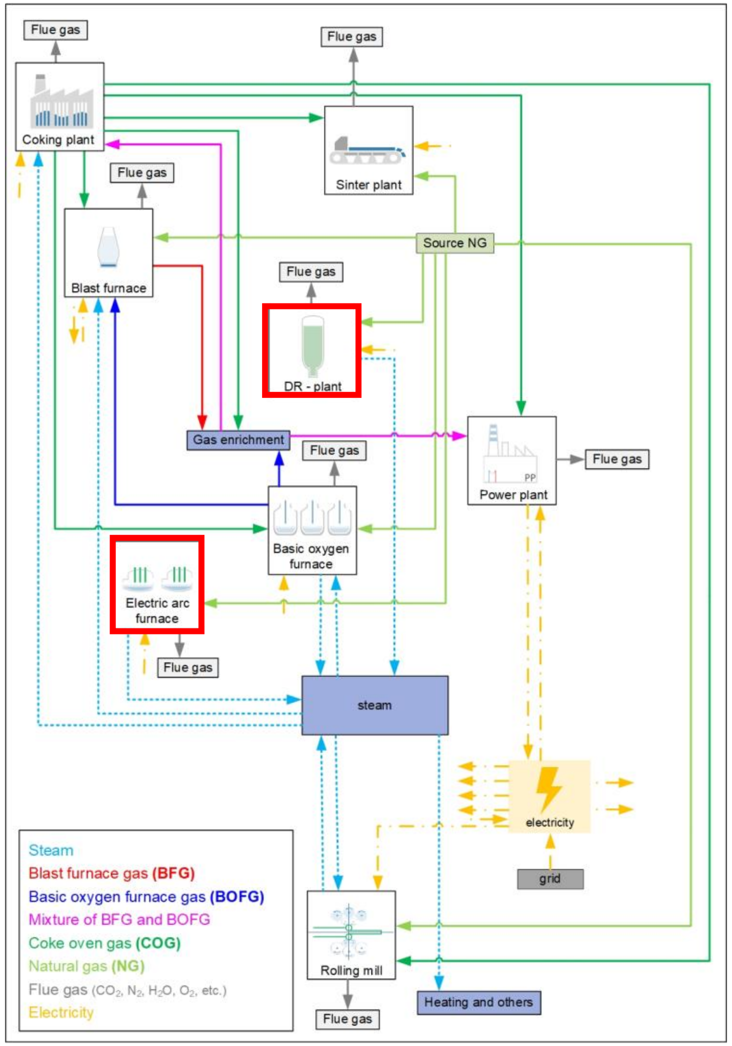
Scenario with 1 EAF



Scenario with 2 EAFs



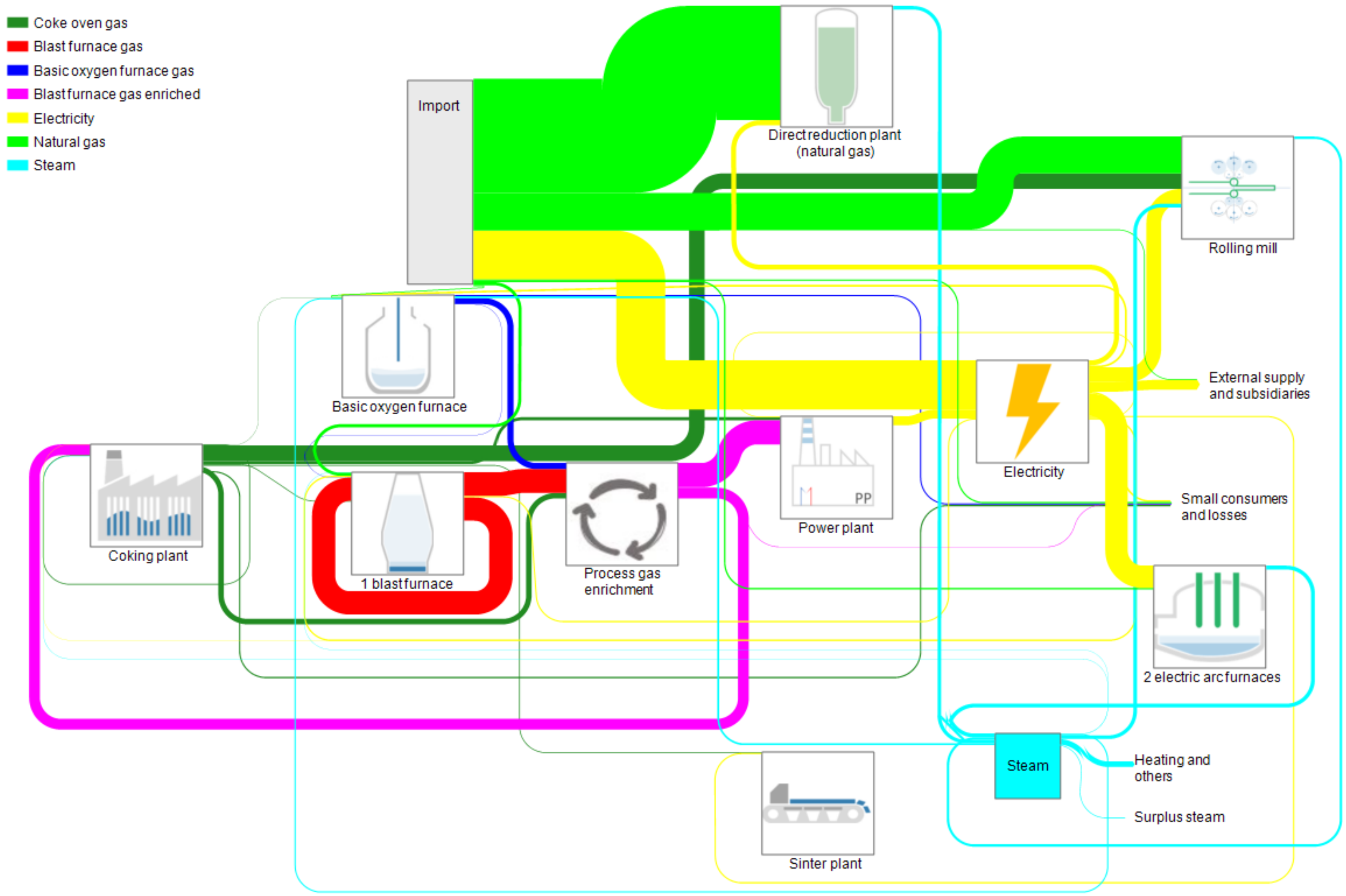
Scenario with 2 EAFs + DR (CH_4)



Simulation of possible decarbonization scenarios

2 BFs replaced by 2 EAFs + DR (CH_4)

K1 MET metallurgical competence center

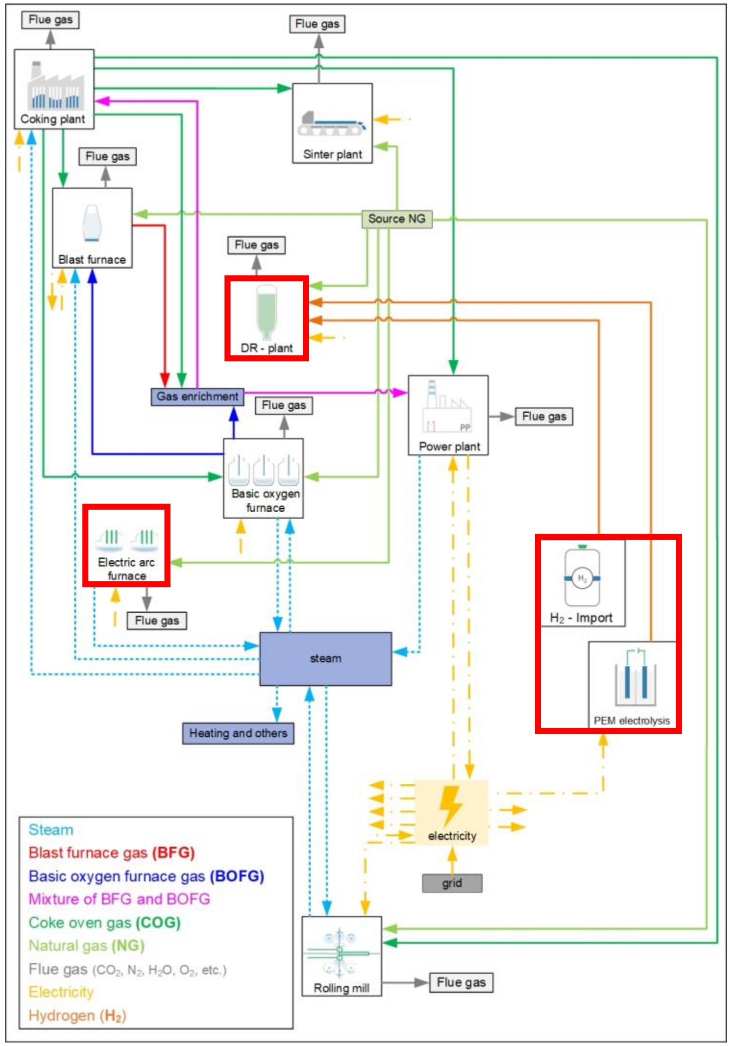


- EAF charge:
  - 75% DRI
  - 25% scrap
- Crude steel production remains unchanged from the base case
- Remaining BF/ BOF account for about 45% of the crude steel production
- External **electricity** demand over **6x**
- External **natural gas** demand nearly **3x**
- **Steam production** power plant: **-100%**

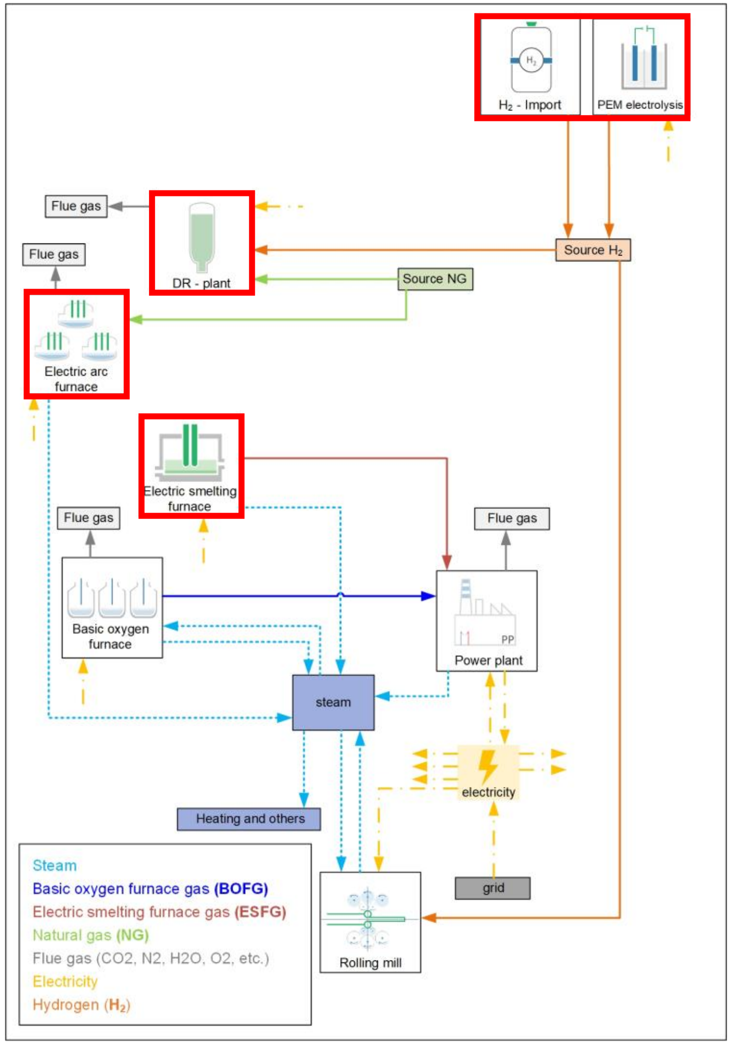
Simulation of possible decarbonization scenarios

Carbon direct avoidance

Scenario with 2 EAFs + DR (H_2)



Scenario with 3 EAFs + DR (H_2) + ESF

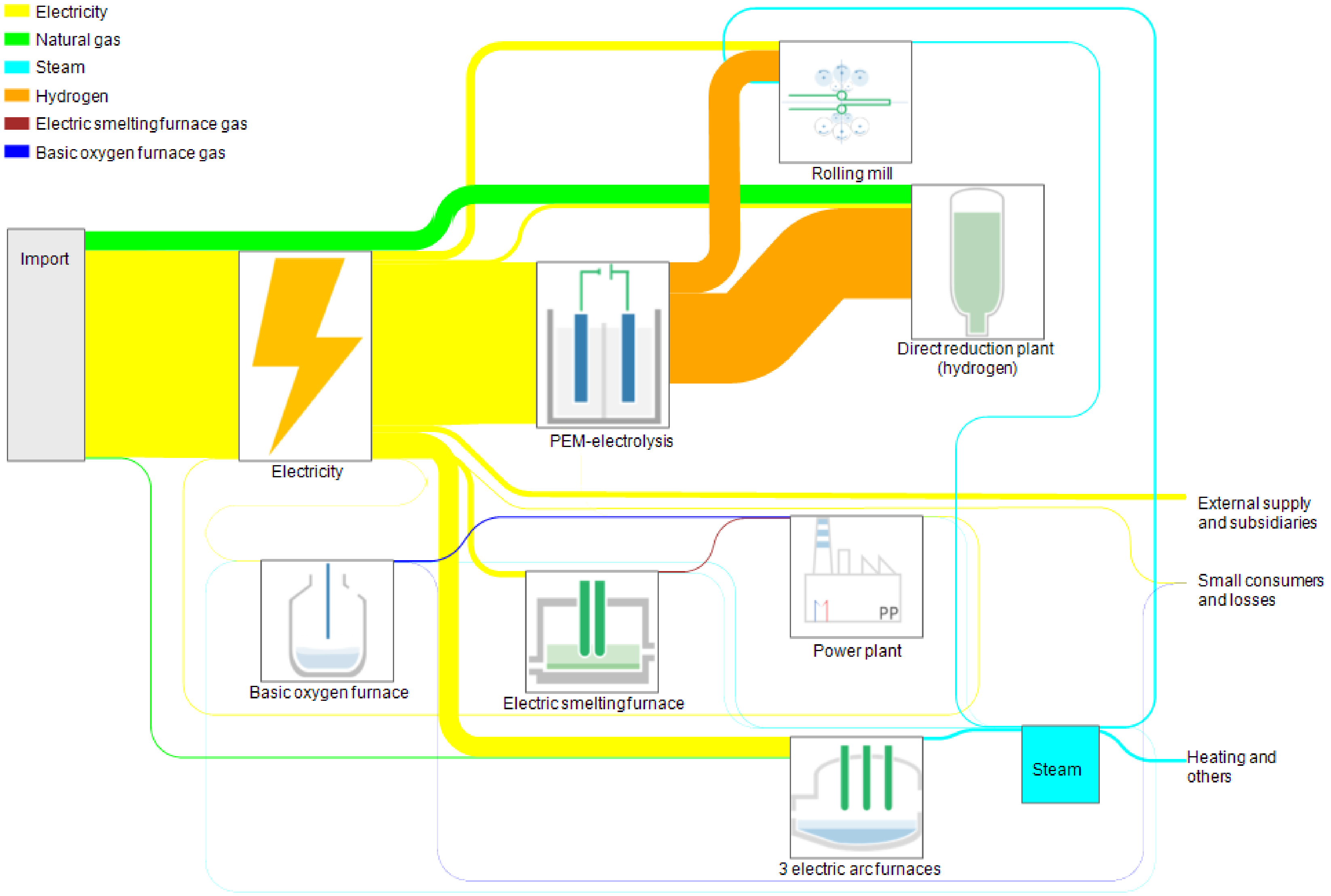


- Each EAF produces the same amount of crude steel
  - EAF charge: 75% DRI
    25% scrap
- Remaining part of the base case production is handled by **ESF/ BOF**
- ESF is charged with HBI, produced by DR of **locally available domestic ores** with lower iron content (with minimal CO_2 footprint)

