The potential of power-to-gas

A technology review and economical potential assessment

18 December 2015

Document produit par ENEA Consulting I 89 rue Réaumur, 75002 Paris I +33 (0) 1 82 83 83 83 I www.enea-consulting.com

Agenda

Introduction

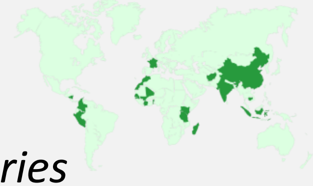
Historical background and technology status

Methodology for case studies analysis

Results of the case studies analysis

ENEA Consulting

Identity



25 people independent consulting company

***Core business**: Energy transition for industry*

***Ethical model:** Pro Bono Energy Access in Developing Countries*

Our offer

Technology: benchmark, roadmaps

Strategy: markets, R&D positioning

Projects: PFS, Performance, Impact

Our clients

Energy players

GDF SUEZ, VEOLIA ENVIRONNEMENT, TOTAL, EDF

Energy consumers

AIR LIQUIDE, ArcelorMittal, RioTinto Alcan, SUEZ environnement, SAINT-GOBAIN

Technology & Engineering

ALSTOM, DCNS, Technip, Schneider Electric

Startups

XYLOWATT xW, ERGOSUP, cristopia ENERGY SYSTEMS, CETH2

Public Sector

ADEME, Caisse des Dépôts, dgcis, ifp Innovation Energie Environnement, Liberté • Égalité • Fraternité République Française, Ministère de l'Écologie, de l'Énergie, du Développement durable et de l'Aménagement du territoire

Our fields of operation

- Energy storage
- Mobility (H2, biofuels, CNG, GNL)
- Biogas, biomass
- Renewable power & Smart grids
- CO_2 capture and utilization

What is the potential for power-to-gas as a solution to valorise power for energy markets ?

- Massive development of renewable electricity production from intermittent sources is underway in Europe.

- With the merit order effects this produces periods of low spot prices of electricity.

- This represents an opportunity for the development of flexible electrointensive processes.

- Power-to-gas is one of these processes that can be considered as a solution to convert power into a fuel gas for energy markets.

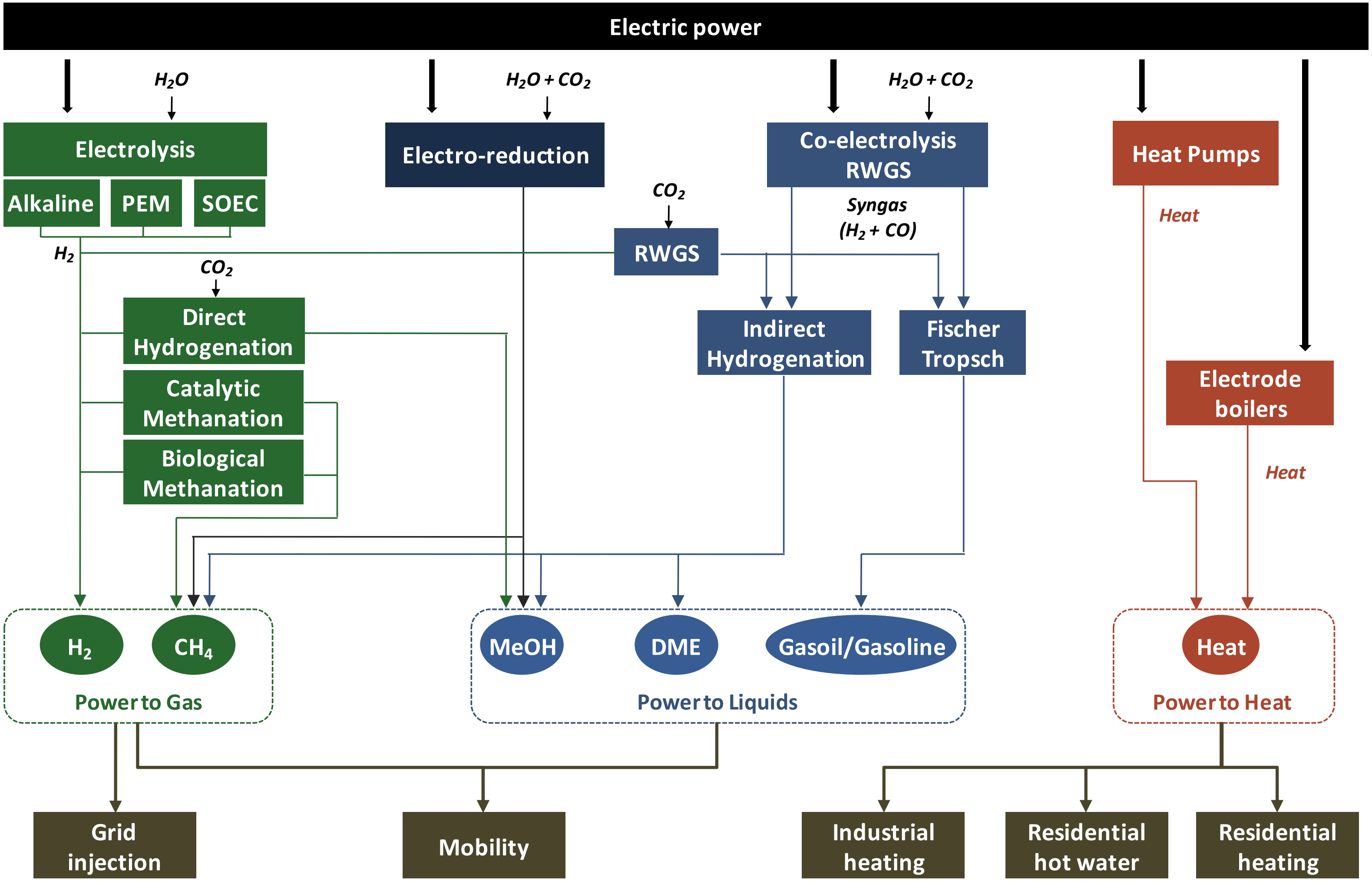
The study assesses the potential of power-to-gas and alternative power-to-X processes targeting energy markets

- Power-to-X is the conversion of electricity in an energy carrier X

- Power-to-gas: production of gaseous fuels (hydrogen or synthetic natural gas)
- Power-to-liquids: production of liquid fuels (methanol, synthetic diesel…)
- Power-to-heat: production of heat (steam, hot water)

- Power-to-power is not considered (electricity storage)

Power-to-X as defined in the study can imply various routes, products and target different market


Electric power

H_2O

Electrolysis

Alkaline

PEM

SOEC

H_2

CO_2

Direct Hydrogenation

Catalytic Methanation

Biological Methanation

$H_2O + CO_2$

Electro-reduction

CO_2

RWGS

$H_2O + CO_2$

Co-electrolysis RWGS

Syngas ($H_2 + CO$)

Indirect Hydrogenation

Fischer Tropsch

Heat Pumps

Heat

Electrode boilers

Heat

H_2

CH_4

Power to Gas

MeOH

DME

Gasoil/Gasoline

Power to Liquids

Heat

Power to Heat

Grid injection

Mobility

Industrial heating

Residential hot water

Residential heating

→ Processes with H_2 production upstream	$H_2O + CO_2$ Chemical input
→ Processes without H_2 production upstream	➞ Electric power input
→ Processes with syngas production upstream	DME : DiMethyl Ether
→ Processes with heat production	RWGS : Reverse Water Gas Shift

Agenda

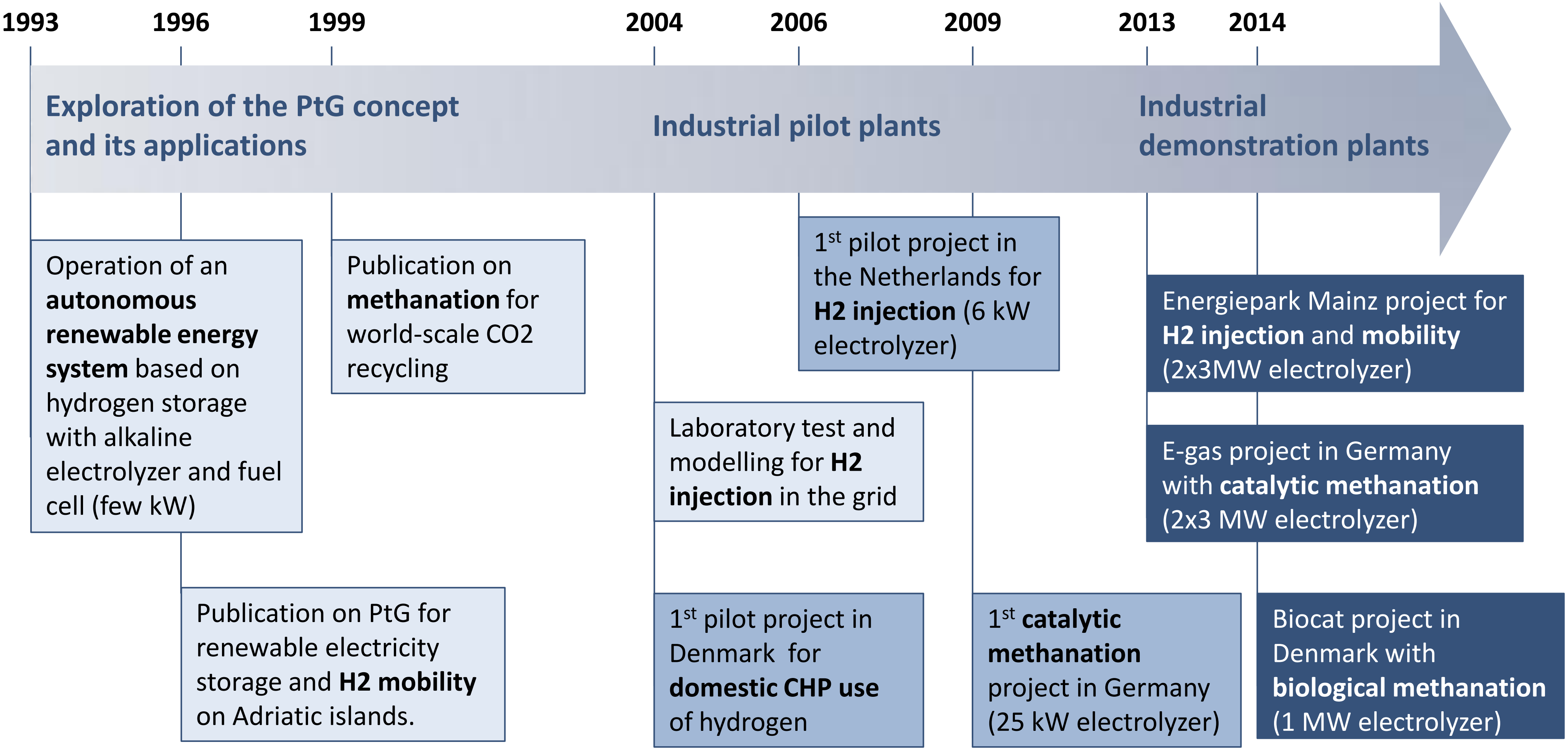
Introduction

Historical background and technology status

Methodology for case studies analysis

Results of the case studies analysis

Historical development of power to gas; from concept to industrial demonstration



1993 1996 1999 2004 2006 2009 2013 2014

Exploration of the PtG concept and its applications

Industrial pilot plants

Industrial demonstration plants

Operation of an **autonomous renewable energy system** based on hydrogen storage with alkaline electrolyzer and fuel cell (few kW)

Publication on PtG for renewable electricity storage and **H2 mobility** on Adriatic islands.

Publication on **methanation** for world-scale CO2 recycling

Laboratory test and modelling for **H2 injection** in the grid

1st pilot project in Denmark for **domestic CHP use** of hydrogen

1st pilot project in the Netherlands for **H2 injection** (6 kW electrolyzer)

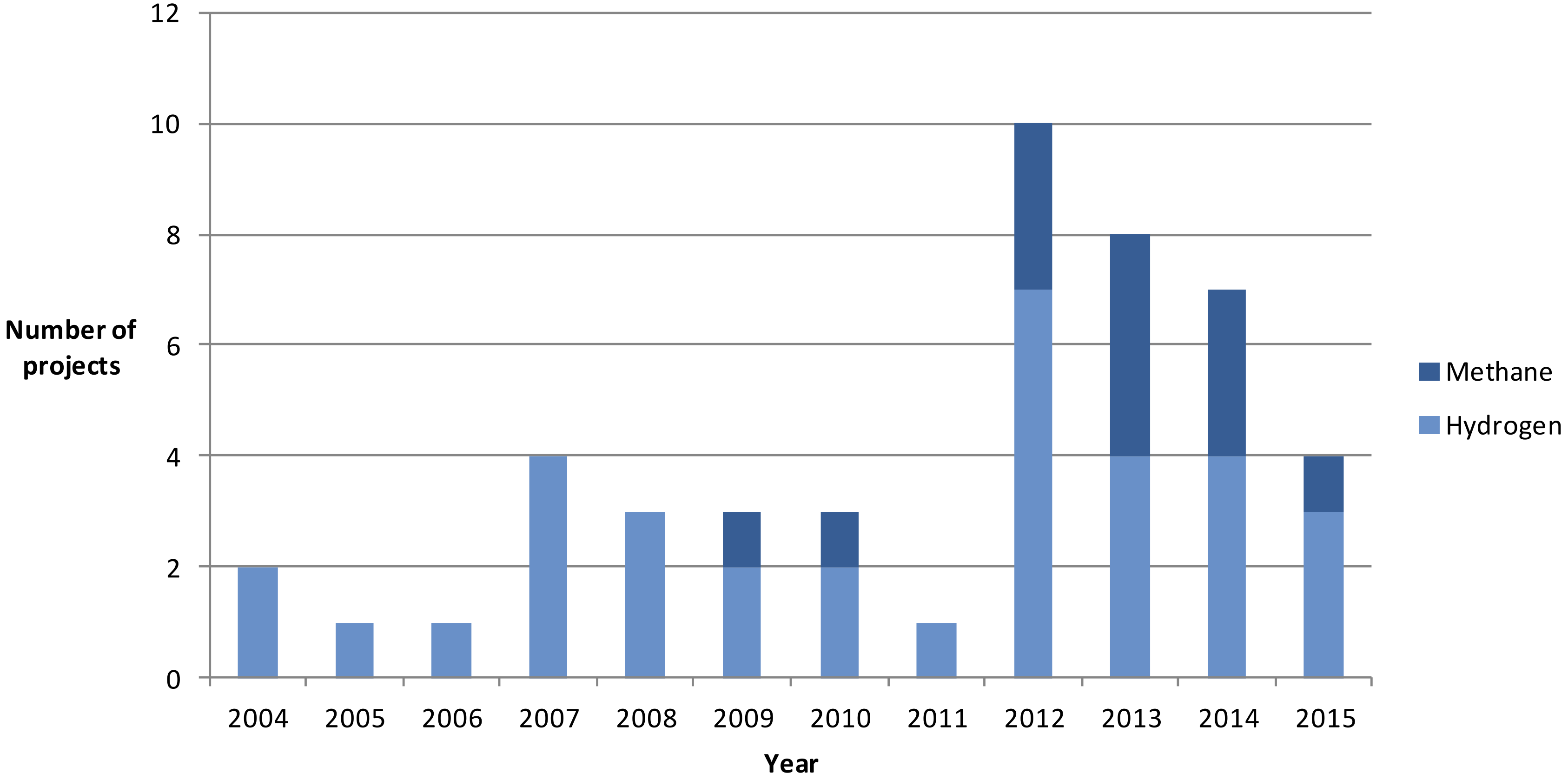
1st **catalytic methanation** project in Germany (25 kW electrolyzer)

