Ref. Ares(2020)6110854 - 29/10/2020

Hydrogen Mobility Europe

H2ME 2, D4.17:
Desirable design changes and operating regimes for electrolyser-HRS for 2020-2030

Shane Slater, Foaad Tahir, Michael Joos

September 2020

A project co-funded by
under the Grant Agreements No 671438 and No 700350

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

WORK PACKAGE SUMMARY/OBJECTIVES

Hydrogen Mobility Europe

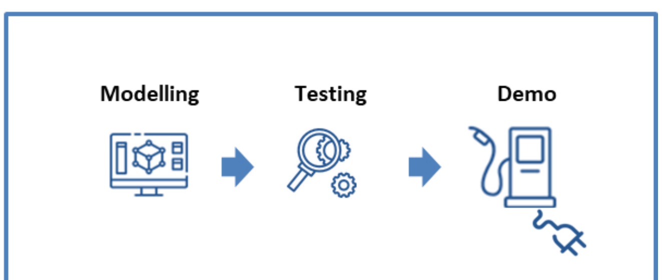
Assess the capability of electrolyser-HRS to monetize grid services

- Understand and collect data on grid services in France, Germany and UK
- Electricity price and balancing services scenarios for future power systems
- Techno-economic modelling of the electrolyser-HRS

Assess the capability of electrolyser-HRS to provide grid services

- Develop test protocols based on technical requirements provided by TSO
- Evaluate the answer response of the electrolyser-HRS to these tests
- Real world demonstration based on TSO signal

H2Me2 – WP4



CNR · eifer by EDF and KIT · elementenergy · ITM POWER · open energi · MANCHESTER 1824 The University of Manchester · FCH

H2ME 2 D4.17: Design and operation of electrolyser HRS 2020-2030

Hydrogen Mobility Europe

Executive Summary

Introduction

Techno-economic assumptions

Methodology

Results and discussion

Conclusions and recommendations

Appendix

D 4.17 Executive Summary (1/2)

Hydrogen Mobility Europe

Key objectives

- Model electrolyser operation at a hydrogen refuelling station (HRS) in a number of EU countries in 2020 and 2030 and archetype settings (LDV, HDV)
- Determine optimal operational parameters (e.g. electrolyser set point and load factor) and response of electrolysers to price signals.
- Determine cost of hydrogen (€/kg) in a range of present and future settings.
- Explore role of grid services in business models for electrolysers.

Modelling approach

- Data collection of current grid services and electricity wholesale prices, grid fees, and policy levies for industrial users in EU countries
- Modelling of future European power systems and electricity price profiles
- Modelling of hourly electrolyser operation responding to price signals

Results: Competitiveness of Hydrogen

- **Cars:** Competition with taxed diesel possible in 2020 in GB and FR given high utilization of refueling stations; increases towards 2030. Competition in DE possible given exemption from policy levies.
- **Busses:** Competition with taxed diesel possible in 2030 given exemption from policy levies.
- Competition with **untaxed Diesel** significantly more challenging. Hydrogen can compete in 2030 in the case of cars given exemption from policy levies and pricing carbon emissions of Diesel. Hydrogen cannot compete with untaxed Diesel in either 2020 or 2030 in the case of busses.
- Competition with **electric vehicles (EVs)** only possible given exemption from levies for electrolysers and full residential electricity prices paid by EVs.

D 4.17 Executive Summary (1/2)

Results: Electrolyser design and operation

- In **2030**, **oversizing** the electrolyser offers **cost savings** due to increased volatility of electricity prices, higher efficiency of electrolysers at lower set points, and reduced electrolyser CAPEX.
- This development is more pronounced in DE and GB, which are expected to have higher average electricity prices as well as higher electricity price volatility (due to high renewable penetration) than FR.
- **Balancing services** can provide a secondary revenue stream for electrolysers but are not expected to be the main pillar of a business model.
- **Exemption from policy levies** as currently available in DE, GB and FR for energy intensive industries would help to **improve** the electrolyser **business case** significantly.
- Given exemption from policy levies, electricity retail prices and subsequently hydrogen costs are similar in DE, GB and FR, while they are higher in DE and GB compared to FR without exemptions, due to higher policy levies in these countries.
- **Reducing the HRS utilization** rate from 100% to 25% would make **HRS and electrolyser dominate green hydrogen cost** (instead of electricity). It would lead to a 74% cost increase of hydrogen cost in 2020 in GB, vs. 21% in 2030 due to expected CAPEX reductions of electrolysers and HRS.

