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Towards an efficient, integrated and cost-effective net-zero energy system in 2050

The role of cogeneration

Presentation of key findings

28 October 2020

Study commissioned by COGEN Europe

Agenda

1. **Overview**
2. **User focus**
   - Methodology & key assumptions
   - Key results
3. **System focus**
   - Methodology & key assumptions
   - Results
4. **Key conclusions & recommendations**

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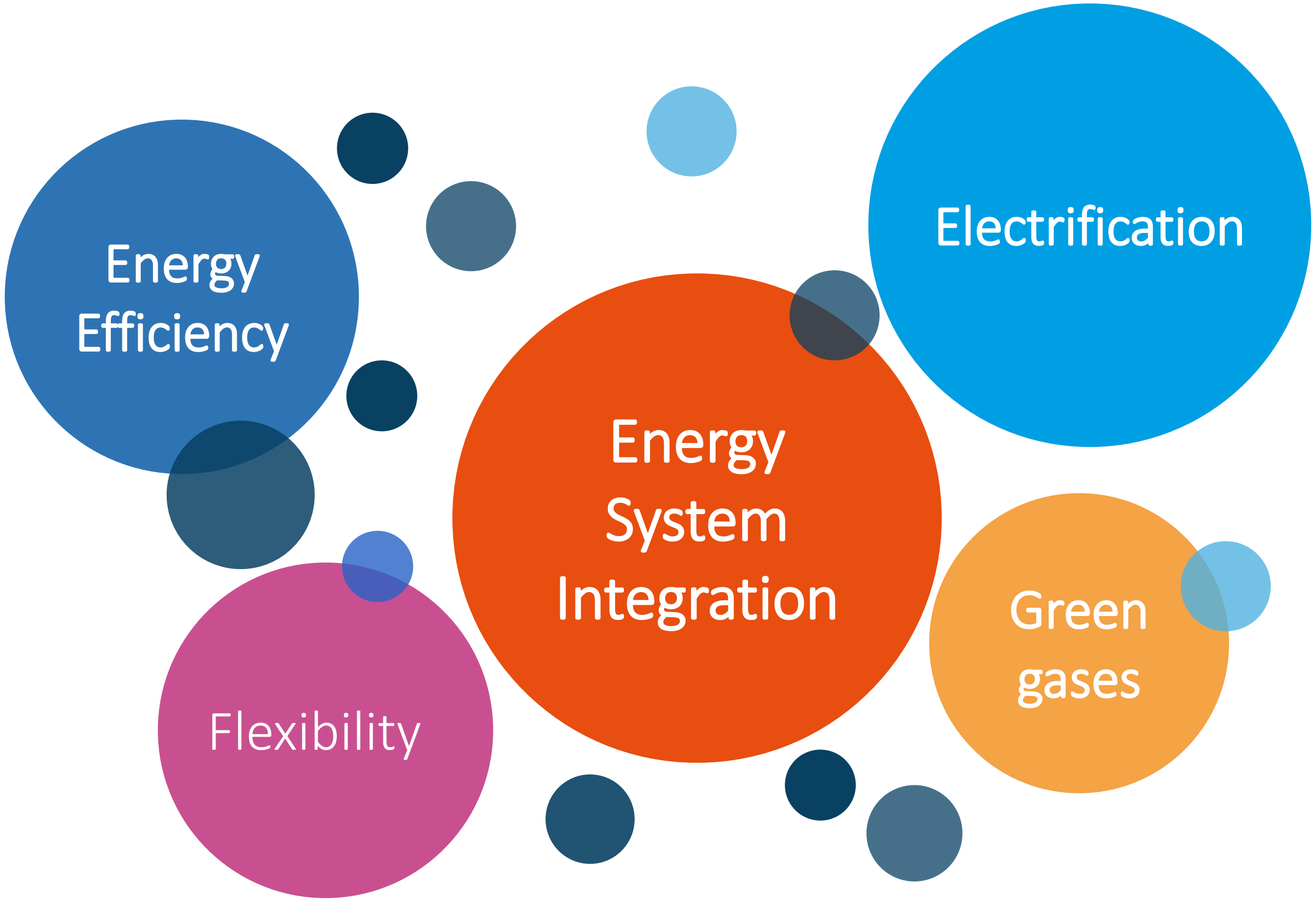
Context

- The **European Green Deal** aims to raise the EU decarbonisation ambitions, and to deliver a net-zero emissions economy by 2050, in a cost efficient and secure way.

- The **key enablers** of a net-zero economy include energy efficiency, energy system integration, as well as the direct and indirect electrification of a number of end-uses.

- Various **policy initiatives** are being taken to ensure the EU can achieve these objectives (e.g. Energy System Integration Strategy, Hydrogen Strategy, Renovation Wave, revision of EE/RES directives, etc.)



Core elements of a cost-effective net-zero emissions economy

Objectives of the study

BACKGROUND

Energy efficiency and energy systems integration are key to reaching carbon neutrality by 2050.

So far, EU scenarios have not fully captured the benefits of efficiently combining heat and power as an enabling solution to move to a net-zero integrated energy system.

This study pursues three objectives

1. Explore the **potential** of further integrating Europe's energy system in an efficient way to reach a carbon-neutral economy cost-efficiently
2. Assess the **role of cogeneration**, building on the EC's Long-Term Decarbonisation Strategy (LTS)
3. Provide **recommendations** to better reap the benefits of efficient and local system integration solutions in policy-making and modelling

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Artelys is a consulting and software edition company specialised in energy systems modelling and decision-support.

In this assignment, the **Artelys Crystal Super Grid** model has been used with European-wide integrated gas, heat and electricity scenarios, capturing key aspects of the energy transition, with a focus on sector integration.

Study content

OVERVIEW

The study proceeds in two steps:
first considering the point of view of a user, then the wider system

USER FOCUS

Identify Cost-competitive CHP Applications

Micro-economic assessment of heat generation solutions (with/without CHP) in different use-cases using various:

- Heat demand profiles
- Technologies
- Energy sources
- Archetypal countries

SYSTEM FOCUS

Explore CHP Benefits for the Energy System

Scenario-based assessment of 2050 European energy mix featuring:

- Benefits for the whole energy system; and
- Cost-optimal high efficiency CHP deployment across 1.5TECH* & Integrated Energy Systems (IES) decarbonisation pathways.

derived from the EC Long-Term Strategy 1.5TECH scenario and additional assumptions, referred to as 1.5TECH in this study for simplicity

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User focus: an analysis of various use-cases

Comparison between two configurations (with CHP, without CHP), in seven use-cases

- The use-cases cover applications in the **residential**, **industrial** and **district heating** sectors
- The different use-cases differ via their **heat demand profiles** and the **price of energy**
- The situation "without" CHP and the characteristics of the CHP are adapted to the end-use
- **Hourly simulations** are performed over one year in **3 EU archetypal countries** (ES, PL, SE)
- Key indicator: **cost of heat provision**

Use-case comparison

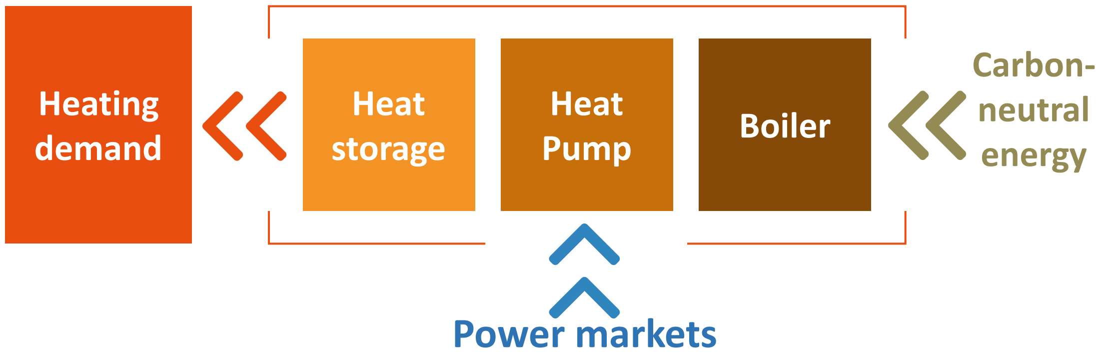
Without CHP (benchmark) *VS* With CHP

User focus: 7 different configurations

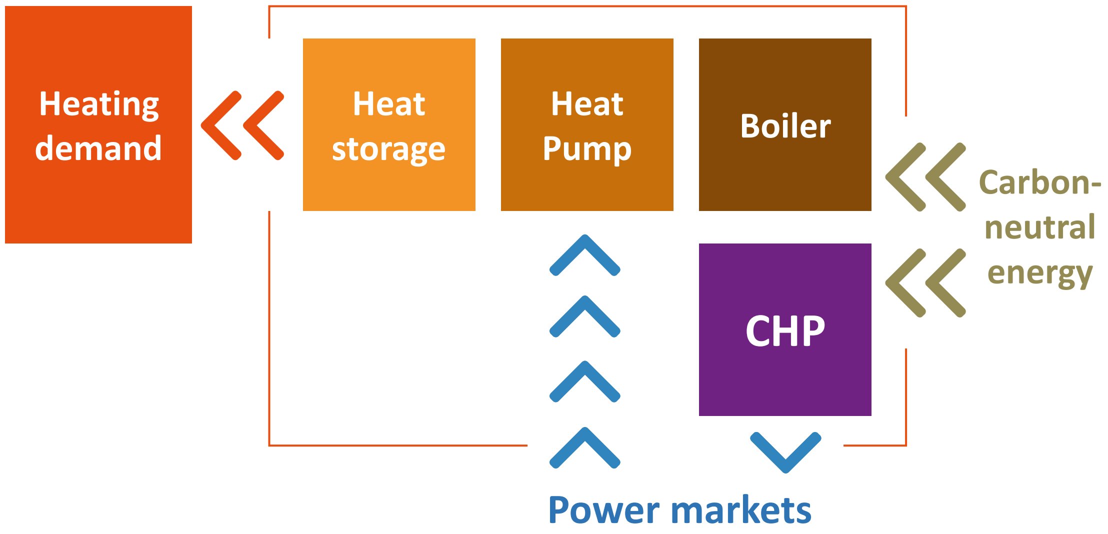
1	2	3	4	5	6	7
Fuel Cell mCHP for **residential power and heating** + heat storage and electric boiler	**Green gas engine CHP** for **hospital micro-grid** + **heat storage** and **gas boiler**	**Green gas engine** CHP for **district heating** + **heat storage** and **gas boiler**	**Green gas turbine** CHP for **district heating** + **heat storage**	**Green gas engine CHP** + **heat storage** for **medium-temperature industrial heat**	**Green gas turbine CHP** for **high-temperature industrial heat** + **power and thermal storage**	**Biomass fluidized bubbling bed CHP** for **industrial heat** and **municipal district heating**
Benchmark: Power markets (retail) – Heat Pump + heat storage + H2 boiler	**Benchmark**: Power markets – Heat Pump + heat storage + gas boiler			**Benchmark**: Power markets – Gas boiler		**Benchmark**: Power markets – Biomass boiler
Sensitivity analysis on H2 prices	**CHP operation :** Power-driven CHP, heat as side-product valuated as avoided heating costs from heating system (HP + heat storage + gas boiler)		**CHP operation :** Heat-driven, power as side-product consumed locally or injected on networks			
						Sensitivity analysis on fuel prices to cover different potential fuels (biomass, waste, etc.)

User focus: Modelling approach (2/2)

Benchmark configuration (example)



CHP configuration (example)



Levelised Cost Of Heat (LCOH)

$$\text{LCOH} = \frac{\text{CAPEX} + \text{OPEX}}{\text{heating demand}}$$

$$\text{LCOH} = \frac{\text{CAPEX} + \text{OPEX} - \textbf{Power sales revenues}}{\text{heating demand}}$$

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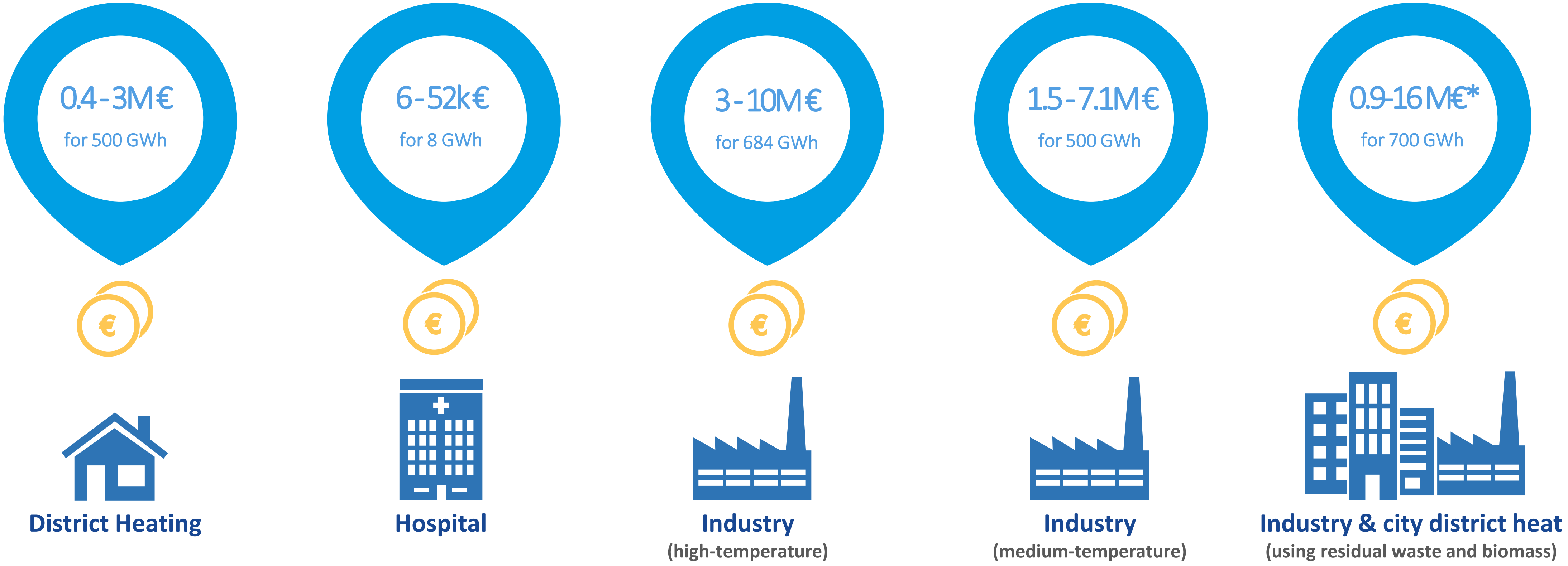
User benefits of CHP (1/2)

In almost all the considered use-cases, installing a CHP can be beneficial to the user from a cost perspective (excluding benefits from network tariffs and tax avoidance by own consumption)

The benefits can vary depending on the use-case, country, fuel prices, technology cost and characteristics.



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*This use-case depends strongly on biomass price, for this range prices between 40 and 60 €/MWh were considered

User benefits of CHP (2/2)

The benefits shown in the previous slide are **system-level** benefits that do not include additional benefits that end-users can capture: avoided **taxes/levies** and **network tariffs.**

When considering the entire consumer bill, CHPs can become even **more competitive** than alternative technologies, and in **more uses-cases**.

For example, **fuel cells** are found to be competitive in the residential sector from a final user point of view, in particular in countries that face high electricity prices in wintertime and high levels of taxes/tariffs.

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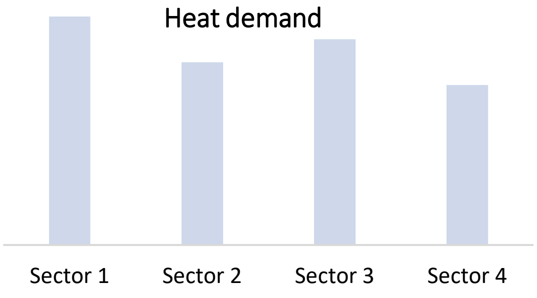
System focus: Methodology (1/3)

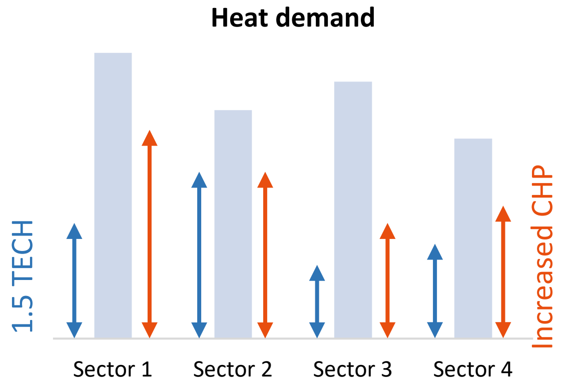
Scenario Definition

Configuration of the power and heat model in two scenarios

- Assumptions on **heat demand by sector** based on the LTS 1.5TECH scenario



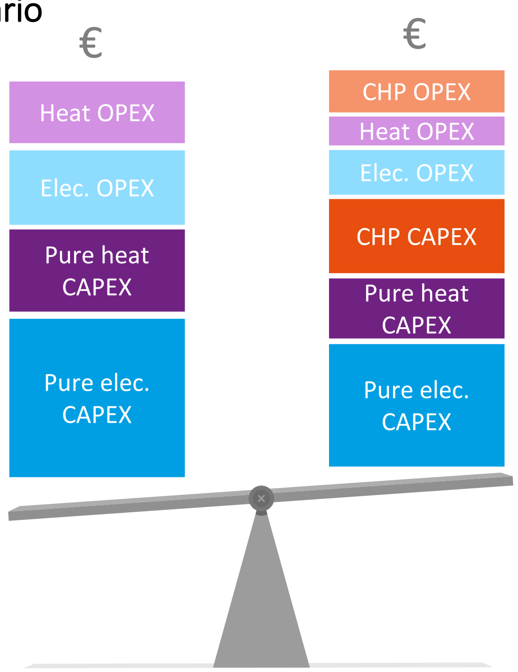
- Definition **of maximum heat demand** that can be supplied by CHP



Scenario Economic Optimisation

Economic optimisation of the heat and electricity generation from a systemic point of view

- Trade-off between investment costs and operational costs to optimise the **integrated** power and heat generation mix for **each scenario**

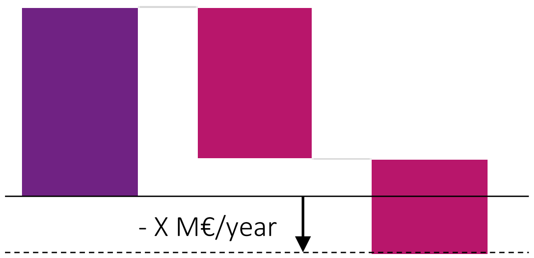


- CHPs are installed in each sector only when economical

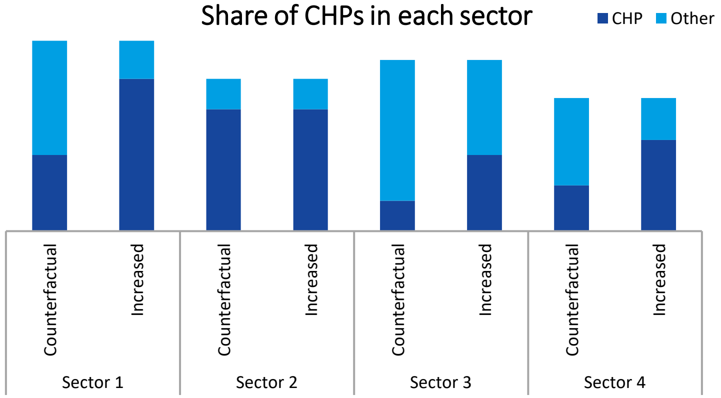
Scenario Result Comparison

Comparison of the costs and deployment of CHPs in both scenarios

- Conclusions at EU level in terms of deployment, costs, GHG emissions, etc.



- Sectoral analysis



System focus: Methodology (2/3)

Electricity generation assets are aggregated by technology for each country

Consumption is modelled by sector with advanced modelling of flexibility solutions (EVs, electricity and heat storage)

Supply and demand are balanced for heat and electricity at each node for each hour

Pan-European heat and power model in Artelys Crystal Super Grid

System focus: an analysis of optimal deployment (3/3)

European-wide integrated heat and power scenarios modelled in **Artelys Crystal Super Grid** based on the following characteristics of the **EC LTS 1.5TECH** scenario

- Energy consumption, heat supply in each sector, levels of energy efficiency and electrification
- Installed capacities of variable RES, hydropower and nuclear
- The rest of the electricity generation mix (biomass, biogas, natural gas, hydrogen) is optimised

The investments in heat and power generation and system operations are **jointly optimised** to meet 2050 energy demand

- Optimisation performed with **hourly time resolution** and **country granularity**, for EU27, Balkans, Switzerland, Norway and UK
- **Technical constraints** of each technology are taken into account: ramping rate, minimum generation for thermal fleets, seasonal hydro management, etc.
- **Reduction of grid losses** and **avoidance of network reinforcements** are implicitly considered in the efficiencies and capital costs of CHP technologies
- Optimisation of CHP deployment in sectors that are not electrified (i.e. the deployment of heat pumps is not optimised) to **minimise total system costs**

System focus: Scenarios

The analysis is performed from two starting points:

1.5TECH*

Energy system derived from EC LTS 1.5TECH scenario

Integrated Energy Systems (IES)

Higher shares of green gases, incl. P2X & H2, reflecting an increased focus on system integration

Economic Optimisation of Thermal Heat & Power (Optimised CHP)

More CHP installed compared to EC LTS 1.5TECH, resulting in a more efficient use of energy and reduced energy system costs.

CHP brings higher system benefits by efficiently replacing a large share of less-efficient non-CHP thermal generation in the energy mix.

CHP DEPLOYMENT POTENTIAL LOW → HIGH

Artelys' understanding and modelling of EC Long-Term Strategy 1.5 TECH scenario that combines all technologies and relies heavily on biomass and CCS, referred to as 1.5 TECH in this study for simplicity.