Simulation of possible decarbonization scenarios

3 BFs replaced by 3 EAFs + DR (H_2) + ESF

metallurgical competence center



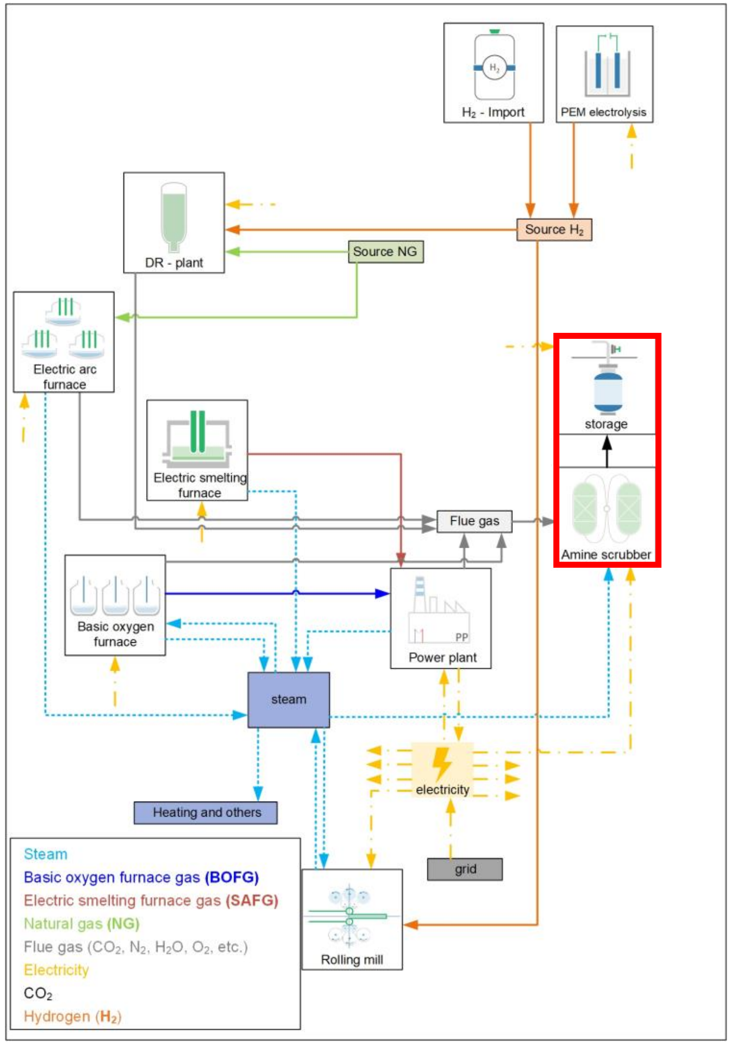
- **PEM electrolysis:** 75% overall efficiency
- Natural gas is required in the hydrogen-based DR plant for carburization
- **Additional hydrogen** is necessary to cover the energy demand for the downstream processes
- **ESF off gas:**
  - Power plant
  - Waste heat recovery

Arrow thickness: half of the previous scenarios

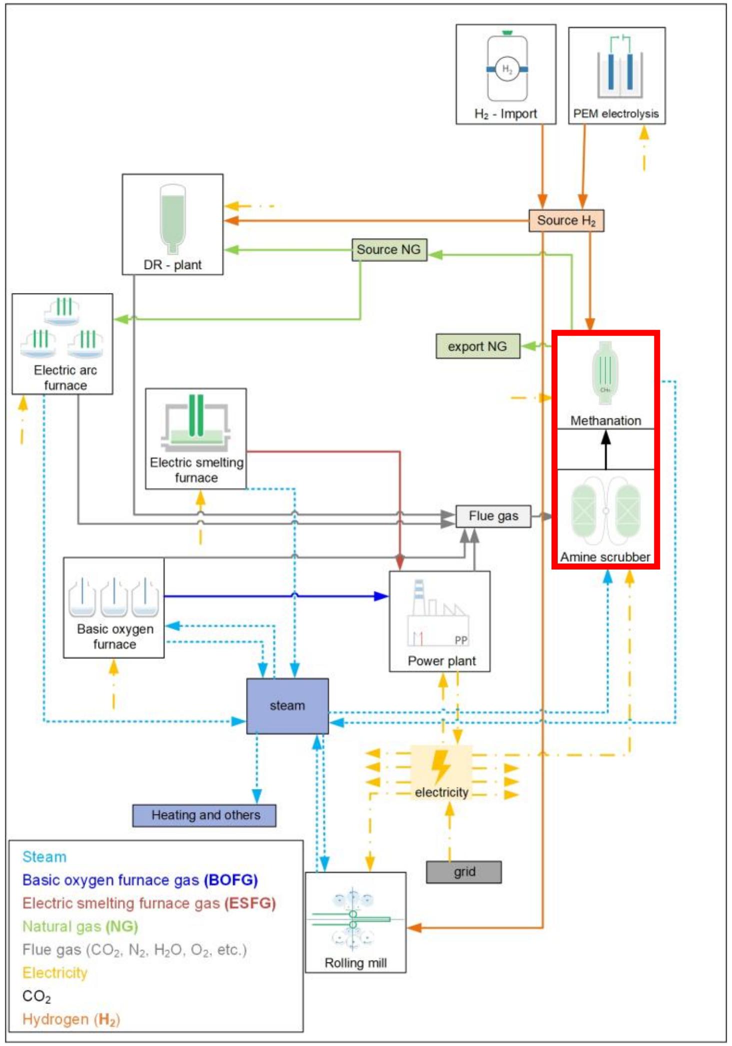
Simulation of possible decarbonization scenarios

Carbon direct avoidance + smart carbon usage (CCUS)