H2ME 2 D4.17: Design and operation of electrolyser HRS 2020-2030

Executive Summary

Introduction

Techno-economic assumptions

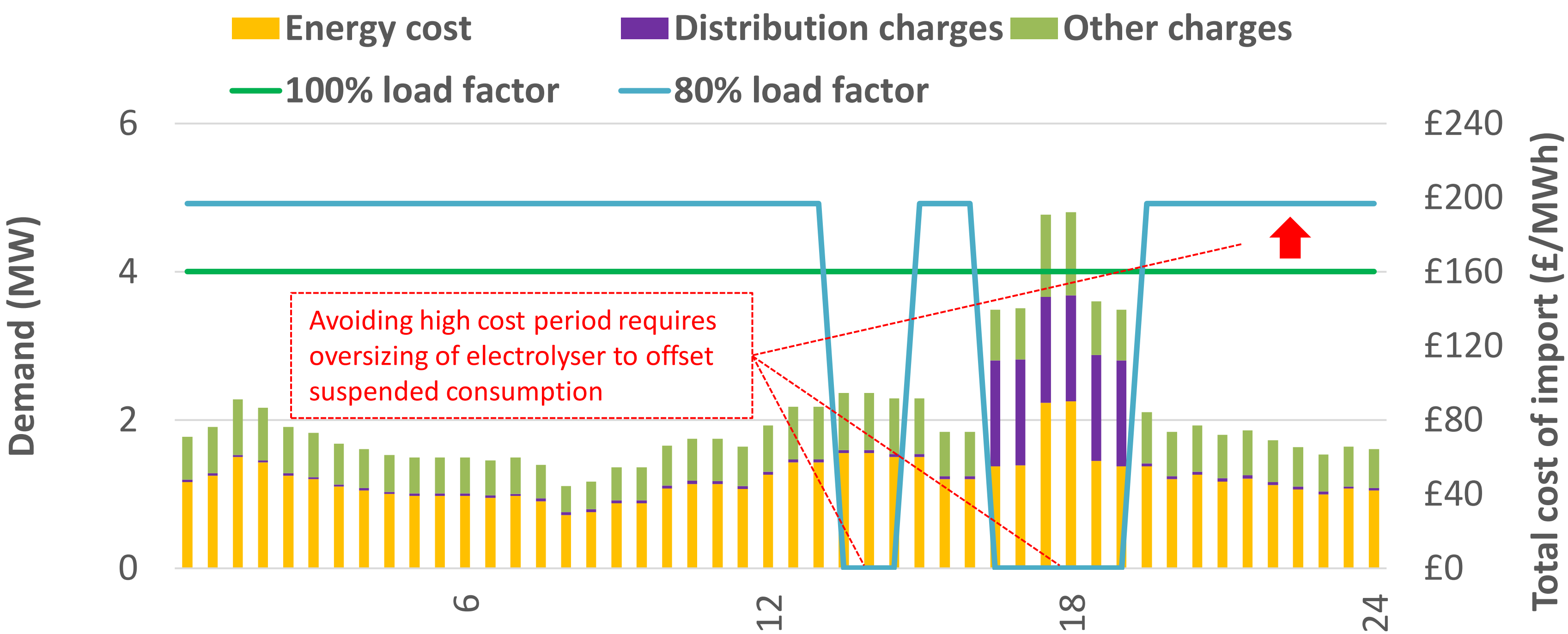
Methodology

Results and discussion

Conclusions and recommendations

Appendix

Excess electrolyser capacity and H2 storage used to offset high import cost during peak hours



- Excess electrolyser capacity allows the avoidance of peak network and energy import costs
- H2 storage is discharged during times of high energy and network costs and charged using excess electrolyser capacity during times of low import cost

WP 4 Task 4.1.3 Techno-economic modelling of electrolysers

Hydrogen Mobility Europe

Key objectives

- Model electrolyser operation at a hydrogen refuelling station in a number of EU countries in 2020 and 2030 and archetype settings (LDV, HDV)
- Determine optimal operational parameters (e.g. electrolyser set point and load factor) and response of electrolysers to price signals.
- Determine cost of hydrogen (€/kg) in a range of present and future settings.
- Explore role of grid services in business models for electrolysers.

Modelling approach

- Data collection of current grid services and electricity wholesale prices, grid fees, and policy levies for industrial users in EU countries
- Utilisation and further development of a power system model to simulate future electricity prices in European countries
- Development of an electrolyser operational model representing electrolyser response to price signals

FCH

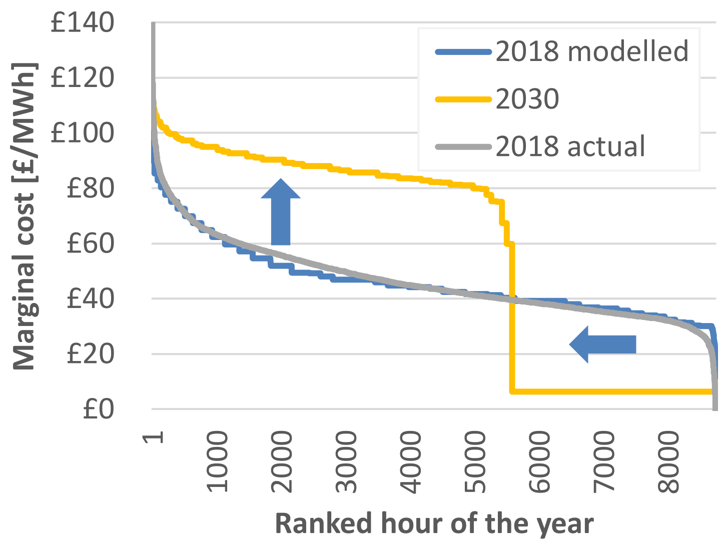
H2ME 2 D4.17: Design and operation of electrolyser HRS 2020-2030