In total, 4 scenarios are compared:

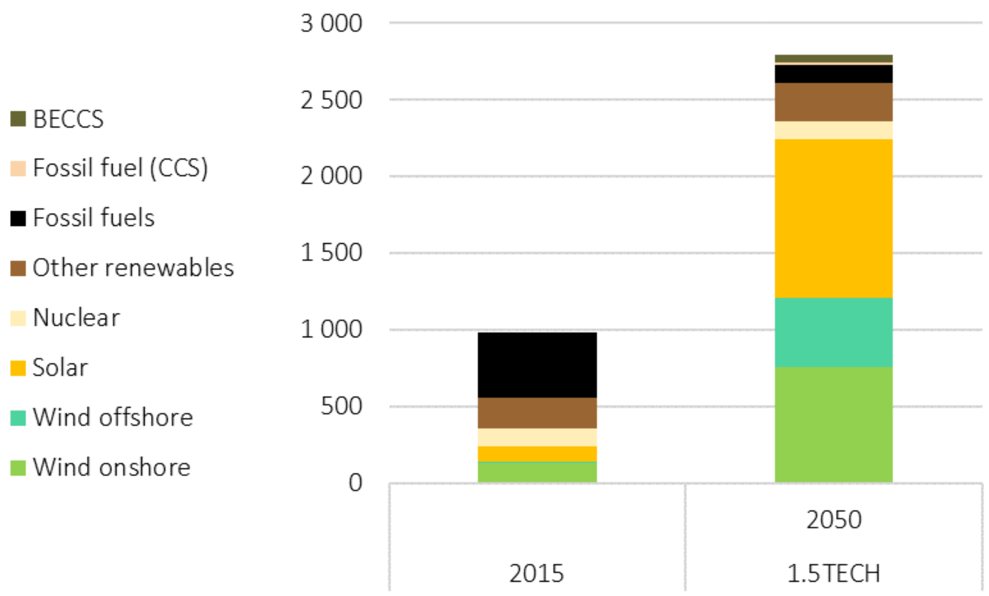
- 1.5TECH*: Baseline vs Optimised CHPs
- IES: Baseline vs Optimised CHPs

System focus: Overview of 1.5TECH

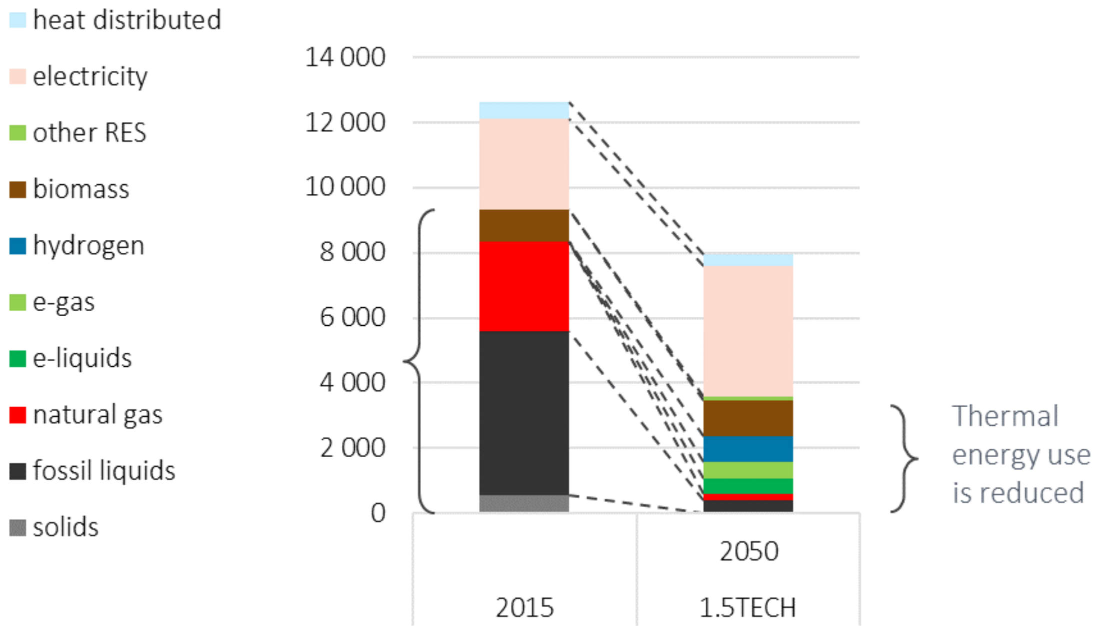
1.5TECH* relies on publicly available assumptions of the 1.5TECH scenario of the EC Long-Term Strategy (LTS)

- Between 2015 and 2050, the fossil fuel consumption reduces drastically as the role of electricity increases and bioenergy and e-fuels develop.
- The 1.5TECH scenario considers an **important system electrification**, especially of transport and heat, and **significant energy efficiency efforts** (high number of renovations, important technological improvements)

Power capacity mix - EU28 (GW)



Final energy consumption by energy carrier - EU28 (TWh)



Source: EU Long Term Strategy

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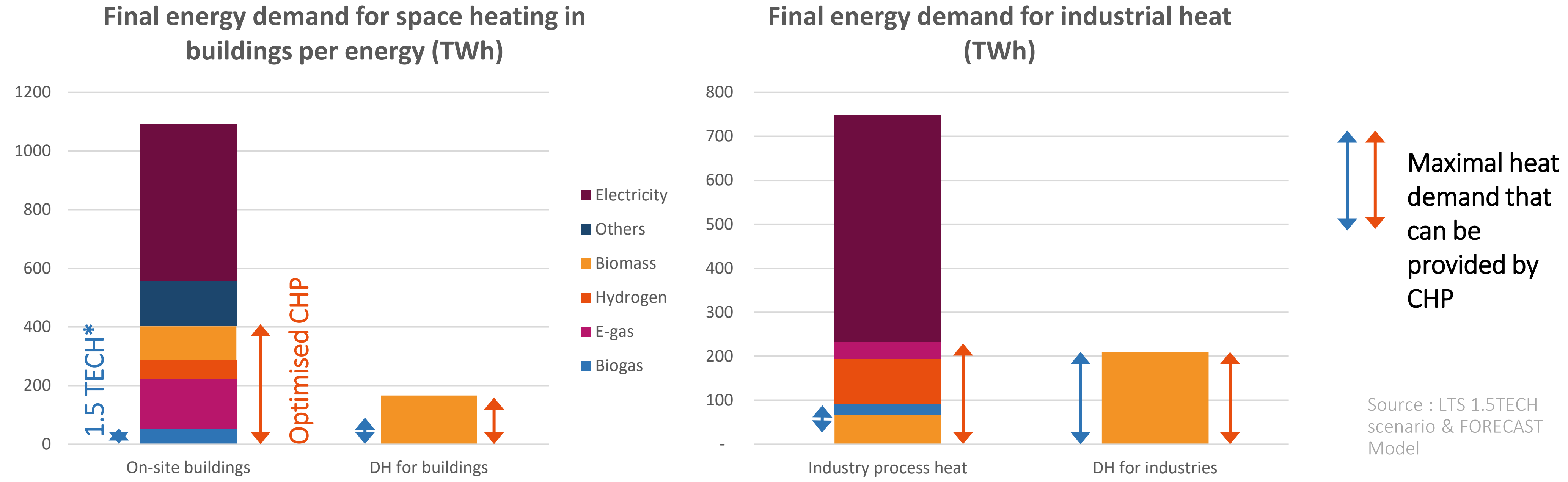
System focus: Heat sector assumptions

The heating sector is modelled jointly with the electricity system:

- 4 sectors are modelled: 1. district heating for industries, 2. district heating for buildings (residential/tertiary), 3. on-site heat generation for industries, 4. on-site heat generation in buildings (collective heat or individual heat)
- The share of each energy source in each sector is an input from the 1.5TECH scenario
- The generation of heat in each sector is optimized between CHP and separated heat generation with a limitation on the maximal share for CHP*.
- Waste heat recovery on industrial furnaces for electricity generation is also optimised.



Source : LTS 1.5TECH scenario & FORECAST Model

* We consider that in any case, the separated heat generation remains in the heat generation mix. CHP is installed only if its energy savings (in both systems) offsets its additional investment costs.

System focus: Integrated Energy Systems scenario variant

In addition to the **1.5 TECH*** scenario, the **Integrated Energy System (IES) scenario variant** was designed to account for the emerging systems integration paradigm.

Key features:

- An increase of the share of thermal generation (biomass, biogas+, syngas, or natural gas with CCS).
- A steady nuclear capacity installation rate comparable to current nuclear increase rate (based on the 1990-2020 period), resulting in a capacity of 50 GW in 2050, compared to the 120 GW in EU in the **1.5TECH*** scenario (-58%)
- A larger share of biogas-based heat demand in **DH for buildings**, in line with increased biogas-based power generation.
- Demand levels, electrification rates and share of variable RES is maintained as in **1.5TECH***
- Like 1.5TECH, it meets a net-zero emissions objective

+ Biogas uptake is increased so that natural gas consumption is the same in both scenarios

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CHP multiple benefits for net-zero in 2050

€4-8 Bn

Costs for energy system

150–220 TWh

Primary energy savings across the energy system

4-5 MtCO2

Reduction of CO2 emissions

13-16%* of total electricity

and **30-36% of flexible thermally generated power** to complement variable RES and to cover peak demand

19-27% of total heat**

and **52-100***% of thermal heat** in buildings, industry & district heating

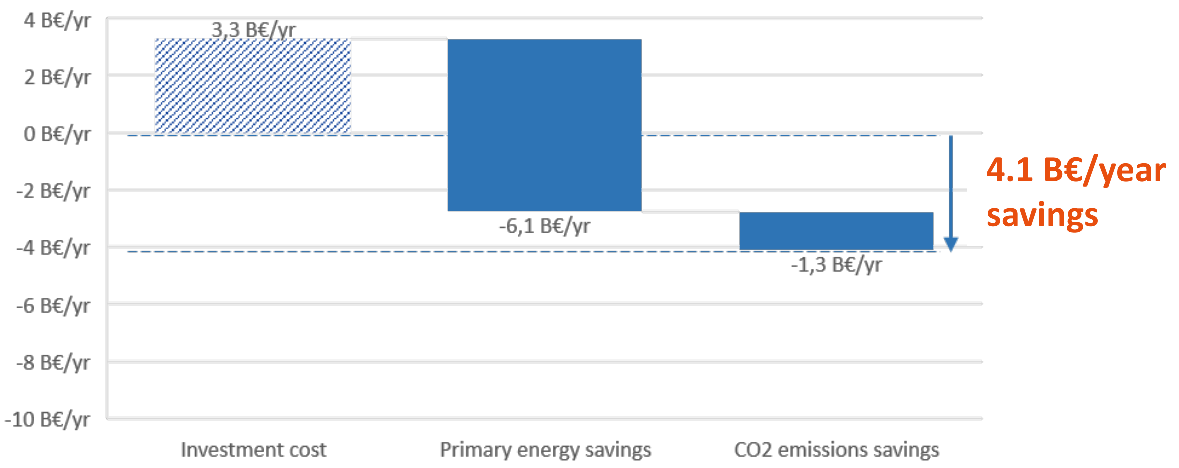
* excluding offgrid RES for P2X generation
** excluding furnaces.
*** excluding furnaces; DHC for industry is 100% CHP.

Energy system savings

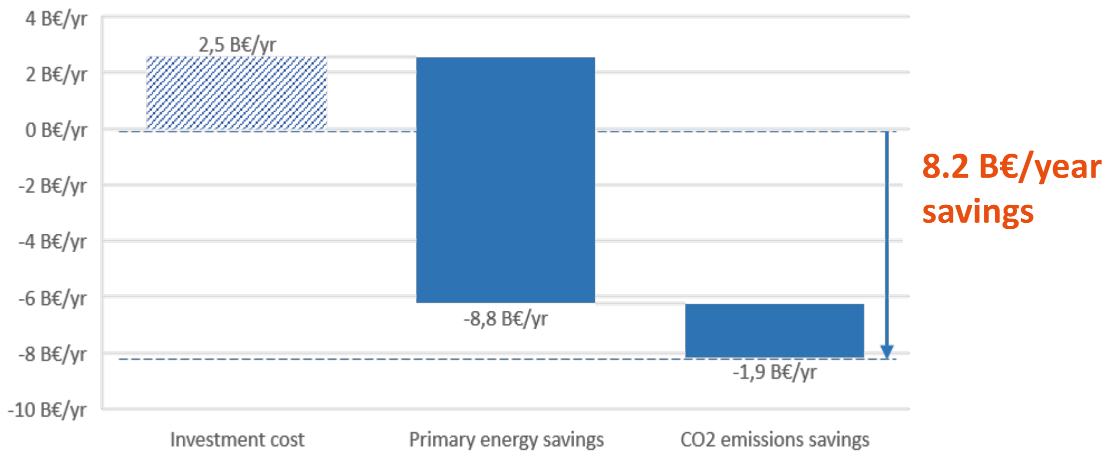
The additional capital cost in CHPs is more than compensated for by energy and CO_2 savings at the European level:

- The addition of CHP in the system reduce system costs by **4.1 - 8.2 B€/year overall at EU level**

Optimised CHP savings for 1.5 TECH* scenario



Optimised CHP savings for IES scenario variant

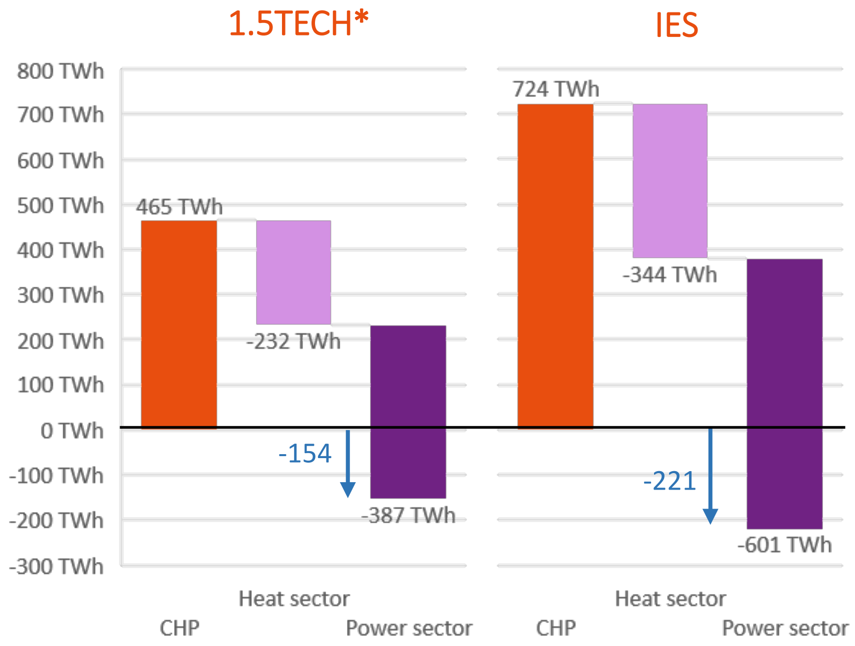


Primary energy savings

Increasing the CHP share in all sectors leads to a reduction of primary energy consumption at system level:

- Reduction of the generation of electricity from natural gas-fired units thanks to a better use of fuels
- Primary energy use is reduced by **154 - 221 TWh per year**

Primary energy consumption in CHP vs. savings in separate heat and power generation



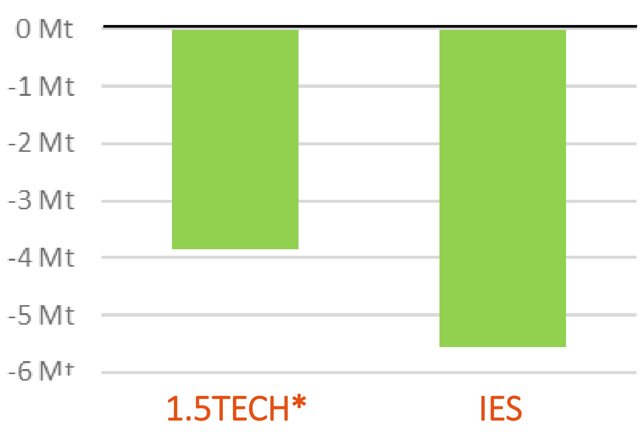
Breakdown of primary energy supply difference between « baseline » and « optimised CHP » for 1.5TECH*

CO2 emissions savings

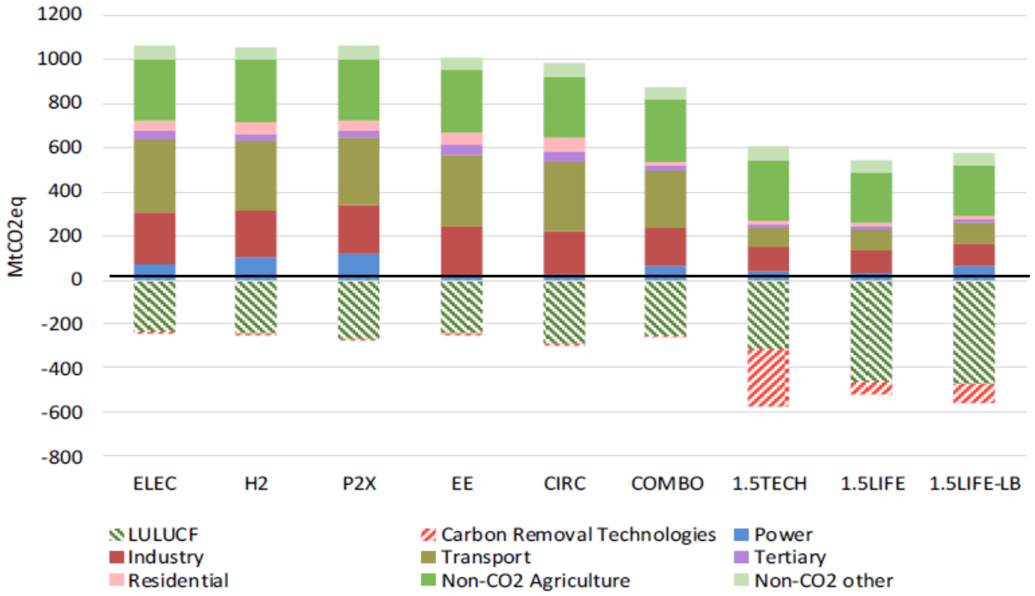
Installing CHPs in all sectors leads to an overall CO2 emissions reduction:

- 3.8 – 5.5 Mt of CO2 emissions saved annually thanks to the reduced use of natural gas in CCS plants (assuming a 90% CO2 capture rate)
- In comparison (on the right), 600 Mt eq-CO2 are emitted and captured (either with CCS or natural sinks) in the LTS 1.5TECH scenario, with net emissions of 26 Mt CO2.
- Potential to reduce circa one fifth of the remaining 26 Mt CO2 emissions in 2050

Effect of optimising CHP uptake on CO2 emission savings



Sectoral emissions by 2050 in LTS pathways



Source: PRIMES-GAINS-GLOBIOM.

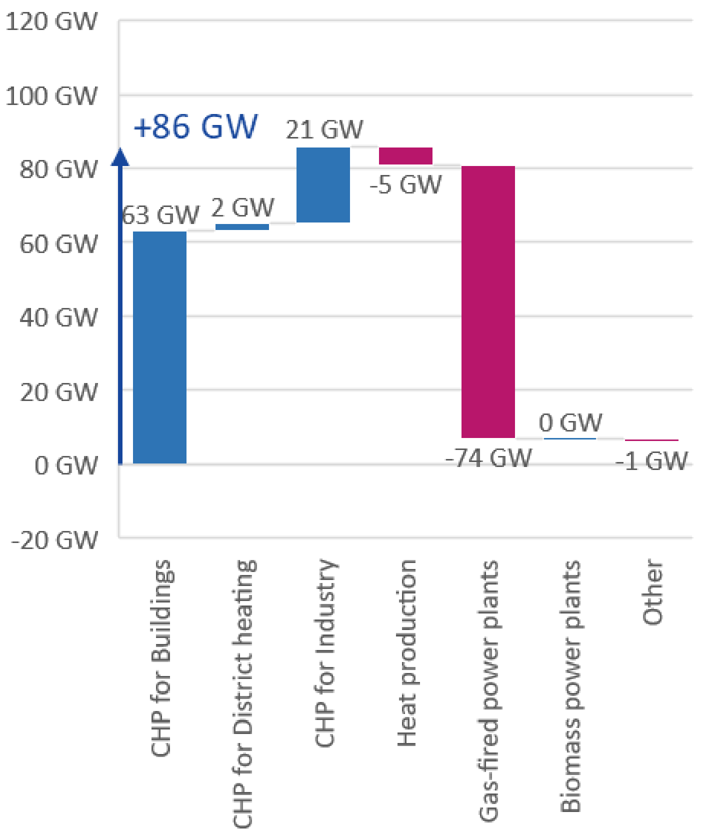
Investment comparison

Overall, **86 – 96 GW of CHP capacity** is added to the mix compared to the 1.5 TECH* scenario:

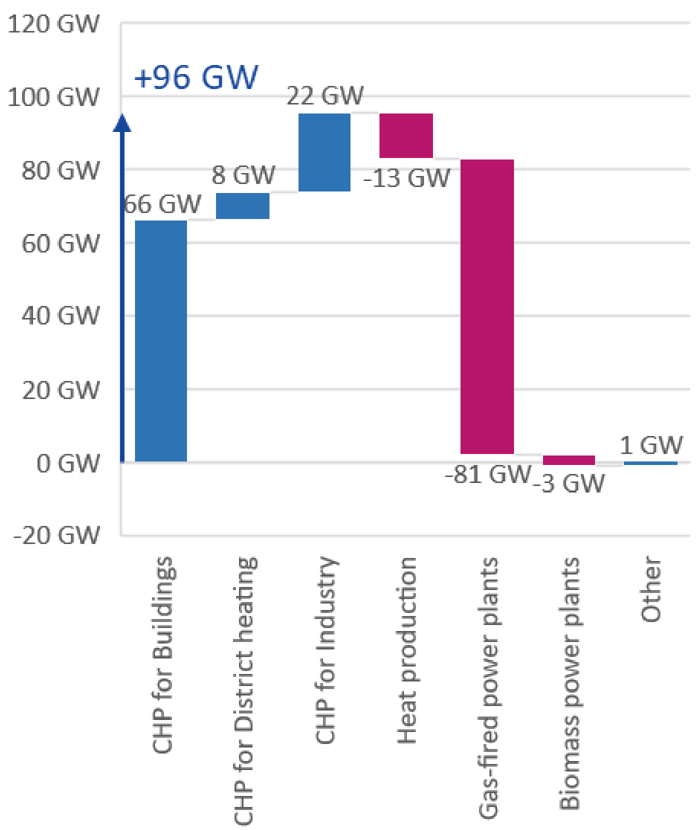
- Adding CHP helps replacing investments in gas-fired boilers and electricity-only generation capacity, which, in combination, are less efficient and more CO_2 intensive.
- The additional investment costs in optimised CHP scenarios (2.5-3.3 B€) are compensated for by the primary energy savings and CO_2 emissions reduction.

Change in installed capacities between "Baseline" and "Optimised CHP scenarios"

1.5TECH* scenario



IES scenario variant

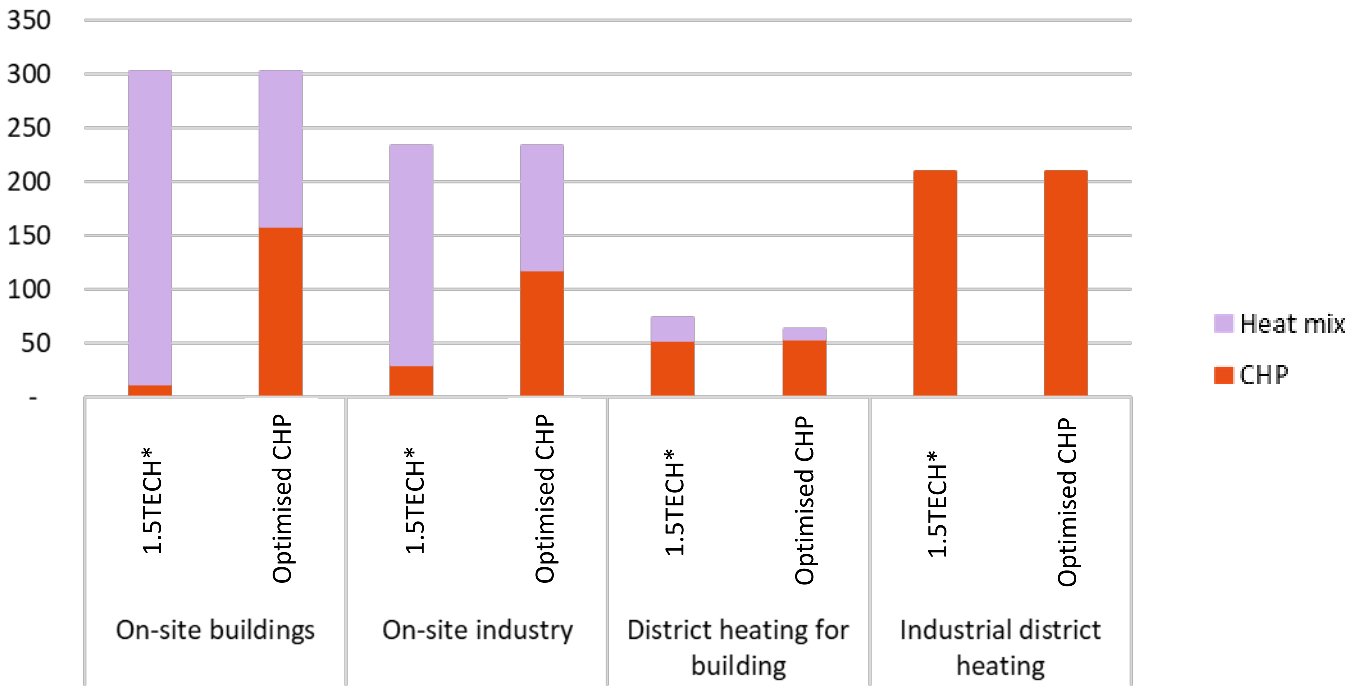


CHP generation by sector (1.5TECH*)

The optimisation of the power and heat generation mix leads to an increase of the share of CHP in thermal heat generation in all sectors :

- The system sees value in increasing the share of CHP in the heat generation : **+ 236 TWh of heat covered by CHP**
- CHP are installed in all sectors. They deliver more than 40% of fuel-based heat demand in most sectors, corresponding to 541 TWh of heat supply.