Energiepark Mainz project for **H2 injection** and **mobility** (2x3MW electrolyzer)

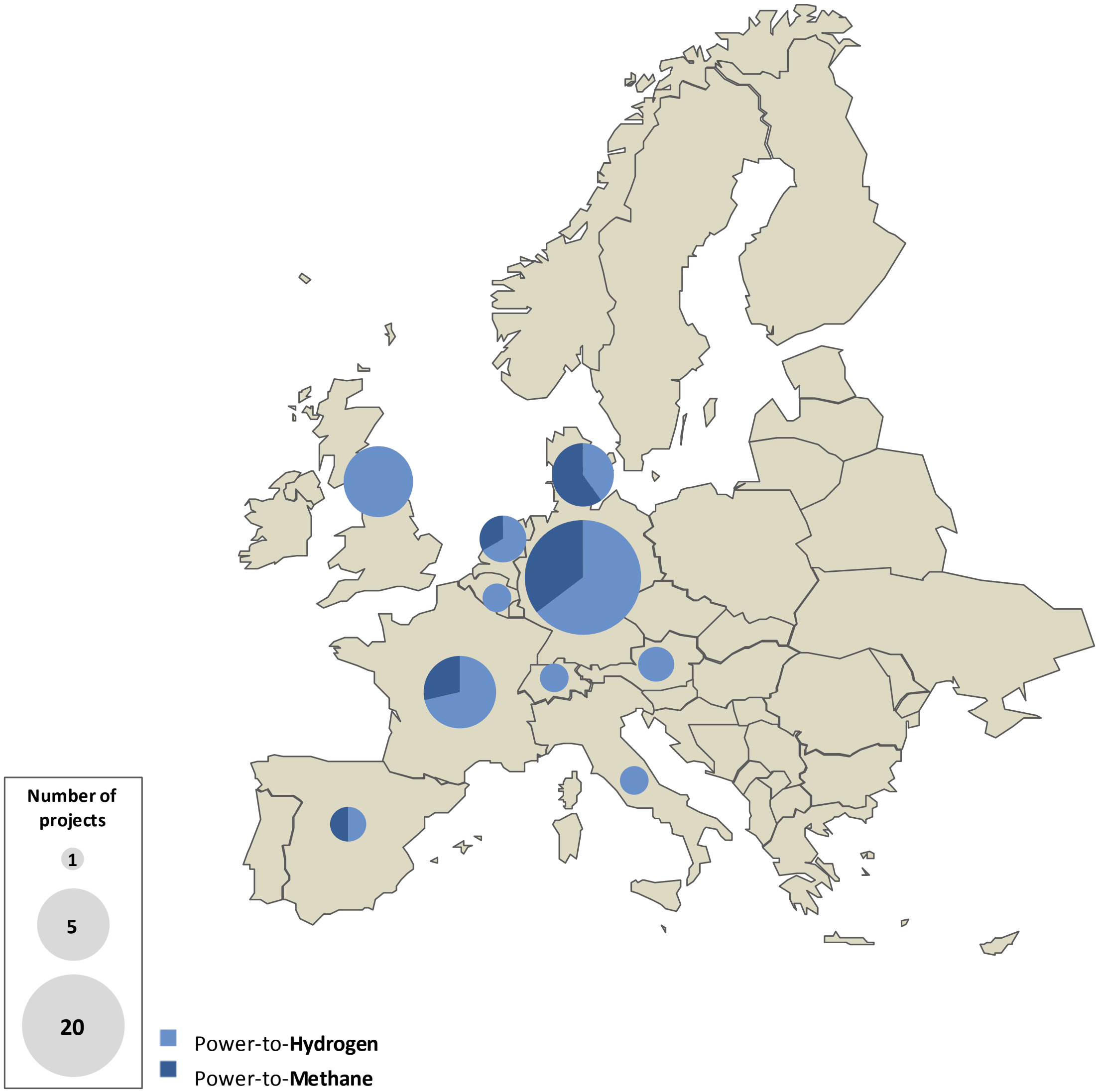
E-gas project in Germany with **catalytic methanation** (2x3 MW electrolyzer)

Biocat project in Denmark with **biological methanation** (1 MW electrolyzer)

Most of R&D projects (pilot & demonstration) have been launched since 2012, specifically for methanation



Europe is leading global R&D activity on PtG, specifically in Germany where 17 industrial pilot and demonstration projects have been launched



And in the rest if the world ?

- R&D activity on PtG is limited outside of Europe
- Japan is active in R&D for the development of hydrogen markets but not on the production side
- USA has recently announced its first PtG project

Water electrolysis: alkaline is the reference technology but could be challenged by PEM in the future, solid oxide electrolysis is still at laboratory stage of development

- Alkaline electrolysers
  - Reference technology used in industry
  - Efficiency between 66% and 74% depending on the pressure of H_2 delivered
  - Installed CAPEX ranges from 1,000 to 2,000 €/kWe depending on the capacity
  - Slight margin of improvement on energy efficiency
  - Cost reduction can be achieved but will remain limited (technology improvement and market volume effects)
- PEM electrolysers
  - Technology under demonstration
  - Efficiency is comparable to alkaline technology
  - Installed CAPEX for large capacities could reach 1,000 €/kWe at commercial stage, and decrease down to 400 €/kWe in 2050
- SOEC operates at high temperature to increase the energy efficiency but requires further development to confirm its performances and costs

Catalytic methanation is the most mature and investigated route for H_2 and CO_2 conversion into CH_4 but still requires technology development

- Catalytic methanation
  - Technology at demonstration status for power-to-gas applications
  - The chemical reaction produces large amounts of heat
  - Methanation is well known and controlled in the industry for large scale units and continuous operation
  - Power-to-gas applications imply smaller scale units and intermittent operation and require new types of reactors (i.e. isothermal instead of adiabatic)
  - R&D challenges are the control of the temperature inside the reactor and its operational flexibility
  - CAPEX estimates for catalytic methanation vary widely in the literature and from project developers (400 to 1,500 €/$kW_{HHV\text{-}SNG}$).
- Biological methanation
  - Offers an alternative with convenient temperatures levels (20-70°C)
  - Faces scale-up challenges due to inherent limitations (mass transfer inside the reactor and kinetics of the reaction)

Agenda

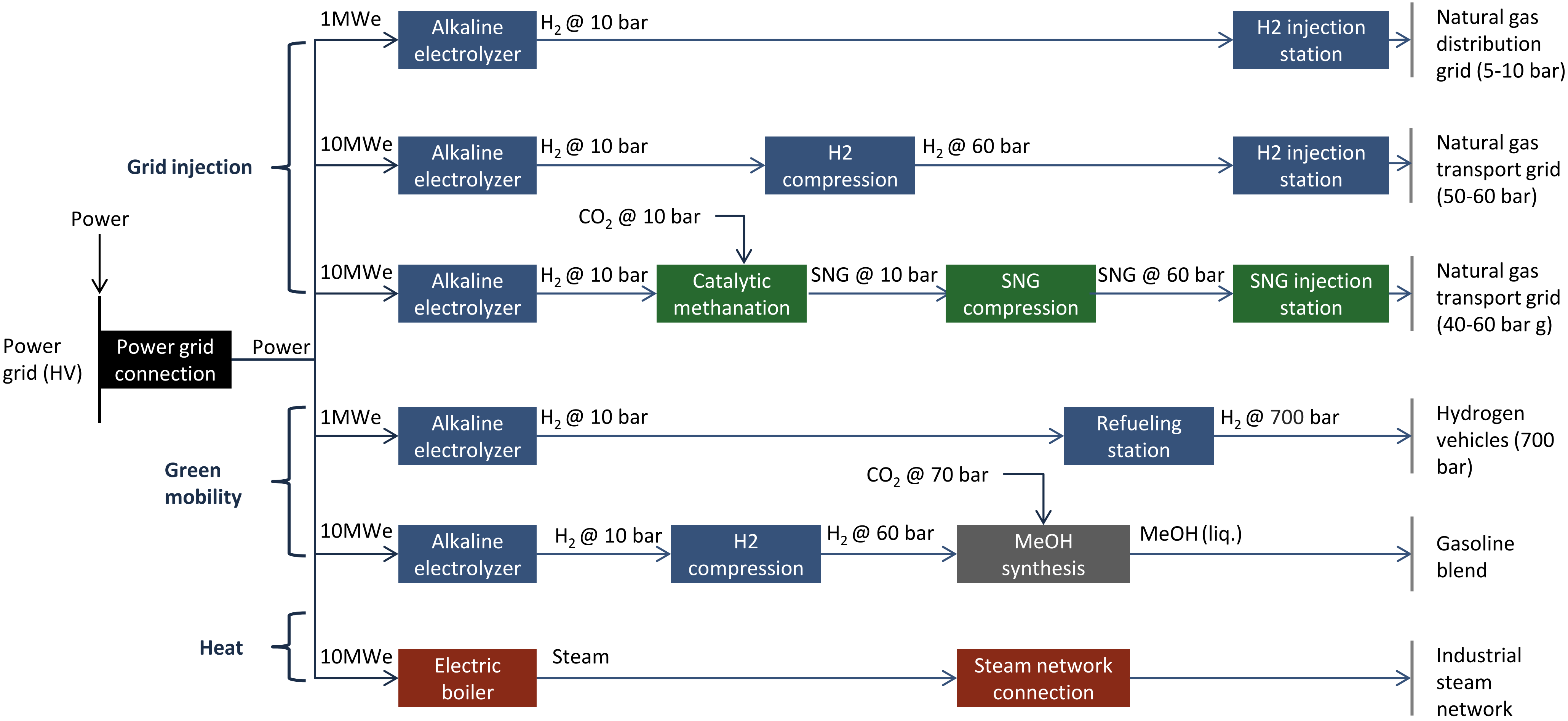
Introduction

Historical background and technology

Methodology for case studies analysis

Results of the case studies analysis

The analysis is based on 6 case studies focusing on potential mass market applications for energy

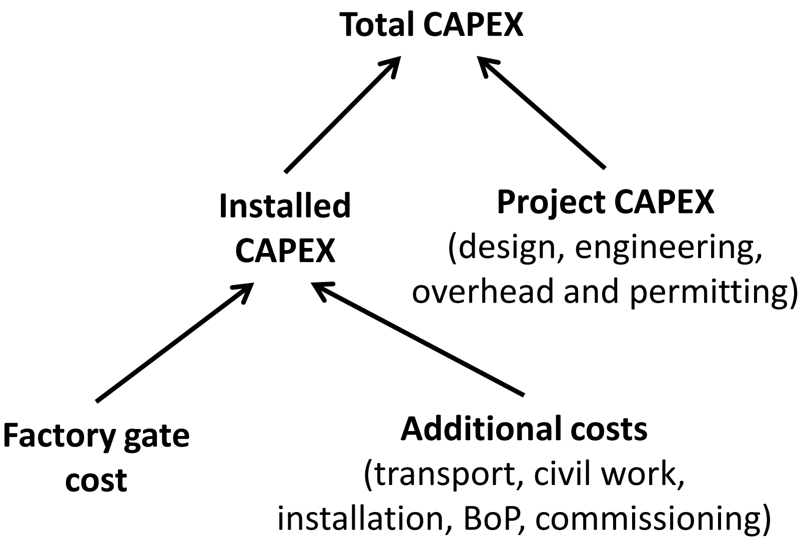


We compare the levelized cost of the final product with the market price of alternative products on the target market, for 3 time horizons (2015, 2030 and 2050)

- LCOX is the levelized cost of the product X, it represents the breakeven selling price of the product
- LCOX is calculated from
  - Capital expenditures (CAPEX) of the plant
  - Operational expenditures (OPEX) of the plant over the lifespan
  - Production of the plant over the lifespan
  - Weighted Average Cost of Capital (WACC)
- CAPEX, OPEX and production are calculated from a process bloc analysis
- WACC is considered as 8%

CAPEX and OPEX are estimated per block for equipment, installation and project costs

- CAPEX & OPEX are calculated **per block** in the plant (electrolyzer, compression, methanation reactor…)
- CAPEX of a block have been assessed as a breakdown of project costs, factory gate cost of equipment and additional costs:
  - With project costs = 30% of Equipments CAPEX
  - Installed CAPEX are assessed from interviews, literature, ENEA's projects
- OPEX = Electricity & CO_2 consumption + O&M costs
- O&M costs are assumed to be fixed and based on the installed CAPEX (%CAPEX/year)



Total CAPEX

Installed CAPEX

Project CAPEX
(design, engineering, overhead and permitting)

Factory gate cost

Additional costs
(transport, civil work, installation, BoP, commissioning)