Hydrogen Mobility Europe

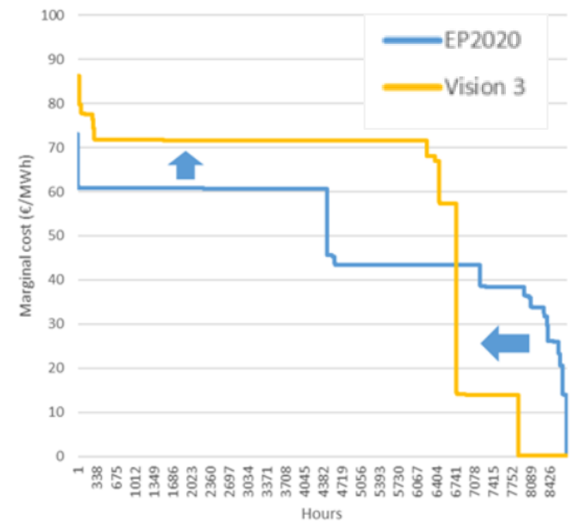
- Executive Summary
- Introduction
- **Techno-economic assumptions**
  - **Electricity prices**
  - HRS archetypes
  - Electrolyser and HRS costs
  - Grid services for the TSO
- Methodology
- Results and discussion
- Conclusions and recommendations
- Appendix

Driven by growth of VRE, marginal electricity costs become more volatile

Hydrogen Mobility Europe



Source: EE Dispatch Model

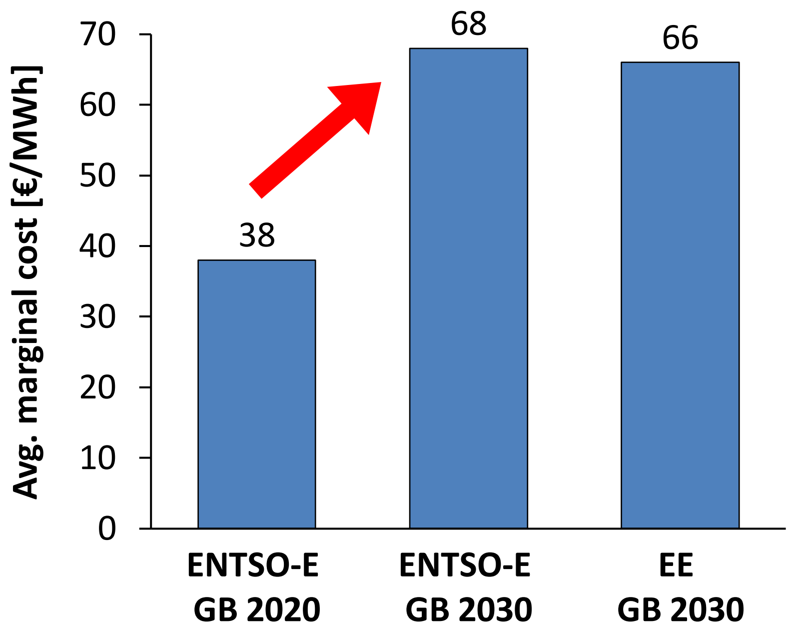


Source: ENTSO-E TYNDP

- The upper left graph shows **short run marginal cost** (SRMC) of electricity generation as modelled by EE's electricity dispatch model of GB in 2018 and 2030.
- **Growth of VRE penetration** as well as **higher carbon prices increase the volatility** of the SRMC of electricity, increasing the cost in the most expensive hours and reducing it in the cheapest hours.
- This is **aligned with external projections** such as the one of the ENTSO-E TYNDP[1] shown above on the right.

1) https://tyndp.entsoe.eu/2016/insight-reports/energy-mix/

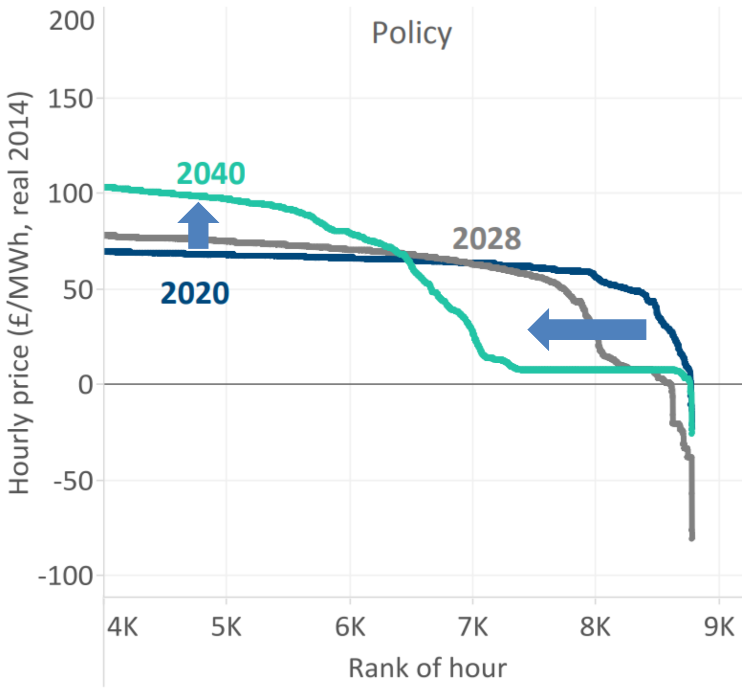
Our model predicts average cost rises (aligned with ENTSO-E predictions), driven by increasing carbon prices