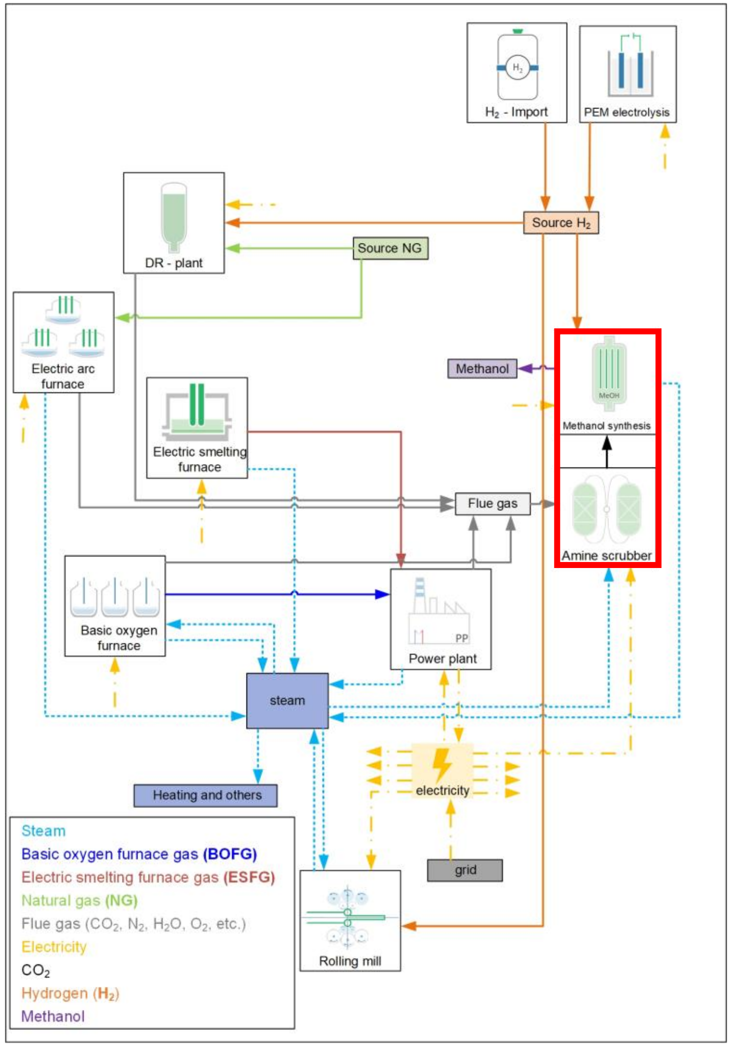
CCS with amine scrubber



CCU with amine scrubber & methanation

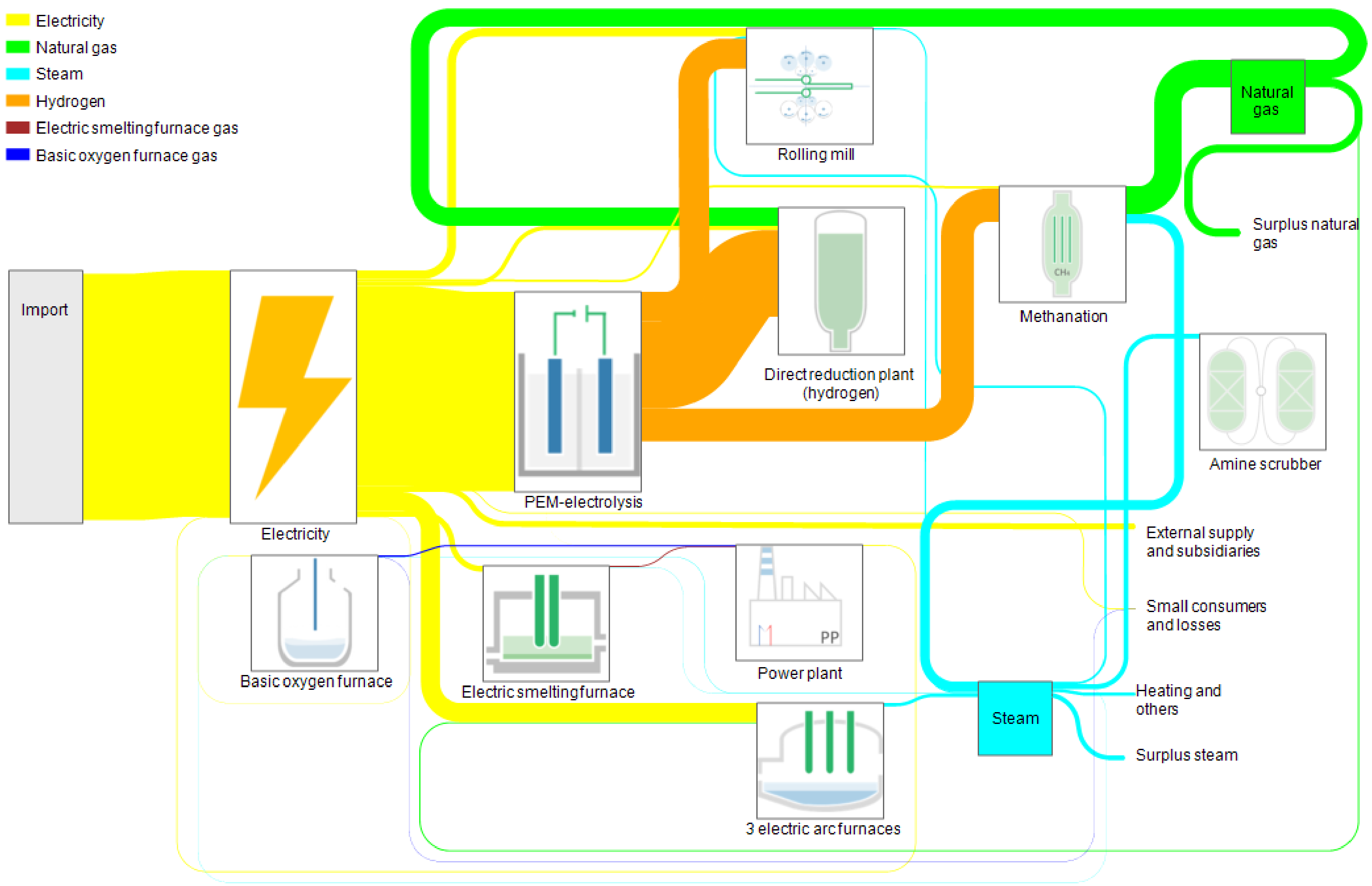


CCU with amine scrubber & methanol synthesis



Simulation of possible decarbonization scenarios

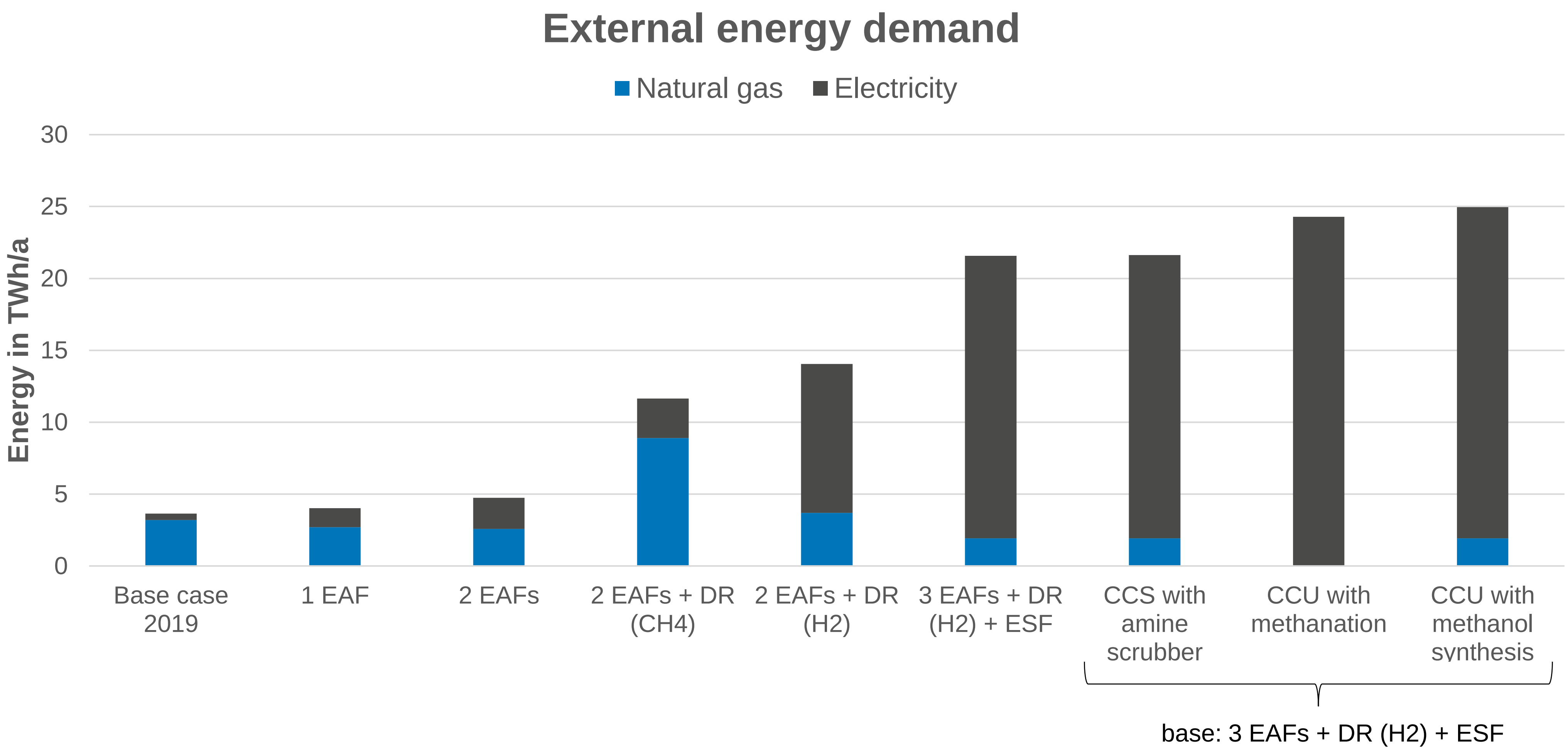
3 BFs replaced by 3 EAFs + DR (H_2) + ESF + CCU methanation



- CCU with **amine scrubber** and **catalytic methanation**
- The total flue gas of the hypothetical future steel mill is directed to an amine scrubber to capture 90 % of its CO_2 using **monoethanolamine (MEA)** as the solvent
- **Specific energy consumption:** 3.2 MJ/kg CO_2
- **Steam demand** of the amine scrubber can be provided through **waste heat recovery** by cooling the gas stream in a catalytic methanation process (exothermic reaction)
- $4H_2 + CO_2 \leftrightarrow CH_4 + 2H_2O$
  - $\Delta H_R^0 = -165\ \text{kJ/mol}$

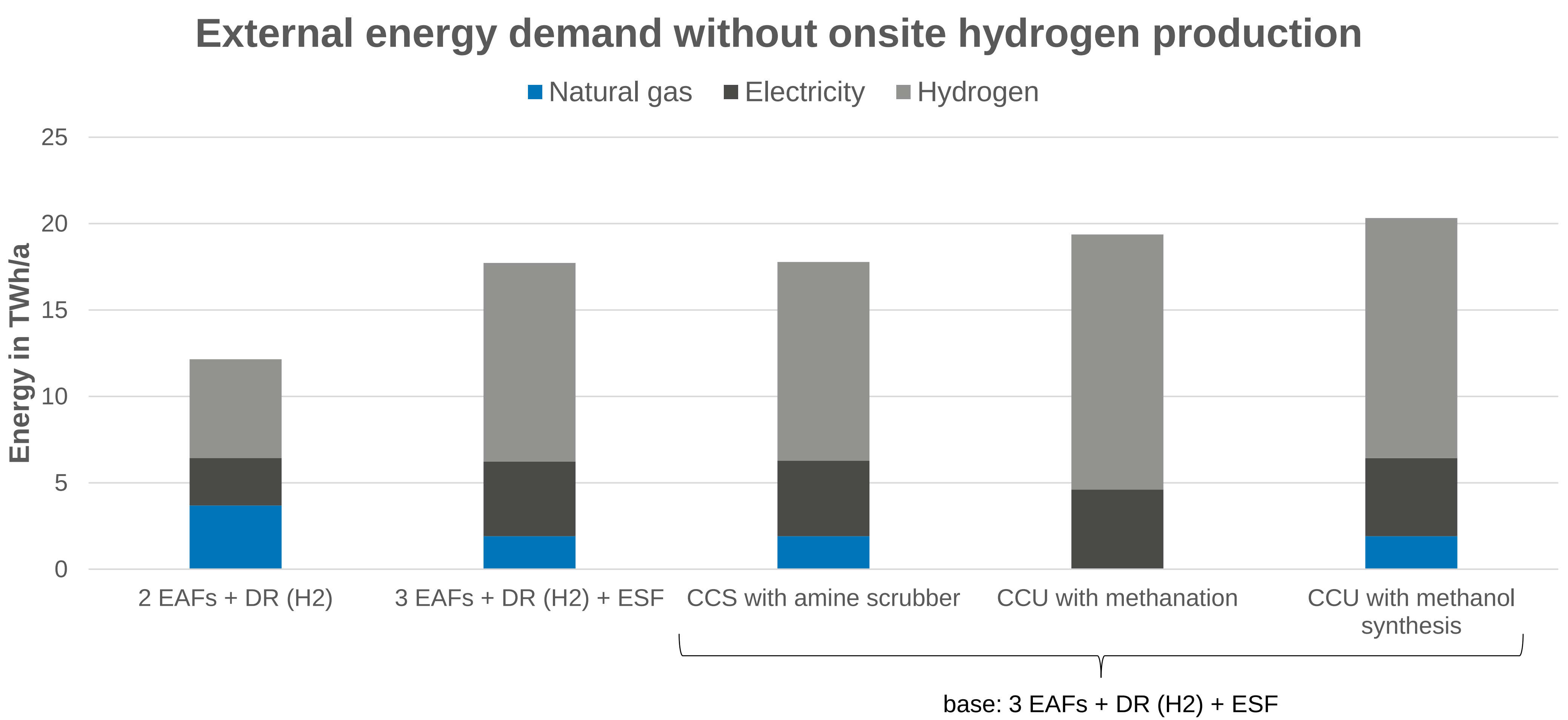
Simulation of possible decarbonization scenarios