Note

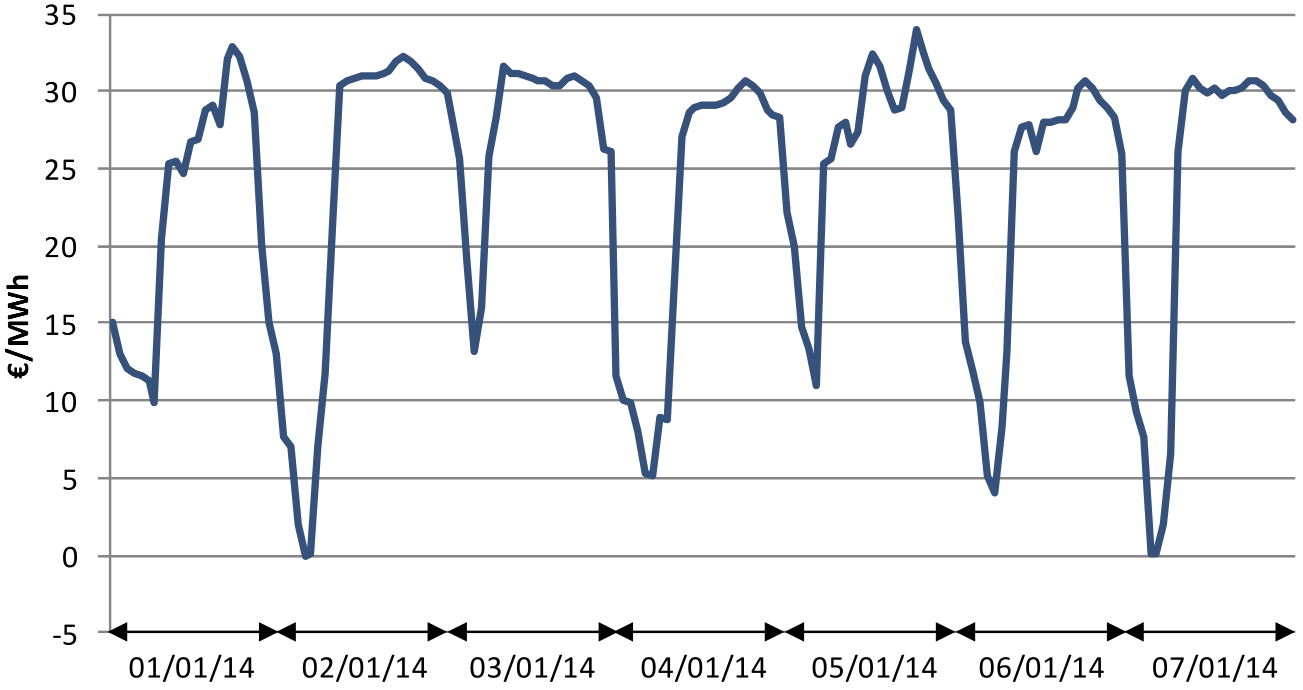
When not available, additional costs are assumed as:

- 50% of factory gate cost for methanation & methanol synthesis
- 15% of factory gate cost for compression

The price of electricity is the most volatile and critical OPEX for power-to-X plants

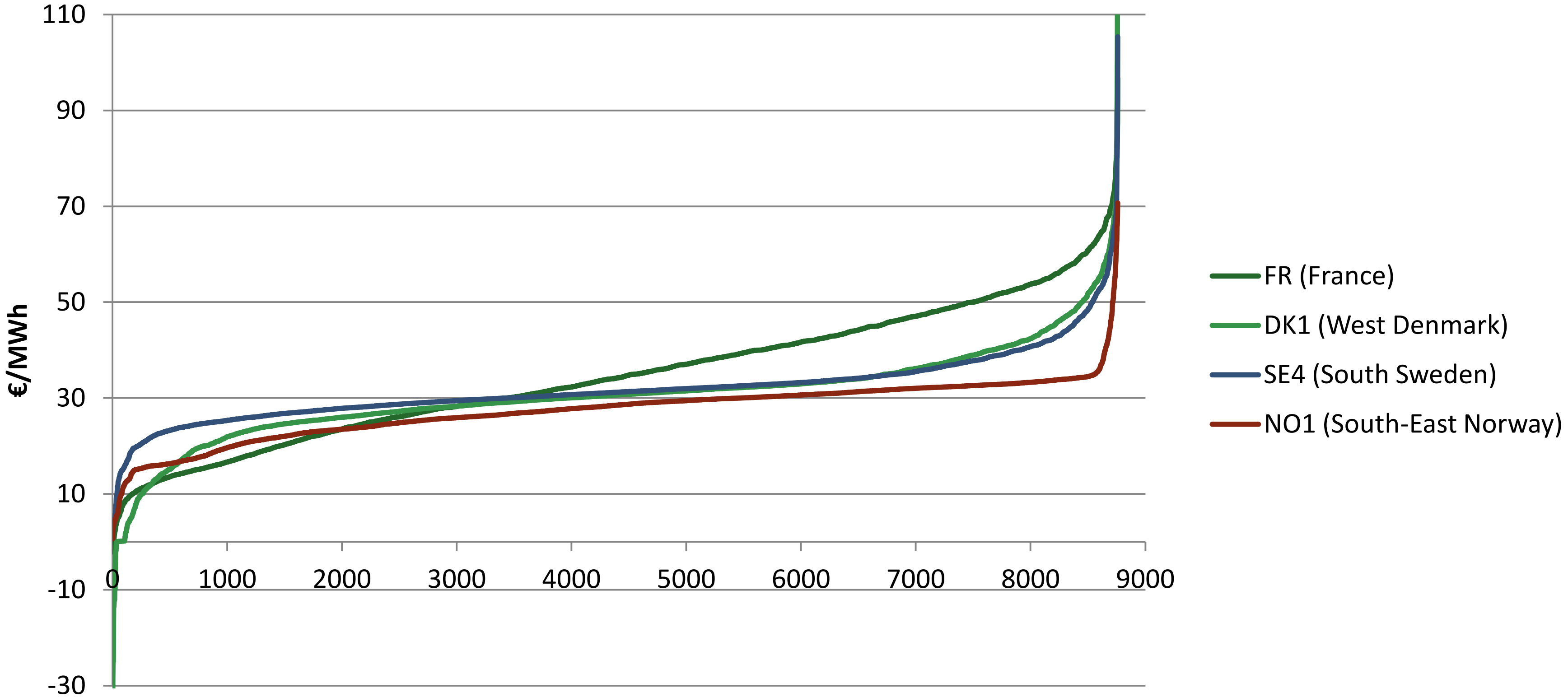
- Power-to-X plants should be operated preferably when the price of electricity is low

Spot NordPool prices of electricity in Denmark (DK1 zone) during the first week of January 2014



Electricity spot prices can be sorted hourly in a year from the lowest to the highest to give a price duration curve

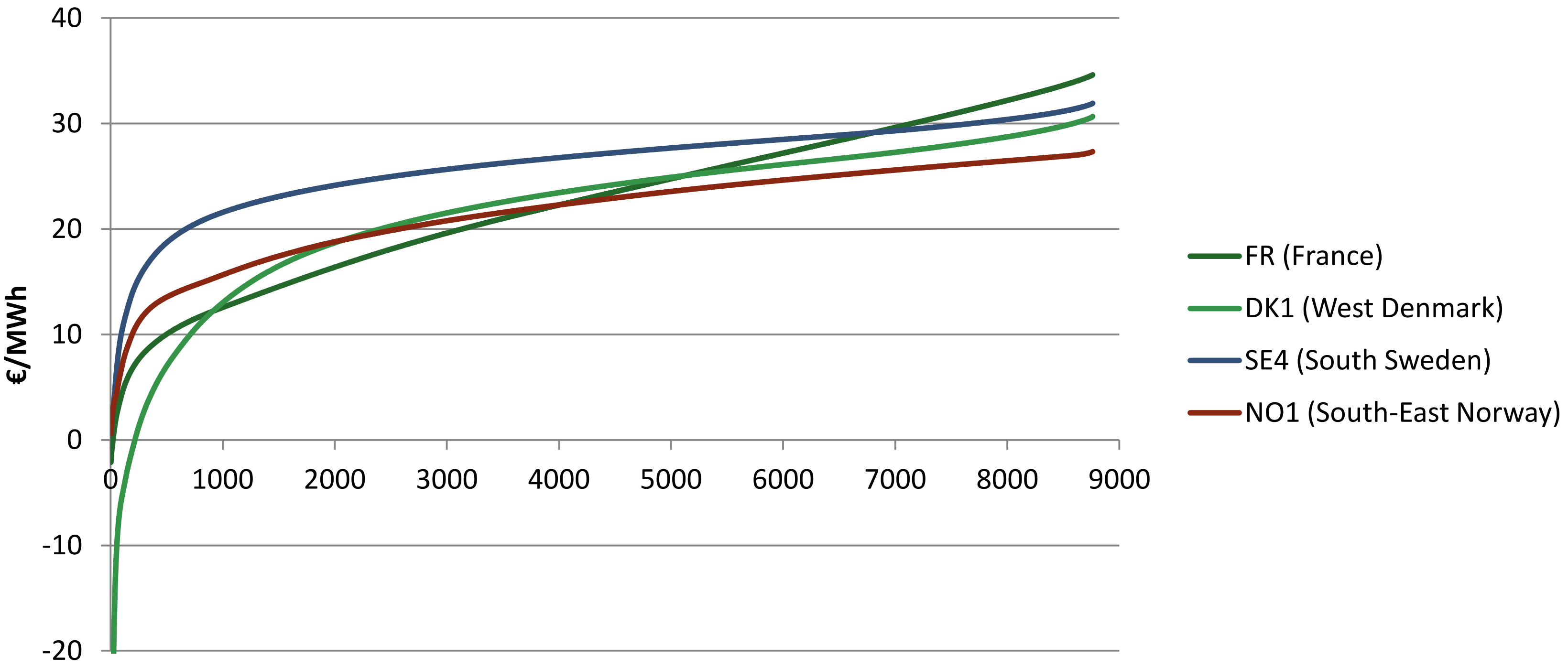
Electricity spot price duration curve for selected European zones in 2014



The average wholesale price of electricity for a power-to-X plant operating at the cheapest hours depends on the load factor and is calculated with the minimum average electricity spot price curve

- Operation on the cheapest hours requires the plant to be ideally flexible

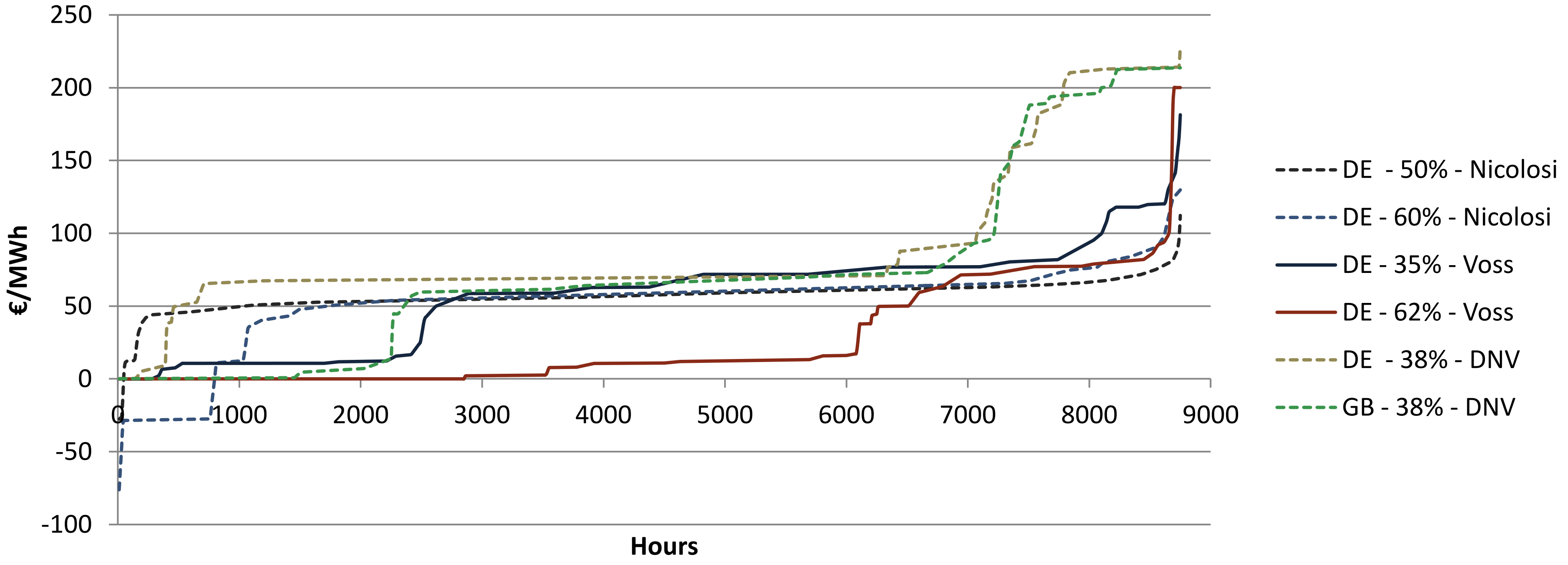
Minimum average electricity spot price for selected European zones in 2014



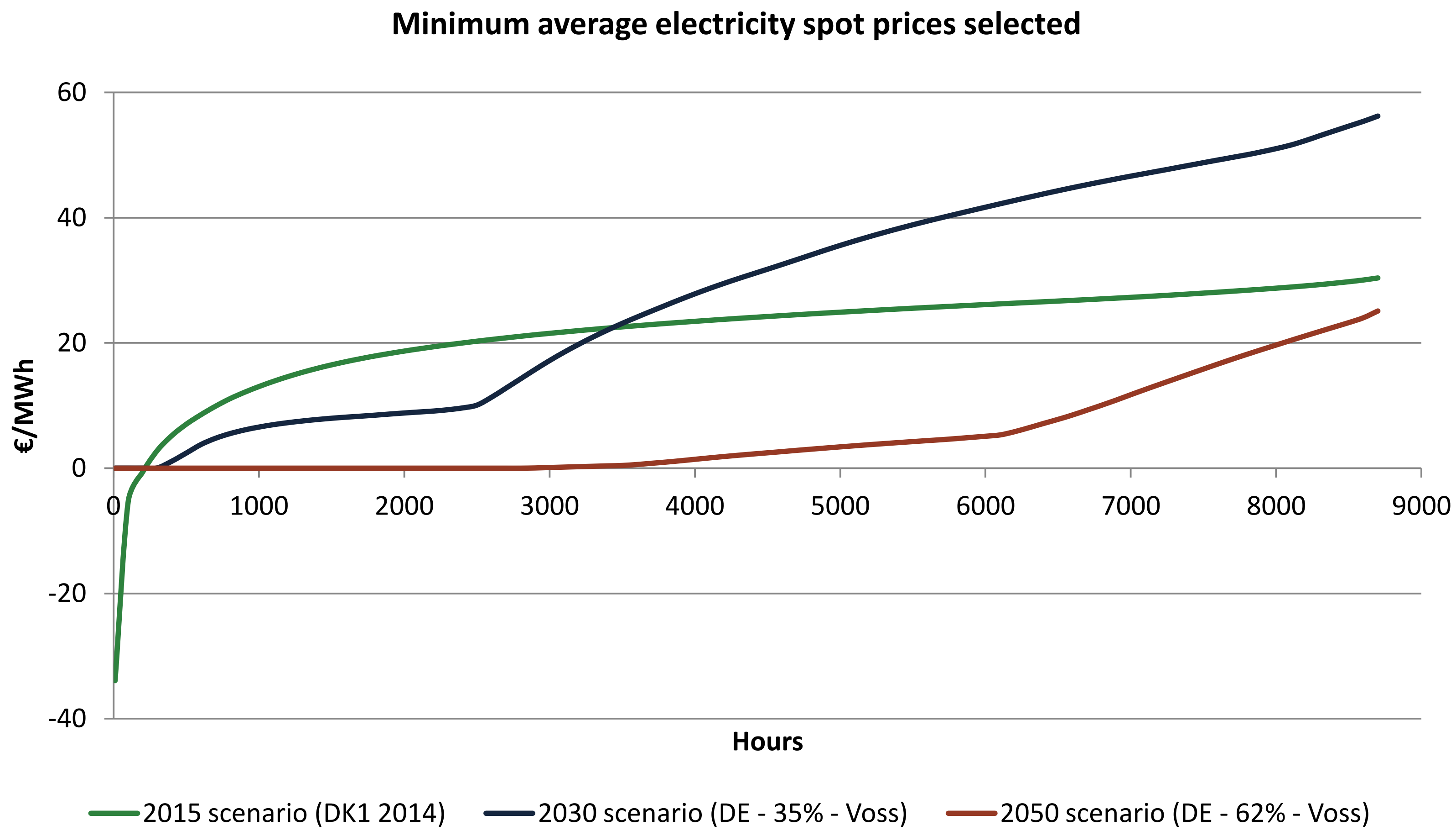
For 2030 and 2050 time horizons, prospective scenarios of electricity price available in the literature were used

- Sources used from the literature
  - Thesis published in 2011 by Marco Nicolisi (EWI – University of Köln)
  - Presentation performed in 2013 by Alfred Voss (IER – University of Stuttgart)
  - Report published in 2014 by DNV GL in cooperation with the Imperial College and NERA Economic Consulting

Prospective price duration curves derived from models and published in the literature.