- Our model predicts an increase of the average SRMC in GB from €53/MWh in 2018 to €66/MWh in 2030.
- This is in line with the 2018 ENTSO-E TYNDP[1], which predicts an increase of average SRMC in GB to €68-83/MWh across their 2030 scenarios.
- Similarly the modelled SRMC for DE and FR is aligned with the ENTSO-E projection for DE and FR.

1) https://tyndp.entsoe.eu/tyndp2018/; graph shows 2030 costs for scenario Distributed Generation

Short run marginal cost serve as an approximation of wholesale electricity prices



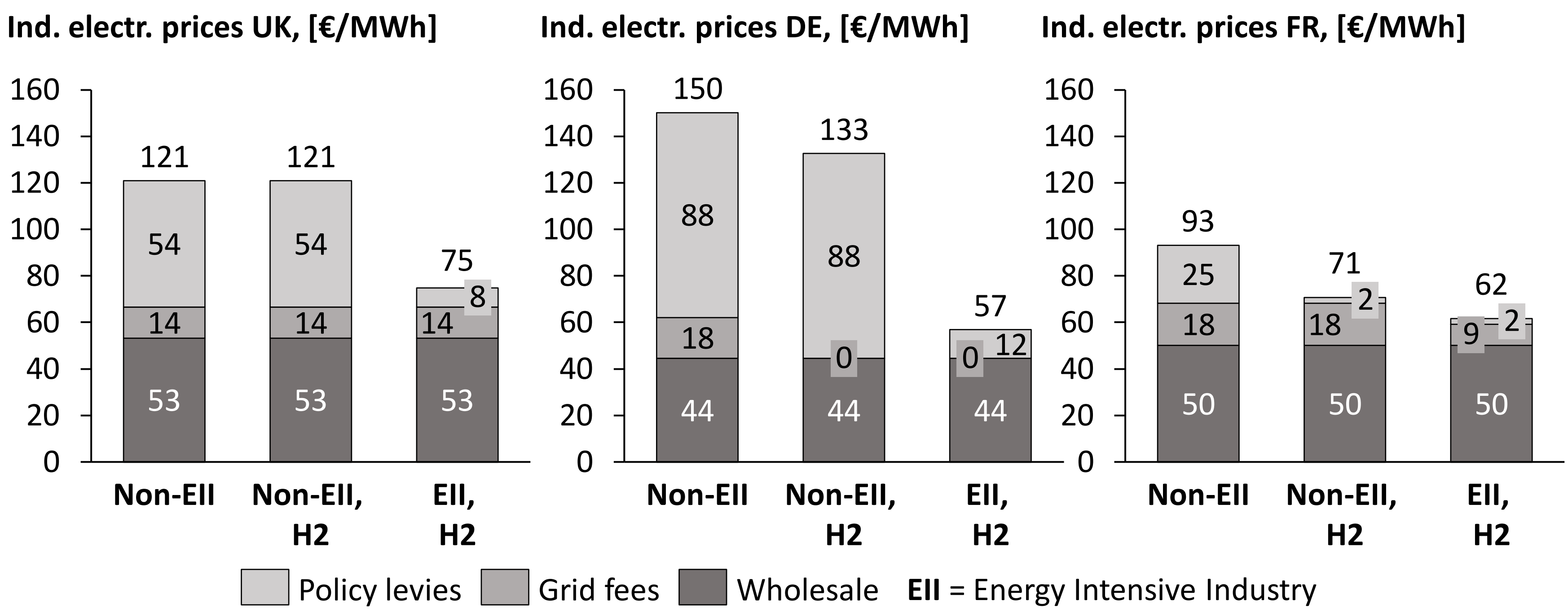
Source: Baringa, 2015

- Our modelling uses **SRMC** as **an approximation of electricity wholesale prices**, due to the marginal pricing mechanism in European wholesale markets.
- The implied expectation of **more volatile wholesale prices** is aligned with external projections (cp. e.g. left graph of a UK govt. report[1]).
- **SRMC** based approaches are the standard method to model wholesale electricity prices, but they have **shortcomings**.
- We are therefore **developing** our **market model further** to address these shortcomings, which seem to be systematic in electricity price modelling[2].
- We plan to integrate other aspects of generators' bidding strategies to model diurnal price variation more accurately.
- While electricity power systems are and will keep transforming up to 2030, a **radical change of electricity market design** is **not expected** in Europe[3].
- The short run marginal cost will therefore continue to be a key variable determining electricity wholesale prices.