Thermal heat production by sector (TWh) – 1.5TECH*



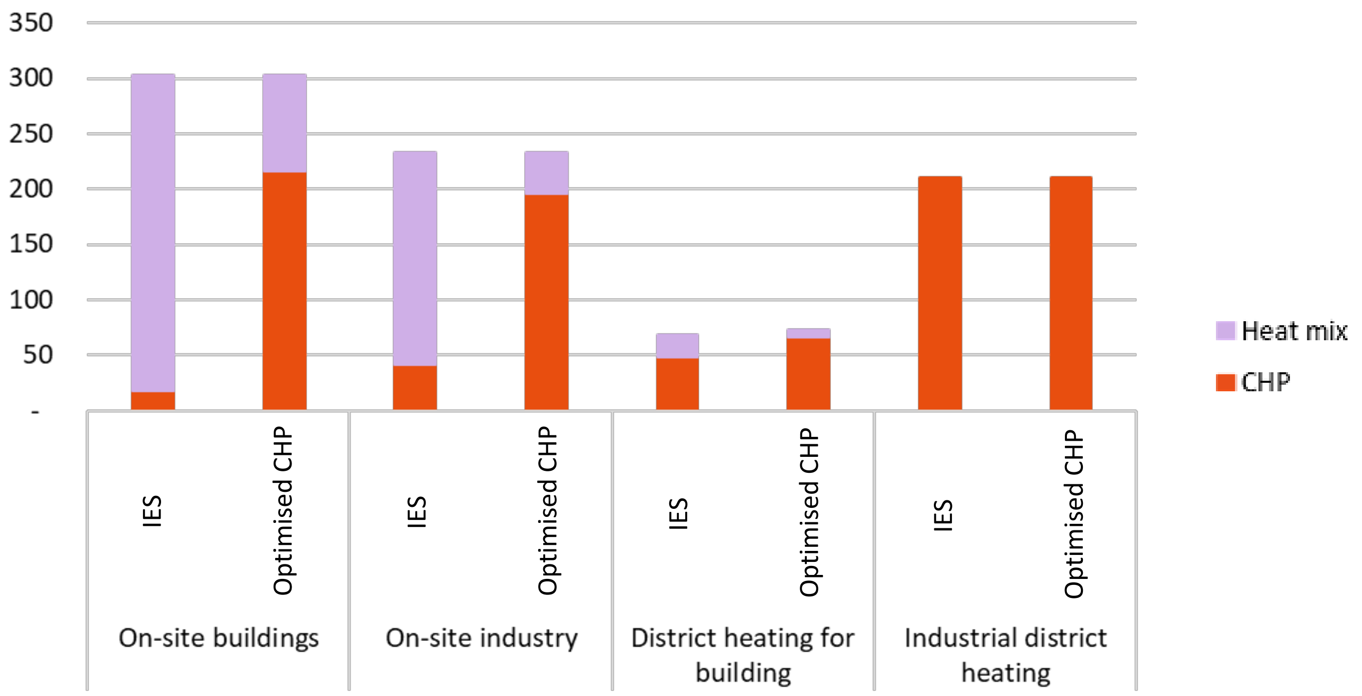
CHP generation by sector (IES)

In the IES scenario, the uptake is even higher, given the larger role of thermal technologies in both heat and power.

- CHP share of thermal heat reaches

81% in industries **and** **70%** in buildings

Thermal heat production by sector (TWh) – IES



CHP operations combine flexibility & efficiency

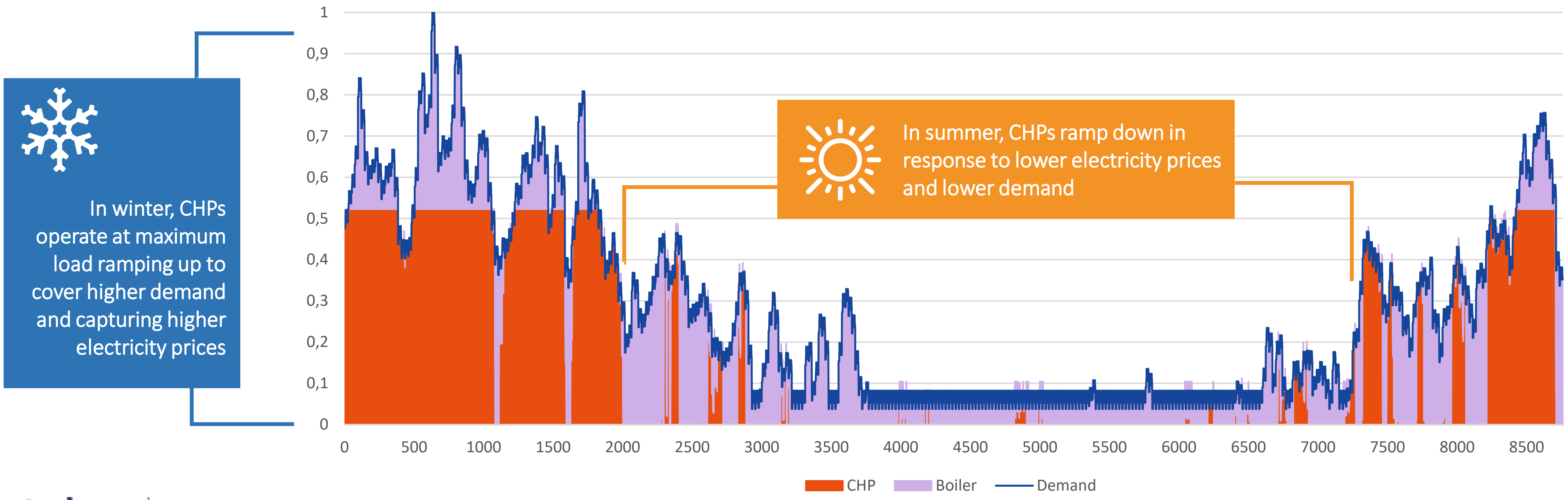
In 1.5TECH, the heat demand is electrified by between 34% and 70% depending on the sector.

Optimised CHP can contribute by 50 to 100% to the supply of the the heat demand that cannot be electrified.

In **summer**, back-up boilers are used because electricity prices are low and fuel-based power generation is not often required (nuclear and RES generation are sufficient to cover the demand for most hours)

In **winter**, CHPs can operate at maximum load, complemented by boilers to cover peak demand

CHP hourly operation – example for a thermosensitive heat demand (district heat for buildings)

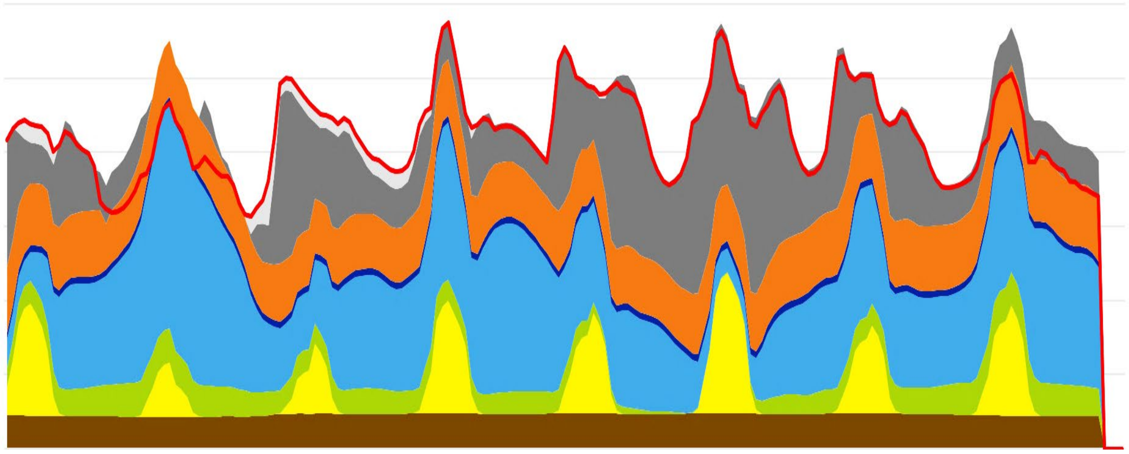


Focus on power: CHP flexibility benefits (1/2)

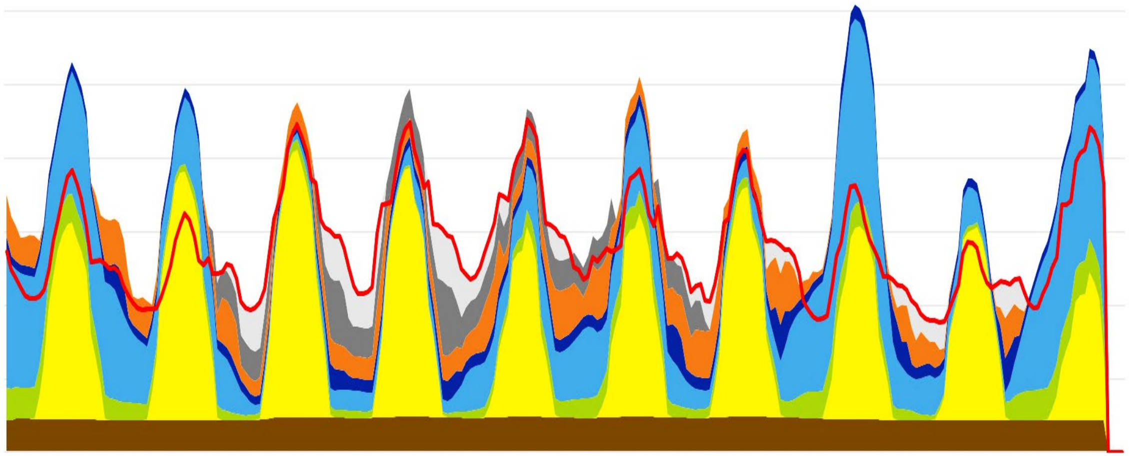
The dynamic operational management of CHPs is simulated with Artelys Crystal Super Grid. CHPs adopt a virtuous behaviour by only generating when it is cost-effective for the joint electricity and heat system.

In particular, CHPs, with a flexible price-driven operational mode, do not compete with, but **complements** variable renewable generation to meet seasonal peak demand due to high shares of electrified heat.

WINTER



SUMMER



CHPs (orange) run as base load during low wind and sun periods, covering a high share of the peak demand.

CHP stops producing when variable renewable generation is sufficient to cover demand, and covers evening peaks.

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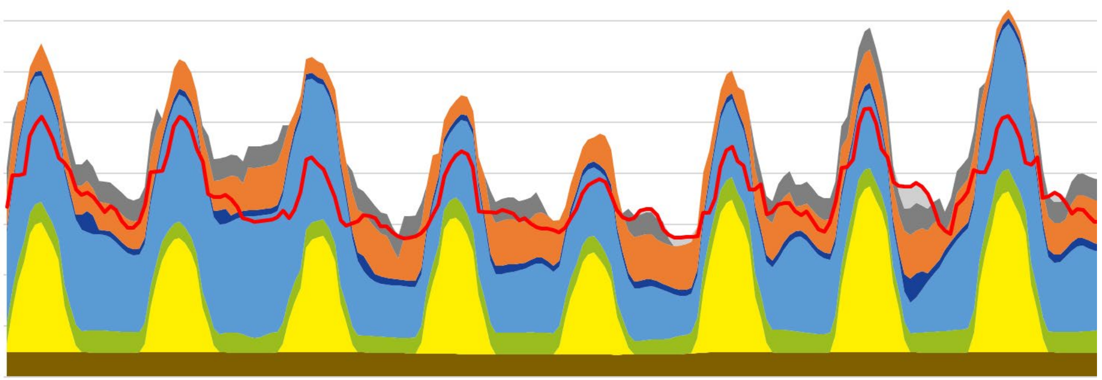
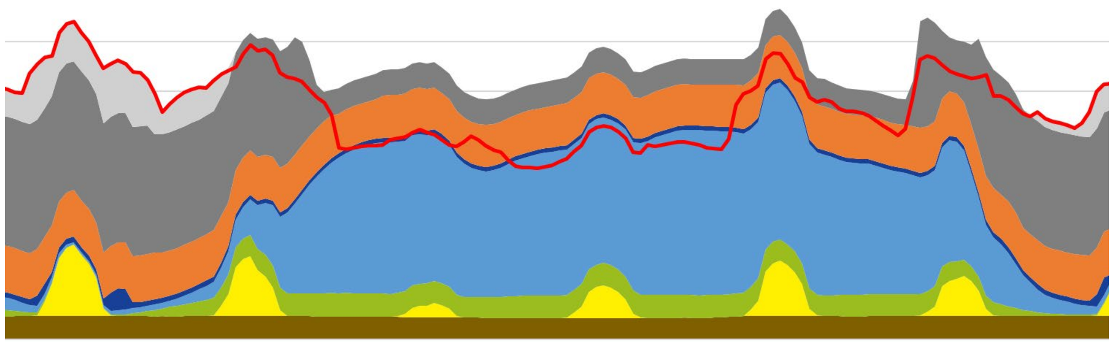
Focus on power: CHP flexibility benefits (2/2)

MID SEASON HIGH WIND



CHPs function most of the time but reduce generation when solar production increases

WINTER WITH HIGH WIND



Peakers (grey) reduce their generation in the high wind period, while CHP continue producing

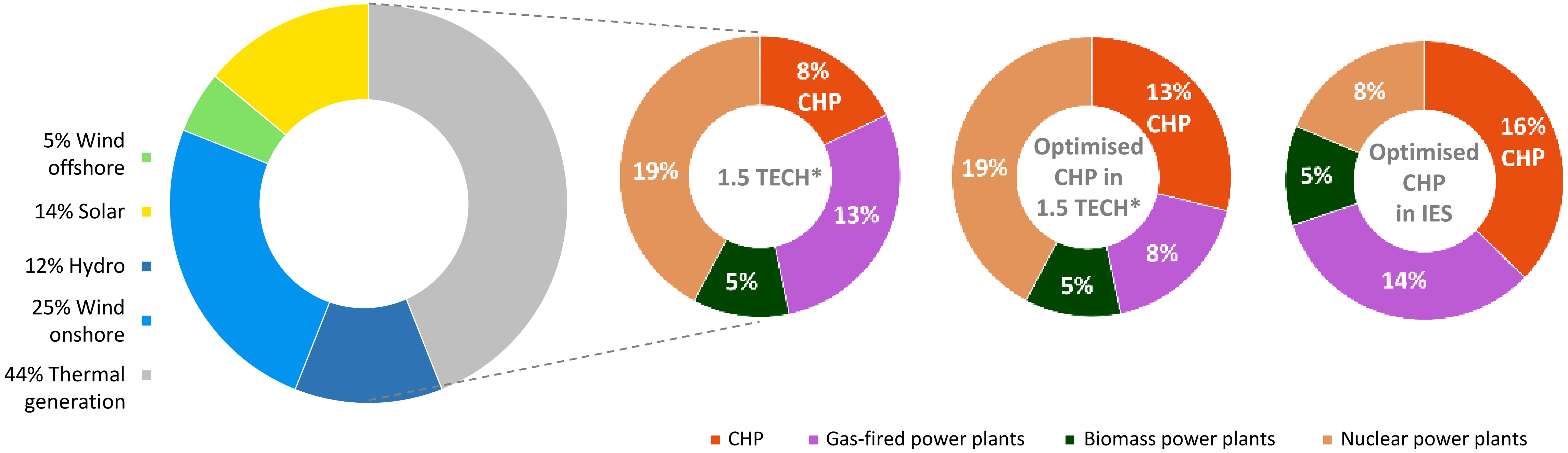
RES baseload | PV | Wind offshore | Wind onshore | Hydro | CHP | Demand | Peakers | Batteries | Transmissions | Loss of load

Focus on power: Generation by technology

Optimising CHP production results in an increase of its share in thermal generation from **18% in 1.5 TECH*** to **30%-36% in Optimised CHP (equivalent to 13-16% of total power generation)***

This leads to:

- a reduction of non-CHP, less efficient and more polluting thermal electricity generation.
- more efficiently using available renewable gases, not requiring additional gas production (notably e-gas).



* In the simulations, in order to match the results of production by technology of the Long Term Strategy, the assumption is made that a large share of offshore wind, onshore wind and PV are connected to P2G installations and do not participate into the electricity market.

Optimal CHP deployment

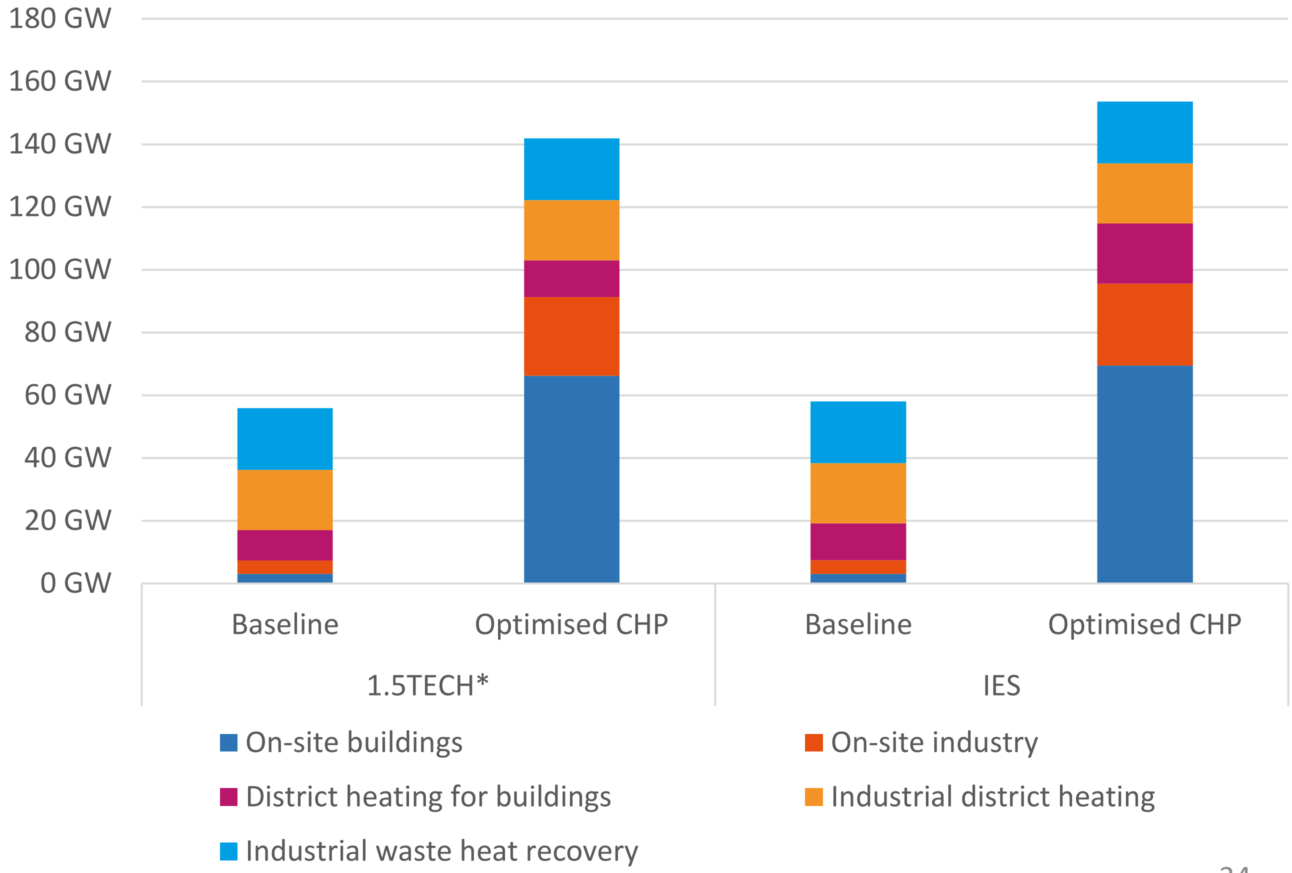
Optimising CHP leads to a total CHP capacity of **142 – 154 GWe** in the 1.5TECH* & IES scenarios respectively, compared to 117 GWe in 2018 and 56 GWe in the 1.5 TECH scenario.

- **On-site building and industry** account for the **largest potential** for further CHP deployment.

- **Further CHP uptake to supply DHC for buildings is identified as cost-effective beyond 1.5 TECH***

- From a system point of view, **investing in industrial waste heat recovery is cost-effective** in all scenarios.

CHP capacity per sector



Focus on heat: CHP delivering efficient heat

ALL SECTORS IN THE EU		TOTAL HEAT	THERMAL HEAT
Buildings	• Micro-CHP empowering householders • In a mix with electric & district heating • Key technologies: fuel cells & engines	26%	52%
Industry & SMEs	• CHP boosting competitiveness • Delivering medium and high temperature heat on-site or via DHC • Optimising waste heat recovery • Key technologies: engines, turbines & fuel cells	26%*	84%**
Cities	• CHP supplying local and affordable heat • Complementing waste heat & heat pumps • Key technologies: engines & turbines	40%	91%

*excluding furnaces.
** excluding furnaces; DHC for industry is 100% CHP.