Finally, one minimum average electricity spot price curve was selected for each time horizon



The final consumer price of electricity also comprises grid fees and electricity taxes

- The consumer price for electricity is composed of:
  - The wholesale price (curves shown previously)
  - Grid fees
  - Electricity taxes, for renewable electricity feed-in tariffs notably

- Grid fees were assumed to be fully variable although they are generally composed of a fixed share. The value used in the model is 10€/MWh.

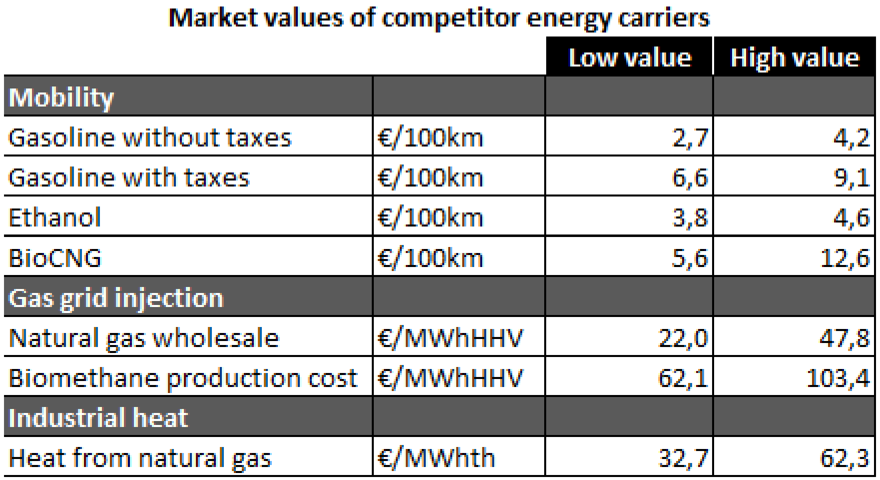
- 4 different assumptions on electricity taxes were used for LCOX calculation
  - No electricity taxes
  - 20€/MWh
  - 40€/MWh
  - 60€/MWh

Note

Grid fees and electricity taxes values do not vary with timeframe (2015; 2030; 2050) in the model.

Market values of competitor energy carriers

- Market values of competitor energy carriers are defined with low/high values
- For fossil fuels
  - The low value is the current market value without CO2 tax
  - The high value is the forecast market value 2030 (IEA WEO 2012) with a CO2 tax of 100€/tCO2
- For renewable fuels
  - The low value is the current (2015) lowest production cost or wholesale price
  - The high value is the current (2015) highest production cost or wholesale price



Market values of competitor energy carriers

		Low value	High value
Mobility			
Gasoline without taxes	€/100km	2,7	4,2
Gasoline with taxes	€/100km	6,6	9,1
Ethanol	€/100km	3,8	4,6
BioCNG	€/100km	5,6	12,6
Gas grid injection			
Natural gas wholesale	€/MWhHHV	22,0	47,8
Biomethane production cost	€/MWhHHV	62,1	103,4
Industrial heat			
Heat from natural gas	€/MWhth	32,7	62,3

Agenda

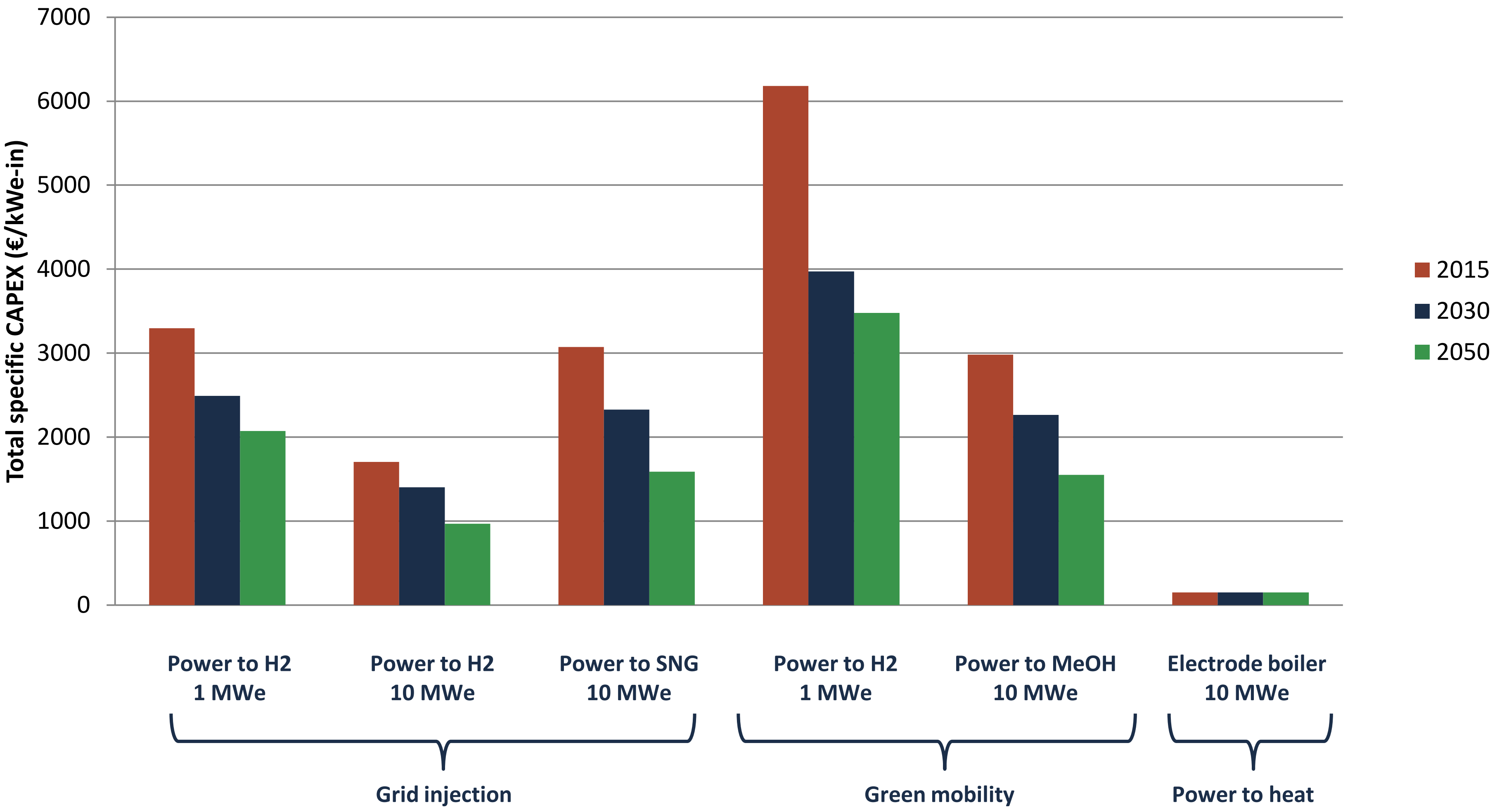
Introduction

Historical background and technology

Methodology for case studies analysis

Results of the case studies analysis

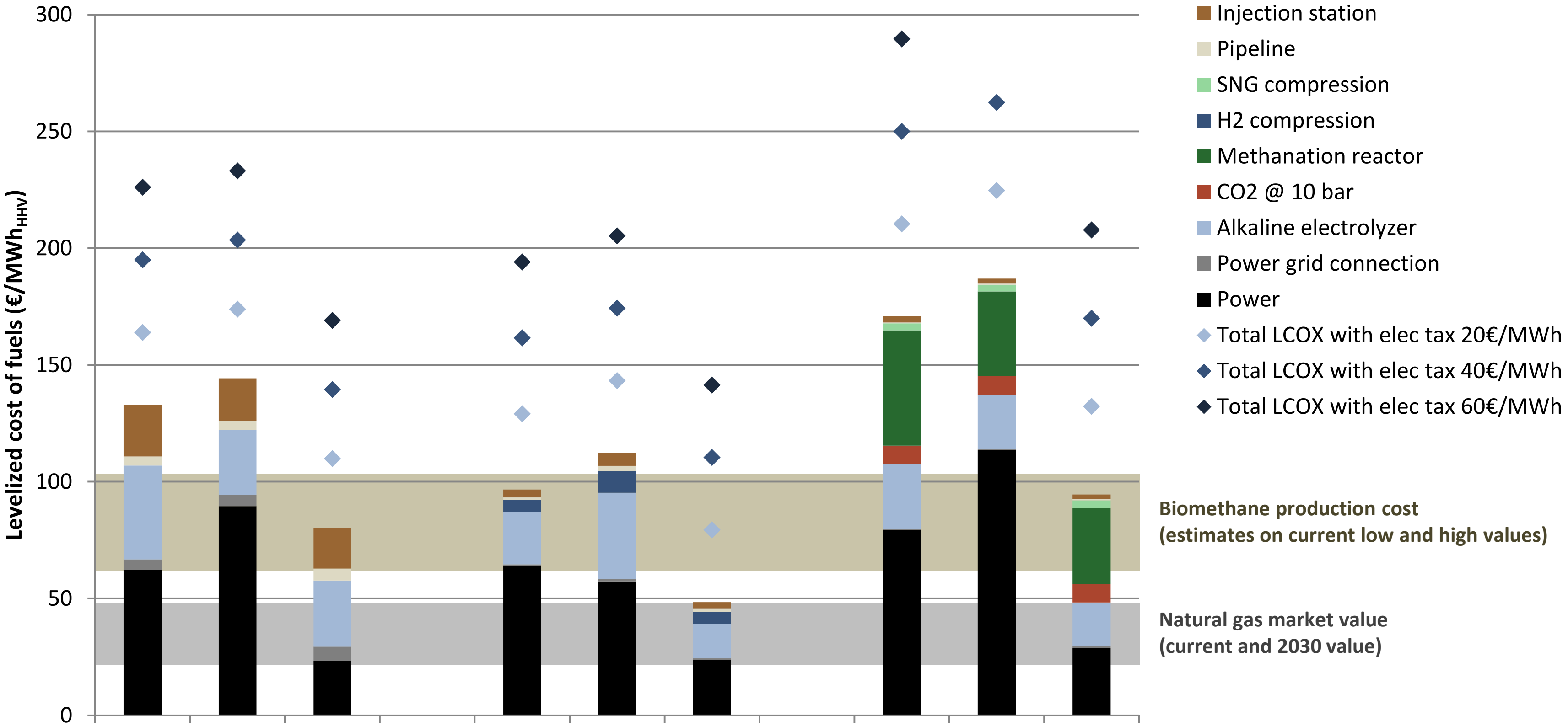
Total CAPEX of a plant varies significantly with scale effect and assumptions used on equipment cost decrease by 2030 and 2050



Total specific CAPEX of plants for the 3 time horizons

To compete with biomethane, power-to-gas with grid injection requires drastic CAPEX reduction, very low electricity prices and relatively high load factor

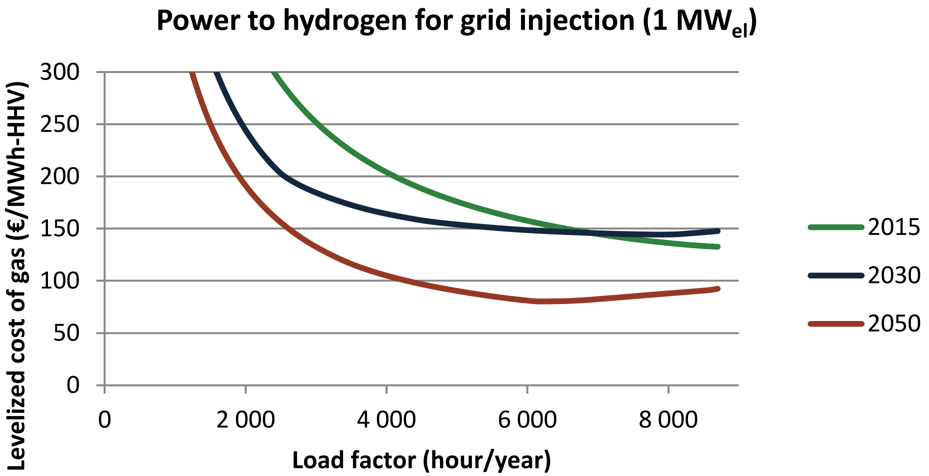
Levelized cost of fuels for grid injection from PtG plants at optimal load factors