1) Baringa 2015, Negative pricing in the GB wholesale electricity market
2) Ward et. al. 2019, Getting prices right in structural electricity market models
3) Pollitt & Chyong, 2018, Europe's Electricity Market Design 2030 and Beyond

Grid fees and policy levies are a major component of electricity prices in EU markets

Hydrogen Mobility Europe



- **Policy levies** (mainly to finance renewable electricity) comprise almost 50% of industrial electricity prices in GB, almost 60% in Germany, and almost 30% in France (based on 2018/2019 data).
- Higher costs in DE and GB due to ongoing high RES transformation of power system.
- Electrolysers are **exempt** from paying **grid fees in Germany**.
- Electrolysers are **exempt** from paying a **policy levy** financing renewables and support for fuel poor households in **France**.
- All countries offer a reduction of levies to **energy intensive industry (EII),** highest impact in DE (highest cost for non-EII, lowest cost for EII)**.**

H2ME 2 D4.17: Design and operation of electrolyser HRS 2020-2030

Hydrogen Mobility Europe

Executive Summary

Introduction

Techno-economic assumptions

- Electricity prices
- **HRS archetypes**
- Electrolyser and HRS costs
- Grid services for the TSO

Methodology

Results and discussion

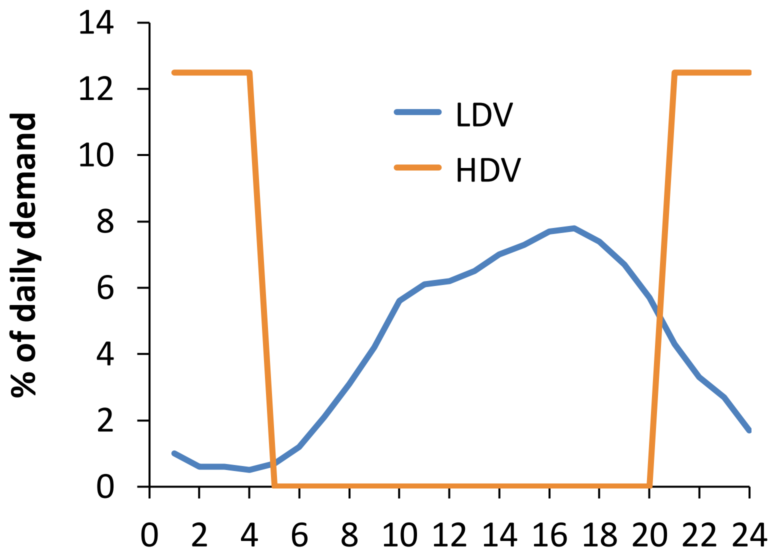
Conclusions and recommendations

Appendix

FCH

Archetypes of refueling stations differ in terms of scale and consumption profile

Hydrogen Mobility Europe



- Two distinct types of electrolyser hydrogen refueling stations (HRS) modelled, one serving light duty vehicles (**LDVs**) and one serving heavy duty vehicles (**HDVs**), for example a bus depot.
- The archetypes of HRS differ in terms of the **daily demand** for hydrogen, the hydrogen consumption profile (pictured above) as well as the costs for building and operating the electrolyser and the HRS (storage and dispensing system).
- The larger daily demand in the case of the HDV HRS enables **economies of scale** leading to lower specific cost of the electrolyser and the HRS.
- Dedicated refuelling stations for a HDV setting like a bus depot offer furthermore the advantage of **reliable H2 demand** from the beginning.
- Storage capacity required to provide the daily demand according to the demand profile and at the same time react to electricity prices is calculated in the model

H2ME 2 D4.17: Design and operation of electrolyser HRS 2020-2030

Hydrogen Mobility Europe

- Executive Summary
- Introduction
- **Techno-economic assumptions**
    - Electricity prices
    - HRS archetypes
    - **Electrolyser and HRS costs**
    - Grid services for the TSO
- Methodology
- Results and discussion
- Conclusions and recommendations
- Appendix

FCH

Main assumptions of techno economic modelling

Quantity	LDV 2020	LDV 2030	HDV 2020	HDV 2030	Source
Electrolyser CAPEX [€/kW]	1270	710	900	500	FCHJU, ITM
Electrolyser OPEX [€/kW/y]	35	18	25	13	FCHJU, ITM
Electr. conspt. [kWh/kg]	50-62[1]	45-56[1]	50-62[1]	45-56[1]	ITM, FCHJU
Electrolyser lifetime [y]	15	15	15	15	Carmo et al., 2013
HRS CAPEX [€/(kg/d)]	4,000	2,400	2,100	1,300	FCHJU
HRS maintenance [€/kg]	1	0.3	1	0.3	FCHJU
HRS lifetime [y]	12	15	12	15	FCHJU
HRS utilisation	100%	100%	100%	100%	See below

- **Future electricity systems** are modelled based on scenarios as published in (Committee on Climate Change, 2018) for GB, (Bundesnetzagentur, 2018) for DE, (ENTSO-E, 2018) for FR
- A **100% utilisation** of the HRS is assumed, as the focus of the modelling are cost reductions through technology learning rather than impacts of initially low and over time increasing utilisation.
- A **50% lower utilisation** would double all CAPEX and fixed cost per kg of hydrogen and thus lead to **significantly higher costs** than those presented (cp. Results section).
- A **4% interest rate** is assumed when annualising capital costs over the lifetime of assets[2].