External energy demand

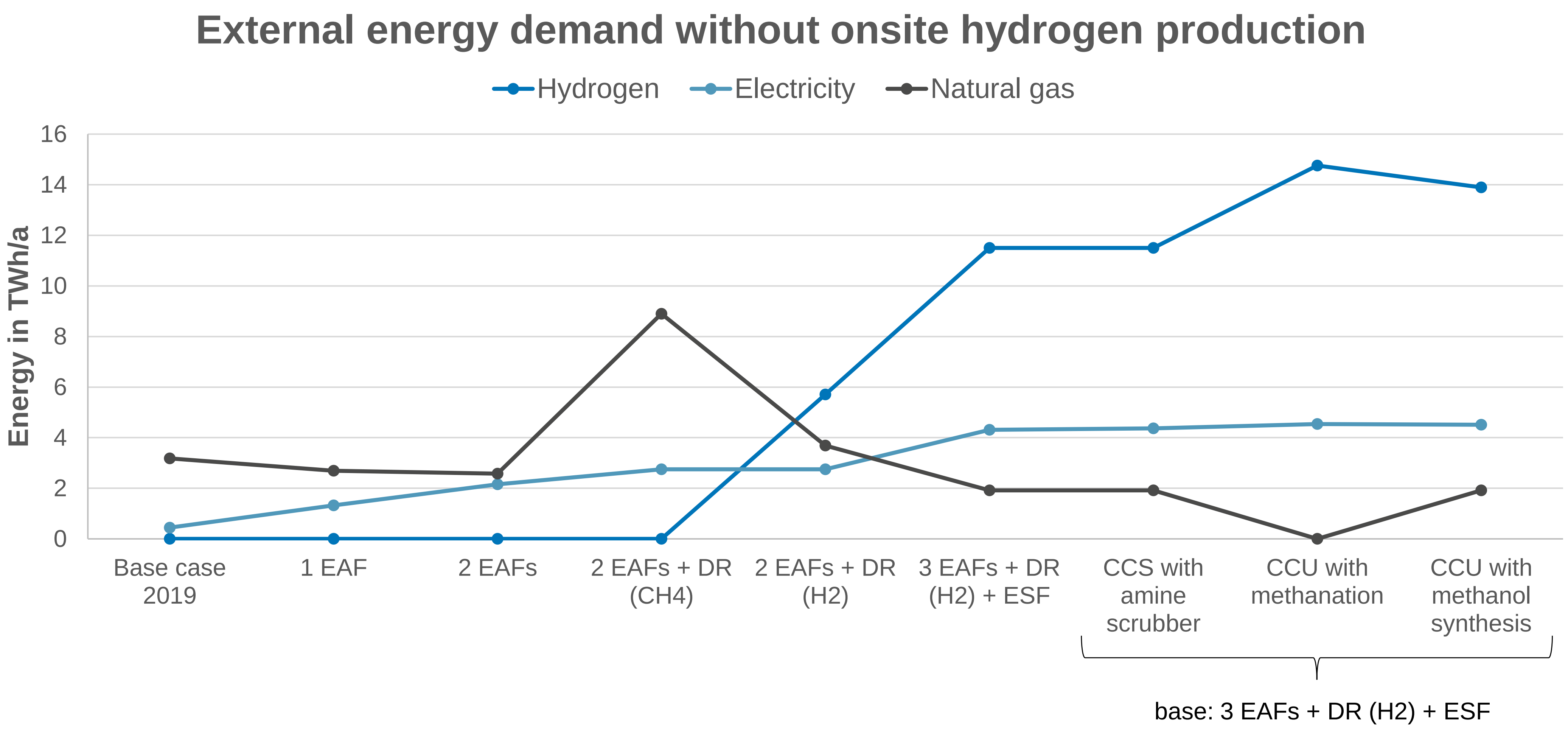


Simulation of possible decarbonization scenarios

External energy demand

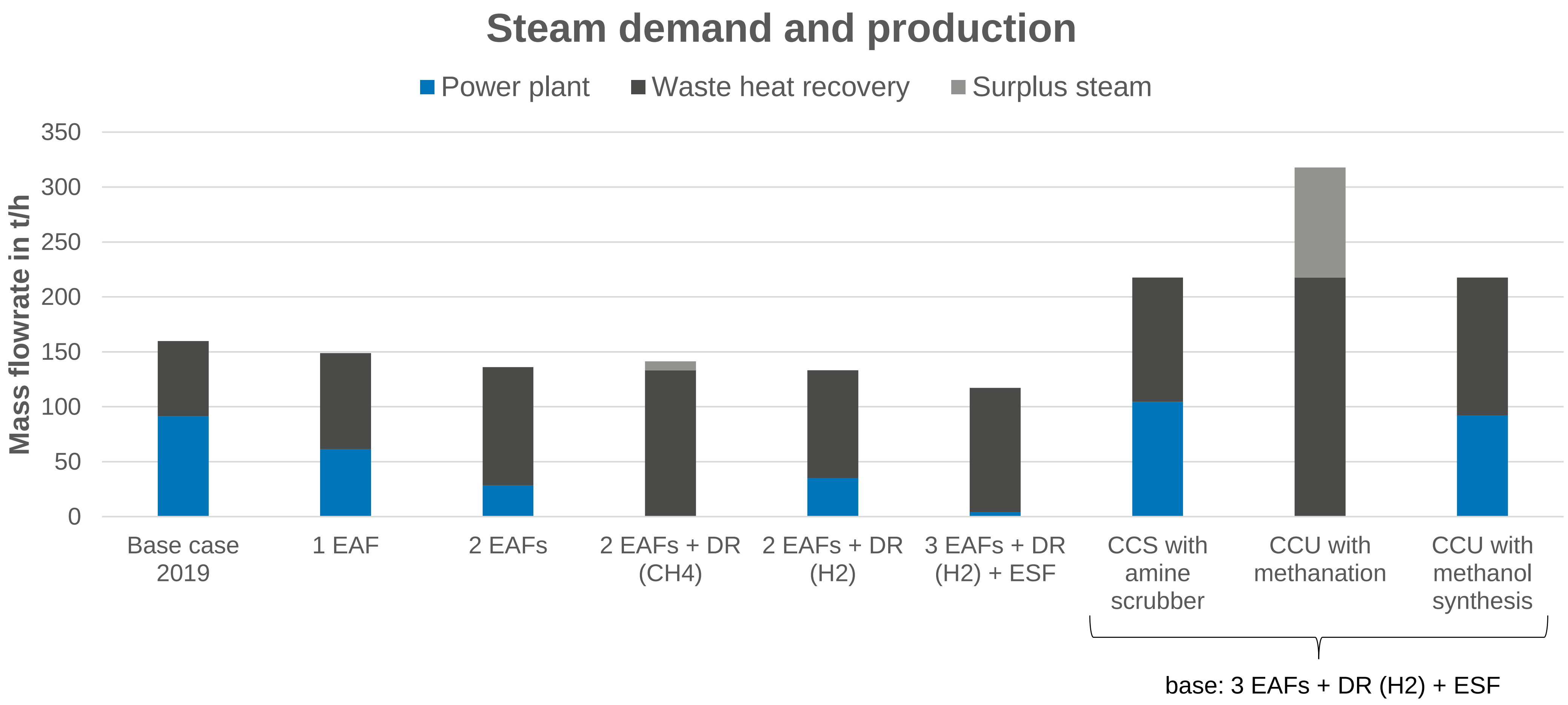


Simulation of possible decarbonization scenarios
External energy demand



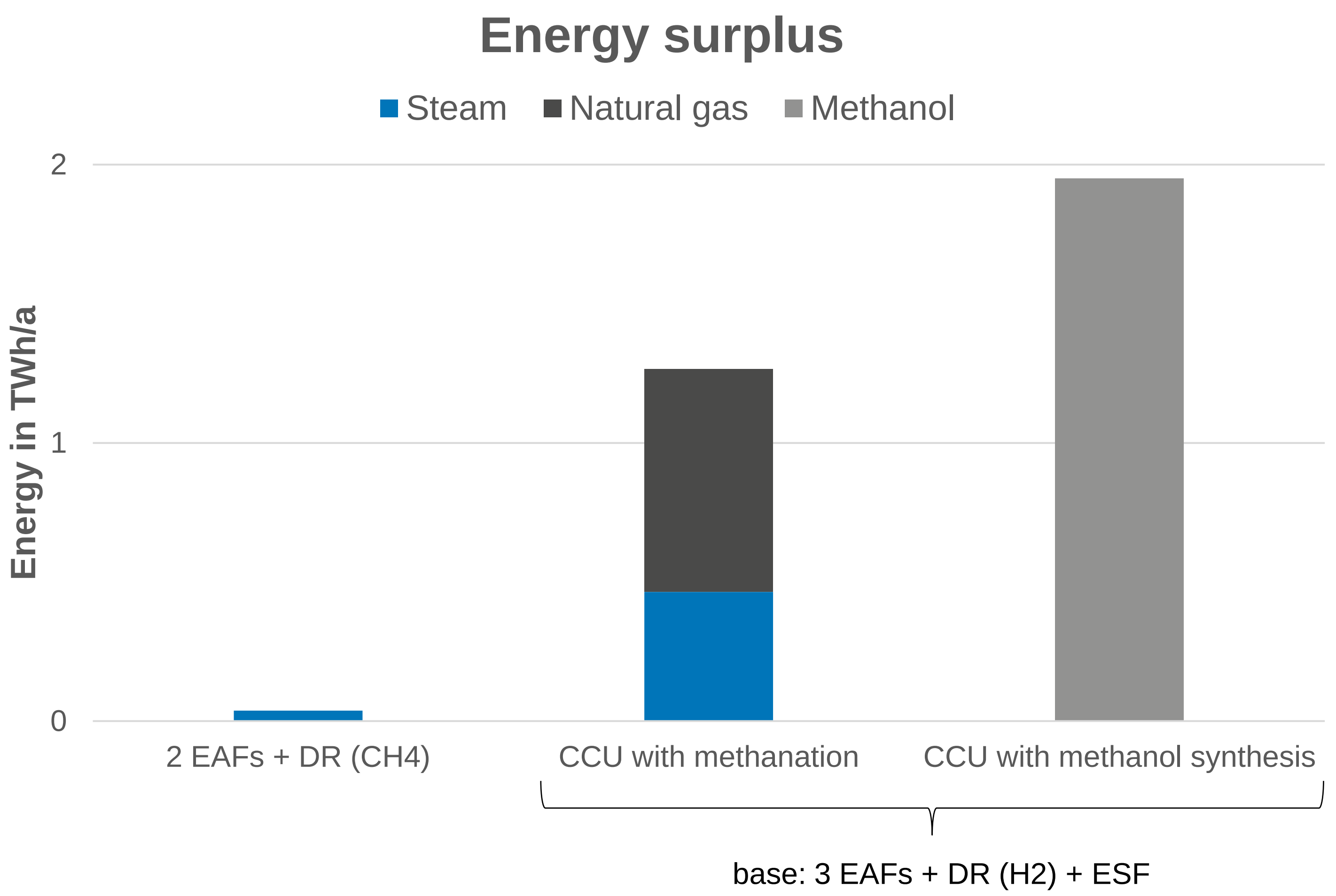
Simulation of possible decarbonization scenarios

Steam demand and production



Simulation of possible decarbonization scenarios

Energy surplus



Conclusion

Carbon direct avoidance must be the preferred pathway to decarbonise the steel sector

- EAF steelmaking
- Hydrogen based direct reduction

CCUS is essential for **unavoidable CO_2 emissions** (e.g., from raw materials)

- Combination of amine scrubber and catalytic methanation appears to be the most efficient approach among the analysed scenarios → eliminates natural gas dependency

Availability and affordability of **green electricity** and **hydrogen** are crucial for decarbonizing steel industry

Thank you for your attention

Linz, 17th of February 2025

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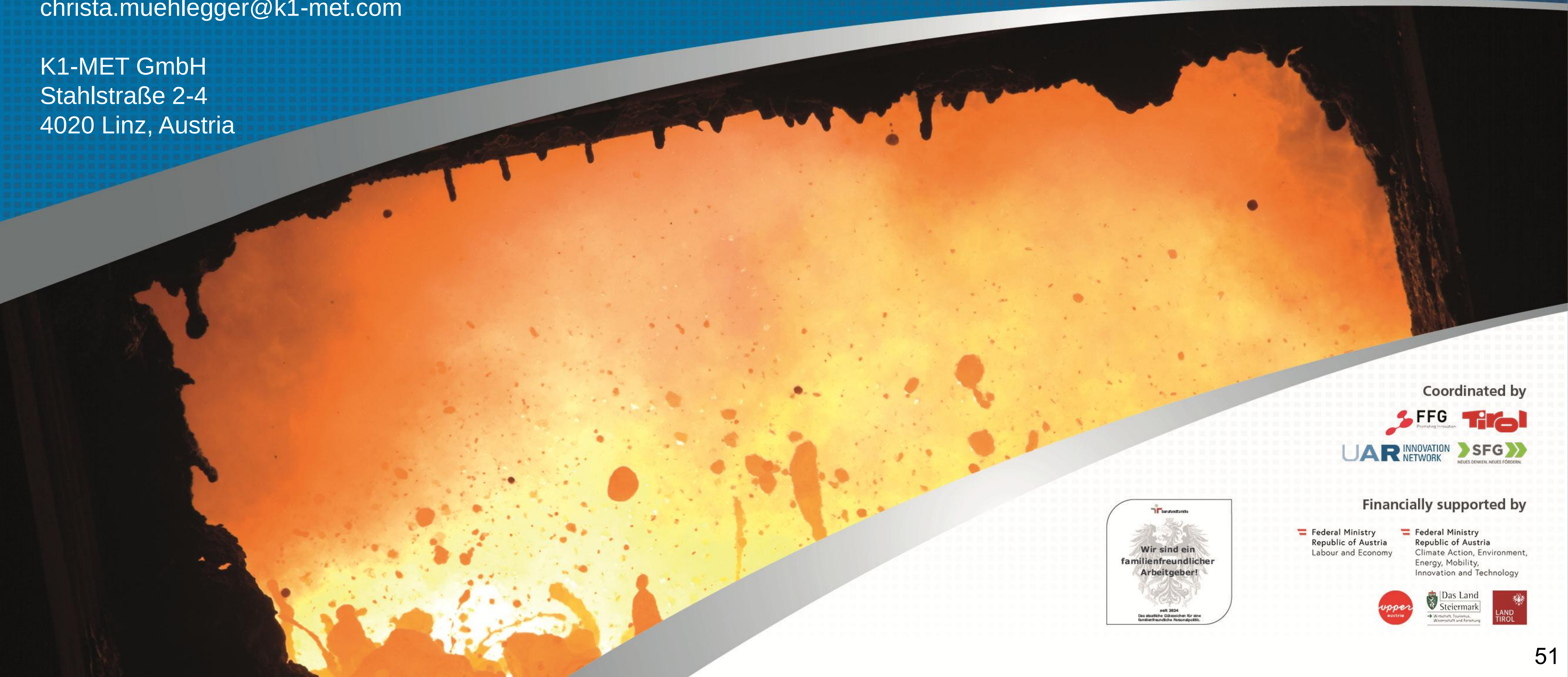
K1 MET metallurgical competence center

voestalpine ONE STEP AHEAD.



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Relaxation of the Mixed-Integer economic Optimization Approach

Andreas Wolff

Smarter Final Workshop, 17.02.2025

BFI Angewandte Spitzenforschung
VDEh-Betriebsforschungsinstitut GmbH

Stahl

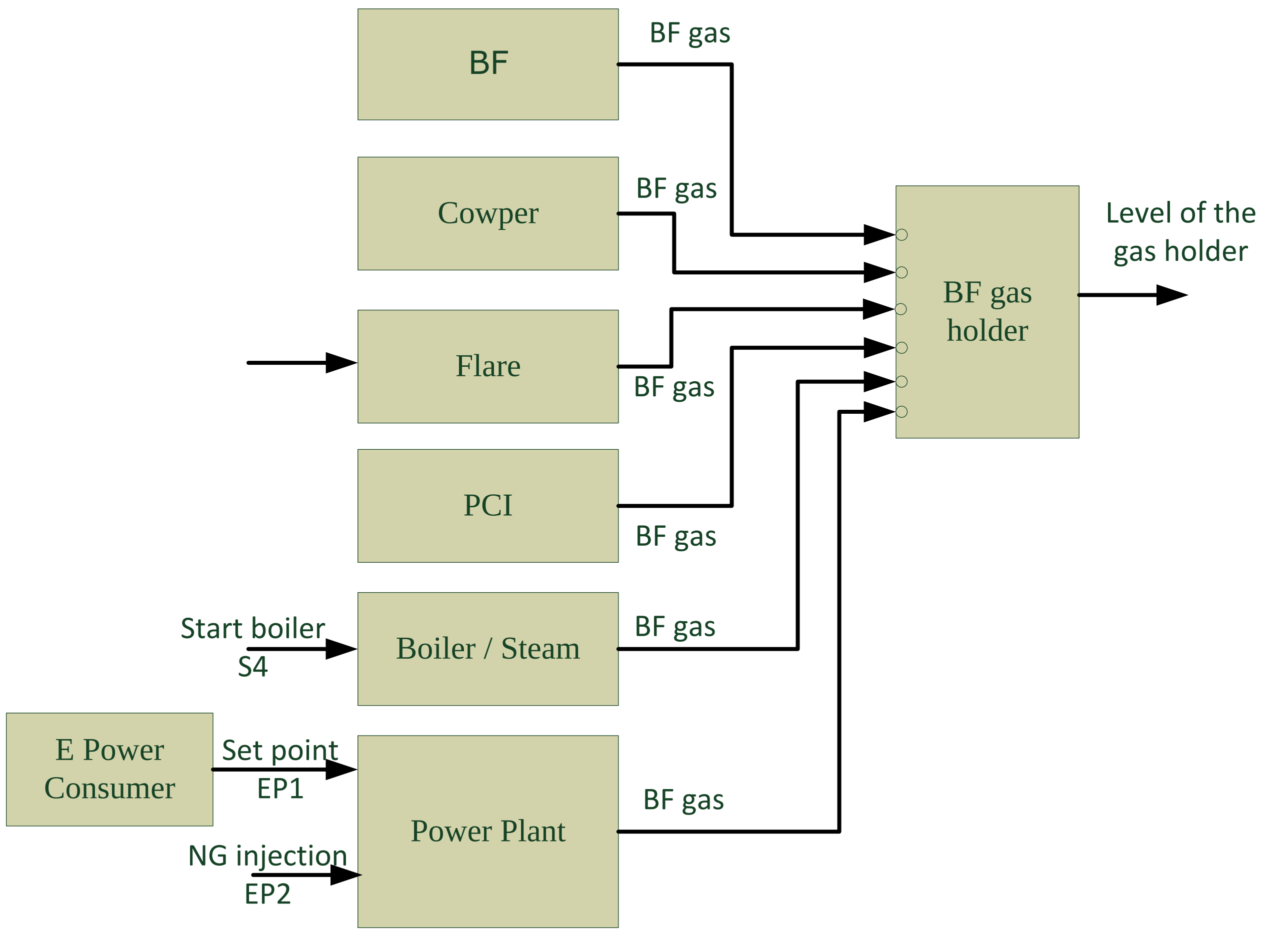
Control engineering analysis of the BF network for essential components to fulfil the control task

Goals:

- Reduction of natural gas consumption
- Maximising profit through the sale of electrical energy
- Minimisation of purchased electrical energy

Boundary condition::

- BFG-tank must not run full or empty
- It is not permitted to sell and buy electrical energy at the same time
- Process behaviour



Mixed-integer MPC for BFG gas network and electrical network

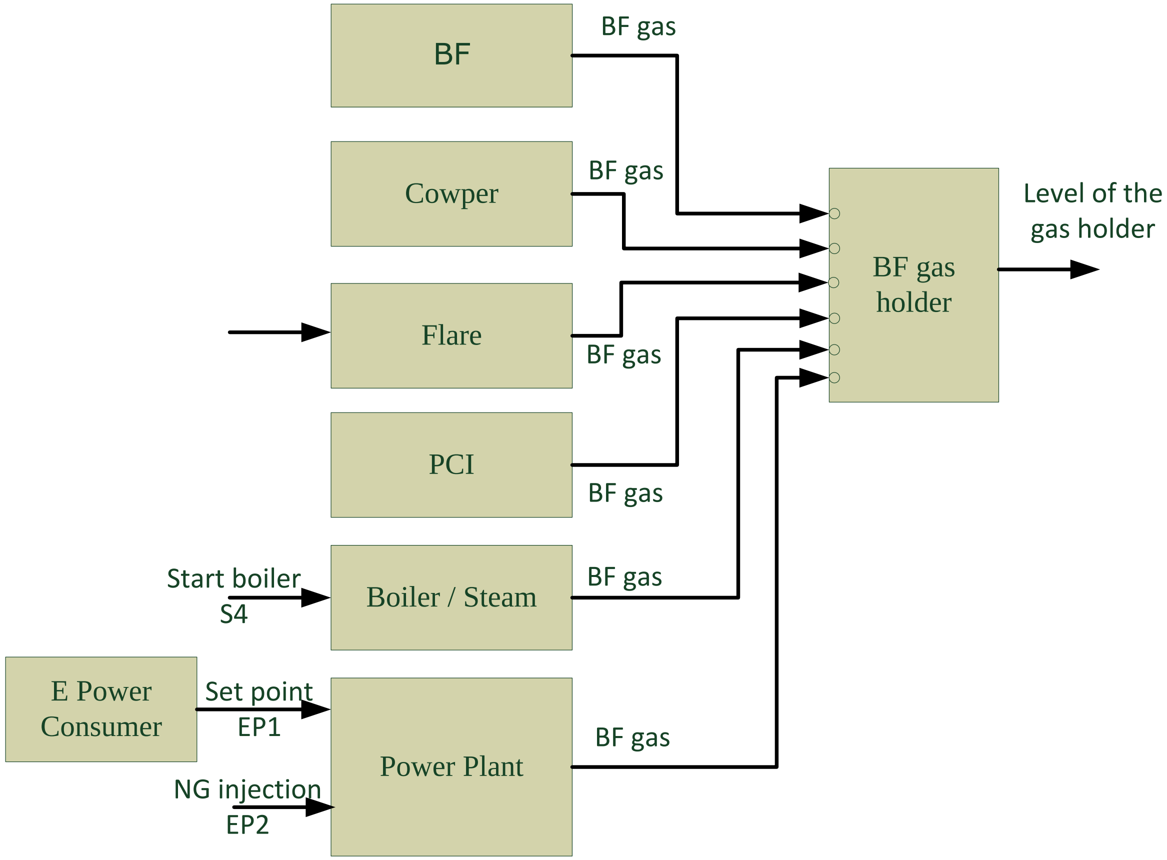
Mathematical formulation of the objectives

$$J = c_{NG}\dot{V}_{NG}(k) + c_{Buy}E_{Buy}(k) + c_{Sale}E_{Sale}(k) +$$

$$c_{holder+}\max(\,0, y_{LBF}(k) - \overline{y}_{LBF}) +$$

$$c_{holder-}\max(0, \underline{y}_{LBF} - y_{LBF}(k)) +$$

$$c_{emmission}\dot{Q}$$



Non-linear mixed-integer overall model of the BF and power grid

Electrical network

- $E_{Buy}(k) + E_{prod}(k) = E_{demand}(k) + E_{Sale}(k)$

XOR condition

- $\delta_{Buy}\ (k) + \delta_{Sale}\ (k) = 1$
- $0 \leq E_{Buy}(k) \leq E_{Buy,max}(k)\delta_{Buy}\ (k)$
- $0 \leq E_{Sale}(k) \leq E_{Sale,max}(k)\delta_{sale}\ (k)$