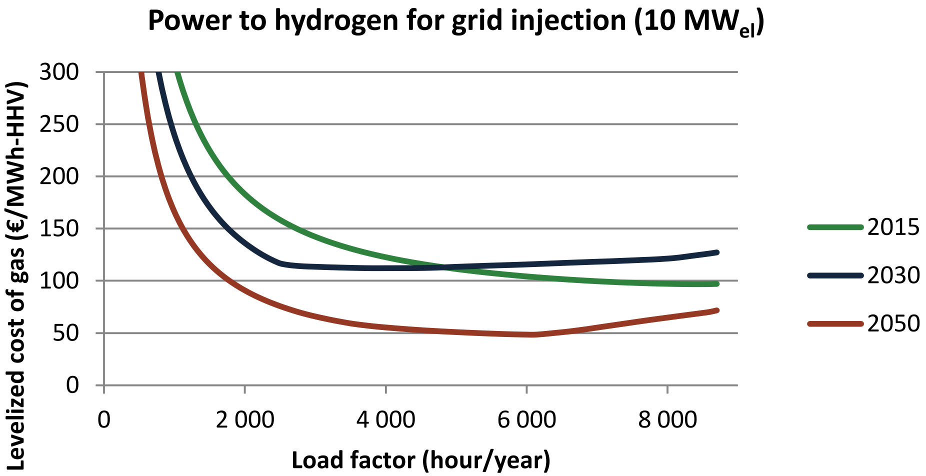


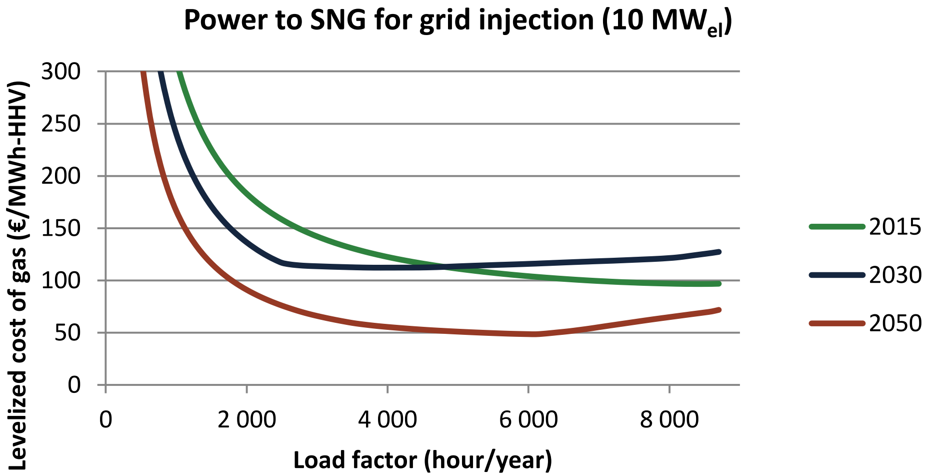
Scenario	2015	2030	2050	2015	2030	2050	2015	2030	2050
Load factor (h/year)	8,600	7,900	6,200	8,400	3,900	6,100	8,600	7,800	6,100
Elec price (€/MWh$_{el}$)	40.5	60.5	15.8	39.5	37.0	15.3	40.0	60.1	15.3
Case study	Power to Hydrogen 1 MW$_{el}$			Power to Hydrogen 10 MW$_{el}$			Power to SNG 10 MW$_{el}$		

CO$_2$ tax on natural gas for 2030 value: 100 €/t$_{CO2}$

To reach low LCOX a power-to-gas plant with grid injection must run at a relatively high load factor (i.e. from 2,500 to 6,000 hours/year)

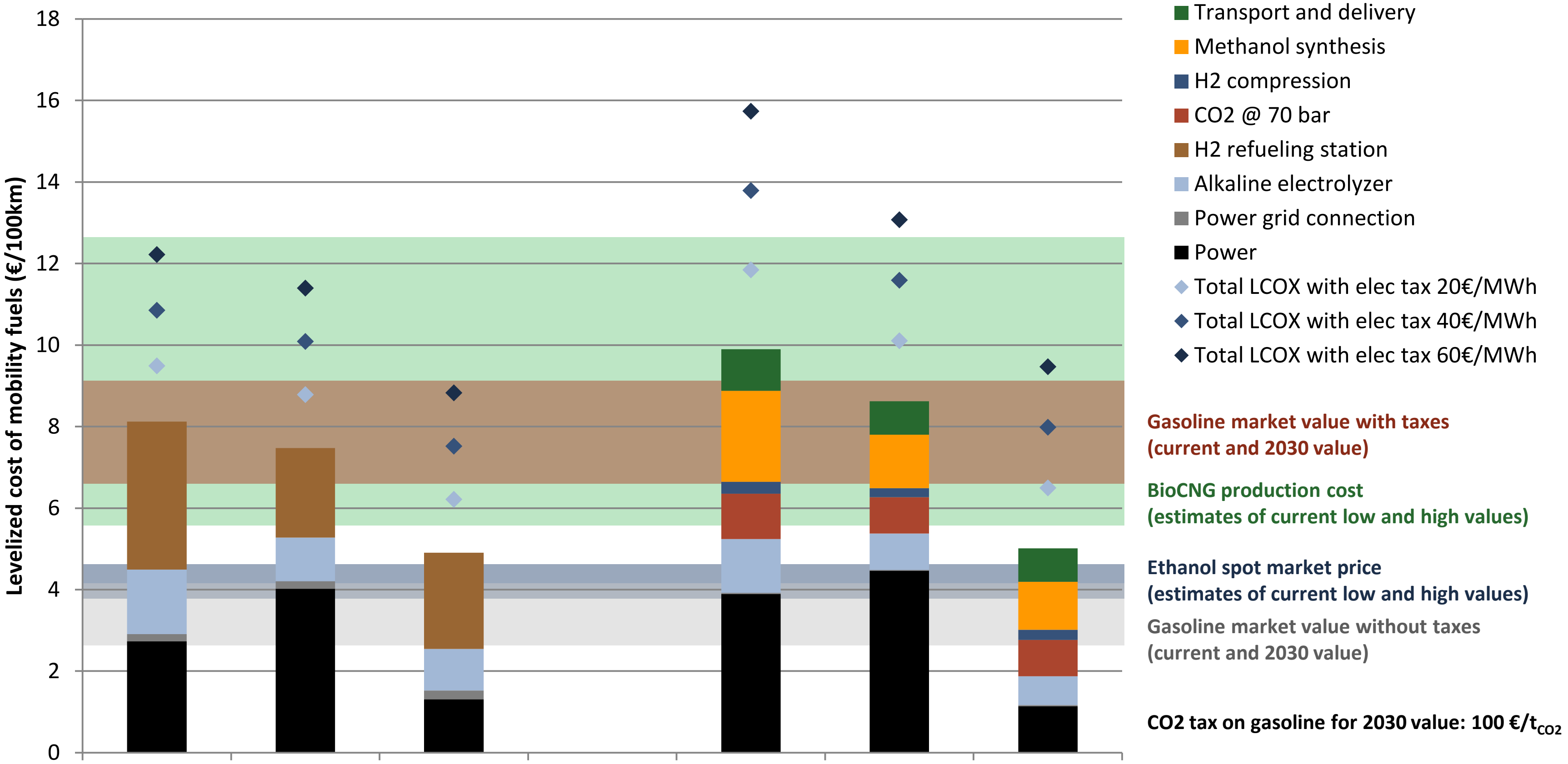

Power to hydrogen for grid injection (1 MW_{el})


Power to hydrogen for grid injection (10 MW_{el})


Power to SNG for grid injection (10 MW_{el})

Hydrogen and methanol produced from power already compete with bioCNG but are not likely to compete with fossil fuels without incentives

LCOX of mobility fuels from PtG or PtL plants at optimal load factor



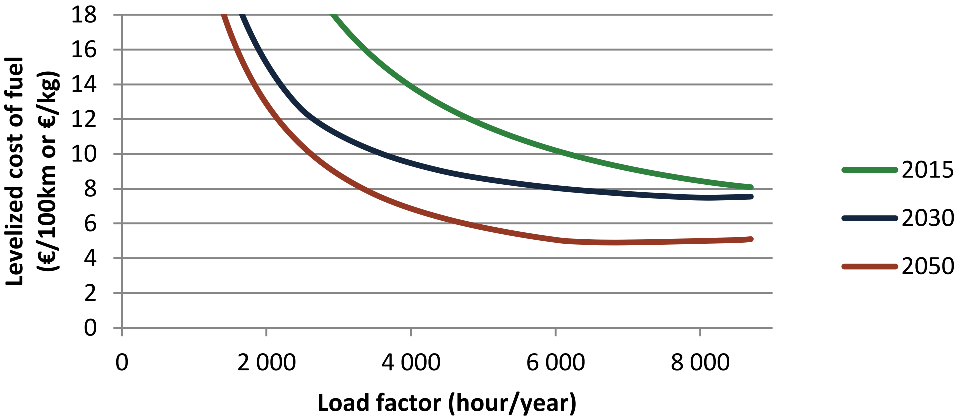
CO2 tax on gasoline for 2030 value: 100 €/t_{CO2}

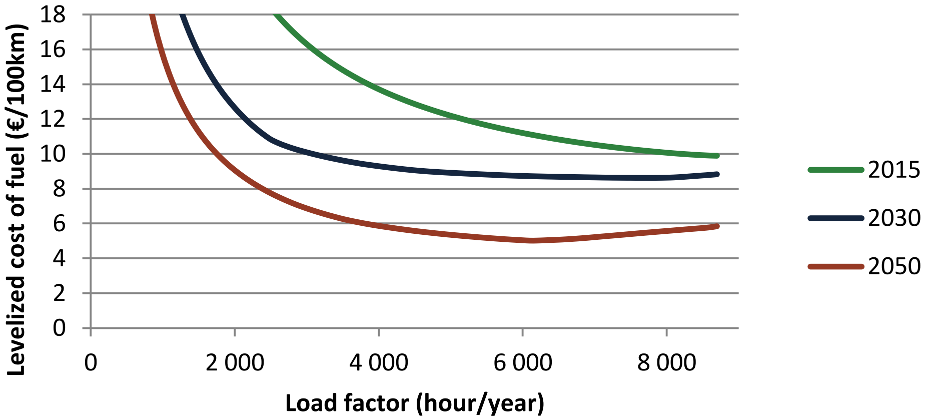
Scenario	2015	2030	2050	2015	2030	2050
Load factor (h/year)	**8,600**	**8,100**	**6,800**	**8,600**	**7,800**	**6,100**
Elec price (€/MWh_{el})	**40.0**	**61.6**	**20.1**	**40.0**	**60.1**	**15.3**
Case study	**Power to Hydrogen** **1 MW_{el}**			**Power to Methanol** **10 MW_{el}**		

Assumptions on fuel consumption for 100 km

- Hydrogen: 1 kg (2015, 2030 & 2050)
- Methanol: 7.7 L (2015), 6.1 L (2030 & 2050)
- Gasoline : 5L (2015), 4 L(2030 & 2050)
- BioCNG: 6.5 kg (2015, 2030 & 2050)
- Ethanol: 7.7 (2015), 6.1 (2030 & 2050)

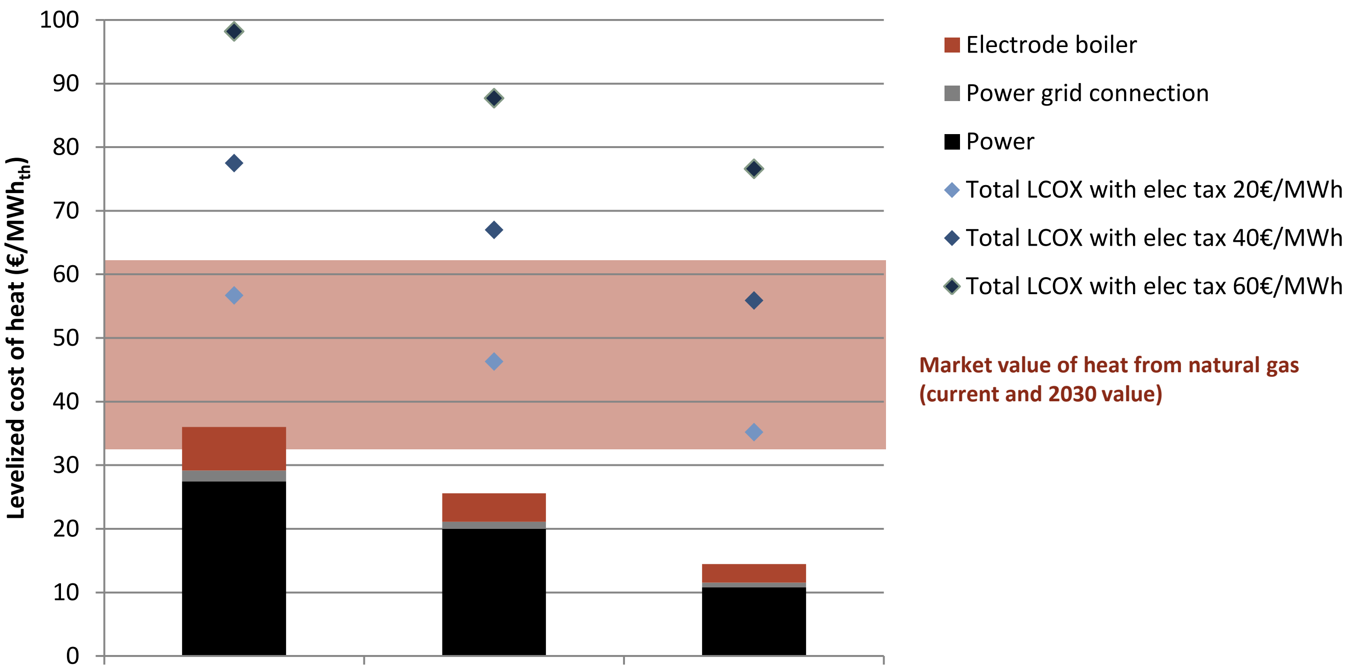
To reach low LCOX a power-to-gas plant for mobility applications must run at a high load factor (i.e. more than 6,000 hours/year)


Power to hydrogen for mobility (1 MW_{el})


Power to methanol for mobility (10 MW_{el})

The competitiveness of power-to-heat for industry with electrode boilers is highly depending on the spread between natural gas and electricity prices