Recap of key figures

154 – 221 TWh

PRIMARY ENERGY SAVINGS

OR

2.5 x annual electricity consumption of Belgium*

3.8 – 5.5Mt

AVOIDED CO_2 EMISSIONS

OR

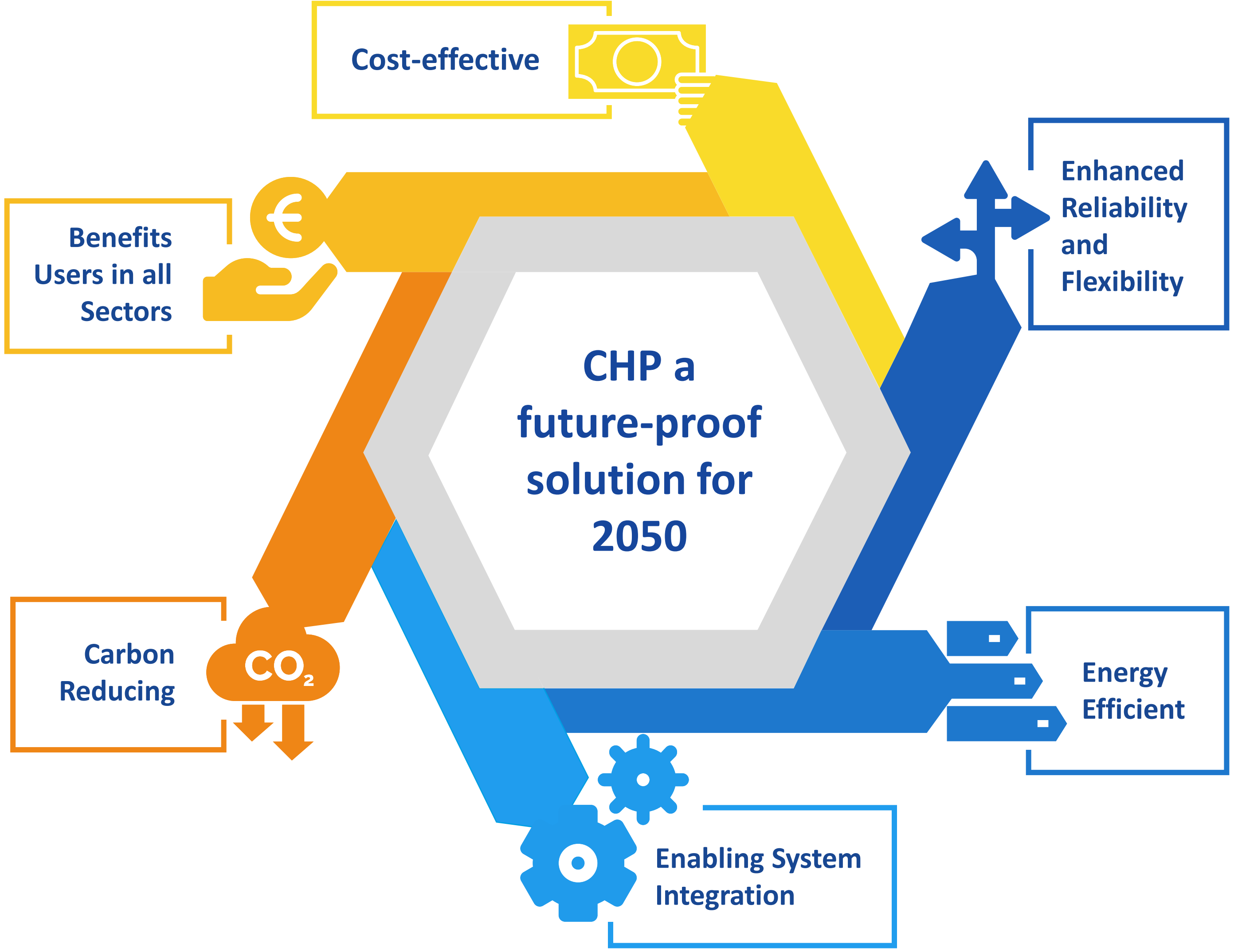
The annual CO2 emission of 3 million petrol cars

4.1 – 8.2 Bn €

SAVED YEARLY

OR

9.5x of LIFE Climate Action Funding



** IEA 2019 statistics*

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2. User focus
   - Methodology & key assumptions
   - Key results
3. System focus
   - Methodology & key assumptions
   - Key results
4. **Key conclusions & recommendations**

Key findings

CHP is found to be an efficient enabler for reaching carbon neutrality by 2050

- There is **cost-effective potential for further CHP deployment** to support a highly electrified and low demand energy system compared to 1.5 TECH LTS scenario.
- In a **scenario with a higher uptake of bioenergy sources**, CHP uptake is even more relevant, fostering the efficient use of these fuels.

Optimised CHP deployment leads to a **system cost reduction of 4.1-8.2 B€** compared with a solution with a lower CHP deployment, and allows to **reduce CO_2 emissions by 4-5 $MtCO_2$** annually

CHP can displace less efficient power-only and heat-only generation technologies, up to **30-36% of thermal power** and **50-100% of thermal heat production** in 2050

CHP can be optimised to **maximise system energy/resource efficiency and flexibility**, complementing high variable RES electricity generation technologies

CHP is relevant in all sectors of the economy: buildings and industry either on-site or when connected to district heating

Identified barriers to CHP efficient deployment

This study demonstrates the **benefits of CHP uptake beyond what is considered in the European Commission's Long-Term Strategy in 2050**, in different carbon neutral scenarios, at both user- and system-levels, across different geographies and in all sectors.

The barriers that may prevent the cost-competitive potential for CHPs to materialise in 2050 include:

- The market structure and the national/European regulatory context do not necessarily allow CHP to capture the all value they bring to the heat and power systems (which impacts distribution, generation and capacity).
- The revenues CHP can get scattered across different markets, some of which being country-specific
- Taxes and tariffs may not always provide the appropriate price signals to projects that are cost-effective from a system point of view.
- In many cases, the value CHP brings to networks (avoidance of electricity network reinforcement costs) cannot be captured by the CHP owner
- While CHP production contribute to peak load, they do not necessarily get a capacity remuneration (contribution to reducing the needs for peak capacity)

Recommendations on modelling

The study shows that a refined modelling of electricity-heat interlinkages is essential to assess the **cost-effective potential for CHPs**, in the context of the EU Green Deal in highly decarbonised contexts.

In particular, several recommendations emerge from this study:

- Prospective studies should **simultaneously** consider the **power system** and **heat sector** with an adequate level of detail
- **CHP operation** should be modelled to **complement renewable variable generation** by adopting a cost-efficient operational management approach. Market models such as METIS could be used for this purpose.
- **Heat consumption** should be modelled with **sufficient detail in each country**, by heat sector (buildings, industrial, district heat) and heat temperature levels
- The **diversity of heat supply solutions** should be accounted for in each sector. The use cases studied highlight many relevant applications for CHPs with a large range of fuels in the different sectors.
- Studies and modelling exercises should aim at capturing the benefits of distributed electricity generation in terms of **avoided distribution network reinforcement costs and avoided electricity losses**.

Thank you for your attention

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Annex 1:

CHP technology survey outcome

1

User focus: CHP technology survey

- Identifies **existing and upcoming CHP technologies** considering different
  - **carbon-neutral fuels**
  - **applications** (industry, district heating networks, decentralised heating in buildings)
- Describes the main **techno-economic parameters** for each technology and their likely evolution until **2050**
  - Parameters compared across different sources
  - Technology comparison for similar applications
  - Integration of feedback from CHP industry
- Survey outcome available in the annexes

Key parameters covered

- Capital expenditures (CAPEX)
- Operational expenditures (OPEX)
- Lifetime
- Conversion efficiency
- Heat-power ratio
- Heat output temperature
- Start-up time / ramping gradients

CHP technologies covered

- Open cycle turbines
  - Gas turbines
  - Steam turbines
- Combined cycle
- Engines
- Organic Rankine Cycle
- Fuel cells
  - PEM
  - SOFC

CHP technology survey: Sources

- Covered sources (non-exhaustive list)
  - **JRC (2018):** Cost development of low carbon energy technologies
  - **Asset project (2018):** Technology pathways in decarbonisation scenarios
  - **Artelys (2018):** METIS study S9
  - **JRC (2017) - Large:** Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU
  - **JRC (2017) - Small:** Techno-economic projections until 2050 for smaller heating and cooling technologies in the residential and tertiary sectors in the EU
  - **Roland Berger (2015):** Advancing Europe's energy systems: Stationary fuel cells in distributed generation
  - **Energy Brainpool:** study *Flexibility needs and options for Europe's future electricity system*
  - **Imperial College**: Benefits of Widespread Deployment of Fuel Cell Micro CHP
  - **Manufacturers** documentation (Eugine, Wartsila, GE)

  Used as data sources in this study

  - Mollenhauer et al. (2016): Evaluation of combined heat and power plants
  - Al Moussawi (2016): Review of tri-generation technologies
  - Elmer et al. (2012): State of the Art Review: Fuel Cell Technologies in the Domestic […]
  - Thilak Raj (2011): A review of renewable energy based cogeneration technologies
  - National technical university of Athens (2016): Long term prospects of CHP

CHP technology survey: Main parameters

- The most exhaustive source is the **Long-term projection from the JRC (JRC – Large, 2017).**
- The other sources provide partial information and deal with a limited range of technologies and fuels

	JRC 2018	ASSET 2018	JRC – Large 2017	JRC Small 2017	Roland Berger 2015
CAPEX	Steam turbines, ORC, Gasification	Fuel cells, Gas engines, µCC Turbines OC turbines	Steam turbines, OC/CC Turbines, Gas engines, ORC, Fuel cells	Gas engines, Fuel cells	Fuel cells
OPEX	Steam turbines, ORC, Gasification	OC Turbines	Steam turbines, OC/CC Turbines, Gas engine, ORC, Fuel cells	Gas engines, Fuel cells	
Lifespan		OC Turbines	Steam turbines, OC/CC Turbines, Gas engine, ORC, Fuel cells	Fuel cells	Fuel cells
Efficiency		Fuel cells, Gas engines, µCC Turbines	Steam turbines, OC/CC Turbines, Gas engine, ORC, Fuel cells	Gas engines, Fuel cells	Fuel cells
Power:heat ratio			Steam turbines, OC/CC Turbines, Gas engine, ORC, Fuel cells		

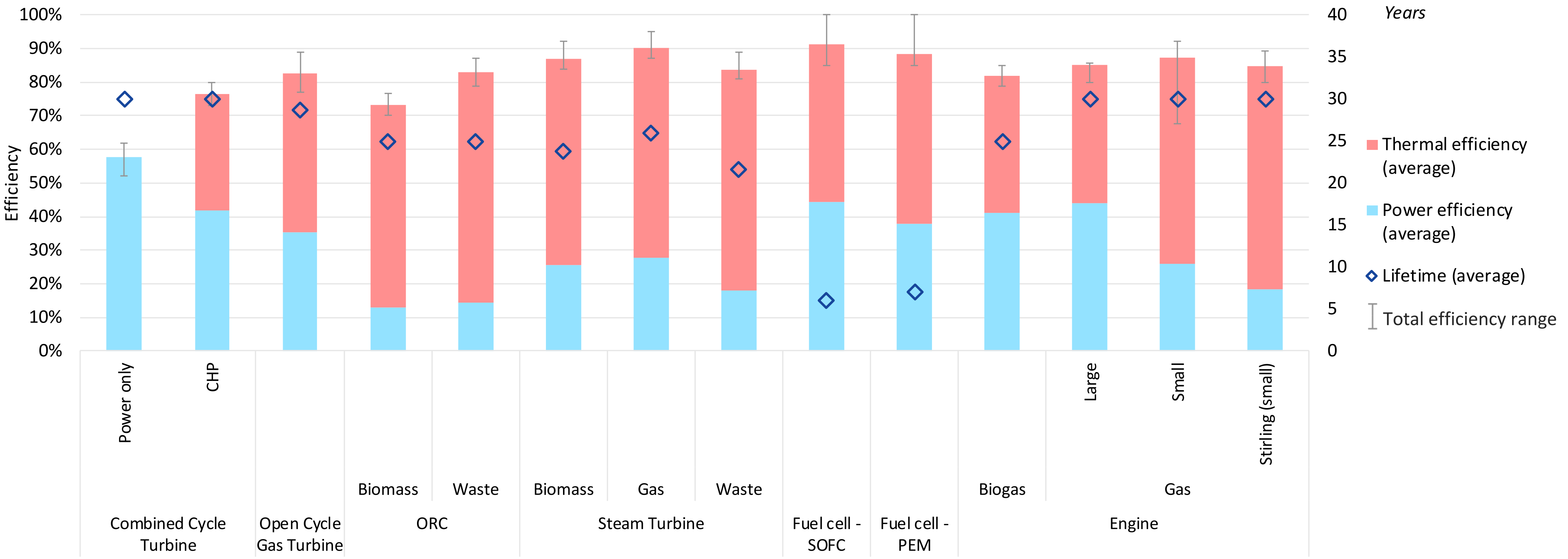
Decentralized heating application size

District heating & Industrial steam application size

CHP technology survey: current technology performance

- Gas turbines, combined cycles and gas engines currently are the prevalent technologies for industrial CHP

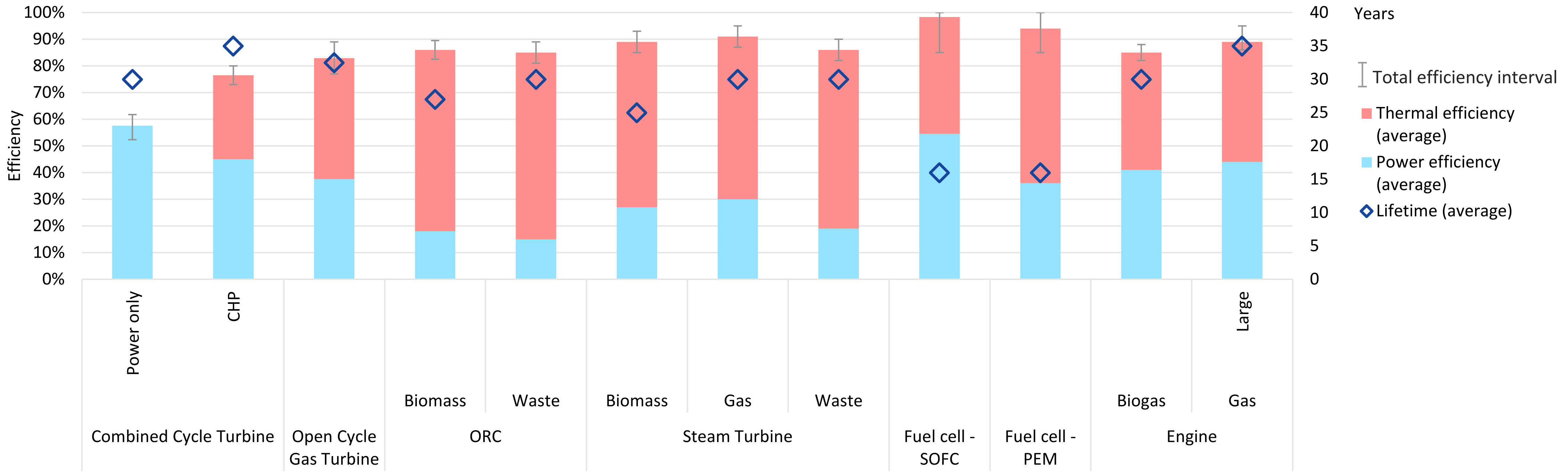
Averaged values for real systems based on public sources reviewed



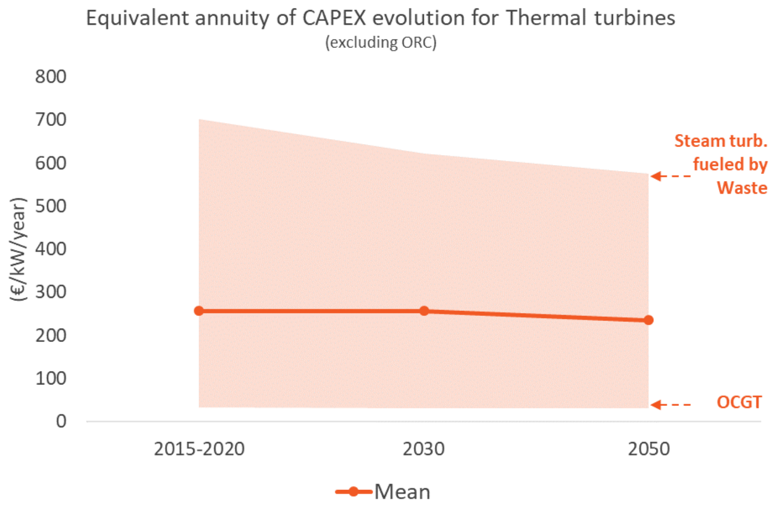
CHP Technology Performance in 2050

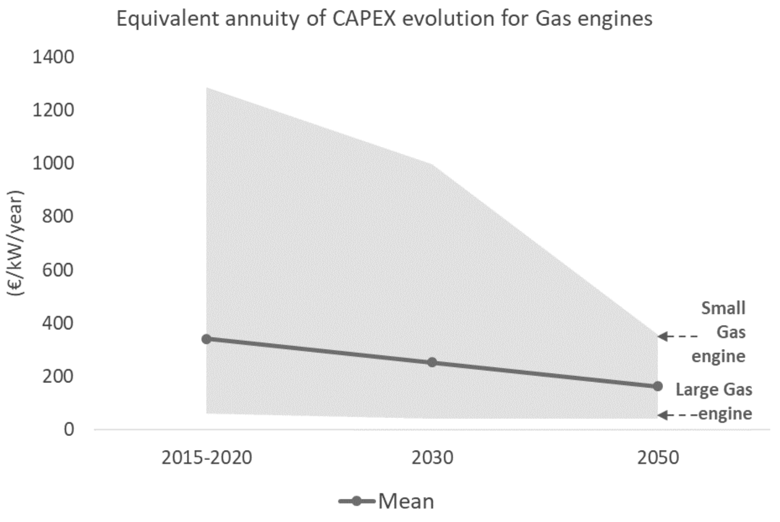
- **Electrical efficiency is expected to increase** (especially for gas engine/turbines and fuel cell).
- **Total efficiency is likely to remain stable**
- **Lifetime is expected to increase** by 5 to 10 years for most technologies

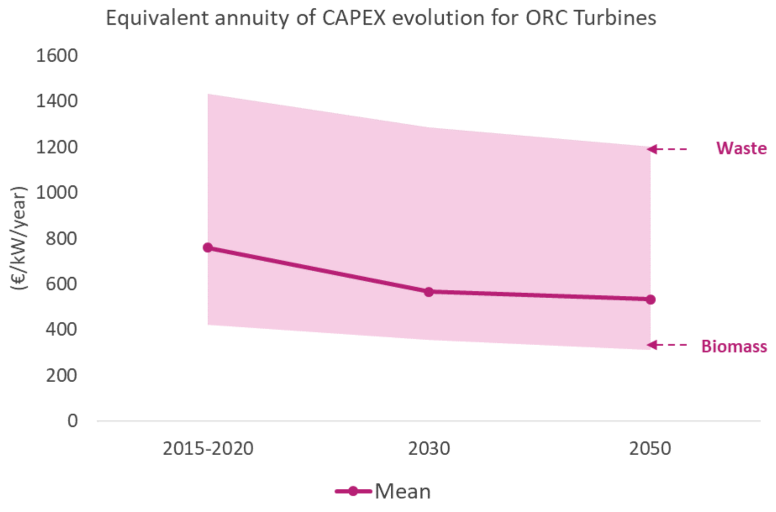
Averaged values for real systems based on public sources reviewed

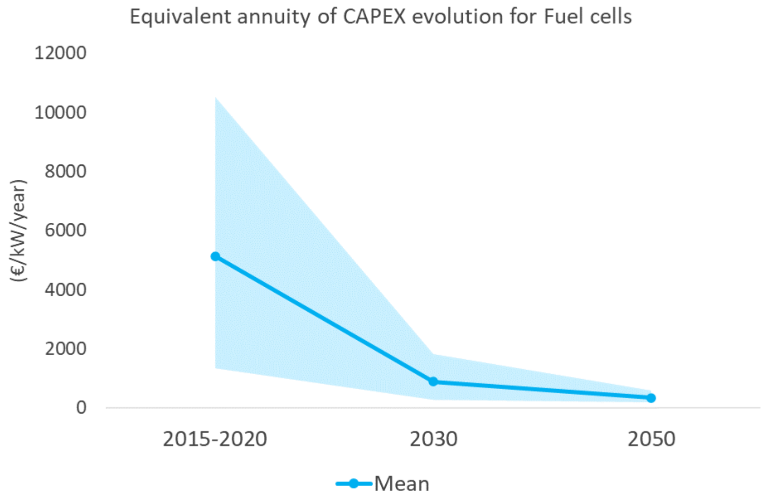


CHP technology prospective





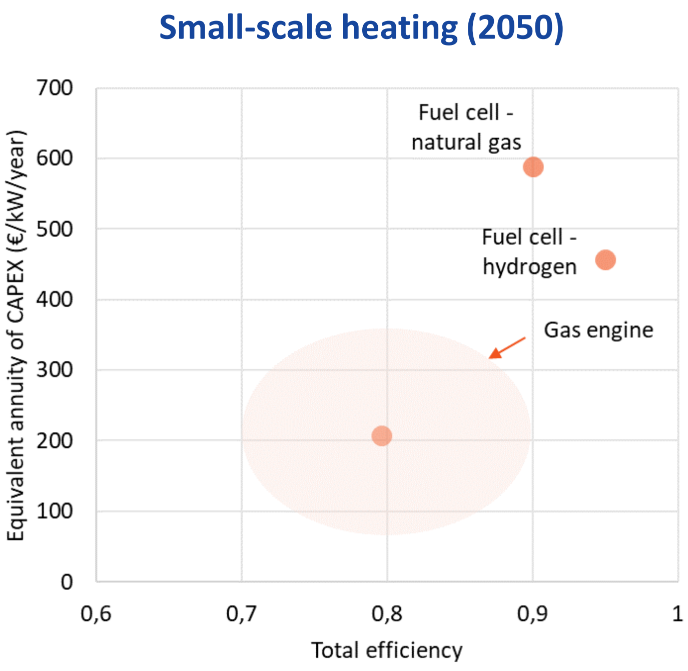


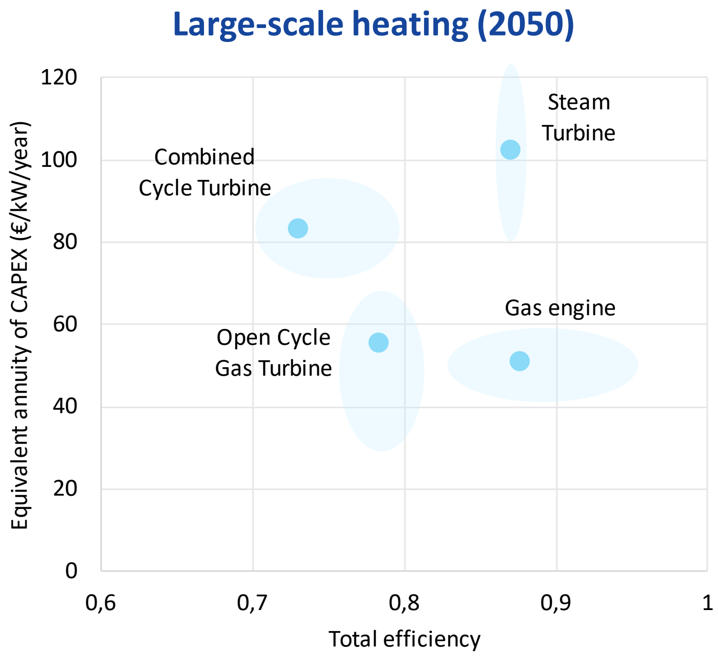


- Engines feature high power efficiencies, very flexible operations and investment costs reduction towards 2050
- Gas/steam turbines can be used for high capacities plants. Mature technologies which are not expected to experience major technological breakthroughs
- While ORC plants allow to convert low-temperature heat to power, the capital costs are found to be higher than steam/gas turbines for common application cases (high/medium temperature heat recovery)
- Expectations of fuel cell CHP learning potential is very high: both CAPEX and lifetime are expected to improve significantly