Power station (non-linear)

- $E_{prod}(k) = \eta\left(E_{prod}(k), \ldots\ldots\right)\dot{V}_{Mix,BF}(k)LCV_{Mix,BF}\ (k)$
- Constraints when starting up the power plant
- Minimal on and off time of the power station

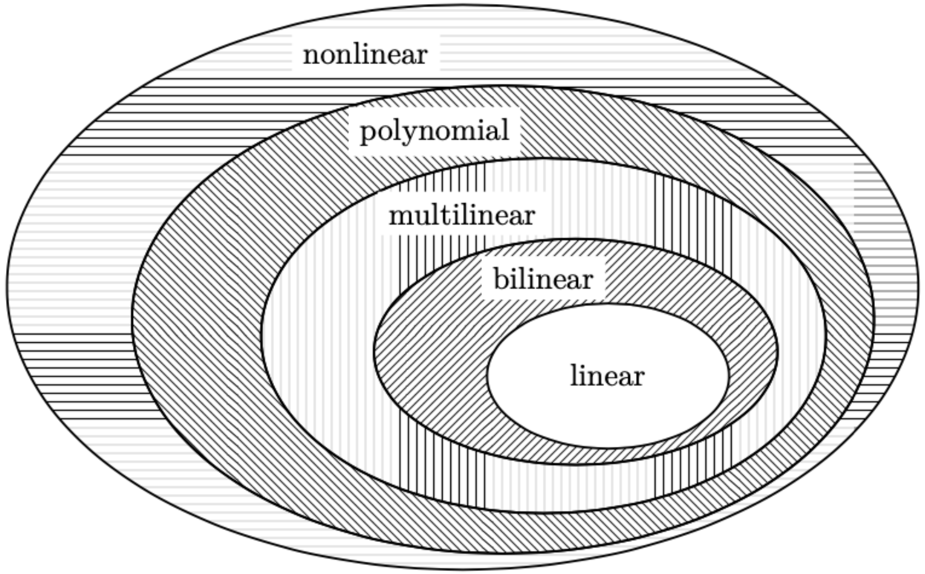
Notes

- The approximation of bilinear systems by discretisation and the Big-M approach leads to many decision variables.

- Mixed-integer calculations for non-linear processes are very computationally intensive.

Is there another approach?

- Many process engineering processes can be described as multi-linear systems and can adequately approximate similarly.



Boolean algebra

Zhegalkin polynomials

Boolean function	algebraic function
NOT x_1	$1 - x_1$
x_1 AND x_2	$x_1 x_2$
x_1 OR x_2	$x_1 + x_2 - x_1 x_2$

$\underline{b}_1$	$\underline{b}_2$	XOR$(\underline{b}_1, \underline{b}_2)$
0	0	0
0	1	1
1	0	1
1	1	0

$$\underline{f}_b(\underline{b}_1, \underline{b}_2) = \underline{b}_1 + \underline{b}_2 - 2\underline{b}_1\underline{b}_2.$$

Boolean state space models

$$\begin{aligned} \underline{\mathbf{x}}(k+1) &= \underline{\mathbf{f}}(\underline{\mathbf{x}}(k)\underline{\mathbf{u}}(k)), \\ \underline{\mathbf{y}}(k) &= \underline{\mathbf{f}}(\underline{\mathbf{x}}(k)\underline{\mathbf{u}}(k)), \\ \underline{\mathbf{x}}(0) &= \underline{\mathbf{x}}_0, \end{aligned}$$

Remark:
Zhegalkin polynomials are multilinear

Saadia Faisal; Gerwald Lichtenberg; Herbert Werner (2008). *Polynomial models of gene dynamics. , 71(13-15), 2711–2719.* doi:10.1016/j.neucom.2007.09.024

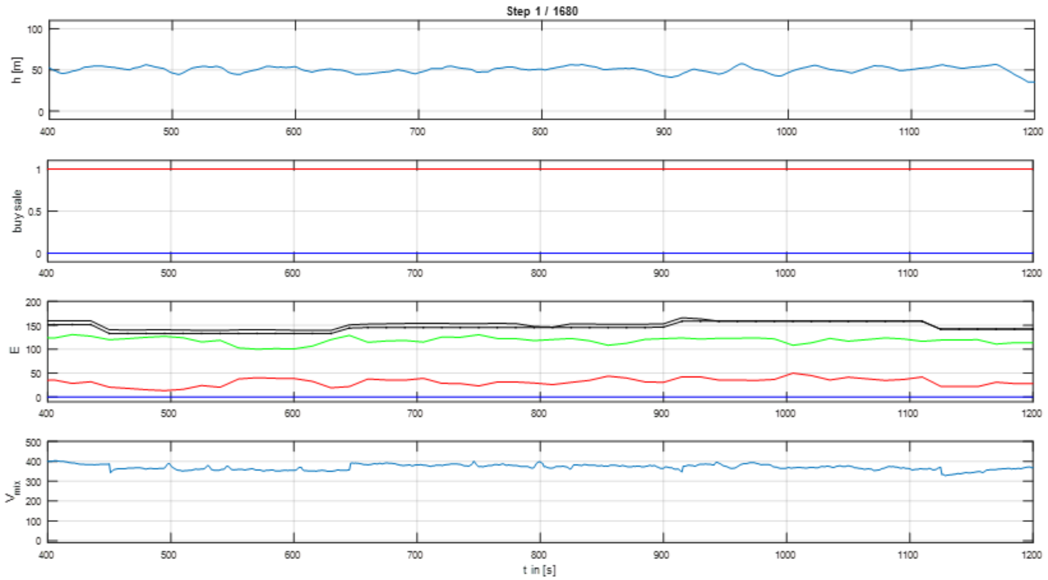
Example BFG Controller

Electrical energy may not be bought or sold at the same time

$$\delta_{Buy}\,(k) + \delta_{Sale}\,(k) = 1$$

It is possible to visualise this in a truth table

$\delta_{\mathrm{Buy},i}$	$\delta_{\mathrm{Sale},i}(k)$	$XOR(x_1, x_2)$
0	0	0
0	1	1
1	0	1
1	1	0



The following Zhegalkin polynomial can represent the truth table.

$f_b = x_{Buy,i} + x_{Sale,i} - 2x_{Buy,i}x_{Sale,i}$ and $f_b == 1$

Quality functionalities should be expanded

$$J_{new} = J + J_2 = p\left(1 - \frac{4}{n}\sum_{i=1}^{n}\left(x_{zone,i} - 0{,}5\right)^2\right) + p\left(1 - \frac{4}{n}\sum_{i=1}^{n}\left(x_{NG,i} - 0{,}5\right)^2\right)$$

Summary

- Process models are usually non-linear
- Mixed-integer calculations for a non-linear process are very computationally intensive.
- The approximation of bilinear systems using discretisation and the Big-M approach leads to many decision variables. => computationally intensive
- Many process engineering processes are multi-linear or approximated with sufficient accuracy as multi-linear systems.
- Zhegalkin polynomials can describe mixed-integer systems.
- Zhegalkin polynomials are multilinear polynomials.

Multilinear optimisation problems can be solved efficiently and quickly.

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Mixing station

$$\dot{V}_{BF}(k) = \left(1 - x_{LCV}(k)\right)\dot{V}_{MIX,BF}(k)$$

$$\dot{V}_{NG}(k) = x_{LCV}(k)\dot{V}_{MIX,BF}(k)$$

$$x_{LCV}(k) = \frac{LCV_{mix}(k) - LCV_{BF}(k)}{LCV_{NG}(k) - LCV_{BF}(k)}$$

BF gas holder

$$x(k+1) = Ax(k) + b_1\dot{V}_{BOF\ to\ BF}(k)$$

$$+b_2\dot{V}_{BF\ to\ E}(k) + \sum_{i}^{n}\dot{V}_{BF,in,i} + \sum_{i}^{n}\dot{V}_{BF,out,i} + b_4\dot{Q}$$

$$y_{LBF}(k) = cx(k)$$

TELECOMMUNICATIONS, COMPUTER ENGINEERING, AND PHOTONICS INSTITUTE

Sant'Anna
School of Advanced Studies – Pisa

ICT COISP
Information and Communication Technologies for Complex Industrial Systems and Processes

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

Lorenzo Vannini

Steel Production impact

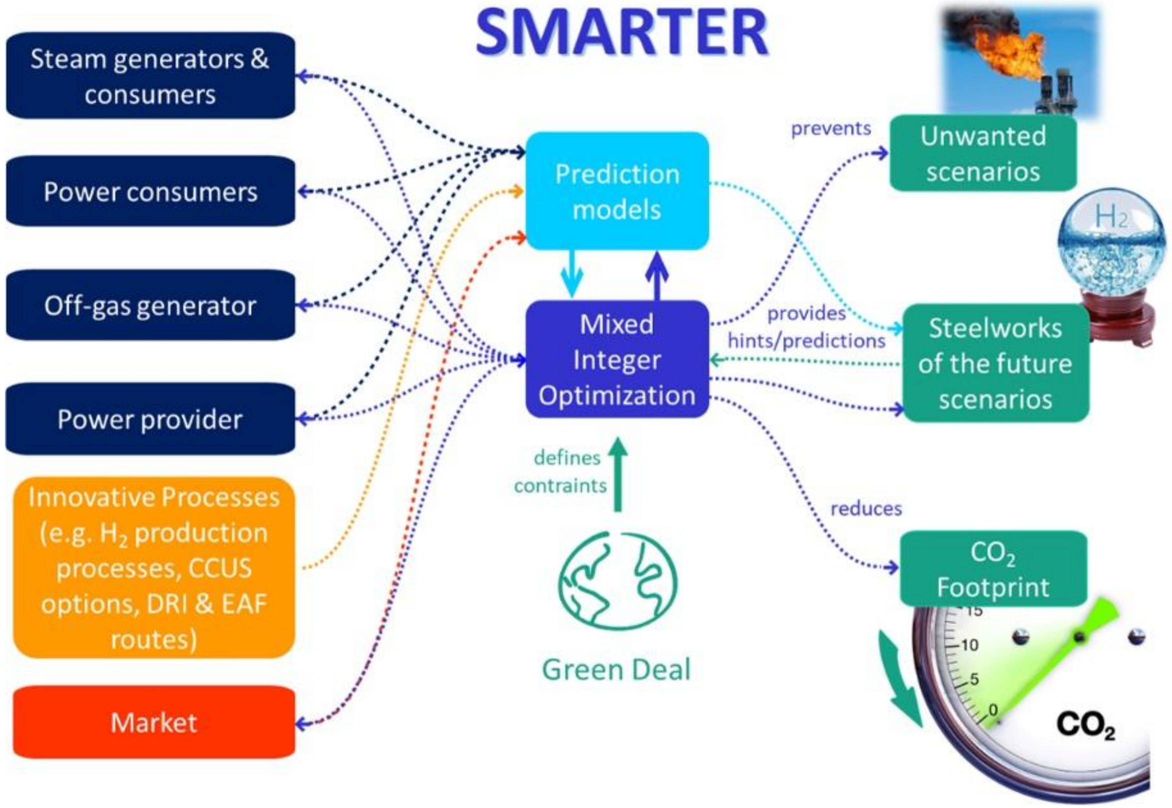
In 2023, around **126 million tons** of steel were produced in the EU.