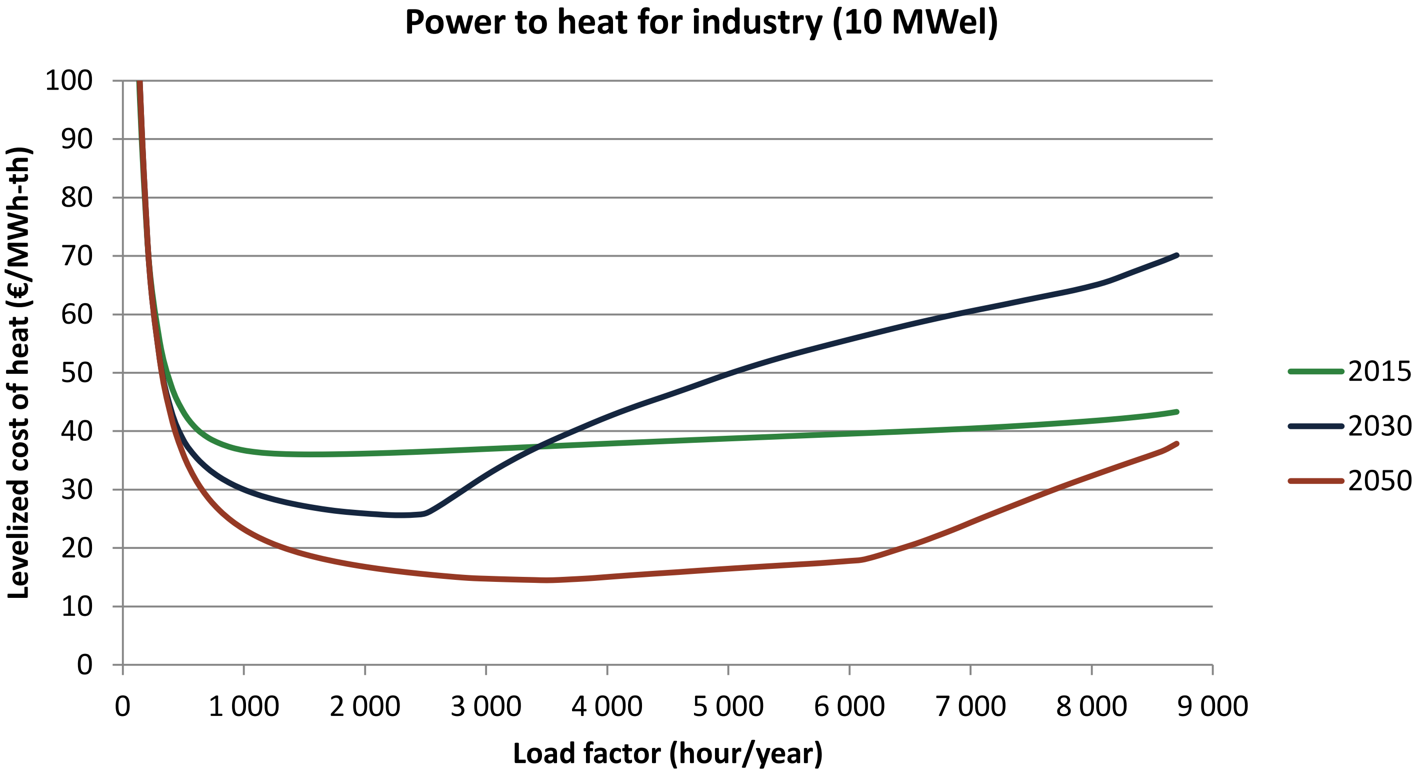
LCOX of heat from electrode boiler at optimal load factor



Market value of heat from natural gas (current and 2030 value)

Scenario	**2015**	**2030**	**2050**
Load factor (h/year)	**1,500**	**2,300**	**3,500**
Elec price (€/MWh)	**26.5**	**19.3**	**10.4**
Case study	**Power to Heat 10 MWe**		

Power-to-heat for industry with electrode boilers is suited for operation at reduced load factors (i.e. 1,000 to 2,000 hours/year)



Green mobility is the most promising market for power-to-gas and should be the first target for large scale deployment of power-to-gas

- To reach competitiveness power-to-gas plants require:
    - To operate at a high load factor
    - To position on high product value markets

- Finally, power-to-gas plant should be resilient to the price level of electricity which means that other power-to-X routes (ex: power-to-heat) potentially competing for the “low cost electricity” resource are not a real threat

- To compete with biomethane, power-to-gas for grid injection requires dramatic CAPEX decrease and electricity available at very low cost which are not likely.

- H_2 production from power for the green mobility market already compete with bioCNG and could be incentivised to compete with fossil fuels in the long term
    - Financial incentives on product taxes are mandatory to compete with fossil fuels
    - The cost structure is relatively resilient to electricity price level
    - In the long term, CAPEX reduction of plants will allow for reduced financial incentives

- But other solutions for green mobility comes in competition

A complementary analysis is worth to better assess the potential of power-to-hydrogen in comparison with the various available options for green mobility

- The present study is not oriented on mobility specifically and thus does not fully compare power-to-hydrogen with all other mobility options such as BioCNG, bioLNG, e-MeOH, biofuels 2G, electricity...

- A detailed comparison of these options, at country level and on multiple parameters is recommended to confirm the potential of power-to-hydrogen for this market:
  - Economics, CO2 emissions and air pollution, service provided (ex: autonomy), technology readiness, geographical coverage and infrastructure required, ramp-up scenario...

- The potential of power-to-X processes for non energy markets has not been considered in this study but could play a role in technology development (ex: H_2 for industrial use).

ENEA Consulting, your energy project partner

Environmental & Social Performance

- Stakeholder Management
- Social Acceptance
- Global Performance

Innovation

- Marketing, competition
- Business model optimization
- Project financing
- Investor advisory

Efficiency & Process

- Energy storage integration in infrastructure and processes
- Energy Efficiency
- AMO, Project management

Total
Technip
Engie
Veolia Environnement
Xylowatt
Cristopia Energy Systems
Air Liquide
CETH2
Rio Tinto Alcan
Suez environnement
Ergosup
Alstom
EDF
Axens IFP Group Technologies
Bouygues
AFD Agence Française de Développement
ADEME
Schneider Electric
fives
U Les nouveaux commerçants
IFP Innovation Energie Environnement
République Française
Ministère de l'Écologie, de l'Énergie, du Développement durable et de l'Aménagement du territoire
Caisse des Dépôts
atee Association Technique Énergie Environnement
Intermarché

ENEA Consulting
89 rue Réaumur, 75002 Paris

Tel : +33 (0)1 82 83 83 83
contact@enea-consulting.com
www.enea-consulting.com

Jacques de Bucy
Project Manager

Tel Fixe +33 (0)1 82 83 83 95
Mobile +33 (0)6 63 51 67 00
jacques.debucy@enea-consulting.com

Appendix

Input parameters used in the model

Sensitivity analysis

Input parameters used in the model (1/5)

Legend

Hard parameter
Calculated from another parameter (grey shading)

General assumptions	Unit	Fixed	2015	2030	2050
Project costs	*% of Total CAPEX of proces blocs*	30,0%			
WACC	*-*	8,0%			
Load factor	*h/year*	6 000			
Electricity cost	*€/MWhe*	20			
CO2 cost @ 10 bar	*€/ton*	50			
CO2 cost @ 100 bar	*€/ton*	100			
CO2 density	*ton/Nm3-CO2*	0,0018			
HHV volumic H2	*MWh/Nm3-H2*	0,0035			
HHV massic H2	*MWh/kg-H2*	0,0394			
HHV volumic SNG	*MWh/Nm3-SNG*	0,0113			
HHV massic SNG	*kWh/kg-SNG*	0,0145			
HHV massic MeOH	*kWh/kg-MeOH*	0,0056			

Power grid connection	Unit	Fixed	2015	2030	2050
Lifetime power grid connection	*years*	40			
Transformer capacity out - 1MW	*MWe*	1,0			
Transformer capacity out - 10MW	*MWe*	10,0			
Transformer losses	*%*	2,5%			
Length HV line	*km*	1,0			
Total CAPEX HV circuit breaker	*€*	125 000			
Specific CAPEX HV line	*€/km*	100 000			
Total CAPEX transformer	*€*	30 000			
Fixed OPEX power grid connection	*%CAPEX/year*	0,00			

Input parameters used in the model (2/5)

Legend

Hard parameter

Calculated from another parameter

Alkaline electrolyzis 10 bar	Unit	Fixed	2015	2030	2050
Lifetime electrolyzer	*years*	25			
Electrolyzer capacity in - 1MW	*MWe*	1,0			
Electrolyzer capacity in - 10MW	*MWe*	10,0			
Electrolyzer efficiency	*kWhHHV-H2/kWhe*		66%	69%	69%
Electrolyzer capacity out - 1MW	*MWHHV-H2*	0,7			
Electrolyzer capacity out - 10MW	*MWHHV-H2*	6,6			
Specific CAPEX electrolyzer - 1MW	*€/MWe in*		1 500 000	1 000 000	800 000
Specific CAPEX electrolyzer - 10MW	*€/MWe in*		1 000 000	800 000	500 000
Fixed O&M electrolyzer - 1MW	*% CAPEX/year*	4,5%			
Fixed O&M electrolyzer - 10MW	*% CAPEX/year*	1,5%			

Methanation	Unit	Fixed	2015	2030	2050
Lifetime methanation reactor	*years*	20			
Methanation capacity out - 10MW	*MWHHV-SNG*	5,24			
Methanation efficiency	*MWhHHV-SNG out/MWhHHV-H2 in*	79,4%			
Specific cost methanation reactor - 10MW	*€/MWHHV-SNG out*		1 500 000	1 000 000	700 000
Additional cost methanation reactor	*% cost methanation reactor*	50%			
Fixed O&M methanation - 10MW	*% cost methanation reactor/year*	7,5%			
Methanation H2 consumption	*Nm3H2/Nm3SNG*	4,0			
Methanation CO2 consumption	*Nm3CO2/NmSNG*	1,0			

Input parameters used in the model (3/5)

Legend

Hard parameter

Calculated from another parameter

Compression H2	Unit	Fixed	2015	2030	2050
Lifetime compressor H2	*years*	15			
Compressor H2 capacity out - 1MW	*MWHHV-H2*	0,66			
Compressor H2 capacity out - 10MW	*MWHHV-H2*	6,60			
Cost compressor H2 - 1MW	*€*	200 000		180 000	160 000
Cost compressor H2 - 10MW	*€*	1 261 915			
Additional cost compressor H2	*% cost compressor*	15,0%			
Fixed O&M compressor H2 10-60bar	*% CAPEX/year*	6,0%			
Power consumption compressor H2 10-60bar	*MWhe/MWhHHV-H2*	-0,93			

Compression SNG	Unit	Fixed	2015	2030	2050
Lifetime compressor SNG	*years*	15			
Compressor SNG capacity out - 10MW	*MWHHV-SNG*	5			
Cost compressor SNG - 10MW	*€*	630 957			
Additional cost compressor SNG	*% cost compressor*	15,0%			
Fixed O&M compressor SNG 10-60bar	*% CAPEX/year*	6,0%			
Power consumption compressor SNG 10-60bar	*MWhe/MWhHHV-SNG*	0,02			

Input parameters used in the model (4/5)

Legend

Hard parameter

Calculated from another parameter

Pipeline H2 & SNG	**Unit**	**Fixed**	**2015**	**2030**	**2050**
Lifetime pipeline	*years*	35			
Pipeline capacity out - 1MW	*MWHHV-H2*	0,66			
Pipeline capacity out - 10MW	*MWHHV-H2*	6,60			
Pipeline length	*km*	1,00			
Fixed CAPEX pipeline H2 @10 bar	*€*	50 000			
Variable CAPEX pipeline H2 @10 bar	*€/km*	130 000			
Fixed CAPEX pipeline H2 @60 bar	*€*	200 000			
Variable CAPEX pipeline H2 @60 bar	*€/km*	300 000			
Fixed O&M pipeline	*% CAPEX/year*	-98%			

Injection station H2 & SNG	**Unit**	**Fixed**	**2015**	**2030**	**2050**
Lifetime injection station	*years*	15			
Injection station capacity out - 1MW	*MWHHV-H2*	0,66			
Injection station capacity out - 10MW	*MWHHV-H2*	6,60			
Total CAPEX distribution injection station - 1MW	*€*		600 000	480 000	360 000
Total CAPEX distribution injection station - 10MW	*€*		700 000	560 000	420 000
Total CAPEX transport injection station - 1MW	*€*		700 000	560 000	420 000
Total CAPEX transport injection station - 10MW	*€*		900 000	720 000	540 000
Fixed O&M injection station	*%CAPEX/year*	8,0%			

Input parameters used in the model (5/5)

Legend

Hard parameter

Calculated from another parameter

Refueling station H2	Unit	Fixed	2015	2030	2050
Lifetime H2 refueling station	*years*	30			
H2 refueling station capacity out - 1MW	*MWHHV-H2*	0,66			
Total CAPEX H2 refueling station - 1MW	*€*		3 000 000	1 800 000	1 620 000
Fixed O&M H2 refueling station - 1MW	*%CAPEX/year*	-92,5%			
Power consumption H2 refueling station	*MWhe/MWhHHV-H2*	-0,82			

Methanol synthesis	Unit	Fixed	2015	2030	2050
Lifetime methanol reactor	*years*	20			
Methanol reactor capacity out - 10MW	*MWHHV-MeOH*	4,99			
Methanol reactor H2 consumption	*kgH2/kgMeOH*	0,19			
Methanol reactor CO2 consumption	*kgCO2/kgMeOH*	1,38			
Methanol synthesis efficiency	*MWhHHV-MeOH out/MWhHHV-H2 in*	0,76			
Specific CAPEX methanol reactor - 10MW	*€/MWHHV-MeOH out*		1 500 000	1 000 000	700 000
Additional cost methanol reactor	*% cost methanol reactor*	50%			
Fixed O&M methanol reactor - 10MW	*%CAPEX/year*	7,5%			

Electrode boiler	Unit	Fixed	2015	2030	2050
Lifetime electrode boiler - 10MW	*years*	40			
Electrode boiler capacity out - 10MW	*MWth*	10			
Electrode boiler efficiency	*MWhth/MWhe*	-1%			
Specific total CAPEX electrode boiler - 10MW	*€/MWth out*	89 999			
Fixed O&M electrode boiler - 10MW	*%CAPEX/year*	-98,8%			

Appendix

Input parameters used in the model

Sensitivity analysis

Conditions used for sensitivity analysis

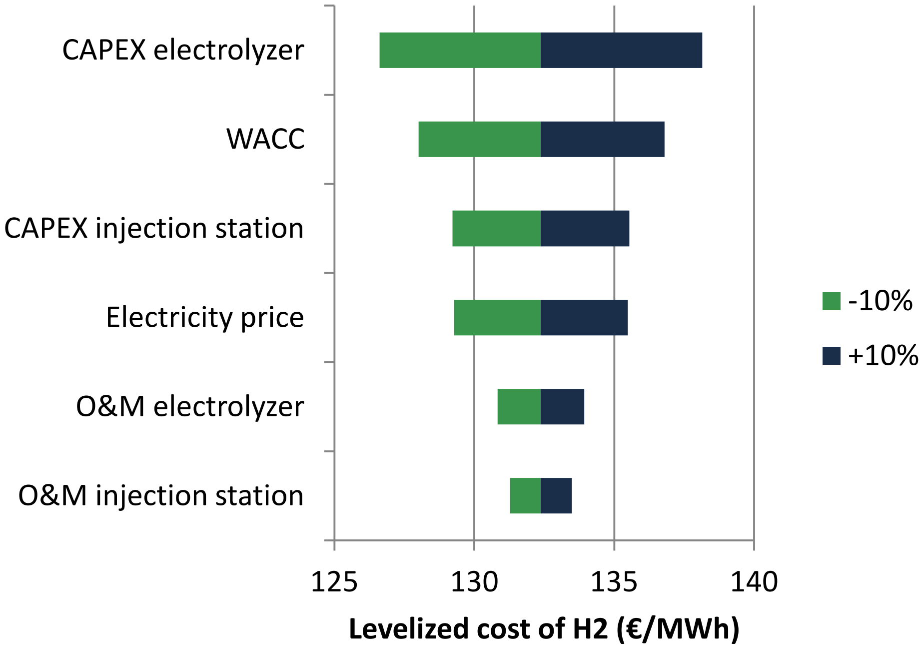
- Common nominal parameters
  - Load factor : 6000 hour/year
  - Electricity price: 20 €/MWh
  - WACC: 8%