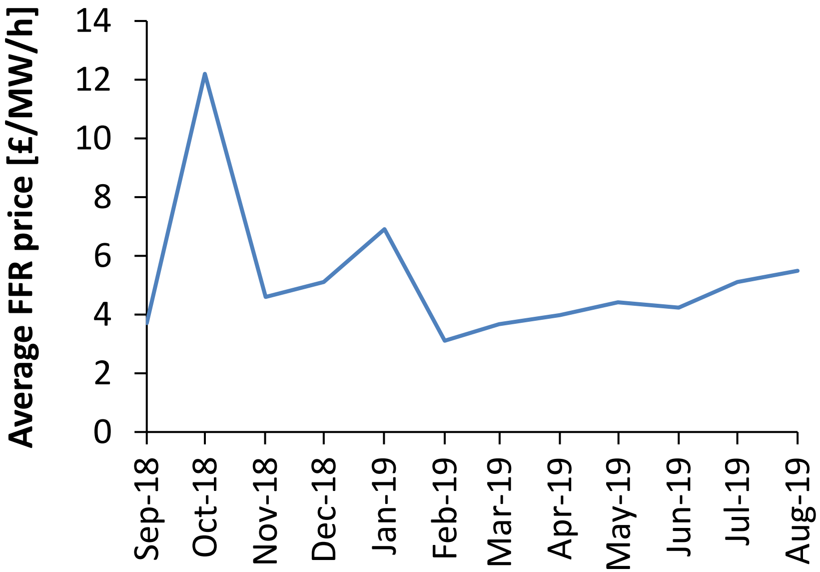
1) Depending on electrolyser set point
2) This corresponds to some amount of public / patient capital funding as fully commercial rates tend to be higher

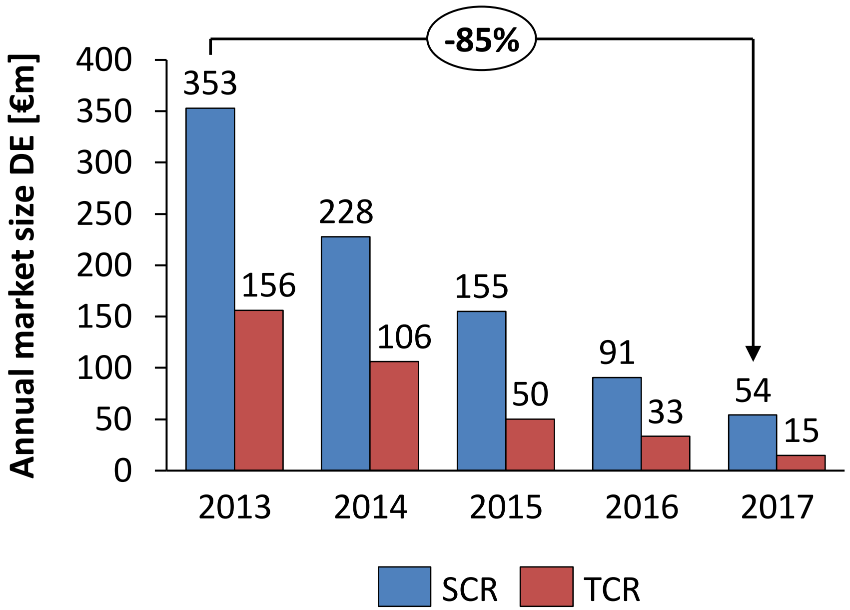
H2ME 2 D4.17: Design and operation of electrolyser HRS 2020-2030

Hydrogen Mobility Europe

Executive Summary
Introduction
Techno-economic assumptions
Electricity prices
HRS archetypes
Electrolyser and HRS costs
Grid services for the TSO
Methodology
Results and discussion
Conclusions and recommendations
Appendix

Balancing services contracted by the TSO – an attractive but quickly changing market





- Contracted services have to be committed ahead of delivery for fixed time windows set by the TSO
- Rewarded with availability payments (in £/MW/h) which are also paid, if service not utilised. Utilisation rate is relatively low (below 10%[1]).
- While an attractive market, emergence of new technologies, mainly batteries, and increased TSO cooperation have led to lower prices and shrinking market size.
- In the UK, prices for Frequency Response have halved since 2017. In 2019 Firm Frequency Response (FFR) prices averaged around £5/MW/h (graph above).
- Similar prices and price development can be observed in France and Germany. In Germany the market size of secondary control reserve has been reduced by 85% since 2013.