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**

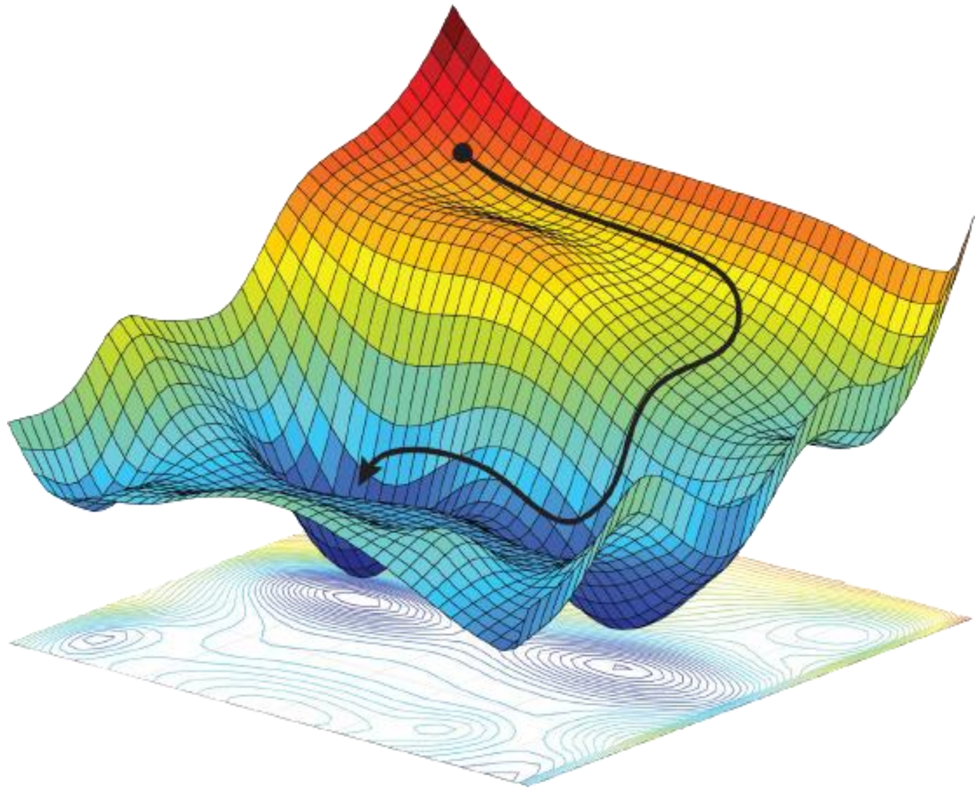
Minimizing **system stress**

Problems

The POGs are produced intermittently

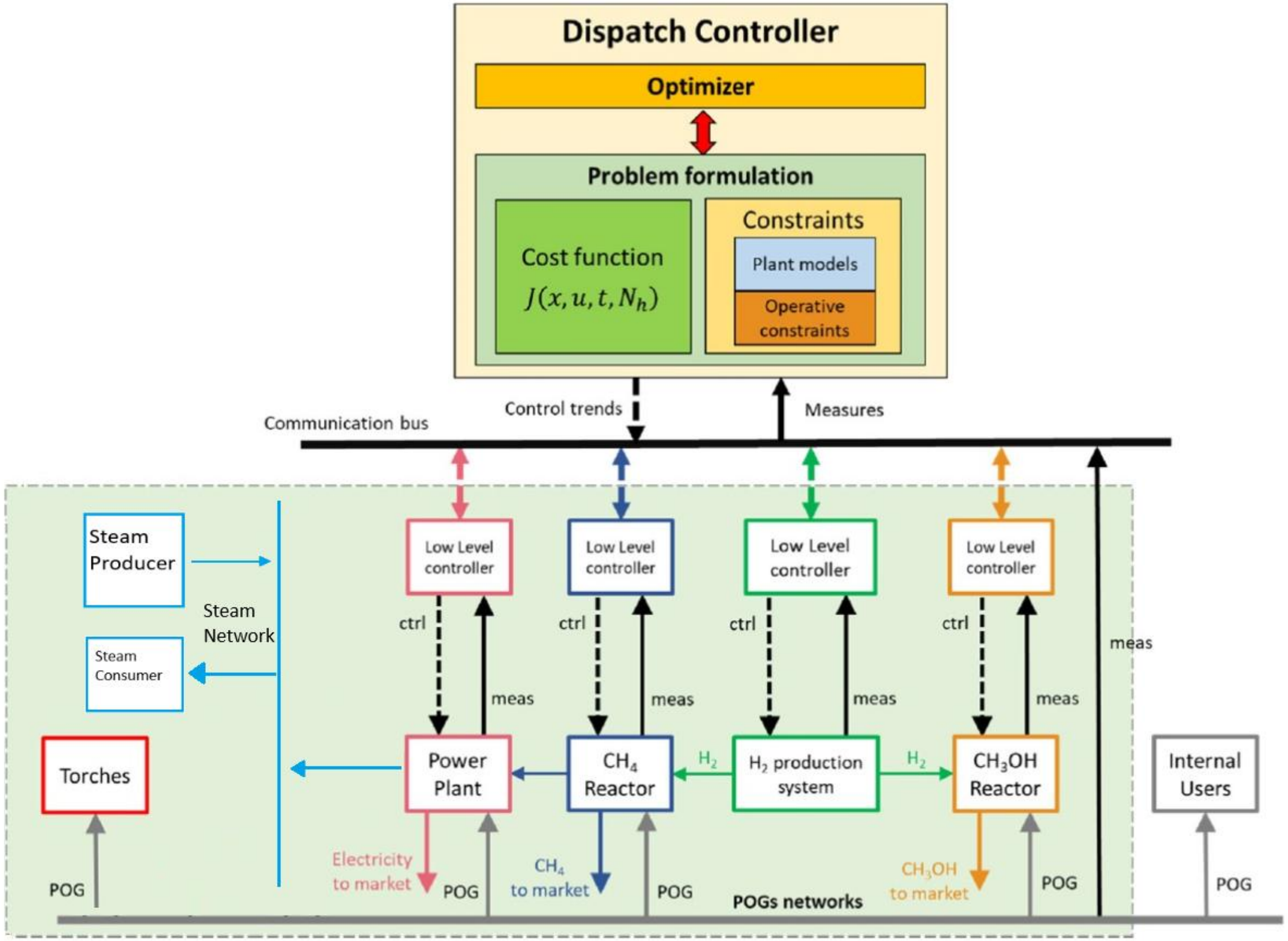
Solution

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 :

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

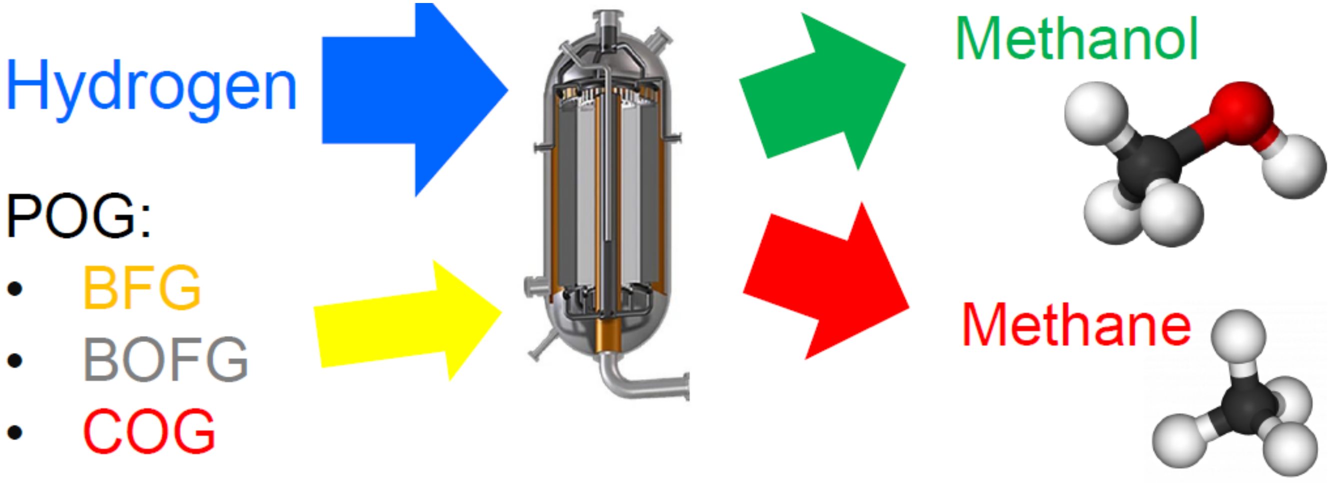
$$KPI_{\text{time}} = k_{\mu}\mu_{\text{time}} + k_{\sigma}\sigma_{\text{time}} + k_{\text{comp}}t_{\text{comp}}^{\max}$$

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

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

Followed approach, Assumptions and New Ideas

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



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

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

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

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

$$\min \quad J$$

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

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

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

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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
- Temporary operational disruption

Reference Scenario

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

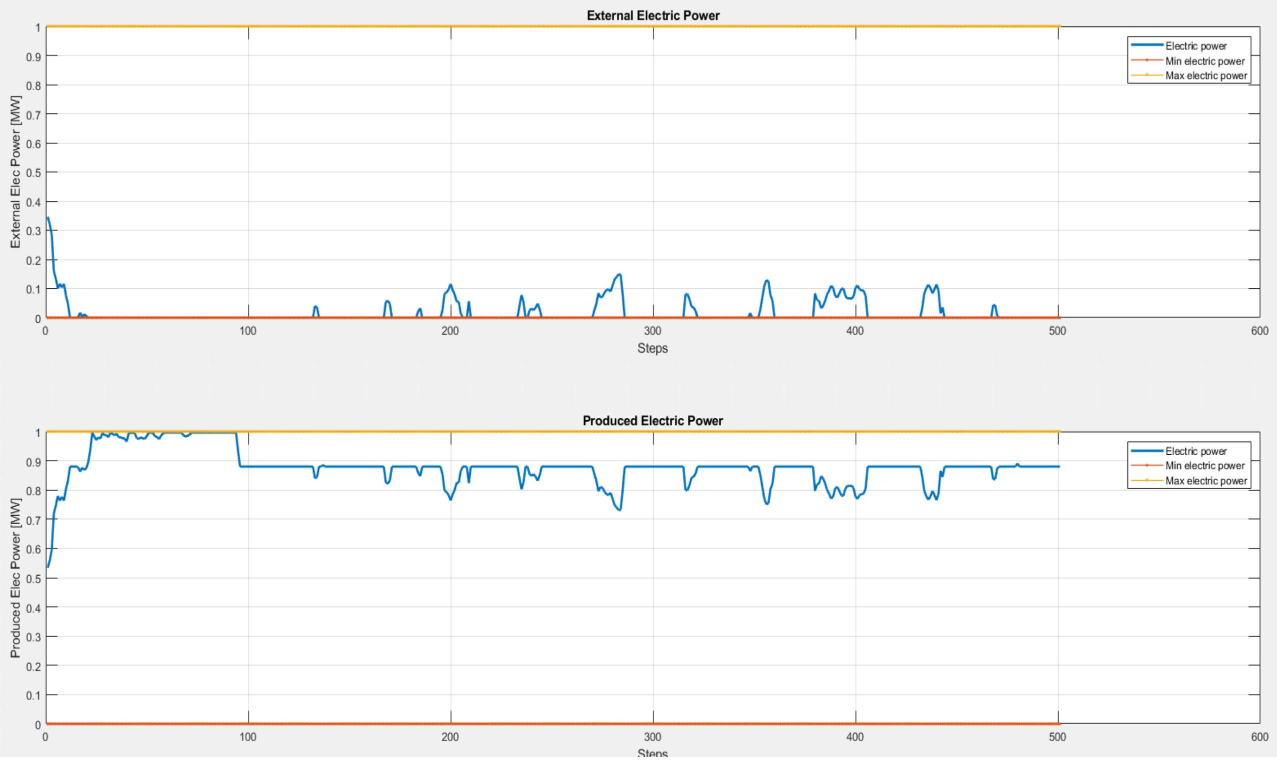
Historical energy prices

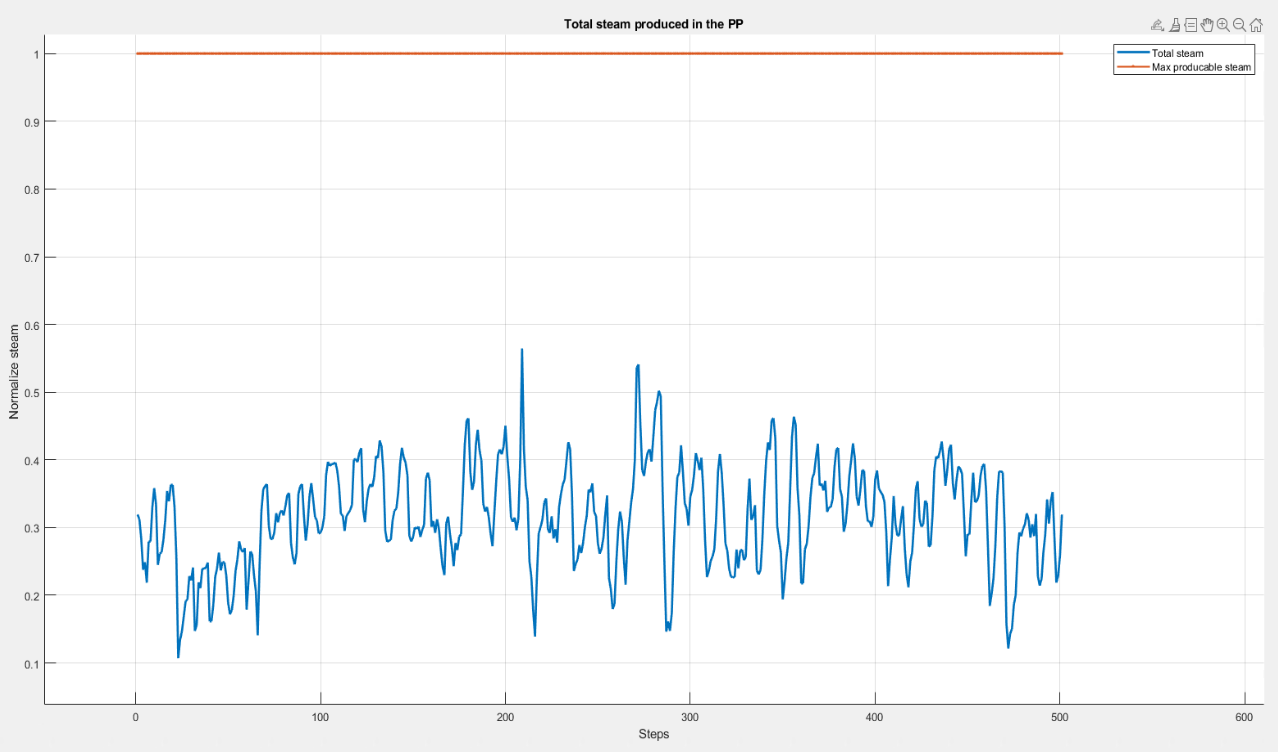
Internal energy (heat, electricity, steam) demands is always satisfied

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 %	≈ 37.21 %
Total KPI CO_2 %	≈ -21.82 %