- Type of sensitivity analysis
  - LCOX structure: variation of +/- 10% on each parameter
  - Project and technologies: ranges on each parameter with uncertainties or potential improvements/underestimates

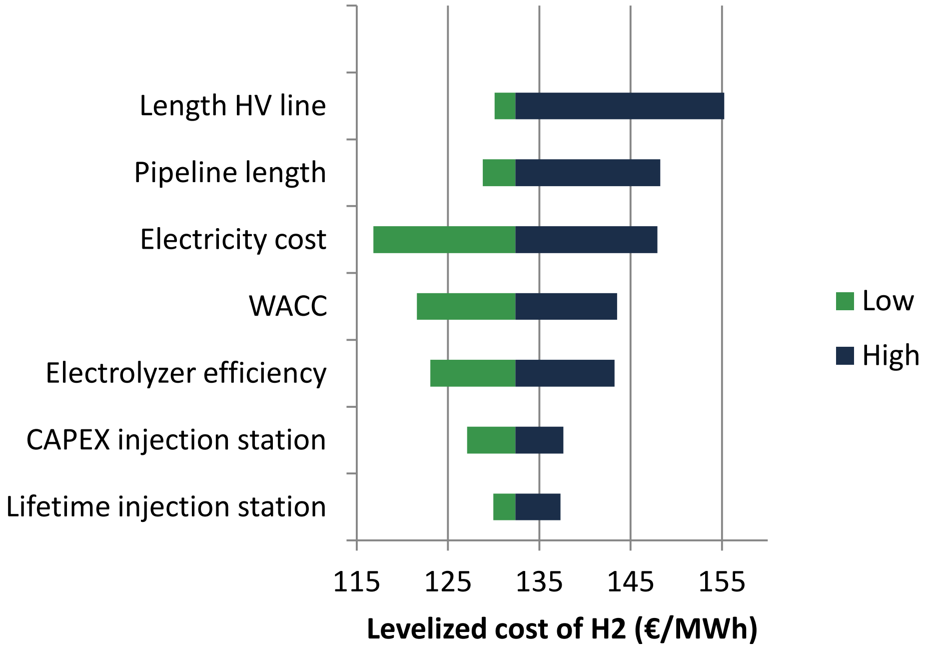
Hydrogen injection at small scale (1 MWe)

- LCOX structure: CAPEX and electricity price
- Project & technologies: HV line & pipeline length, electrolyzer efficiency

H2 injection 1 MWe
Sensitivity analysis (+/- 10%)

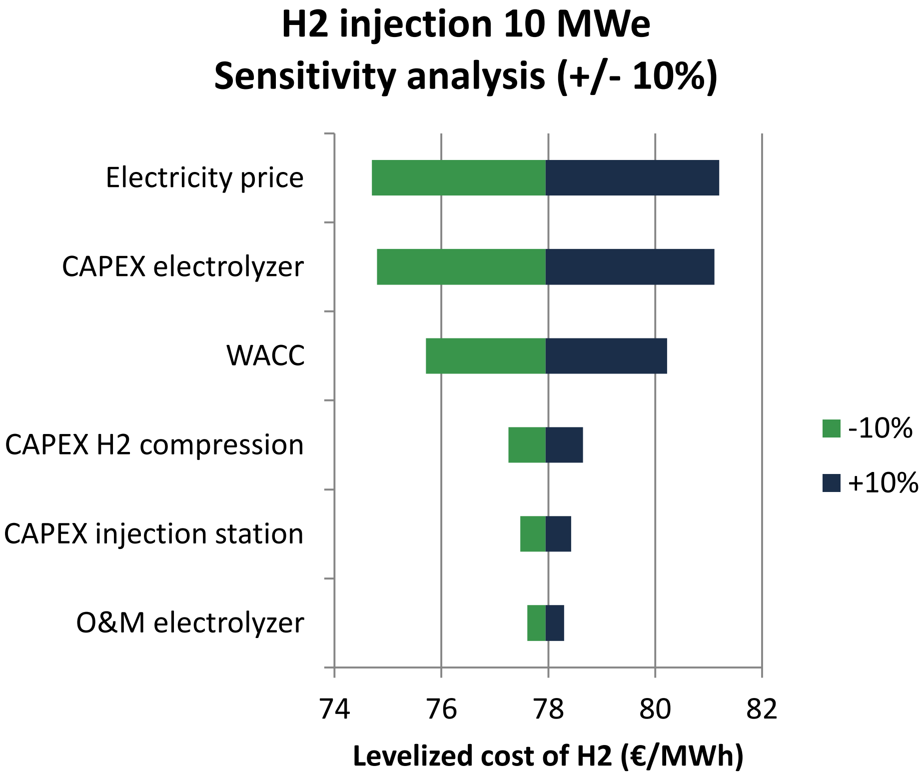


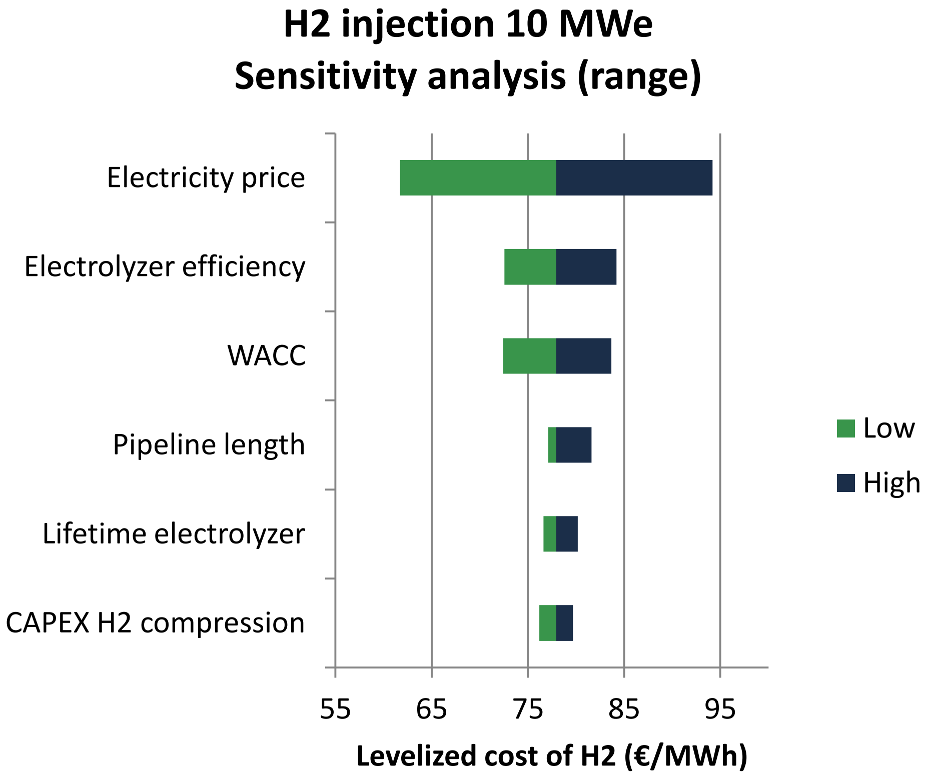
H2 injection 1 MWe
Sensitivity analysis (range)



Hydrogen injection at medium scale (1 MWe)

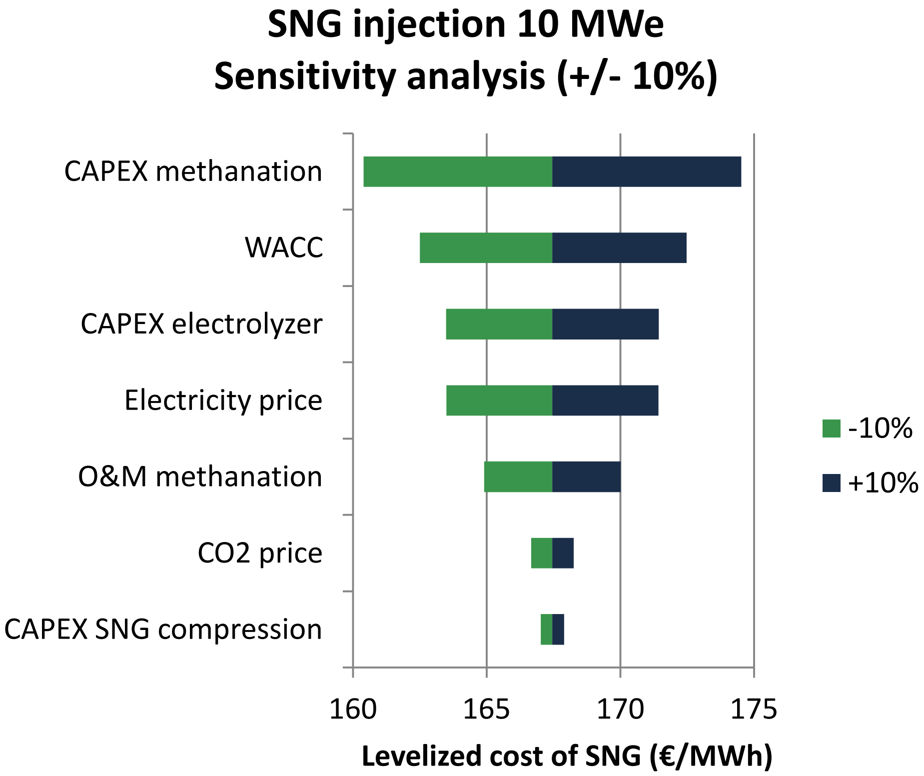
- LCOX structure: CAPEX and electricity price
- Project & technologies: Electricity price, electrolyzer efficiency, WACC

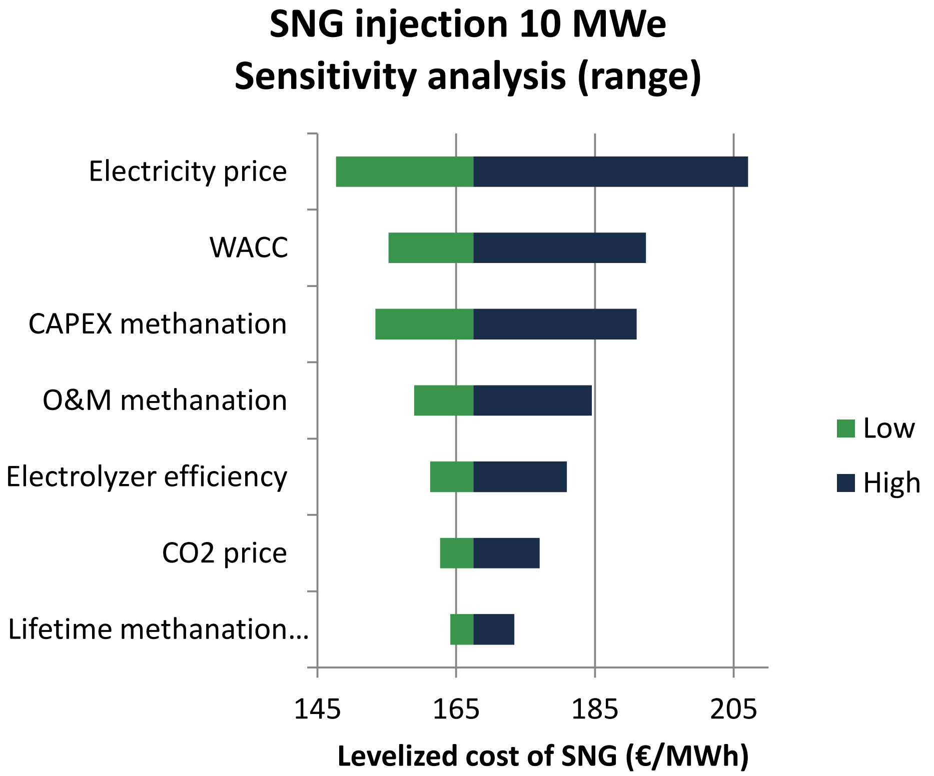




SNG injection (10 MWe)

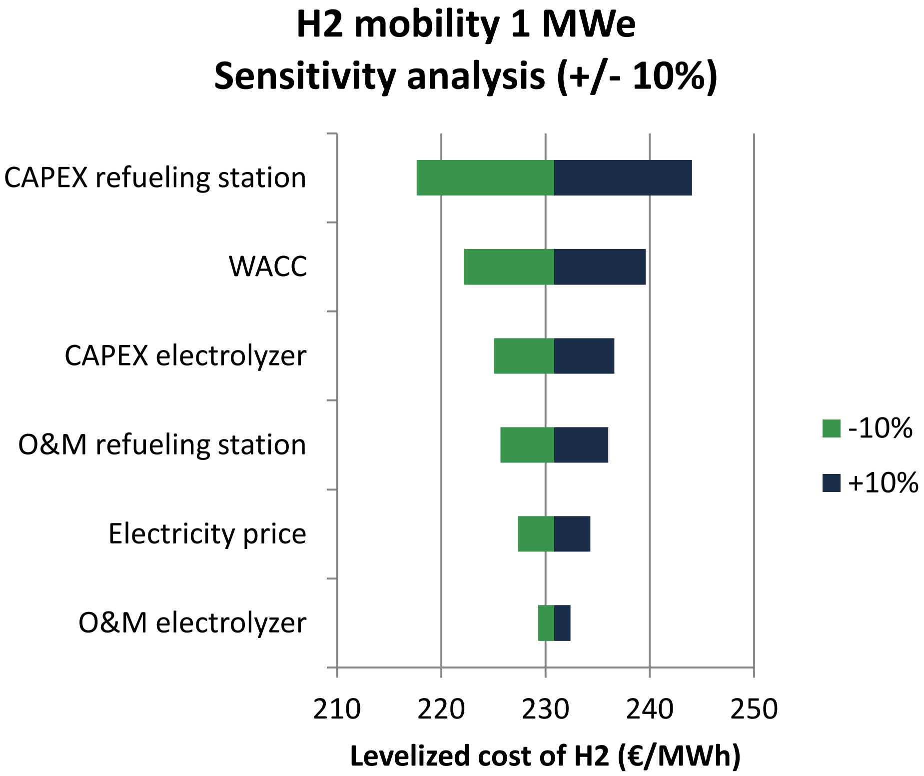
- LCOX structure: CAPEX, electricity price and O&M methanation
- Project & technologies: electricity price, CAPEX and O&M methanation