CAPEX-Performance overview for gas-fueled CHP

- Different technologies have different techno-economic profiles



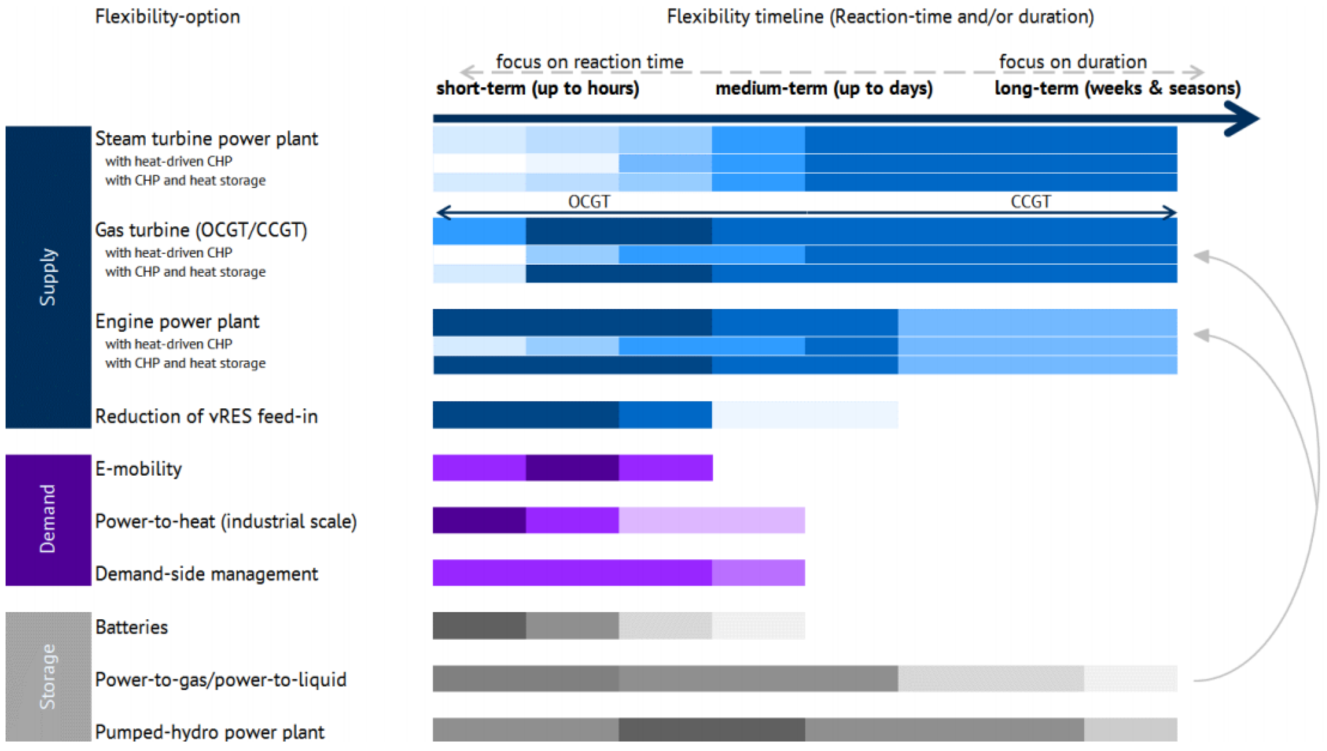


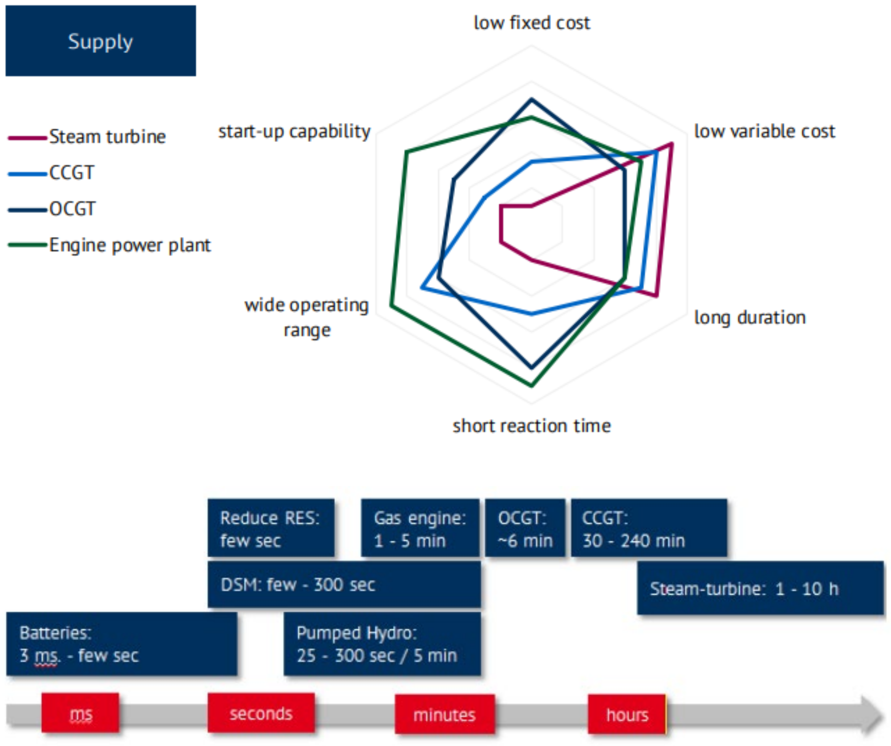
- **Fuel cells** could be interesting in a 2050 context involving high penetrations of hydrogen and well distributed access to it

- **Internal combustion engines** can be an efficient solution for district heating or industrial applications
- **Gas turbines** with heat recovery can be better suited to large (industrial) plants as they can provide higher capacities and higher power-to-heat ratios

Flexibility of CHP technologies (1/2)

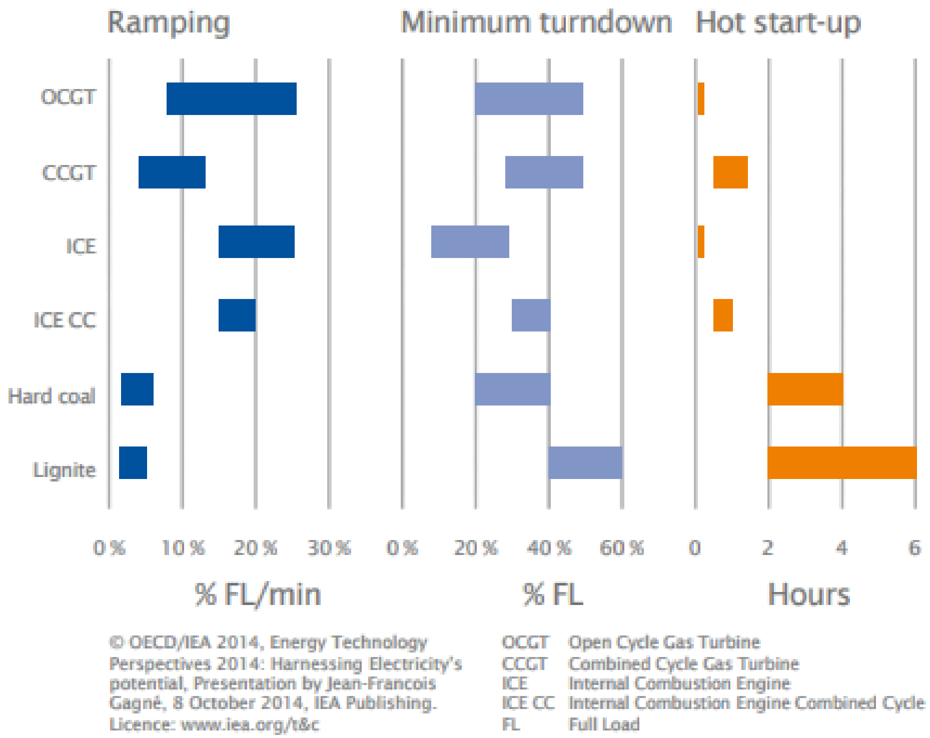
- While this study fully integrates the CHP flexibility value within timeframes from 1h to 1 year, technologies like gas engines can also compete with batteries, hydro storage and demand-side management to provide even shorter flexibility services (e.g. ancillary services)
  - However, the ability to provide short-term flexibility may depend on the CHP applications (heat or power driven)



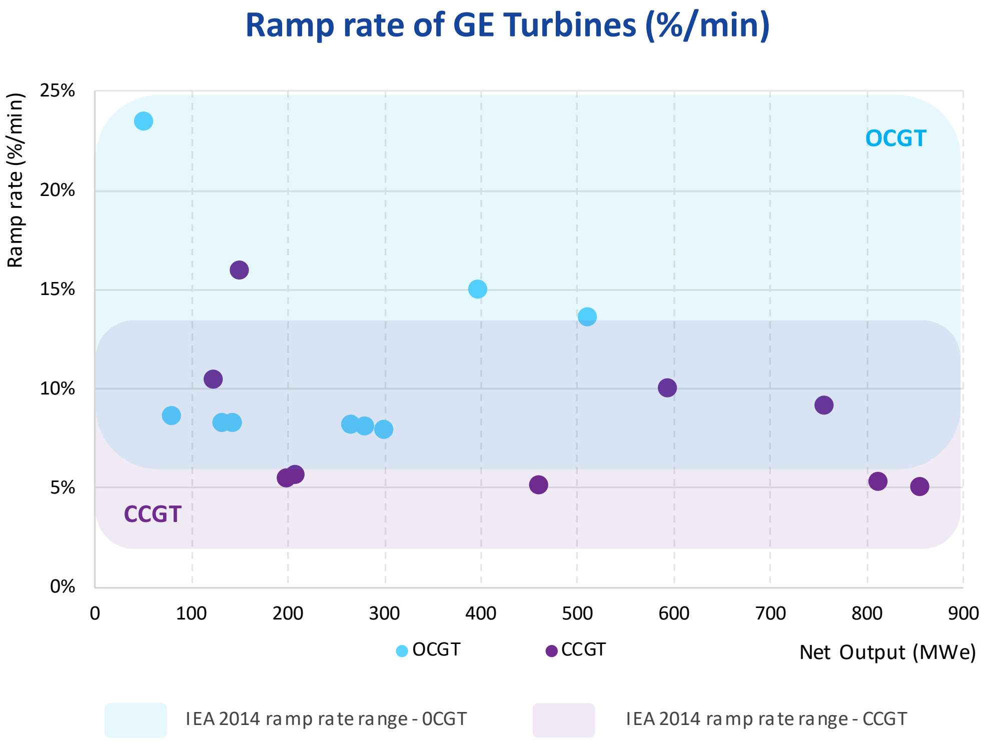


Source : *Flexibility needs and options for Europe's future electricity system*, Energy Brainpool

Flexibility of CHP technologies (2/2)



Source : IEA



Source : General Electric

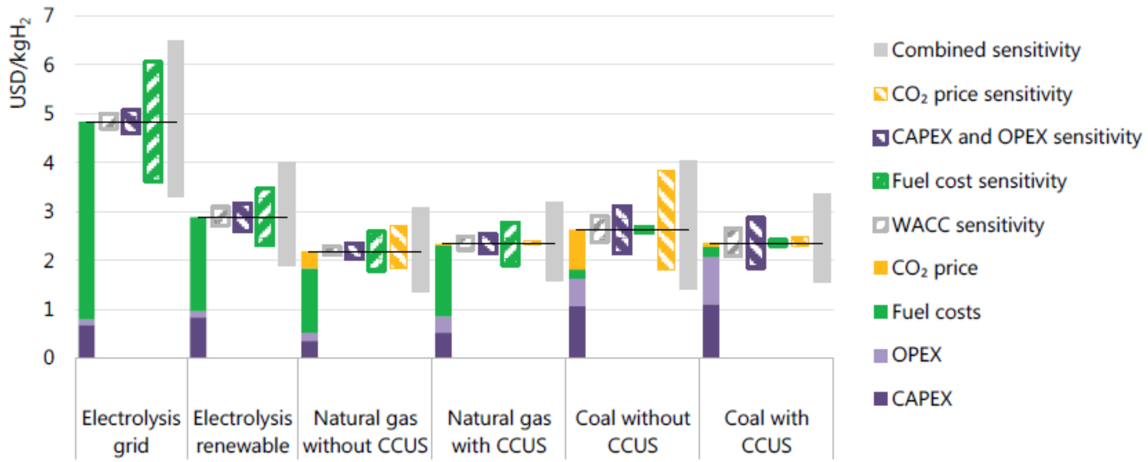
Annex 2:

Complementary assumptions for the user focus

2

Hydrogen price projections (IEA, 2019)

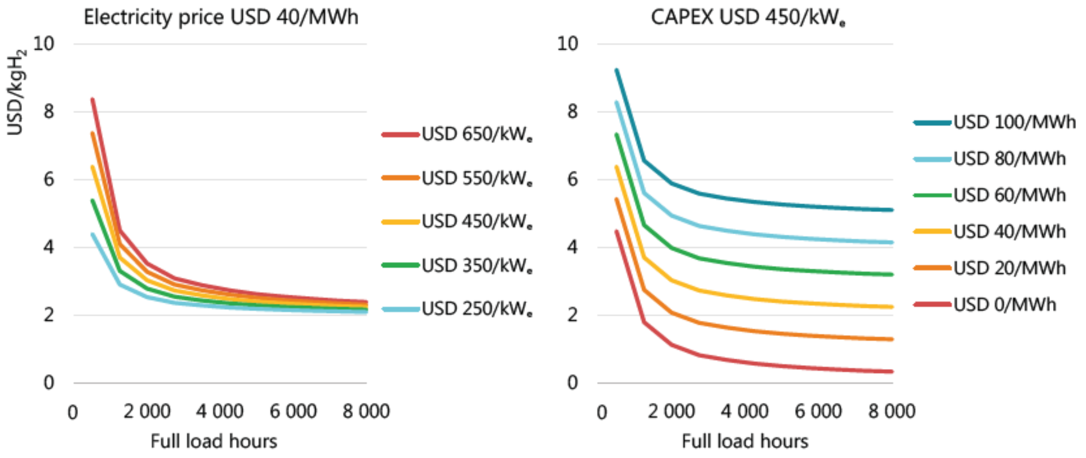
Hydrogen production costs for different technology options, 2030



Notes: WACC = weighted average cost of capital. Assumptions refer to Europe in 2030. Renewable electricity price = USD 40/MWh at 4 000 full load hours at best locations; sensitivity analysis based on +/-30% variation in CAPEX, OPEX and fuel costs; +/-3% change in default WACC of 8% and a variation in default CO_2 price of USD 40/tCO_2 to USD 0/tCO_2 and USD 100/tCO_2. More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

Source: IEA 2019. All rights reserved.

Future levelised cost of hydrogen production by operating hour for different electrolyser investment costs (left) and electricity costs (right)



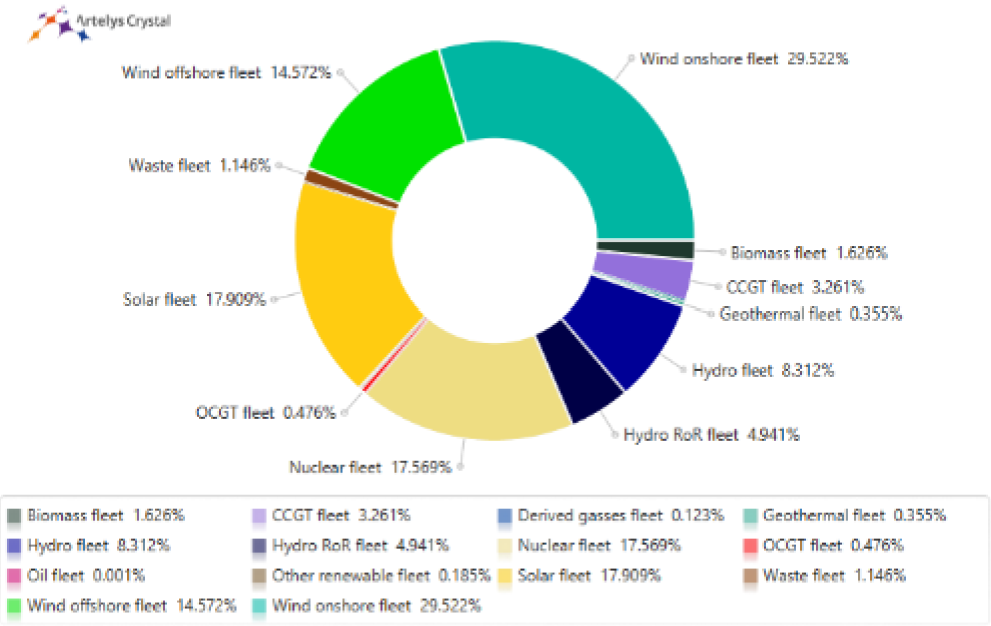
Notes: MWh = megawatt hour. Based on an electrolyser efficiency of 69% (LHV) and a discount rate of 8%.

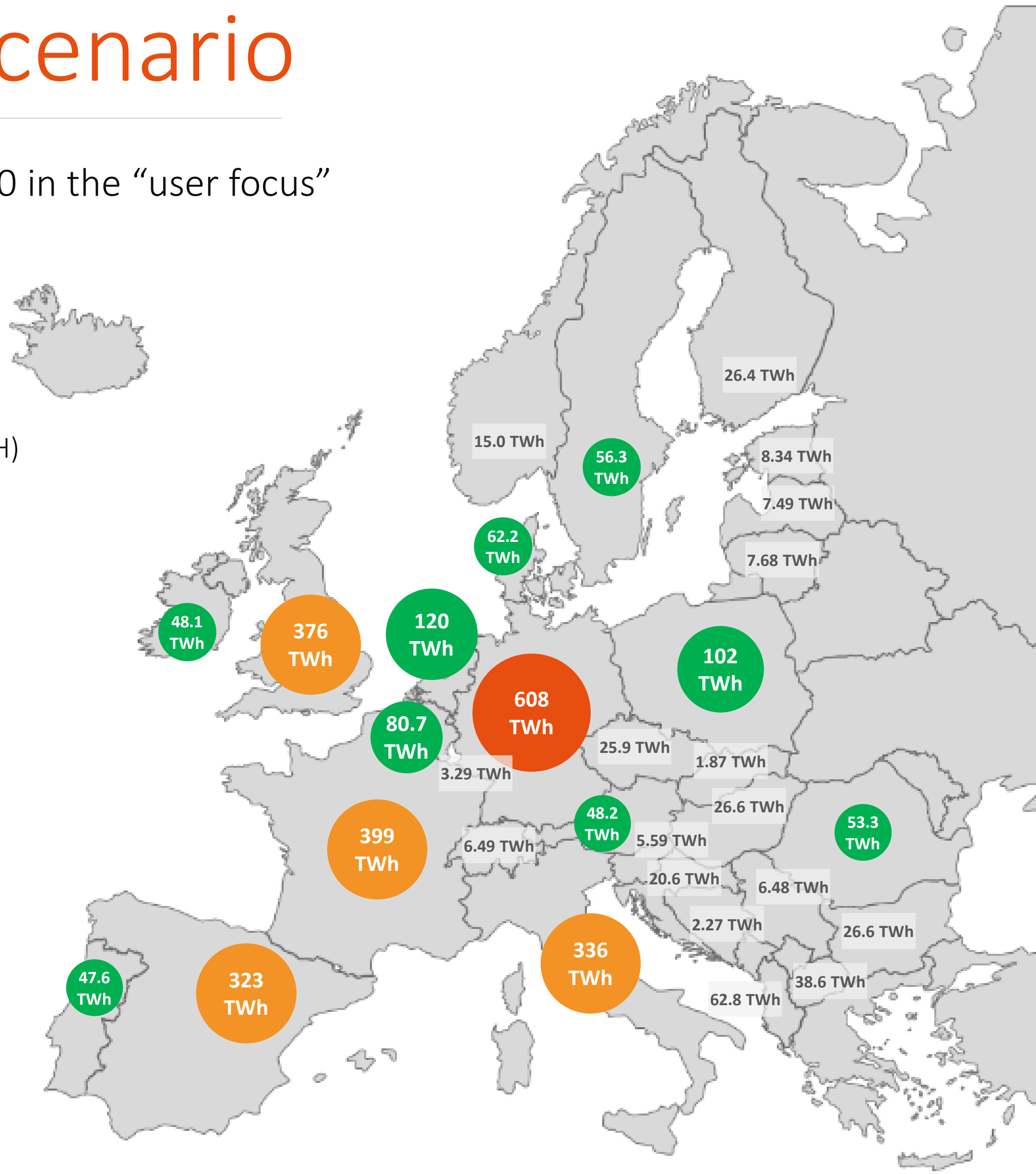
Source: IEA 2019. All rights reserved.

With increasing full load hours, the impact of CAPEX on hydrogen costs declines and the electricity becomes the main cost component for water electrolysis.

METIS S1 2050 scenario

- METIS S1 2050 scenario was used as a basis to derive electricity prices in 2050 in the "user focus"
- Main characteristics of the scenario
  - EU annual generation is 4800 TWh
  - PV and WP accounts for 62% of the EU power production (less RES than in 1.5TECH)
  - Overall RES share exceeds 80%
  - 260 TWh (HHV) of biogas consumed / 44 TWh de synthetic CH4 (much less P2G than in 1.5TECH)
  - ≈100% decarbonised power mix





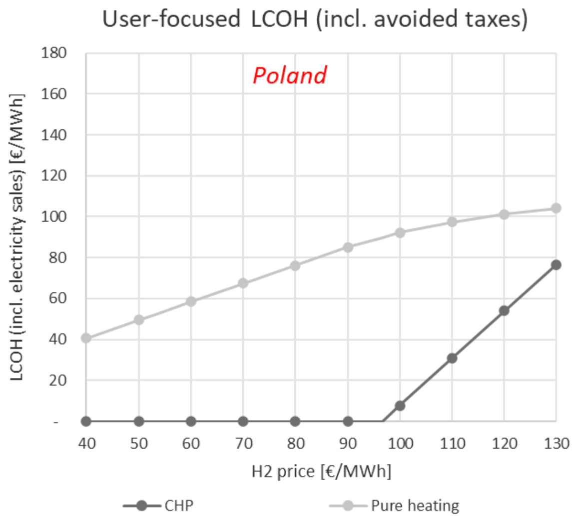
Solar PV and wind power annual production

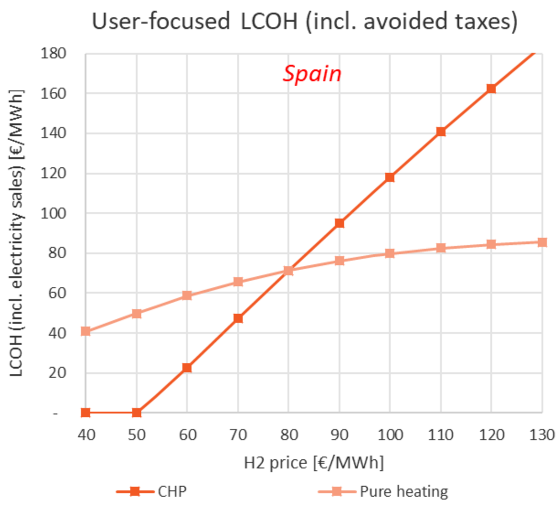
Artelys | SOLUTIONS EN OPTIMISATION

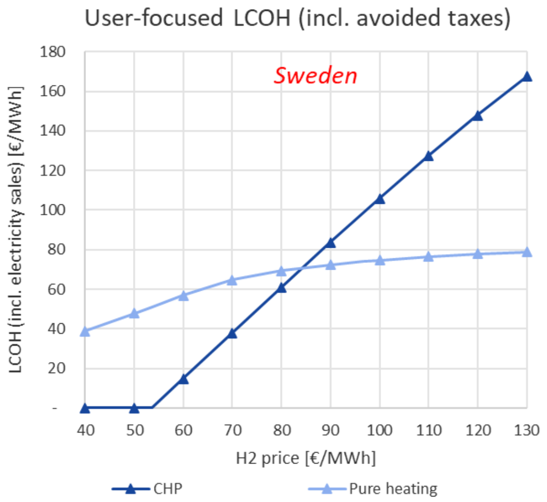
Annex 3:
Use cases – detailed results

Use case 1: Fuel Cell mCHP for residential power and heating

- This use case focuses on a domestic consumer equipped with a fuel cell mCHP that aims at minimizing its total heat and power bill, accounting for taxes. All of its electricity production is **self-consumed**, therefore avoiding taxes and transportation costs on the electricity.
- The LCOH presented below includes these avoided taxes, assumed to be twice the average wholesale price.
- This LCOH is computed for a large range of values for hydrogen prices given their uncertainty.







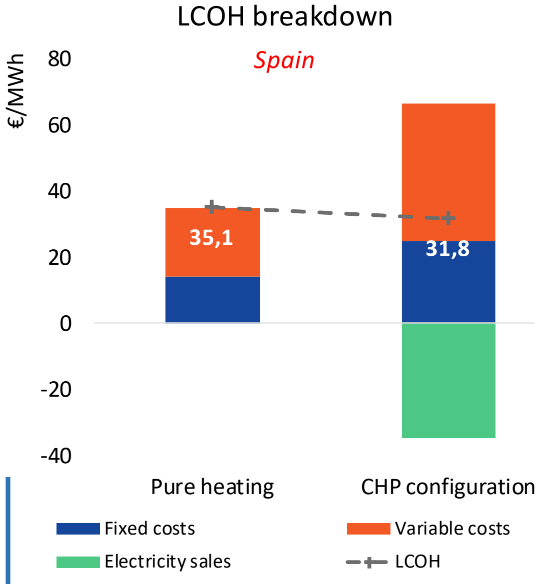
- The result shows that **FC can be competitive** from the perspective of a user minimizing its energy bill.
- The competition with other solutions depends on hydrogen prices. As an illustration, the *Gas Decarbonisation Pathways 2020-2050* report (Gas for Climate, 2020) expects **production costs** in **2050** to be around **52 €/MWh** (excl. transport/distribution, storage taxes)
- FC will be more competitive in countries where **power prices are high in winter**, i.e. in countries where the decrease of temperature is significant in winter and who do not have significant flexibilities.