1) For Frequency Response in the UK and Secondary and Tertiary Control Reserve in Germany

H2ME 2 D4.17: Design and operation of electrolyser HRS 2020-2030

Hydrogen Mobility Europe

Executive Summary

Introduction

Techno-economic assumptions

Methodology

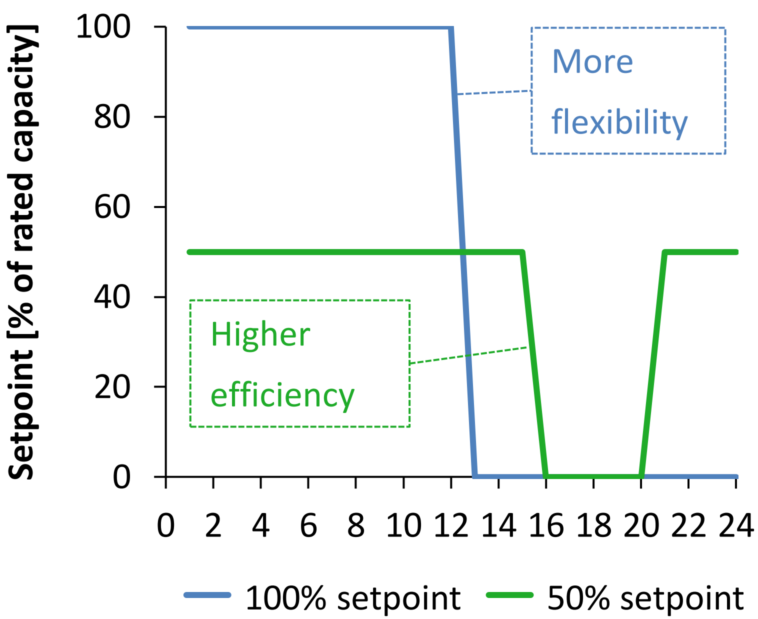
Results and discussion

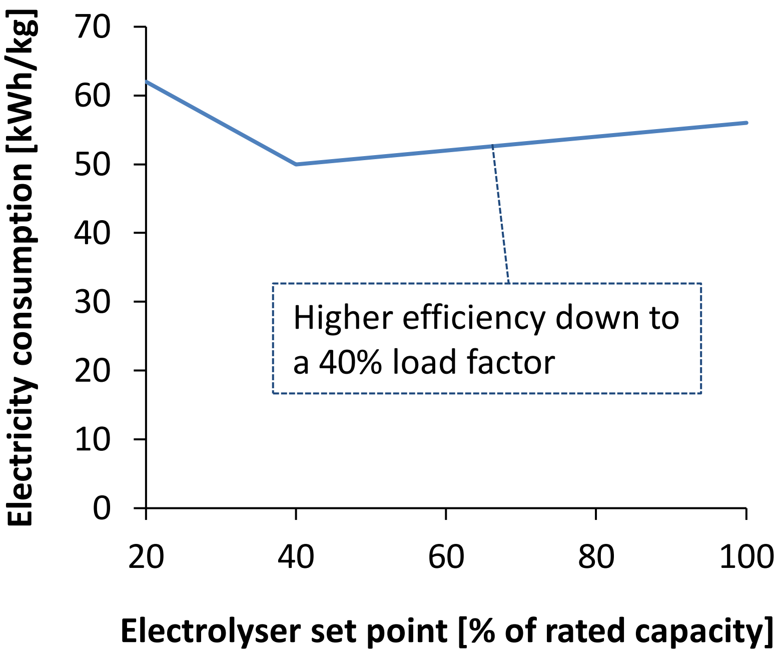
Conclusions and recommendations

Appendix

Key characteristics of operational strategies of electrolysers: when to run and at which set point