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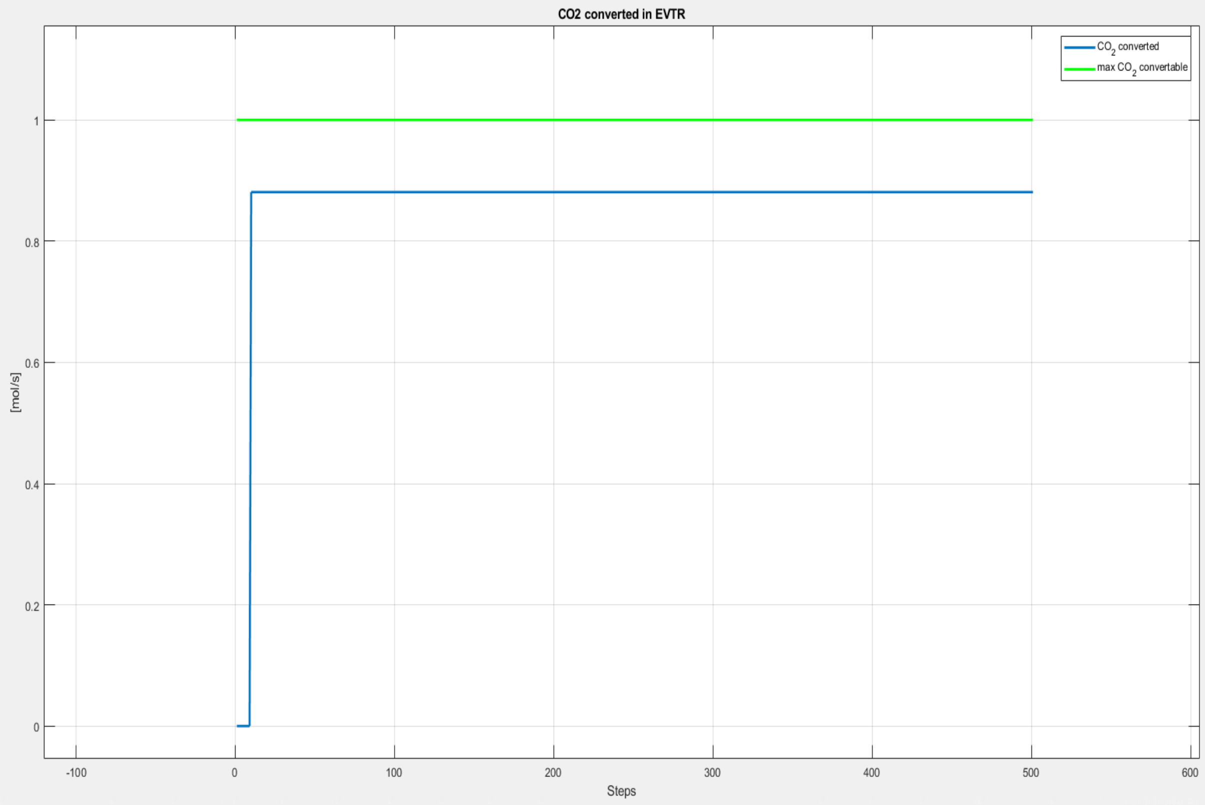
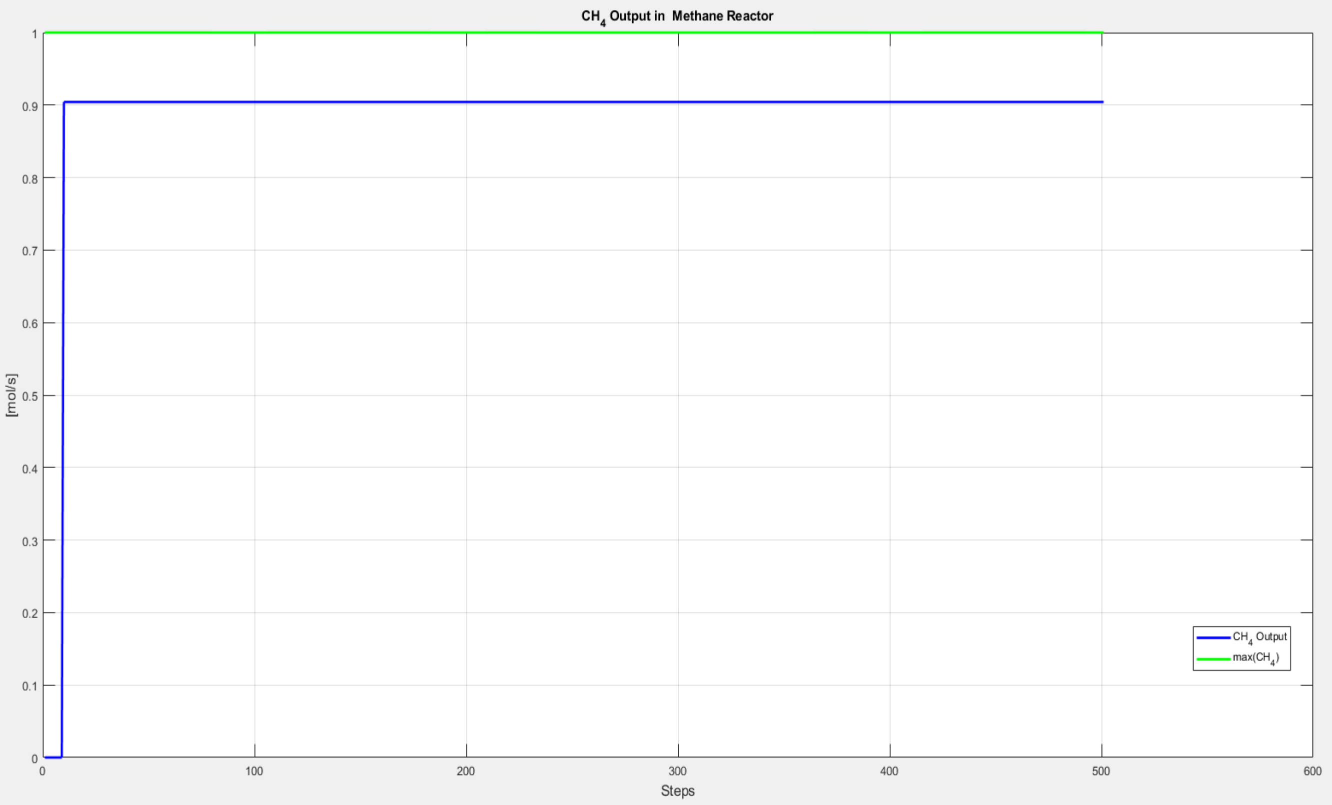
Results





CO_2 converted

CH_4 output

New Scenarios

Standard Route

POGs can only be rerouted to PP and torches

Novel Route

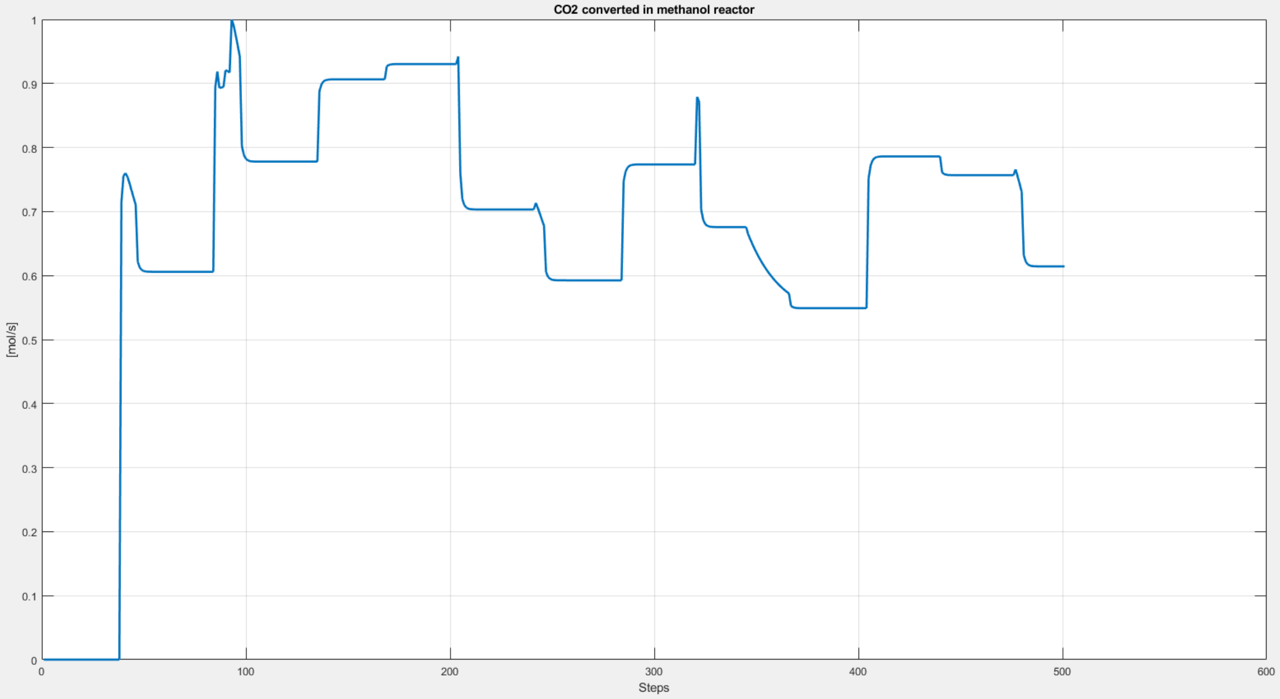
POGs can be rerouted to PP, torches and methanol reactor

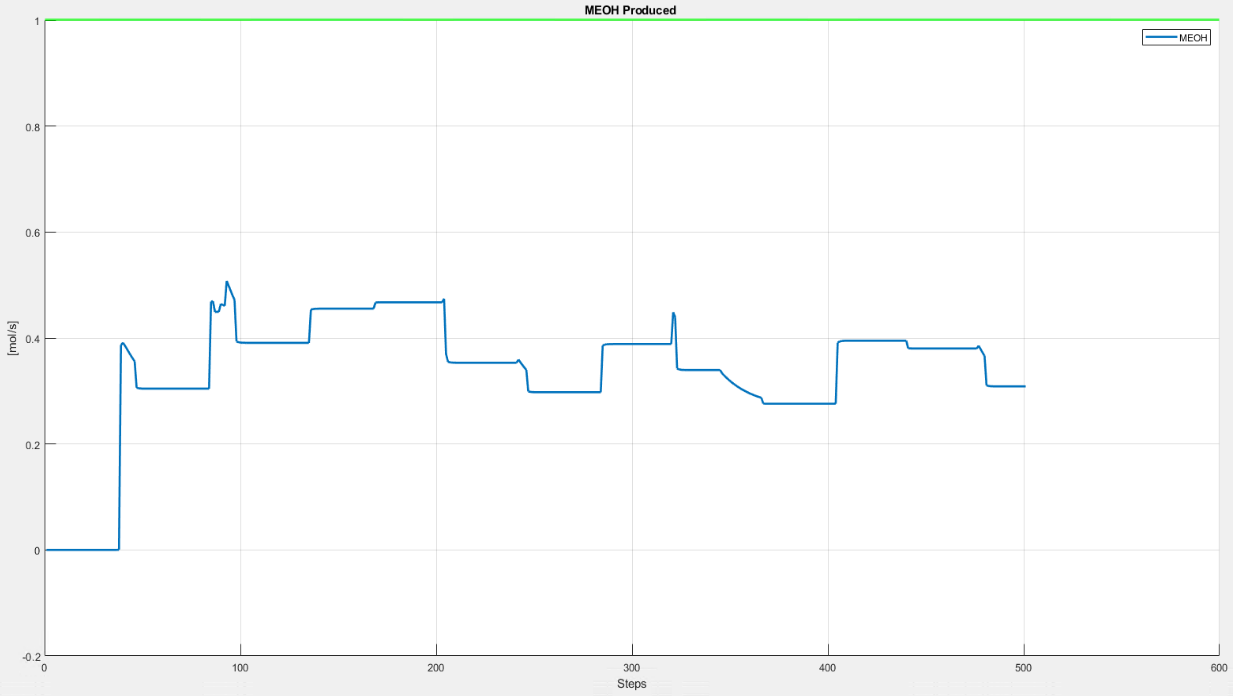
Remark:

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

KPI	Value
Money KPI %	$\approx$ 50.28%
Total KPI CO_2 %	$\approx$ -7.76%

Results



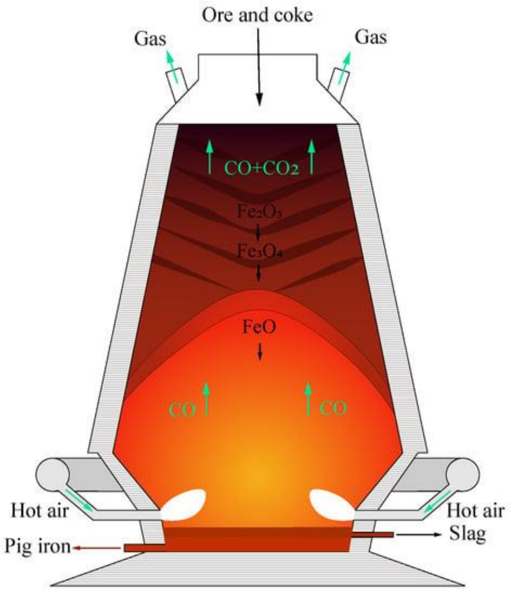


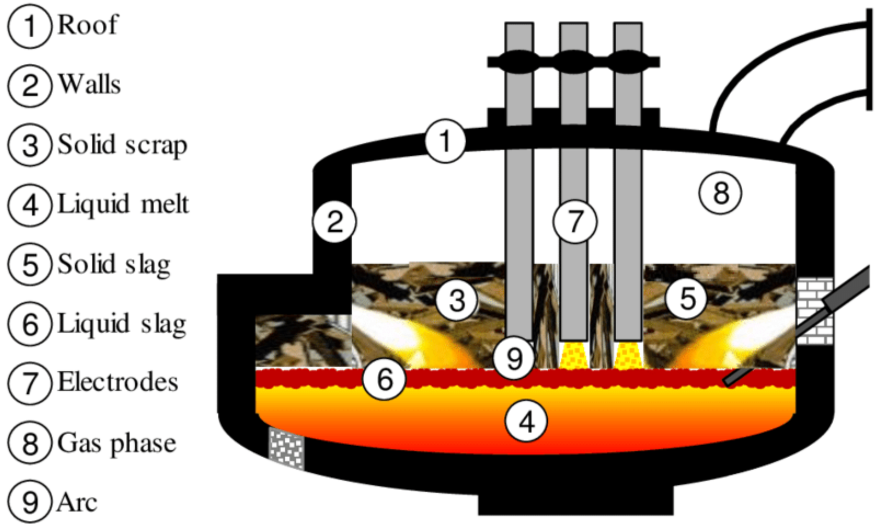
CO_2 converted

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)

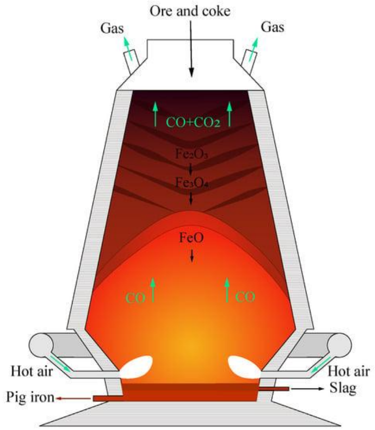
$$\mathrm{CO}_2^{\mathrm{EAF}} = 9.002 \times \left(\frac{M_{\mathrm{DRI}}}{M_{\mathrm{scrap}} + M_{\mathrm{DRI}}} \right) + 327.109 \quad [\mathrm{kgCO_2/ton}]$$

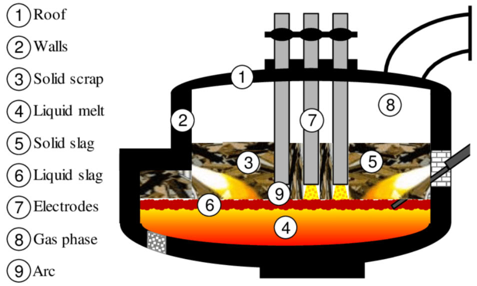
KPIs Results

KPI	Value
Money KPI %	$\approx$ -60.02 %
Total KPI CO_2 %	$\approx -17.52\%$

New Scenarios

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

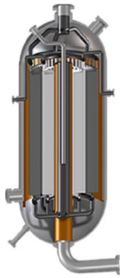




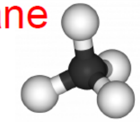
Hydrogen

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

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

$\mathbf{CO_2}$ **equivalent** output from the whole DRI process in $kg/tDRI$.