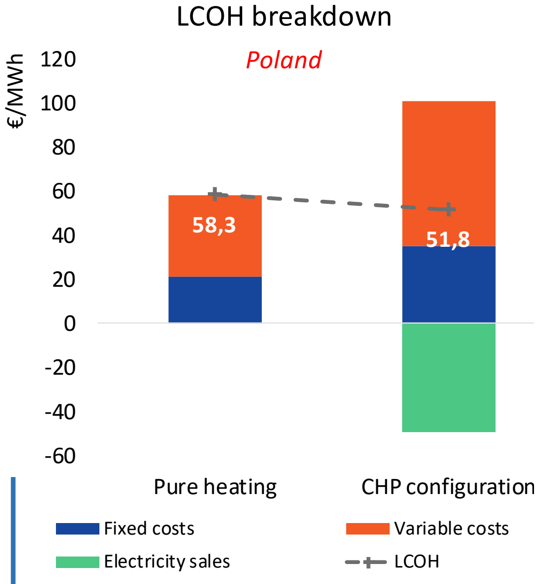
	Use case 1
Heat demand type	Decentralized domestic
CHP configuration	Solid Oxid Fuel Cell µCHP* Electricity boiler Heat storage (8h / hot water – max 300 l)
Operations	Power driven
CHP plant sizing	Optimized
Other elements sizing	Electricity boiler + storage cover demand peaks
Pure heating configuration	Heat-pump H2-boiler Heat storage (8h / hot water – max 300 l)
Sizing	Optimized in Artelys (cost-miniminzing) model

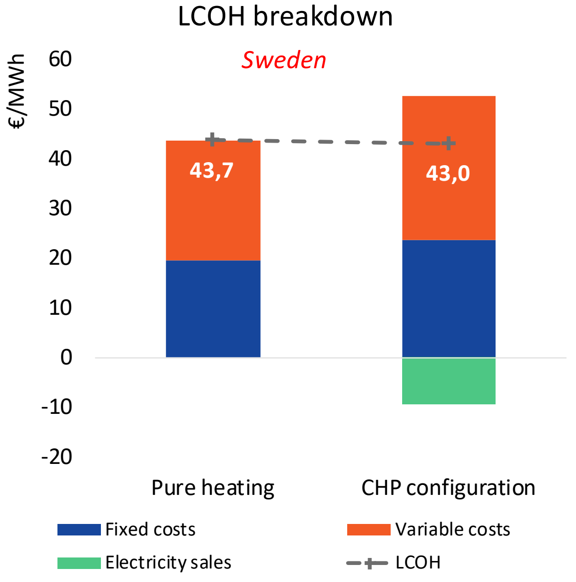
- As a distributed technology, FCs enable **self-consumption** and can help a consumer lower his total energy bill.
- The competitiveness of FC is dependent on **H2 end-use prices**, which can be affected by many factors (electricity and gas prices, H2 penetration, H2 infrastructure, CCS costs and potential), and on **the level of tax in each country**.

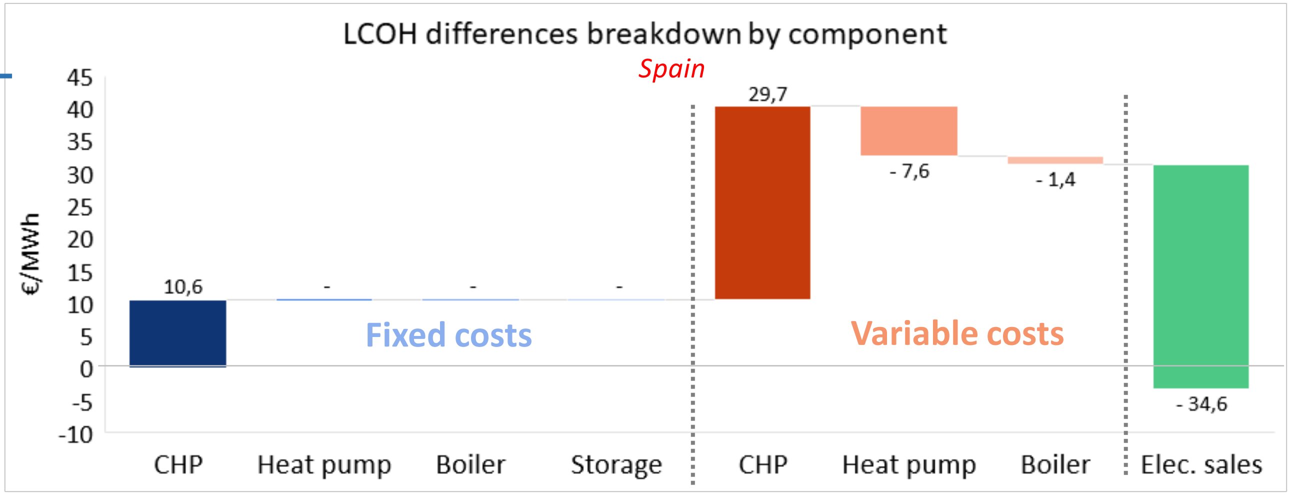
*Fuel cell end consumer assumptions: CAPEX 4692 €/kWe, fixed OPEX 143 €/kWe/y, lifetime 20 years, thermal efficiency 46%, electrical efficiency 57%, LHV

Use case 2: Gas engines CHP for a hospital micro-grid





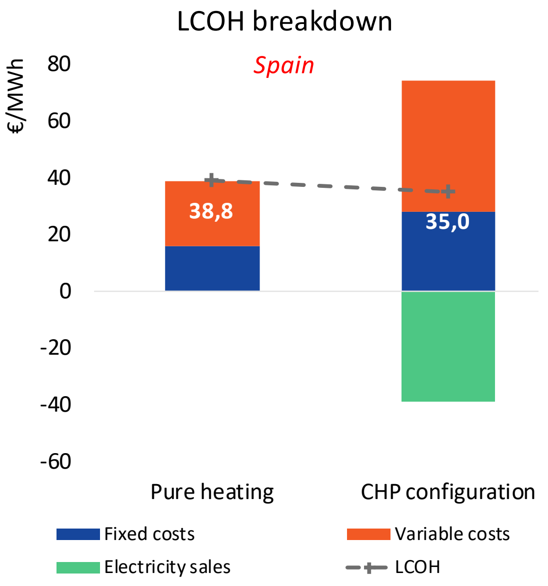


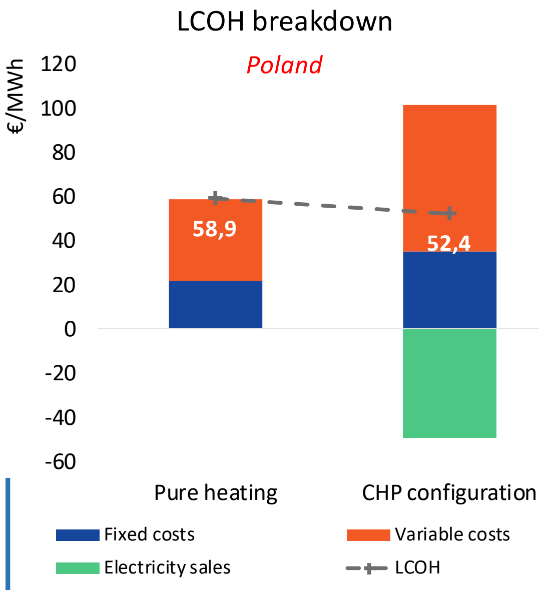


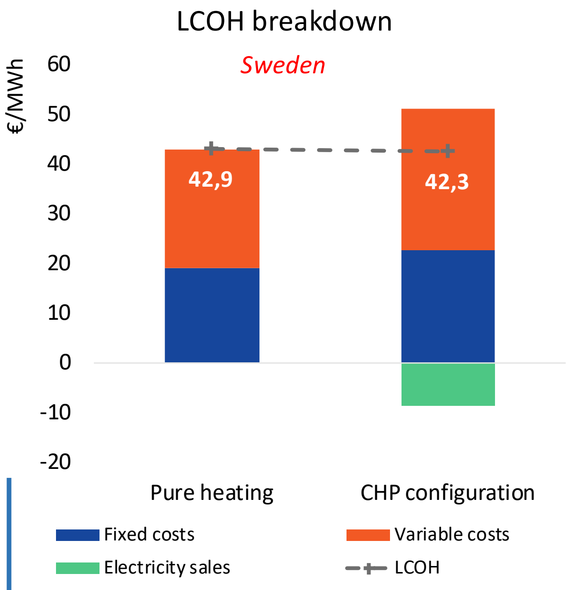
	Use case 2.1
Heat demand type	Hospital microgrid
CHP configuration	Gas-engines CHP Heat-Pump Gas boiler Heat storage (8h / hot water)
Operations CHP plant sizing Other elements sizing	Power driven Optimized in Artelys (cost-miniminzing) model Fixed at pure-heating-configuration sizing
Pure heating configuration	Heat-Pump Gas boiler Heat storage (8h / hot water)
Sizing	Optimized in Artelys (cost-miniminzing) model

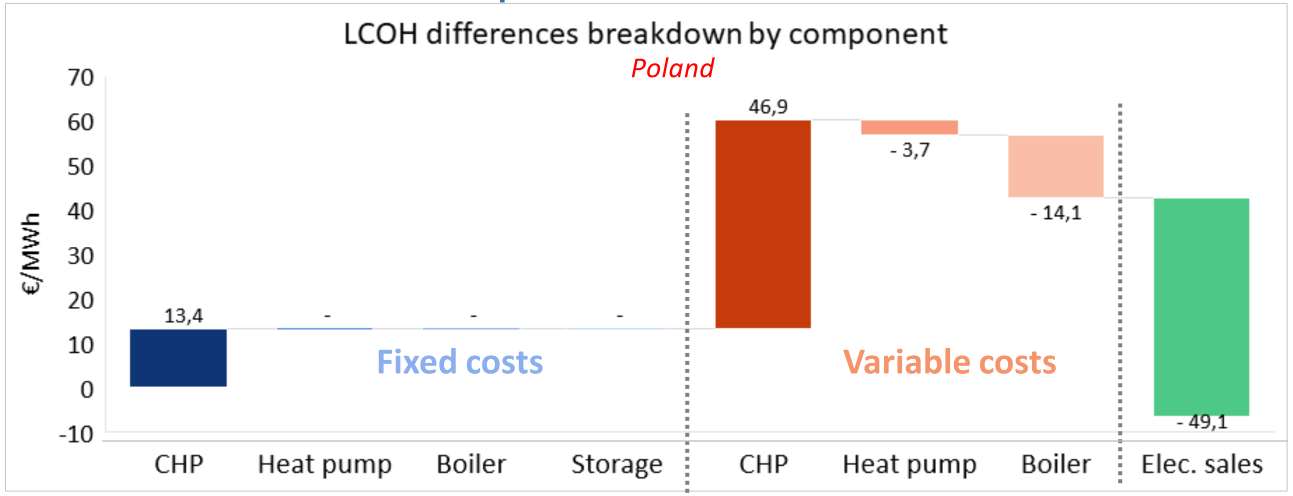
- In a **power driven** configuration, the CHP plant can value the generated power and the heat recovery as avoided heat variable generation costs
- The optimized CHP configurations lead to a gain of **0.7 – 6.3 €/MWh of heat**

Use case 3 : Gas engines CHP for district heating





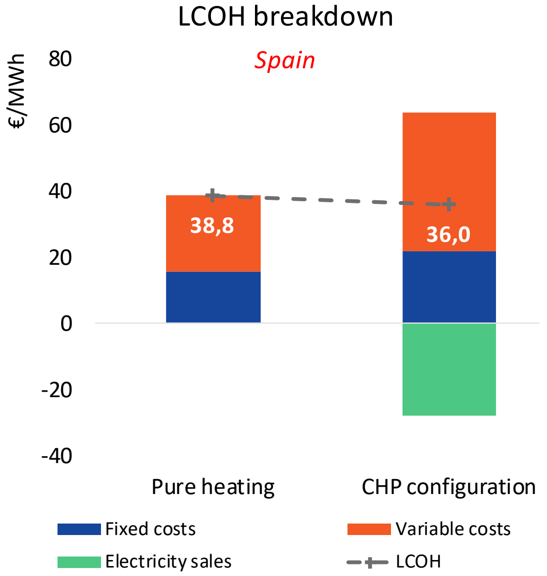


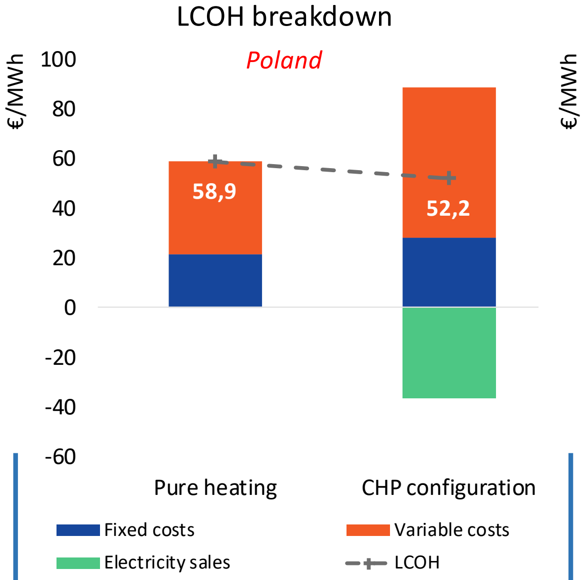


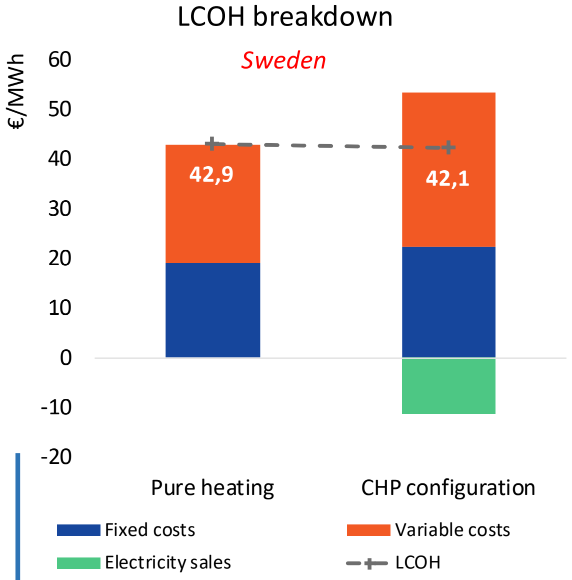
	Use case 2
Heat demand type	District heating - residential
CHP configuration	Gas-engines CHP Heat-Pump Gas boiler Heat storage (8h / hot water)
Operations CHP plant sizing Other elements sizing	Power driven Optimized in Artelys (cost-miniminzing) model Fixed at pure-heating-configuration sizing
Pure heating configuration	Heat-Pump Gas boiler Heat storage (8h / hot water)
Sizing	Optimized in Artelys (cost-miniminzing) model

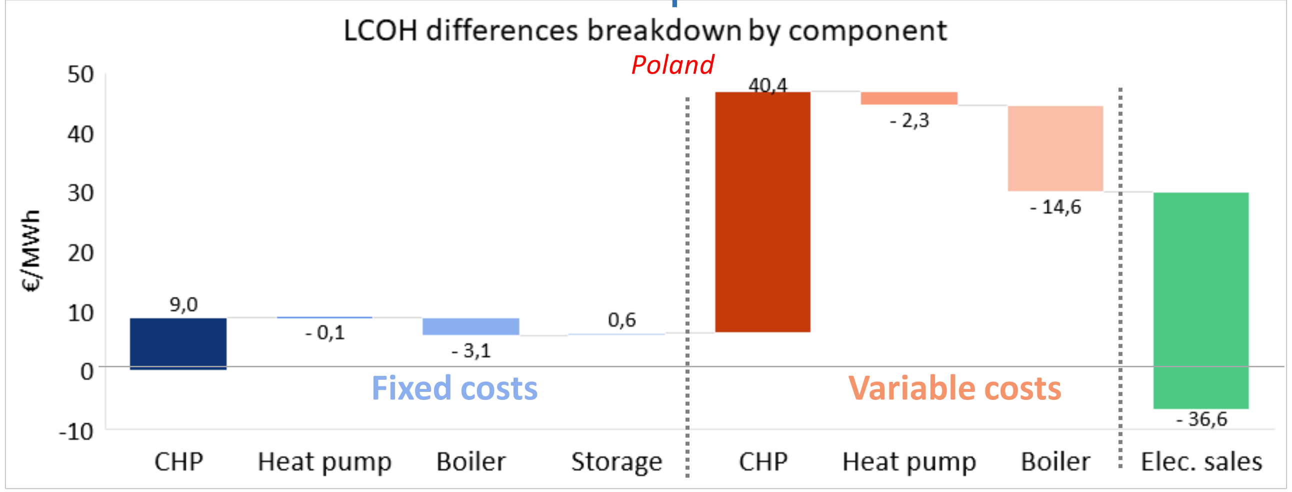
- In a **power driven** configuration, the CHP plant can value the generated power and the heat recovery as avoided heat variable generation costs
- The optimized CHP configurations lead to a gain of **0.6 - 4.5 €/MWh of heat**

Use case 4: Gas turbine CHP for district heating





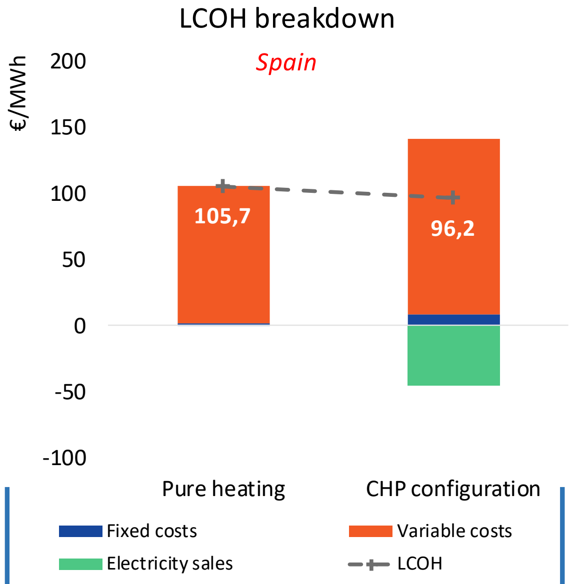


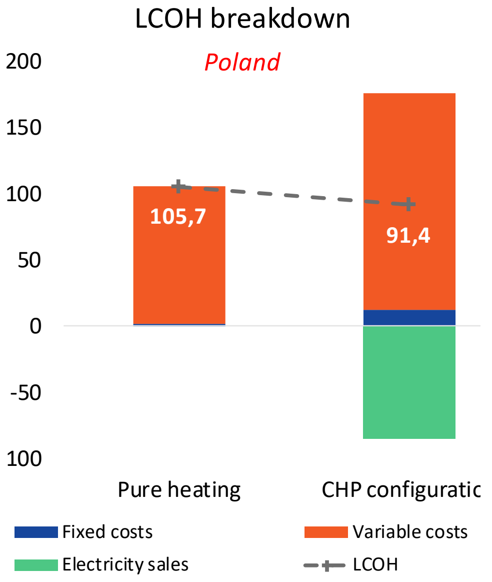


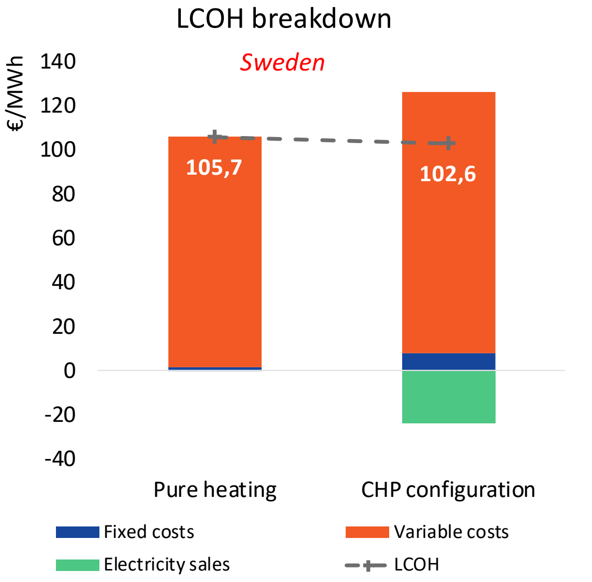
	Use case 3
Heat demand type	District heating - residential
CHP configuration	Gas turbine CHP Heat pump Gas boiler Heat storage (8h / hot water)
Operations CHP plant sizing Other elements sizing	Heat driven Jointly optimized in Artelys modelling
Pure heating configuration	Heat pump Gas boiler Heat storage (8h / hot water)
Sizing	Optimized in Artelys (cost-miniminzing) model

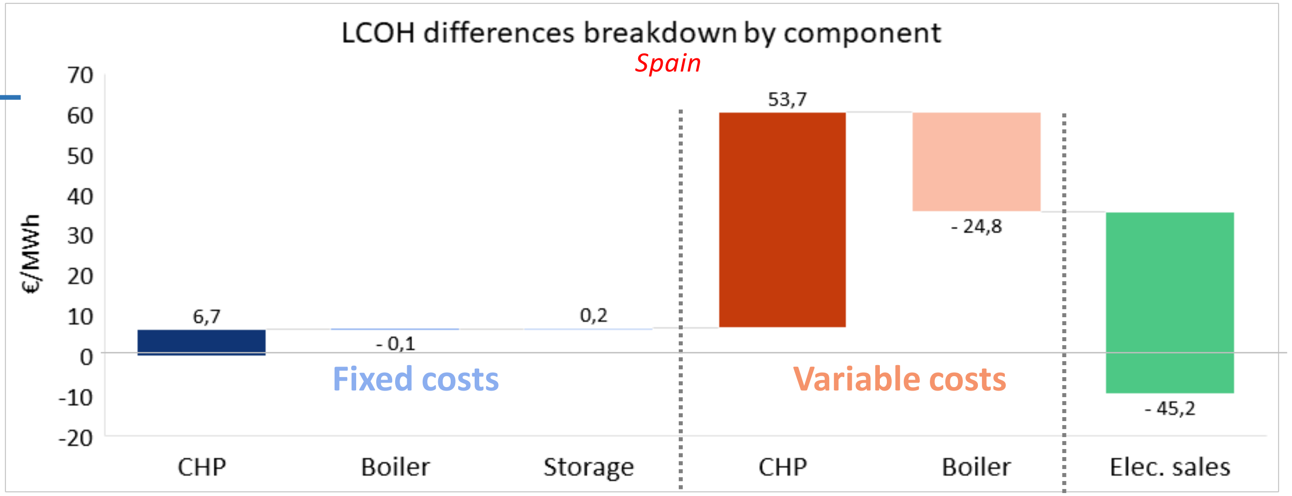
- In a **heat driven** configuration, CHP can displace other heating technologies, avoiding investment costs
- The optimized CHP configurations lead to a gain of **0.7 – 6.7 €/MWh of heat**

Use case 5: Gas engine CHP and heat storage for medium-temperature industrial heat