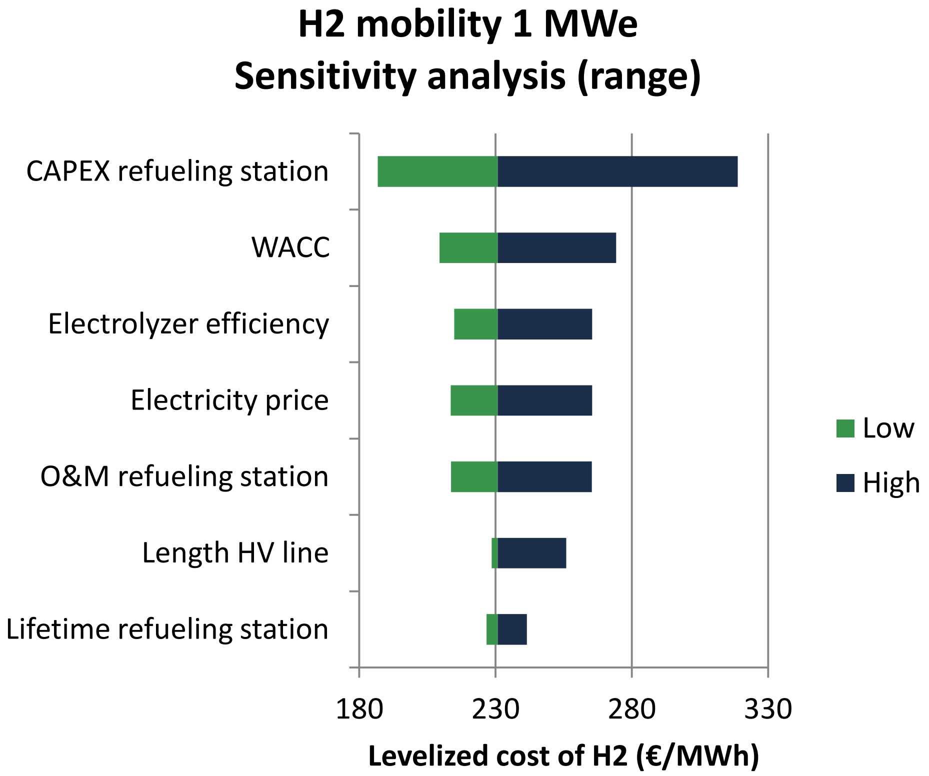




H2 mobility (1 MWe)

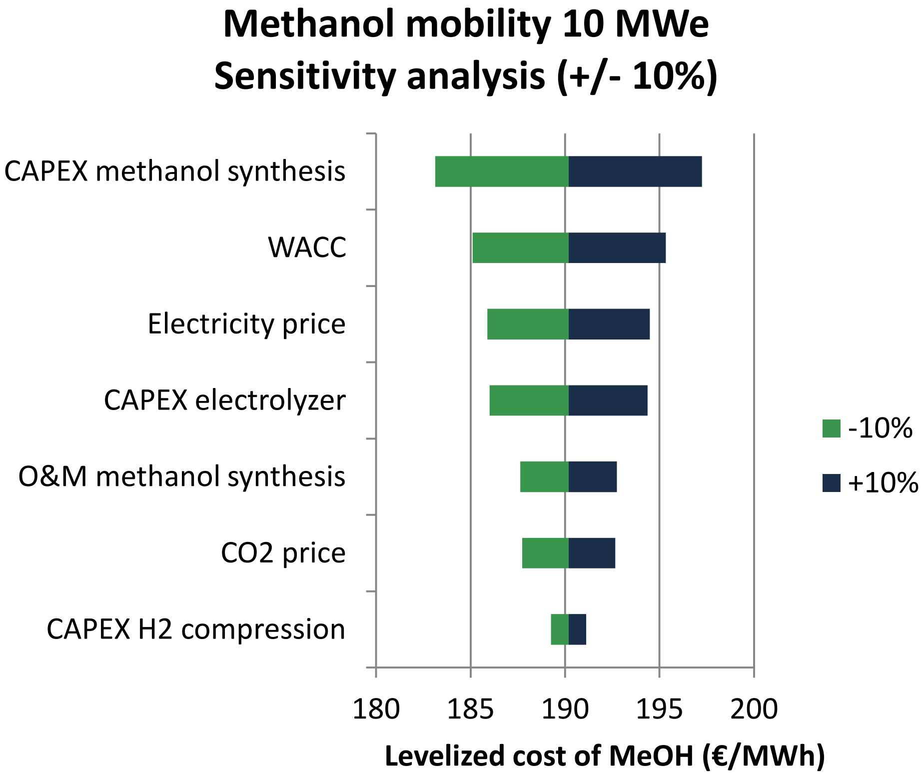
- LCOX structure: CAPEX, O&M refueling station
- Project & technologies: CAPEX, electrolyzer efficiency, electricity price, O&M refueling station

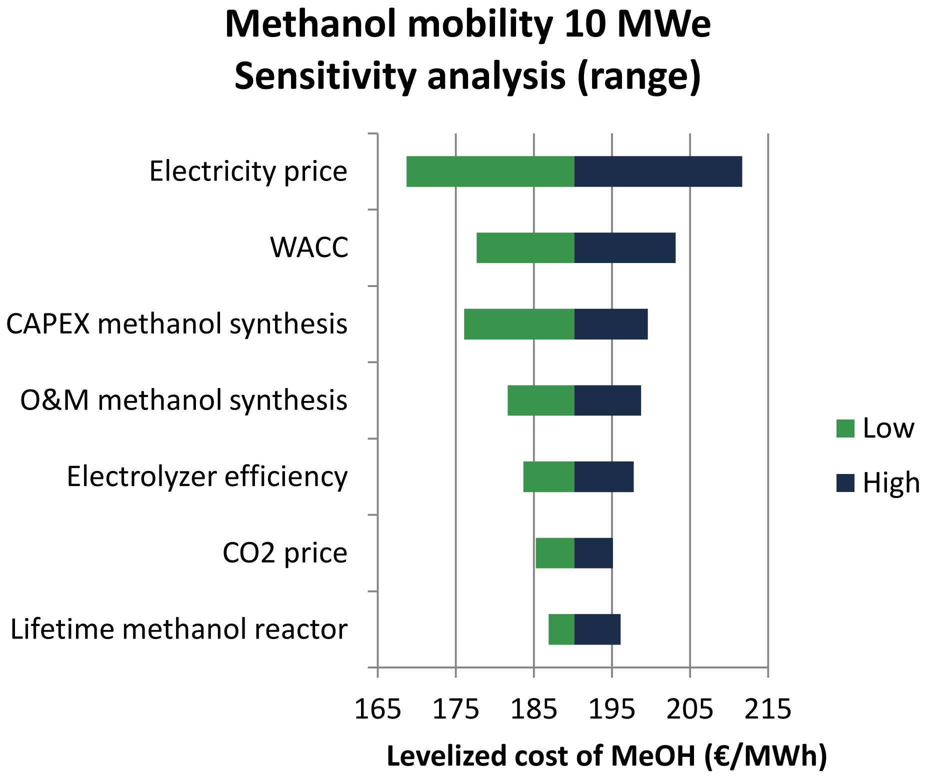




Methanol mobility (10 MWe)

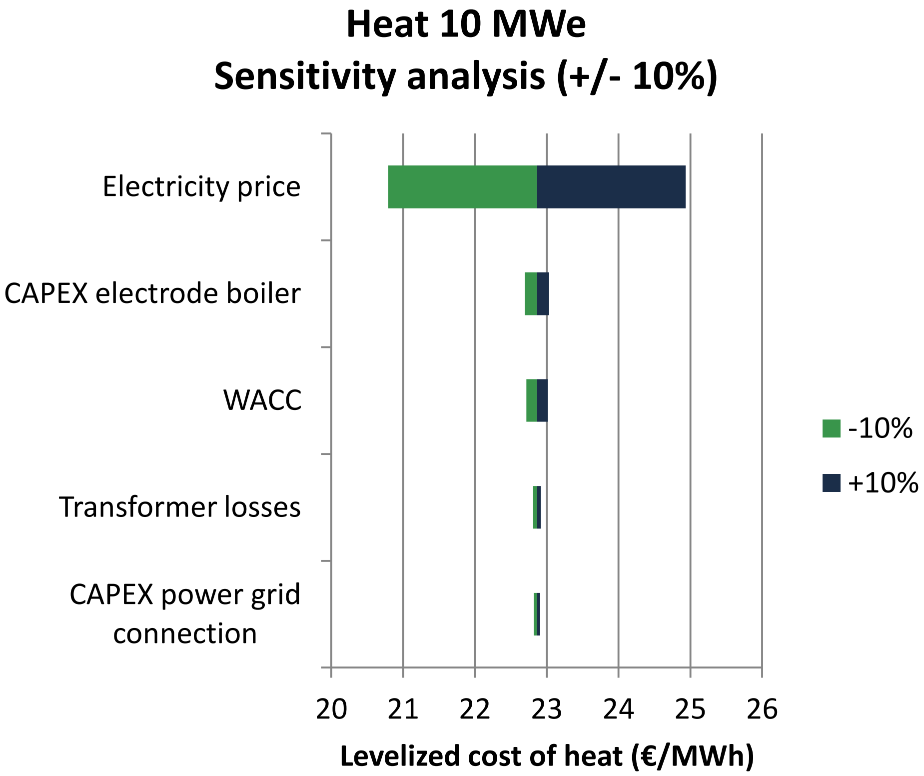
- ► LCOX structure: CAPEX, electricity price, O&M methanol synthesis
- ► Project & technologies: electricity price, CAPEX, O&M methanol synthesis, electrolyzer efficiency

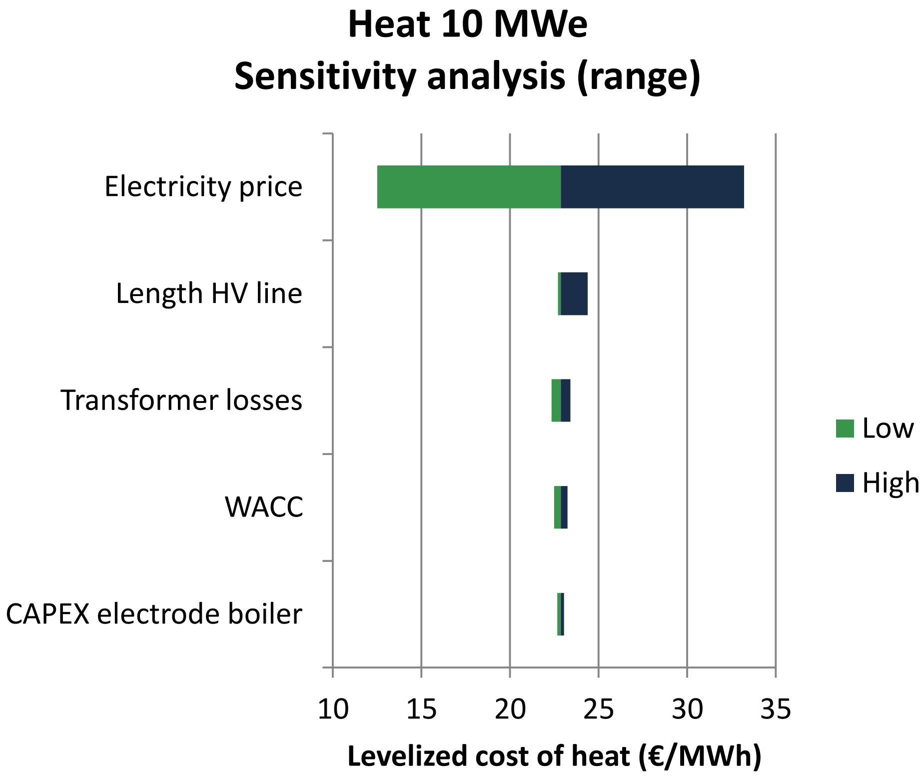




Heat (10 MWe)

- LCOX structure: electricity price
- Project & technologies: electricity price





Variations on costs of technologies under development can significantly modify the LCOX (high uncertainty)

- CAPEX intensive blocks and O&M based on the CAPEX
- Wide range of value due to the lack of commercial maturity and feedback on the actual cost of these blocks

Type of parameter	Technology/block	Range (Low/Nominal/High)	Variation on LCOX
CAPEX	Injection station (distribution)	500/600/700 k€ for H2 injection (1 MWe)	-4% to +4%
CAPEX	H2 refueling station	2/3/4 M€ for 1MWe	-19% to +19%
CAPEX	Methanation reactor (without integration costs)	1200/1500/1700 €/kWout	-8% to +5%
CAPEX	Methanol synthesis (without integration costs)	1200/1500/1700 €/kWout	-7% to +5%
O&M	H2 refueling station	6%/8%/10% of CAPEX (with integration costs)	-8 to +8%
O&M	Methanation reactor	6%/8%/10% of CAPEX (with integration costs)	-5% to +5%
O&M	Methanol synthesis	6%/8%/10% of CAPEX (with integration costs)	-5% to +5%

Variations on input consumption and price impact all case studies concerned but are controlled (low uncertainty)

- Electricity price and load factor are critical parameters that are the focus of our modelling with electricity price duration curves
- Electrolyzer efficiency
  - Current value (66% with auxiliaries) is well known from commercial operation
  - A slight improvement is assumed by 2030 (69%) due to auxiliaries mutualization
- CO2 price
  - The impact on the LCOX is limited
  - The purchase of CO2 can be discussed for methanation (free CO2 from biogas upgrading facility)

Type of parameter	Technology/block	Range (Low/Nominal/High)	Variation on LCOX
Energy efficiency	Electrolyzer	61%/66%/71%	-7% to +8% for H2 cases -4% to +4% for SNG & MeOH cases
CO2 price	Methanation	20/50/80 €/t_{CO2}	-3% to +3%
CO2 price	Methanol synthesis	80/100/120 €/t_{CO2}	-3% to +3%

Long distances to power grid and gas grid can rapidly increase costs

- These parameters are sensitive for small scale capacities (1 MWe) and depend on the project
- A plant located at 10 km from the power grid or the gas grid and with a small production capacity (1 MWe) will be highly impacted by the CAPEX of HV line or pipeline.
- With a nominal value set at 1 km for both HV line and gas pipeline the potential for cost reduction is low.

Type of parameter	Technology/block	Range (Low/Nominal/High)	Variation on LCOX
Length	HV line	0/1/10 km	-2% to +17% for H2 1 MWe -1% to +10% for H2 mobility
Length	Gas pipeline	0/1/5 km	-3% to +12% for H2 1 MWe -1% to +5% for H2 10 MWe