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

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 %	≈ -31.56%
Total KPI CO_2 %	≈-28.08%

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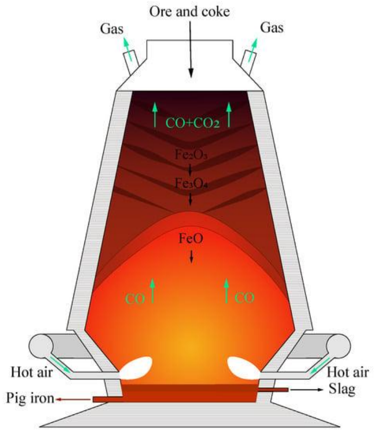
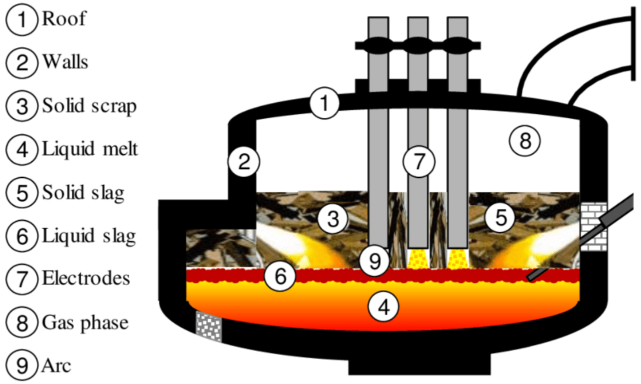
New Scenario

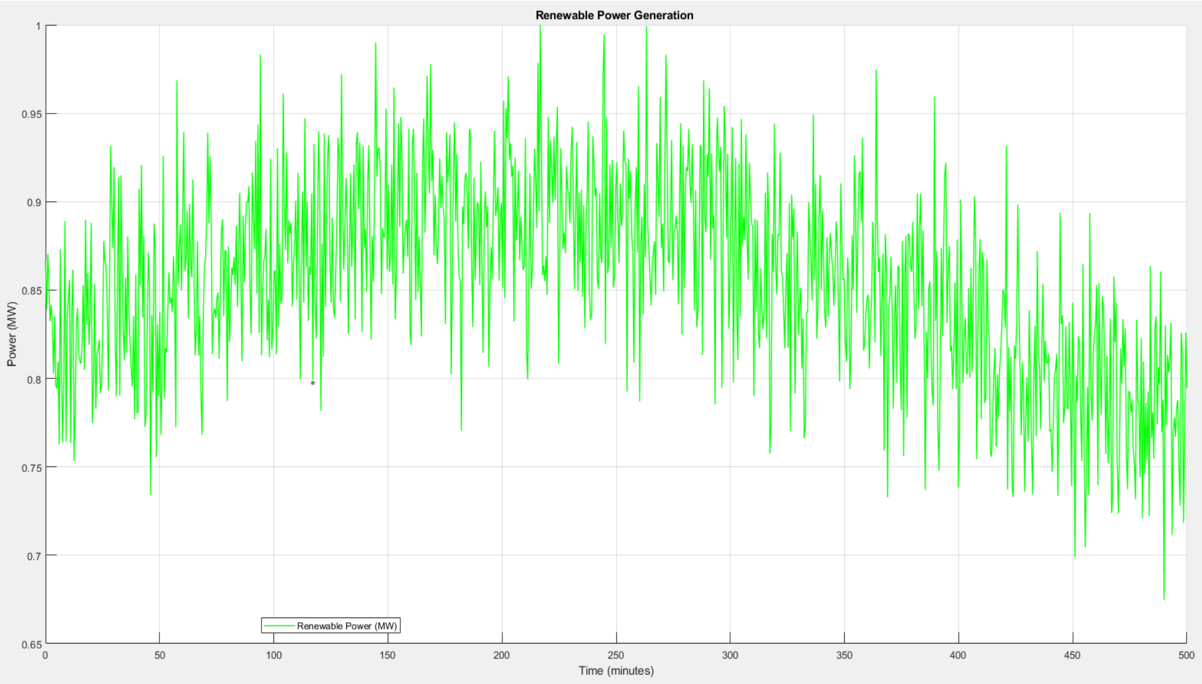
Replace 1 small BF with **EAF** and **renewable energy is considered**

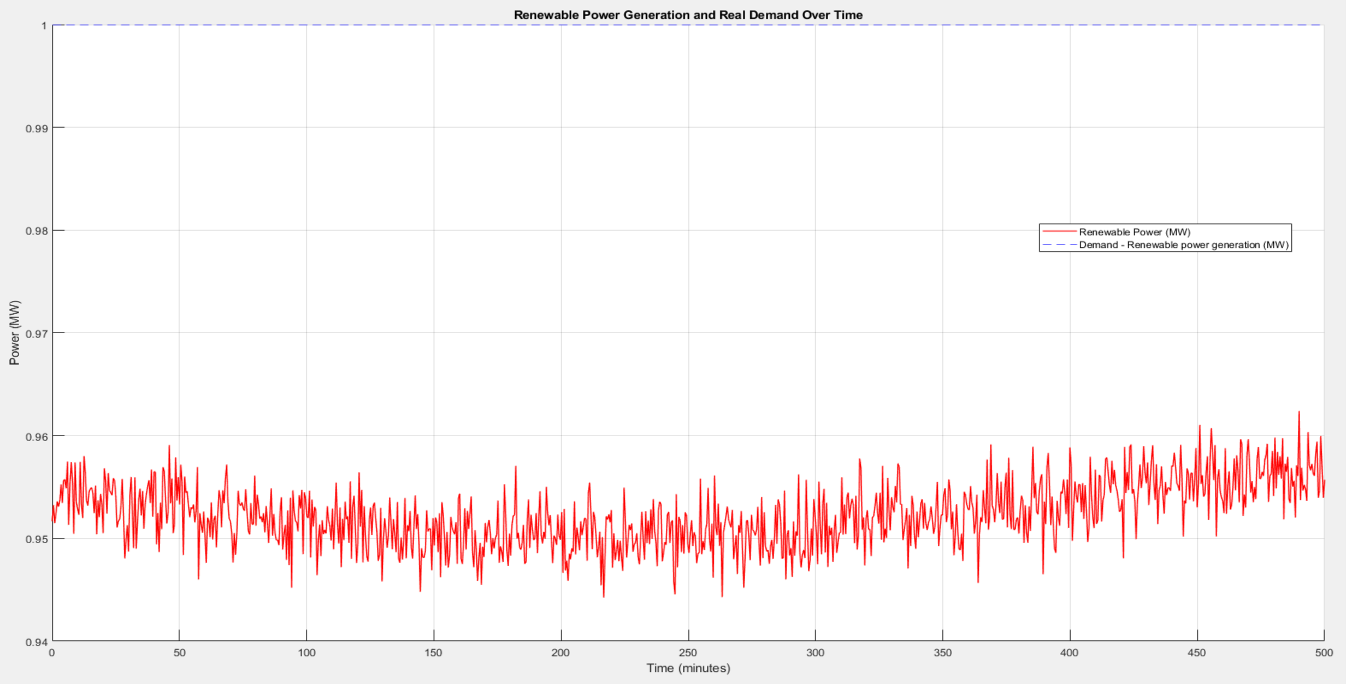




$$P_{\text{renewable}}(t) = P_{\text{avg\_ren}} + A\sin(\omega t + \phi) + \epsilon$$

Considerations and KPIs results





Renewable Power

Internal Demand

KPIs Results

KPI	Value
Money KPI %	≈ -50.76%
Total KPI CO_2 %	≈ −19.52%

Temporary operational disruption

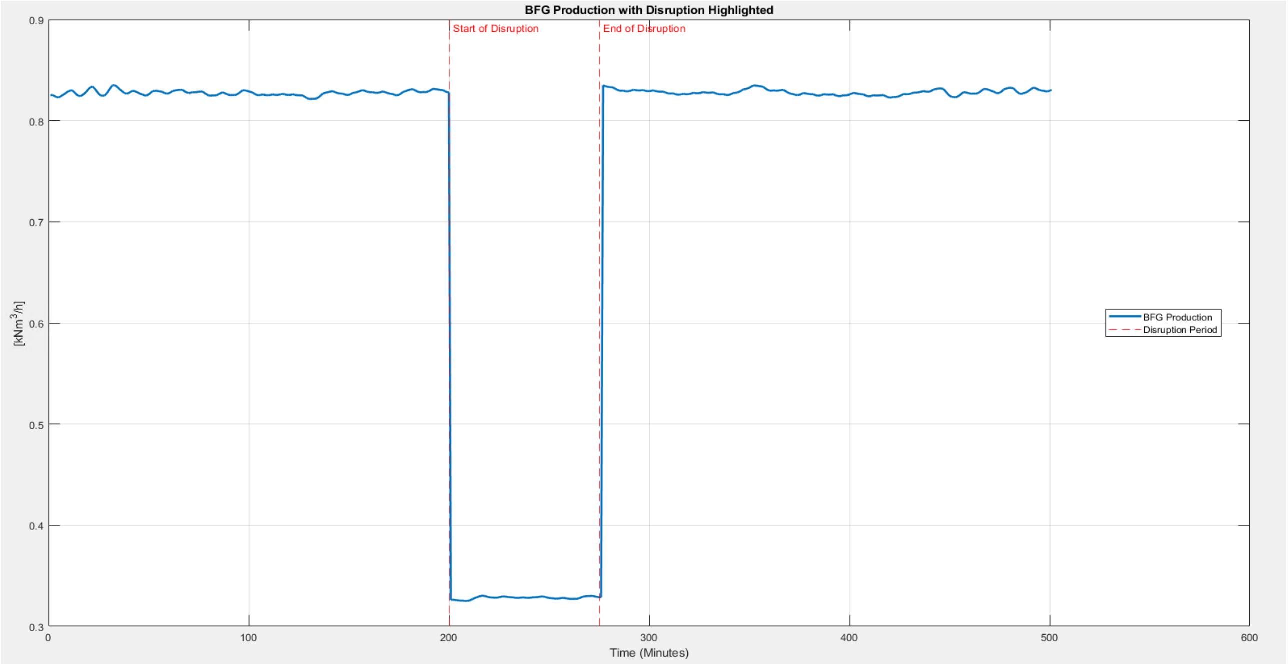
In this analysis, we aim to evaluate the impact of **a temporary operational disruption in one of the three blast furnaces within the system.**

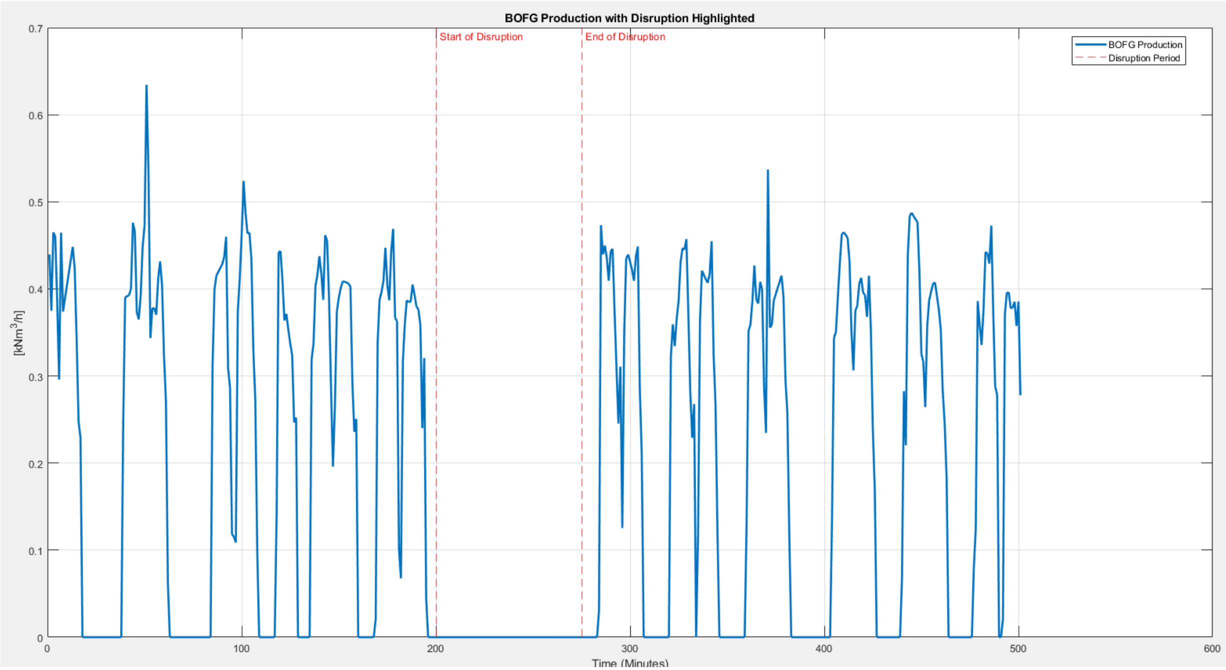
This reduction **directly impacts downstream operations, specifically the Basic Oxygen Furnace Gas** , which operates in 15-minute intervals, peaking before declining to zero over a 20-minute cycle.

During this period, **the Electric Arc Furnace is activated to compensate for the missing steel production**, ensuring the same quality is maintained.

Coke Oven Gas remains relatively stable throughout the scenario, exhibiting minimal fluctuations

Temporary operational disruption: results





BFG plot

BOFG plot

KPIs Results

KPI	Value
Money KPI %	≈ -5.46%
Total KPI CO_2 %	≈ -2.18%

Final scenario KPIs comparison

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

Standard route + Methane Reactor

KPI	Value
Money KPI %	$\approx$ -5.46%
Total KPI CO_2 %	$\approx$ -2.18%

Temporary operational disruption

KPI	Value
Money KPI %	$\approx +50,3\%$
Total KPI CO_2 %	$\approx -4.6\%$

Standard route + Methanol Reactor

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

1 small BF replaced with EAF and externally purchased DRI

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

BF partially replace with EAF+ Renewable energy

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

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 V.,..& Rompalski, P. (2021). **Hydrogen role in the valorization of integrated steelworks process off-gases through methane and methanol syntheses**. *Matériaux& Techniques*,

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Thank you

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