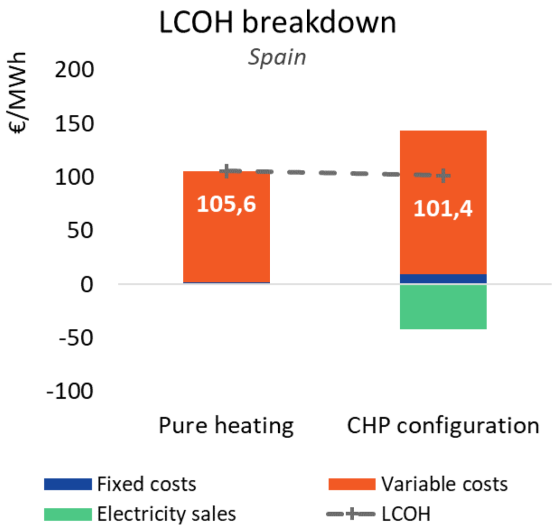


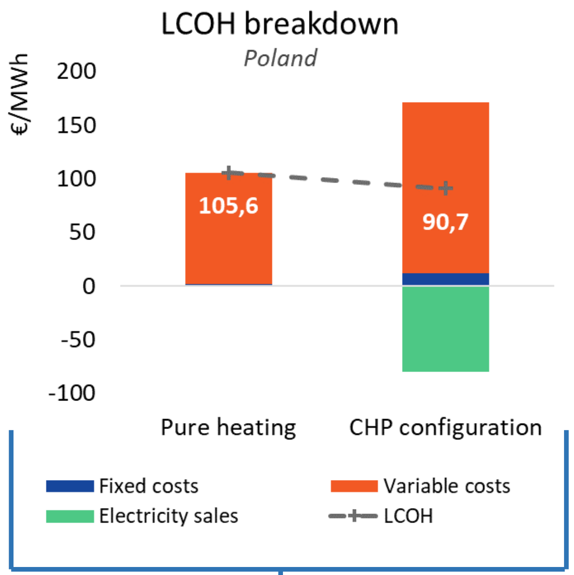


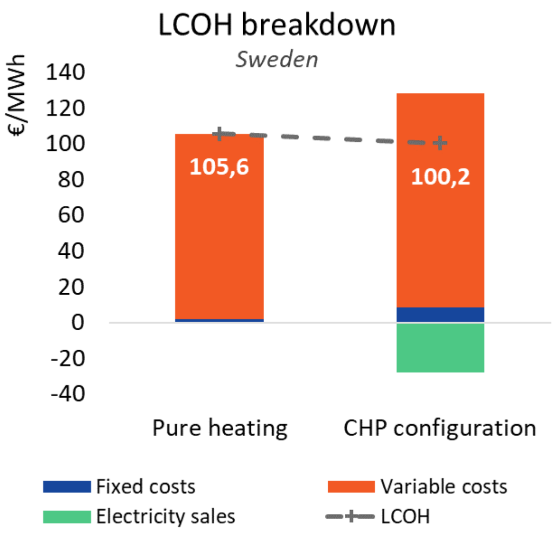
	Use case 5
Heat demand type	Industrial – Medium temperature
CHP configuration	Gas engines CHP Gas boiler Heat storage (8h / hot water)
Operations CHP plant sizing Other elements sizing	Heat driven Jointly optimized in Artelys modelling
Pure heating configuration	- Gas boiler Heat storage (8h / hot water)
Sizing	Optimized in Artelys (cost-miniminzing) model

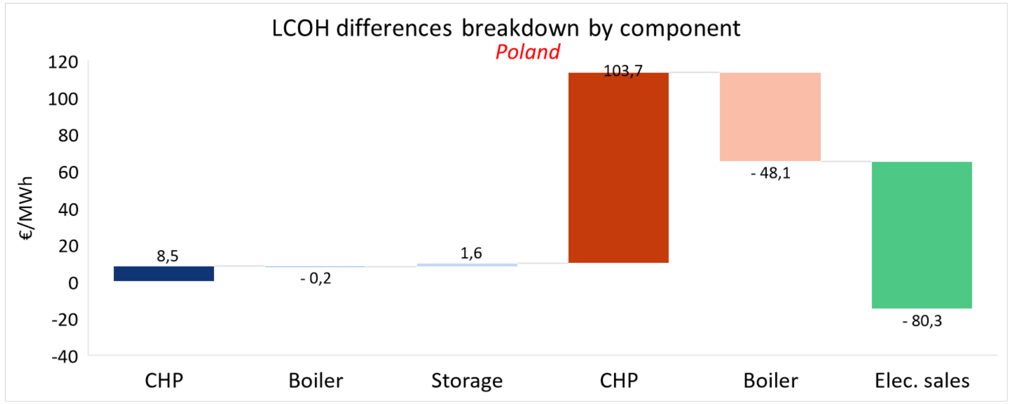
- For some industrial applications, electrical heating is not possible and **CHP is the main option for sector coupling** and multi-energy synergies
- The economic relevance of a CHP is sensitive to electricity prices
- The optimized CHP configurations lead to a gain of **3.1 – 14.3 €/MWh of heat**

Use case 6: Gas turbine CHP for high-temperature industrial heat – chemical industry





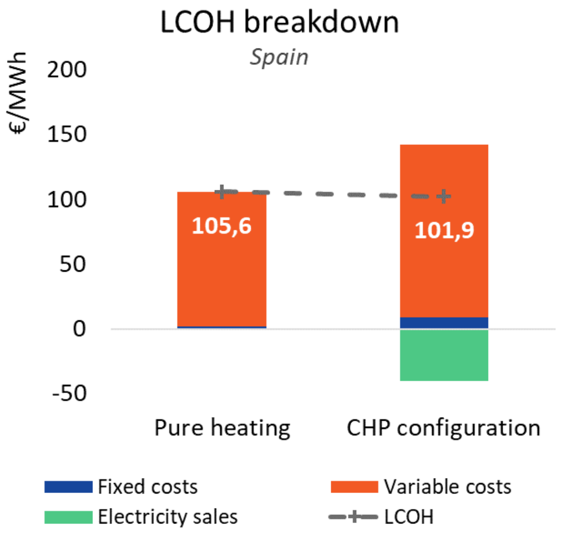


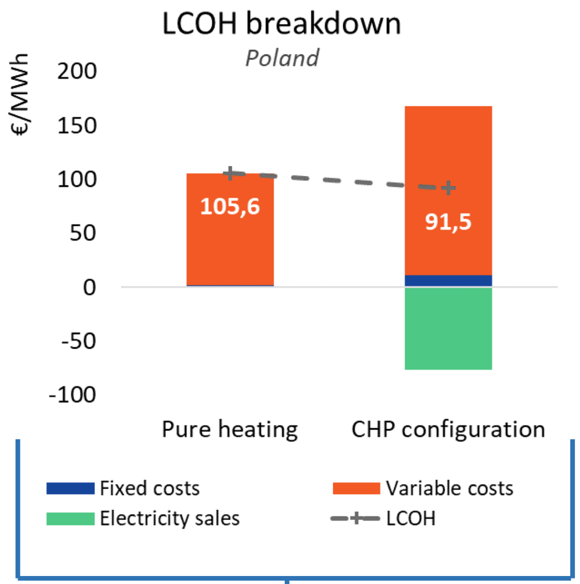


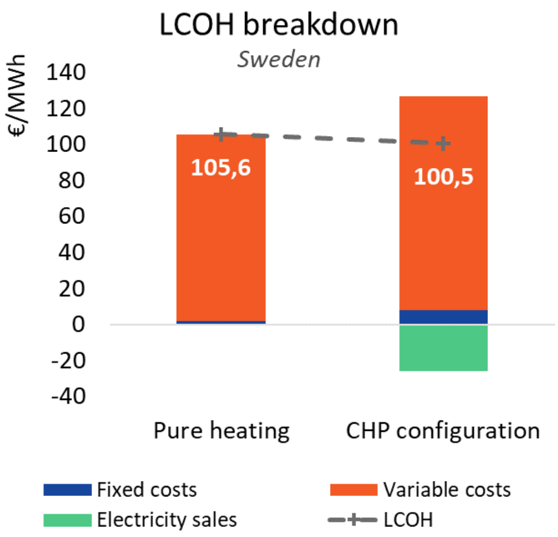
	Use case 4
Heat demand type	Industrial – High temperature
CHP configuration	Gas turbines CHP Gas boiler Heat storage (12h)
Operations CHP plant sizing Other elements sizing	Heat driven Optimized in Artelys modelling
Pure heating configuration	- Gas boiler Heat storage (12h)
Sizing	Optimized in Artelys (cost-miniminzing) model

- In the **high temperature heat industry**, storage development for demand shifting purposes remains moderate due to high capacity costs.
- Results are **highly similar** over the demand profiles of the different industries, except for flatter profiles that decrease capacity needs.
- The optimized CHP configurations lead to a gain of **3.2 – 14.9 €/MWh of heat**

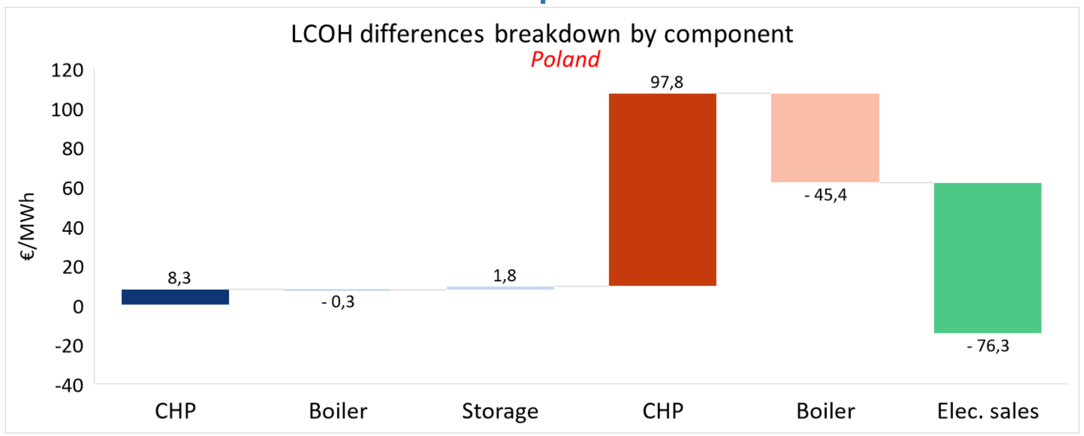
Use case 6: Gas turbine CHP for high temperature industrial heat – alumina industry







	Use case 4
Heat demand type	Industrial – High temperature
CHP configuration	Gas turbines CHP Gas boiler Heat storage (12h)
Operations CHP plant sizing Other elements sizing	Heat driven Optimized in Artelys modelling
Pure heating configuration	- Gas boiler Heat storage (12h)
Sizing	Optimized in Artelys (cost-miniminzing) model



- In the **high temperature heat industry**, storage development for demand shifting purposes remains moderate due to high capacity costs.
- Results are **highly similar** over the demand profiles of the different industries, except for flatter profiles that decrease capacity needs.
- The optimized CHP configurations lead to a gain of **3.7 – 14.1 €/MWh of heat**

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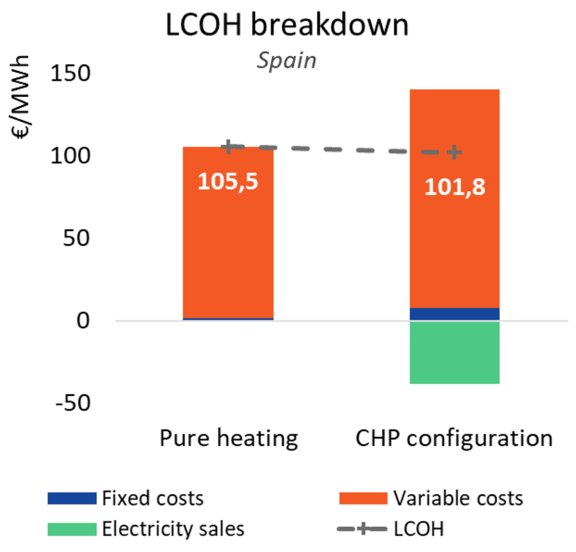
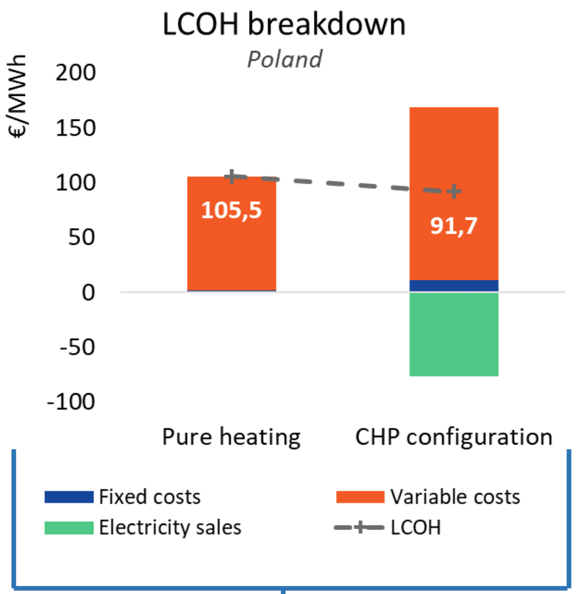
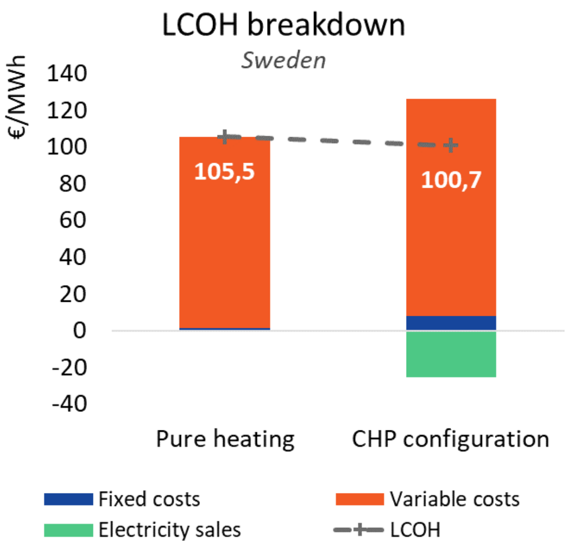
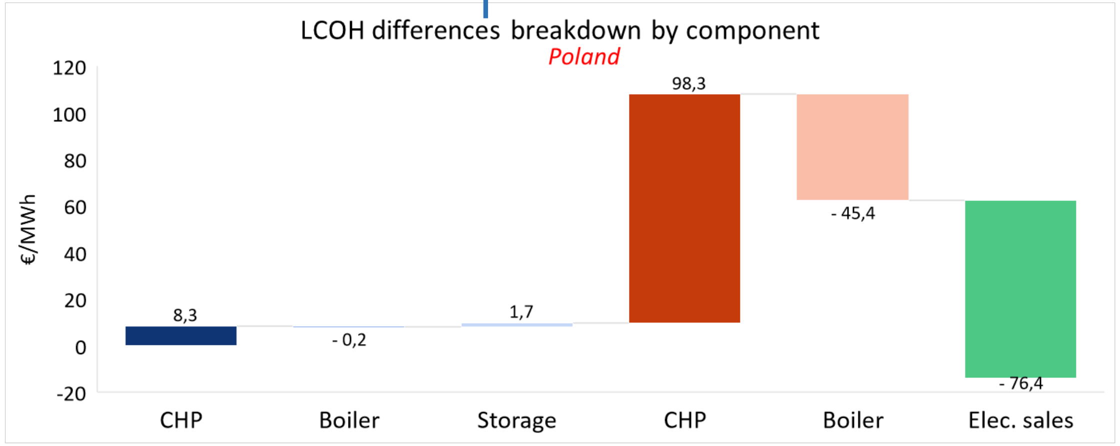
Use case 6: Gas turbine CHP for high temperature industrial heat – generic industrial profile







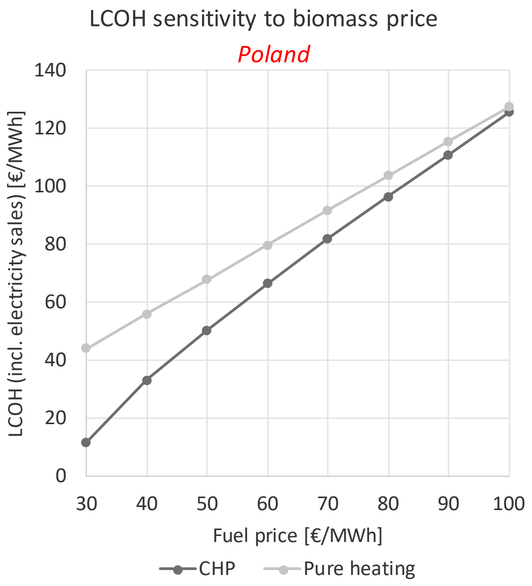


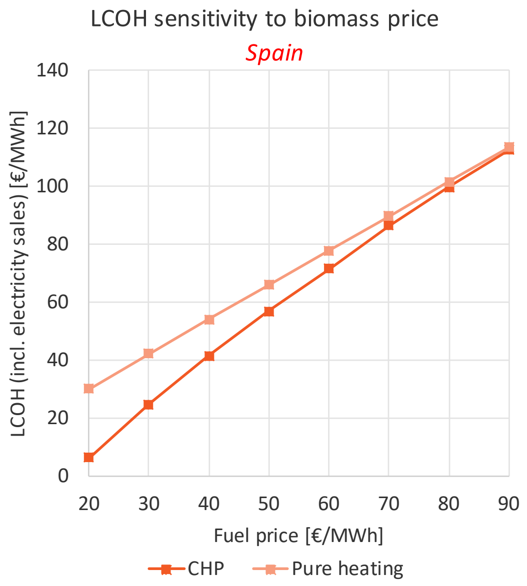
	Use case 4
Heat demand type	Industrial – High temperature
CHP configuration	Gas turbines CHP Gas boiler Heat storage (12h)
Operations CHP plant sizing Other elements sizing	Heat driven Optimized in Artelys modelling
Pure heating configuration	- Gas boiler Heat storage (12h)
Sizing	Optimized in Artelys (cost-miniminzing) model

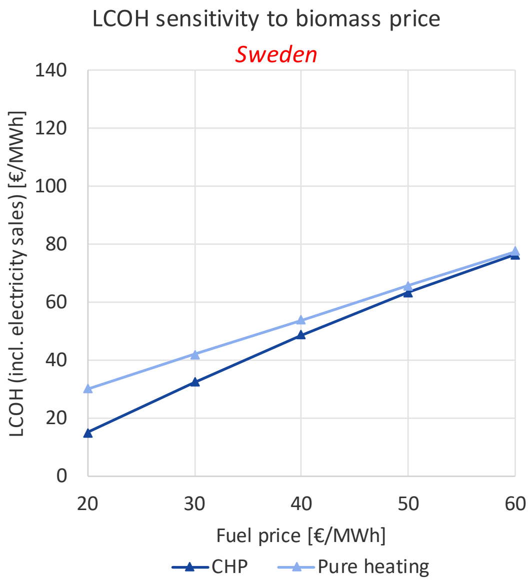
- In the **high temperature heat industry**, storage development for demand shifting purposes remains moderate due to high capacity costs.
- Results are **highly similar** over the demand profiles of the different industries, except for flatter profiles that decrease capacity needs.
- The optimized CHP configurations lead to a gain of **3.7 – 13,8 €/MWh of heat**

Use case 7: Biomass fluidized bubbling bed CHP for industrial heat and municipal district heating

- In this use case different fuel prices were considered to cover **various fuel types** (different types of biomass and waste)







	Use case 6
Heat demand type	Industry + municipal DH
CHP configuration	Bubbling Fluidized Bed Boiler CHP (biomass) Biomass boiler Heat storage (8h / hot water)
Operations	Heat driven
CHP plant sizing	
Other elements sizing	Jointly optimized in Artelys modelling
Pure heating configuration	Biomass boiler Heat storage (8h / hot water)
Sizing	Optimized in Artelys (cost-miniminzing) model

- In a 2050 decarbonized power system, **biomass-fired CHP technologies can be competitive with gas-to-power** on power markets
  - Most CCGTs would be running on green gas, which can be more expensive than biomass energy crops or residues
  - Biomass-fired CHP has a higher overall efficiency than power-only gas turbines
- Consequently, **using biomass or waste in CHP applications can result in greater benefits** than only supplying local heat.

- Using biomass in CHP instead of in boilers is **economically relevant in most cases**
- The additional investment cost of a configuration with CHP is directly compensated by a better overall efficiency
- The price of biomass or waste remains important for the competitiveness of the solution.

Annex 4:

Appendix to system focus

4

Appendix - Techno-economic parameters

Electricity generation

	CAPEX (k€/MW/y)	Fixed O&M costs (k€/MW/y)	Variable O&M cost (€/MWh)	Electrical efficiency (LHV)
Biomass power plant	138	38	3,6	40%
Biomass power plant w. CCS	244	61	5,8	32%
Gas power plant – high efficiency	64	15	1,7	63%
Gas power plant – low efficiency	47	17	11,0	42%
Hydrogen power plant	74	17	1,7	63%
Gas power plant w. CCS	129	34	2,8	49%

Heat generation

	CAPEX (k€/MW/y)	Fixed O&M costs (k€/MW/y)	Variable O&M costs (€/MWh)	Thermal efficiency (LHV)
Heat pump	49	2	1,6	381%
Gas boiler	8	2	0,2	105%
Biomass boiler	23	4	0,2	100%
Hydrogen boiler	9	2	0,2	112%

Heat storage

	Capacity CAPEX (k€/MW/y)	Storage CAPEX (€/MWh/y)	Discharge time (h)
Heat Storage – Large	8,3	1,0	8
Heat Storage – Small	22,8	1,9	12

Combined heat and power

	CAPEX* (k€/MW/y)	Fixed O&M costs (k€/MW/y)	Variable O&M costs (€/MWh)	Electrical efficiency (LHV)	Thermal efficiency (LHV)	Equivalent electrical efficiency (avoided losses)	Primary energy savings***
CHP biomass – District heating	172	20	0,6	32%	63%	34%	14%
CHP biomass – On-site industry	172	20	0,6	32%	63%	34%	14%
CHP gas – On-site industry	76	8	5,3	39%	53%	42%	14%
CHP gas – On-site buildings	112	9	10,1	46%	48%	52%	22%
CHP Hydrogen – On-site industry**	88	9	5,3	40%	55%	43%	14%
CHP Hydrogen – Fuel Cell	450	143	0,0	57%	46%	63%	29%
Organic Rankine Cycle running on waste heat	180	25	0,0	24%		25%	

*CHP CAPEX includes grid reinforcement cost savings from distributed generation
**CAPEX for on-site industry hydrogen-based CHPs are based on CAPEX of engines or turbines. They are derived from gas-based engines or turbines, considering a 15% cost-increase due to hydrogen technical specificities.
***CHPs allow for 14% to 29% of primary energy savings compared to separate heat and power production, thus ensuring high efficiency CHPs are considered (PES higher than 10%).

Data sources:
- JRC, datasheet key indicators for large scale heating and cooling technologies, 2017
- COGEN members

Distributed generation grid cost savings: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/dg-grid_cost_and_benefits_of_dg_connections_to_grid_system.pdf

Appendix - Assumptions for avoided grid losses

The methodology for taking into account "avoided grid losses" is to consider that a MWh produced at a lower level of the grid has more value than one produced at a higher level of the grid. Self consumption also avoids energy flows in the network and reduces losses even further.

To take this into account, we use the official Journal of the European Union* which provides correction factors for avoided grid losses.

Correction factors for avoided grid losses for the application of the harmonised efficiency reference values for separate production of electricity (referred to in Article 2(2))

Connection voltage level	Correction factor (Off-site)	Correction factor (On-site)
≥ 345 kV	1	0,976
≥ 200 - < 345 kV	0,972	0,963
≥ 100 - < 200 kV	0,963	0,951
≥ 50 - < 100 kV	0,952	0,936
≥ 12 - < 50 kV	0,935	0,914
≥ 0,45 - < 12 kV	0,918	0,891
< 0,45 kV	0,888	0,851

For instance, 1 MWh produced at a connection voltage level between 0,45 and 12kV and self-consumed at 80% is equivalent to

$$\frac{1}{0{,}918 * 20\% + 0{,}891 * 80\%} = 1{,}116 \text{ MWh produced at 345kV}$$

* Source: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:2015:333:FULL&from=EN

Appendix - Assumptions for avoided grid losses (2)

To compute the corresponding "equivalent increase in power output", we specify below average connection levels and average self-consumption for each heat consumption sector modelled.

Note that self-consumption corresponds here to the amount of electricity that is not injected to higher voltage levels (electricity could be consumed by neighbours, in the same part of the grid)

	Assumptions		Results
	Average connection level	Average self-consumption in 2050	Equivalent increase in power output
District heating (industry, buildings)	[50 kV ; 100 kV]	20%	+ 5,4 %
On-site industry	[50 kV ; 100 kV]	20%	+ 5,4 %
On-site buildings	[0,45 kV ; 12 kV]	80%	+ 11,6 %

This increase in power output will be applied in the modelling to the different technologies of each sector. For instance, for small CHP in buildings (electric efficiency of 43%), equivalent efficiencies while taking into account the avoided grid losses is : 43% *(1 + 11,6%) = **47,7%**

Appendix – Assumptions for fuel and CO2 costs and bio-fuels potentials

- Fossil fuel and CO2 prices are provided by the Long Term Strategy.
- Biomass and biogas prices are determined endogenously based on the optimization of the consumption of their limited supply (provided in the Long Term Strategy).

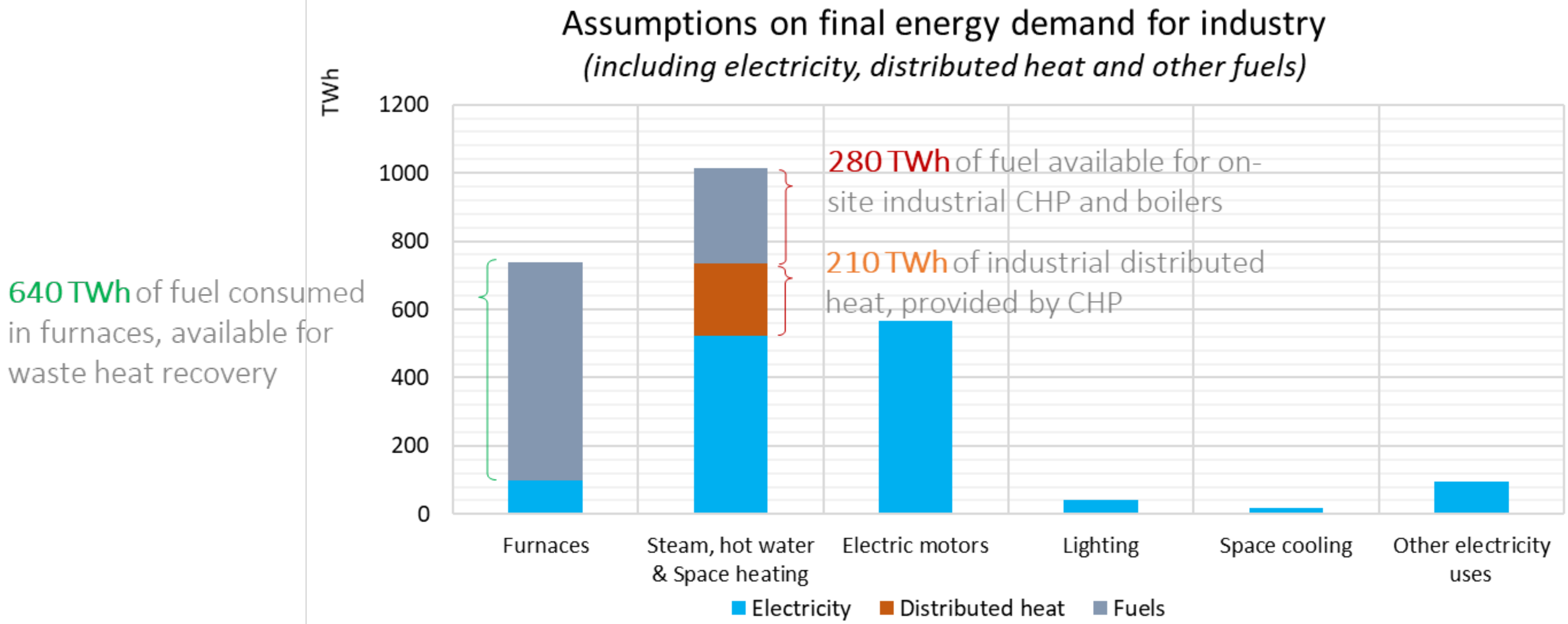
	Natural gas	CO2
Price	39,6 €/MWh	350 €/t

	Biomass	Biogas	
		1.5TECH scenario	IES scenario*
Available energy for system modelling	1 261 TWh	570 TWh	1150 TWh

* Biogas potential is increased so that natural gas consumption is the same in both scenarios (approx. 300 TWh)

Appendix – Assumptions for on-site industrial heat assumptions

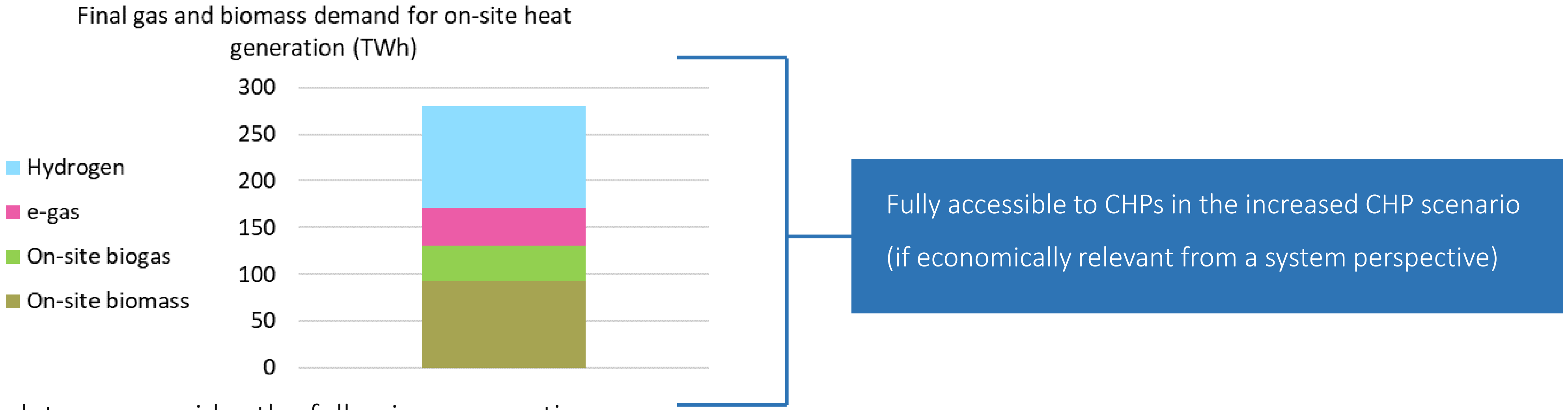
- The LTS does not provide data about on-site CHP deployment
- The disaggregation by end-use and carrier of the industrial fuel consumption from 1.5 TECH based on complementary sources* shows that 280 TWh of fuel is used for space heating and steam/hot water production. This heat can be provided by CHPs (as displayed in red).
- According to the Long Term Strategy, 210 TWh of distributed heat are provided to industries and produced by CHPs (in **orange**).
- In addition, waste heat recovery modules are assumed to be installed in the "furnaces" end-use (in green). In this case, it would represent an additional electricity generation that would come at no cost, as waste heat is assumed to be recovered from furnaces.



*additional source: ISI Industrial scenario published in the LTS

Appendix – Assumptions for on-site industrial CHP assumptions

- In more details, the **280 TWh** of fuel consumed for heat generation (low to high temperature) are the following*:



- Based on this data, we consider the following assumptions:

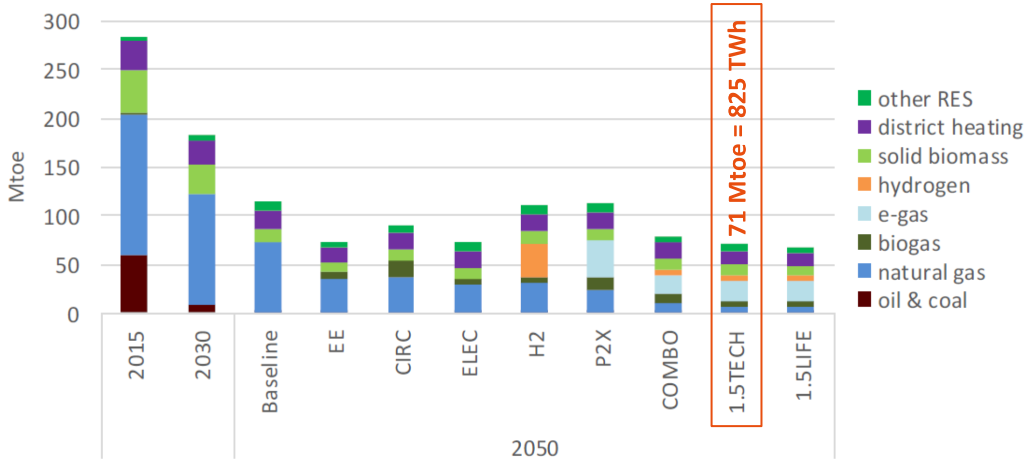
Energy carrier	1.5TECH* and IES	Optimised CHP scenarios
Biomass	CHP can cover up to 50% of the heat/steam consumption (if economically relevant)	CHP can cover up to 100% of the heat/steam consumption (if economically relevant)
Biogas		
E-gas	No CHP	
Hydrogen		

*repartition by fuel based on the fuel consumption from industry (excluding electricity) from the LTS 1.5TECH scenario

Appendix – Assumptions for on-site heat generation in buildings

- The fuel consumption of building is of 825 TWh according to the 1.5TECH scenario (including district heating, excluding electricity). These fuels are mostly used for space heating, hot water and cooking.
- 340 TWh are from biogas, e-gas and hydrogen, of which 84% (286 TWh) are used for heating purposes (space and water heating).

Non-electricity fuel consumption in buildings

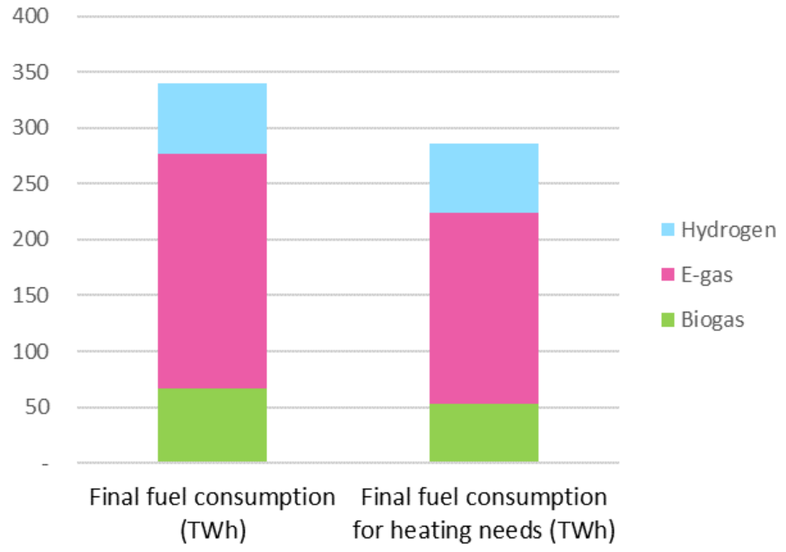


Source: PRIMES

Focus on

green gases

Final green gas consumption in buildings
Total consumption and consumption for heating



Appendix – Assumptions for on-site heat generation in buildings

Assumptions for scenarios :

1.5TECH* and IES scenarios

- The LTS 1.5TECH scenario does not mention CHP as an individual or small heating technology.
- Consequently, this scenario assumes there are no CHP in buildings (excluding from district heat)

Optimised CHP scenarios

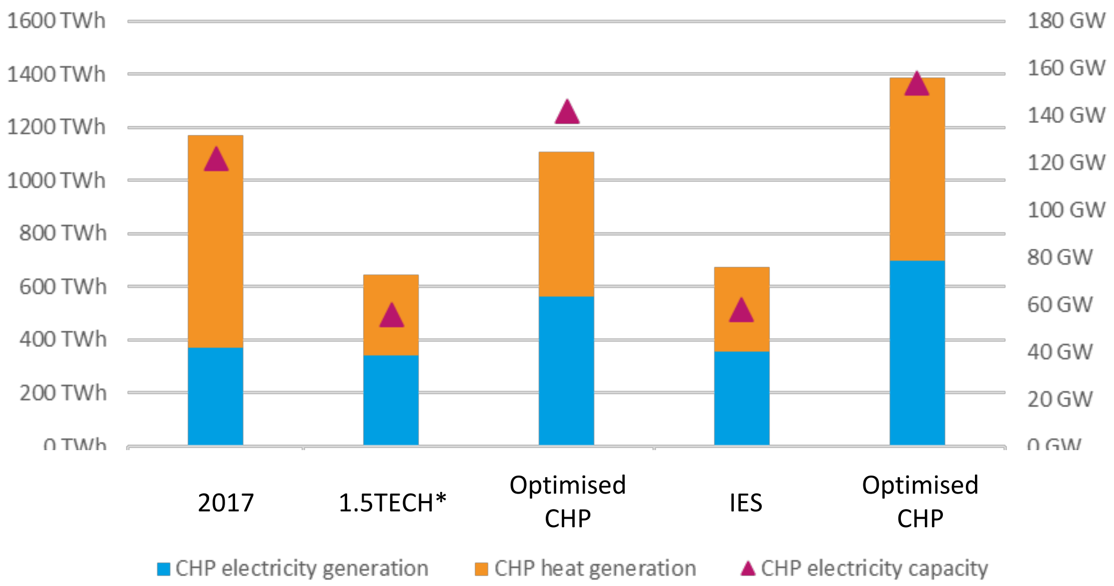
- This scenario goes beyond what is proposed by the LTS 1.5TECH scenario
- Biogas, e-gas and hydrogen **CHP capacities are optimized** up to the full share of heat covered with these carriers in buildings (i.e. up to 286 TWh of fuel consumption)

Energy carrier	1.5TECH* and IES scenarios	Optimised CHP scenario
Biogas	No CHP	CHP can cover up to 100% of the heat consumption (if economically relevant)
E-gas		
Hydrogen		

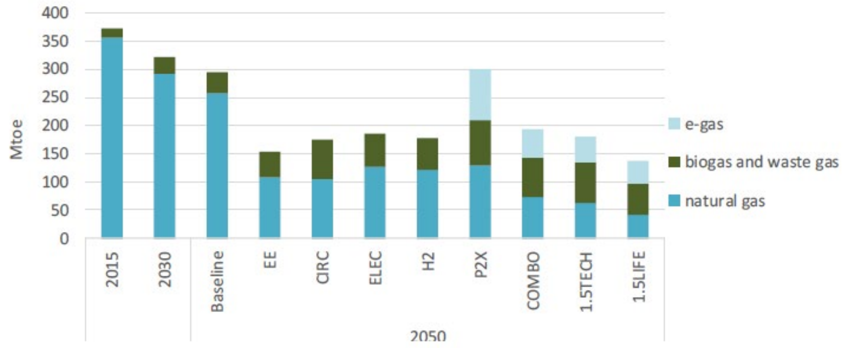
Comparison of results with 2017

CHP capacities in both scenarios are comparable to current ones, despite important direct electrification and energy efficiency (renovation, reduction of heat needs) at EU level.

- CHP potential as foreseen in the Long Term Strategy 1.5TECH may be underestimated
- Its deployment is larger when not bounded to LTS assumptions
- In IES, which includes lower nuclear energy capacities, CHP heat and power production increases significantly. The capacity increases relatively less.

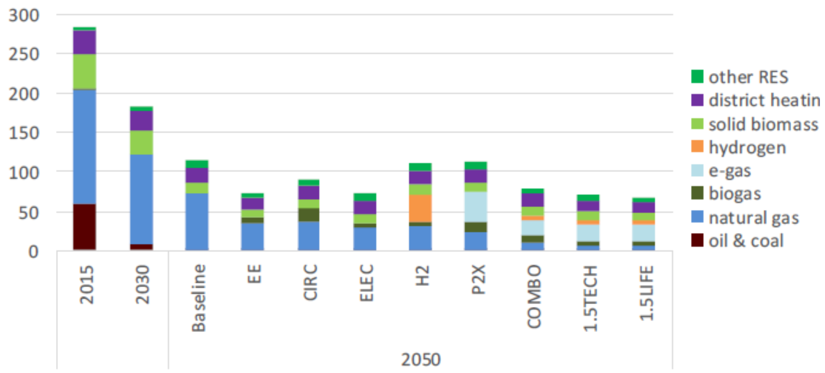


Total gas consuption per gas type



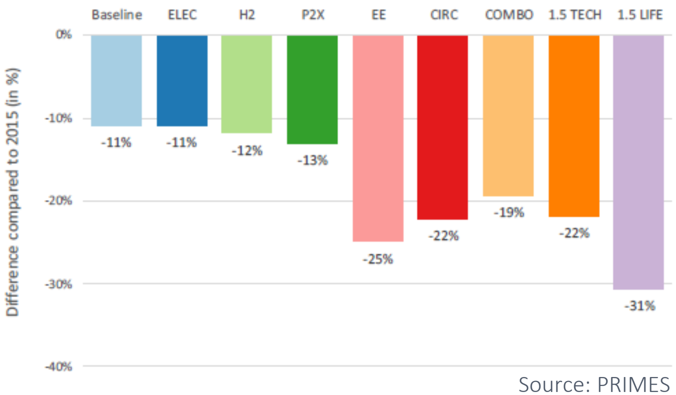
Source: Eurostar (2015), PRIMES

Non-electricity fuel consumption in buildings



Source: PRIMES

Total final energy consumption in industry by scenario compared to 2015



Source: PRIMES

Annex 5:

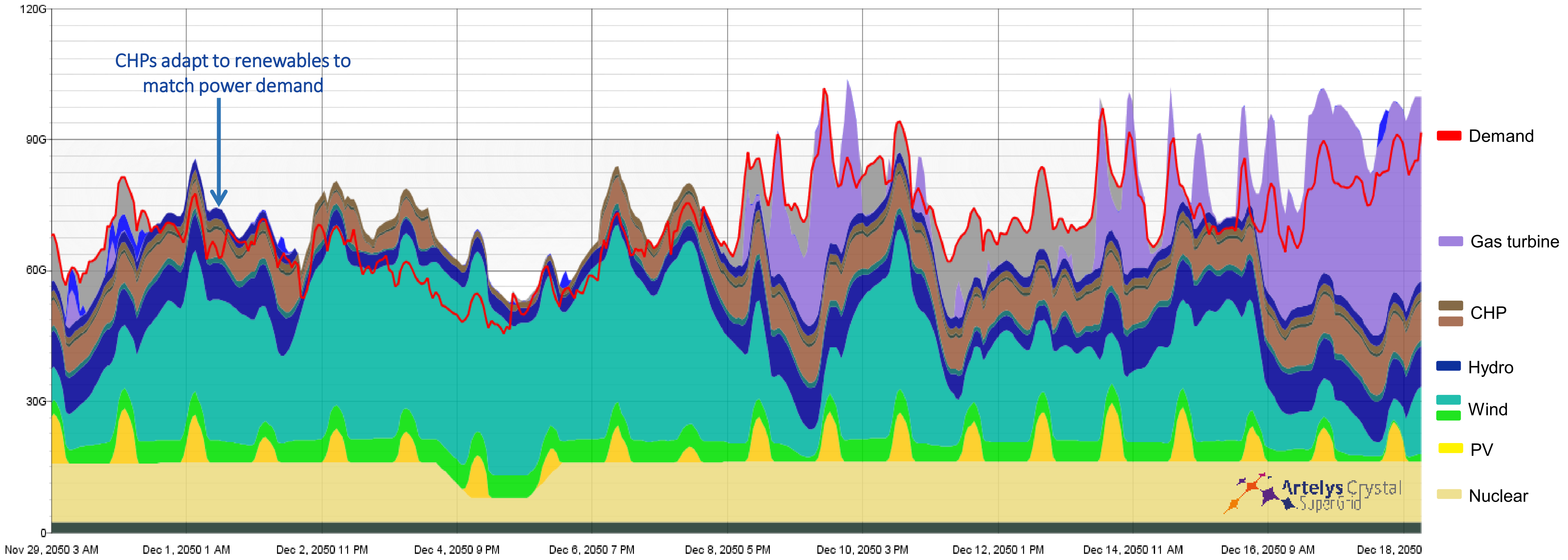
Appendix to system focus results

5

Hourly power supply-demand equilibrium

The cost-efficient operation of CHP also depends on the electricity system:

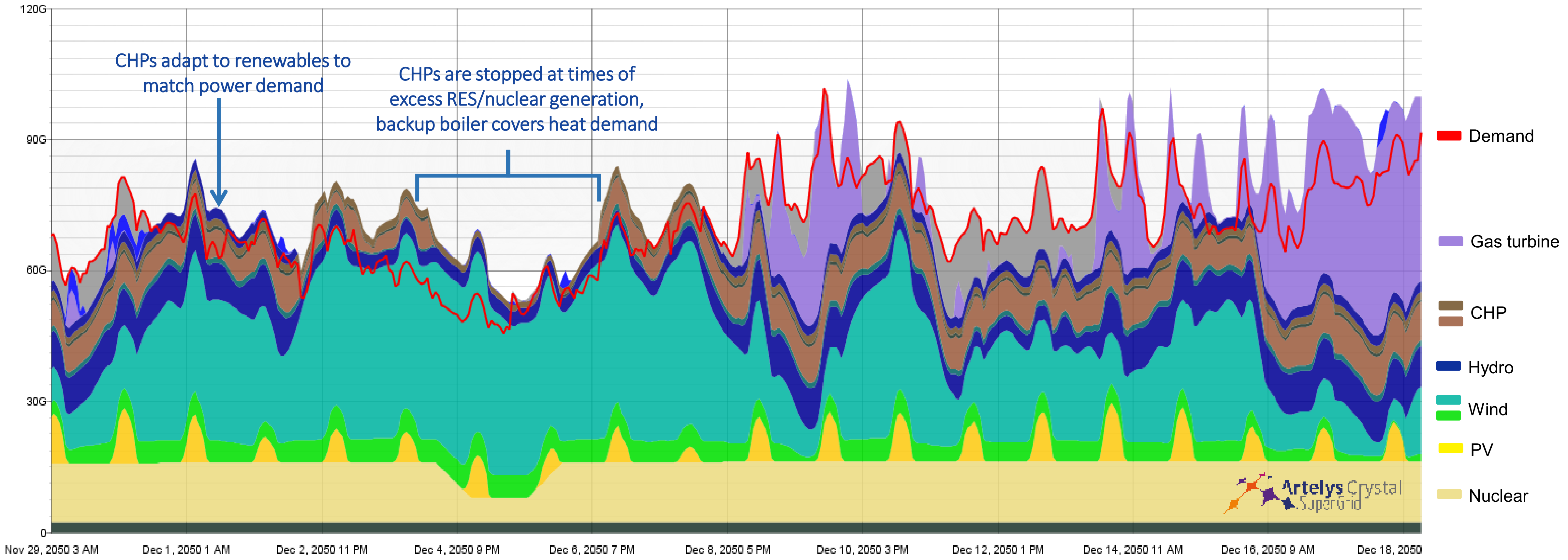
- CHP are used as a mid-merit technology.



Hourly power supply-demand equilibrium

The cost-efficient operation of CHP also depends on the electricity system:

- CHP are used as a mid-merit technology. They stop producing when renewables and nuclear generation are sufficient to cover the demand.
- Therefore, CHP do not displace variable renewables or nuclear power.



Hourly power supply-demand equilibrium

The cost-efficient operation of CHP also depends on the electricity system:

- CHP are used as a mid-merit technology. They stop producing when renewables and nuclear generation are sufficient to cover the demand.
- Therefore, CHP do not displace variable renewables or nuclear power.
- Thermal electricity-only generation (OCGTs/CCGTs) are still required for peak hours.