Hydrogen Mobility Europe



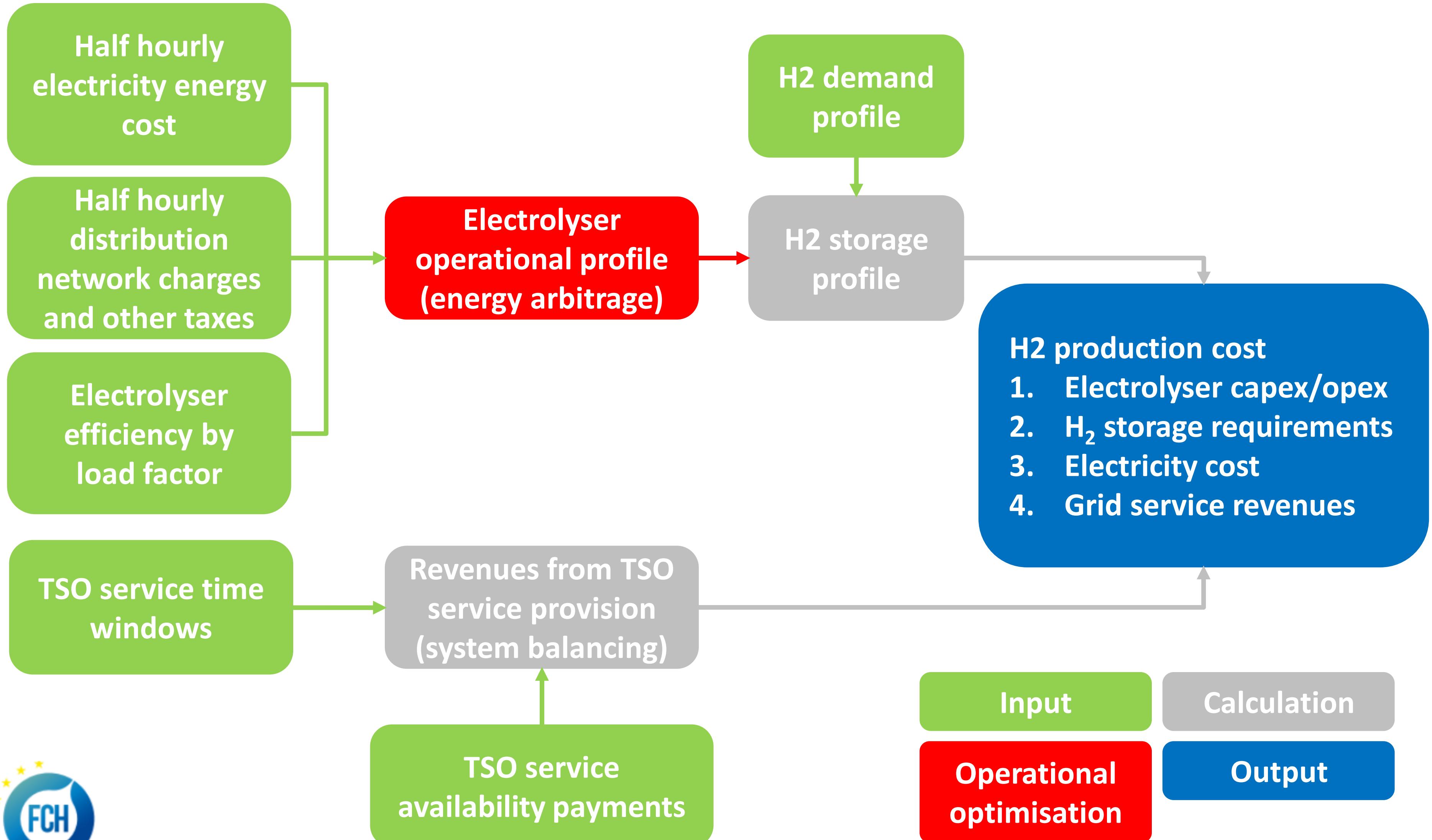


- Once a certain size of the electrolyser for a given daily demand is chosen, operational strategies to run the electrolyser will differ in terms of 1) the hours **when** the electrolyser is run and 2) the **set point** at which the electrolyser is run
- The electrolyser could either be utilised at a **high set point** for a **small number of hours** or at a **low set point** for a **large number of hours**, compare the upper left graph showing two ways how to operate at a 50% load factor.
- The **efficiency** of the electrolyser **improves at lower set points** (down to 40%, right graph above).

Running the electrolyser at a low set point therefore reduces the electricity consumption per kg H2 produced but it also reduces the flexibility to shift consumption to low price periods.

FCH

Electrolyser operational asset model: Modelling schematic



Operational and design optimization in the model

Operational optimization

- For a given daily hydrogen demand (kgH_2/d), the **model tests** a given number of electrolyser designs in terms of **set point** (% of rated MW capacity, at which the electrolyser is run) and **utilization rate** (% of annual hours in which electrolyser is run) which can supply this demand.
- For each combination of set point and utilization rate, the model **simulates the operation of the electrolyser** for one year in **hourly resolution** using this particular utilization rate and set point.
- The **set point** determines the **efficiency** of the electrolyser, the **utilization rate** in **how many hours** the electrolyser can avoid charging.
- The model **optimizes the electrolyser daily operational profile** by avoiding the hours of highest electricity cost on each day.
- The **required H2 storage** is determined based on the optimized operational profile and the consumption profile of the HRS.

Design optimisation

- Among the tested combinations of utilization rate and set point, the **model picks** the combination which leads to the **lowest hydrogen cost** in €/kg.
- **Reducing the set point increases** the electrolyser **CAPEX**, as a larger electrolyser capacity is needed to produce the same amount of hydrogen. However it **increases the efficiency** of the electrolyser and thus reduces electricity cost.
- **Reducing the utilization rate also increases the electrolyser** CAPEX, but **increases the flexibility** of the electrolyser to pick the hours of the day when to consume electricity, and thus reducing electricity cost.

WP 4: Electrolyser modelling

Hydrogen Mobility Europe

Executive Summary

Introduction

Techno-economic assumptions

Methodology

Results and discussion

- **Competitiveness vs taxed Diesel**
- Competitiveness vs untaxed Diesel
- Trends and sensitivities

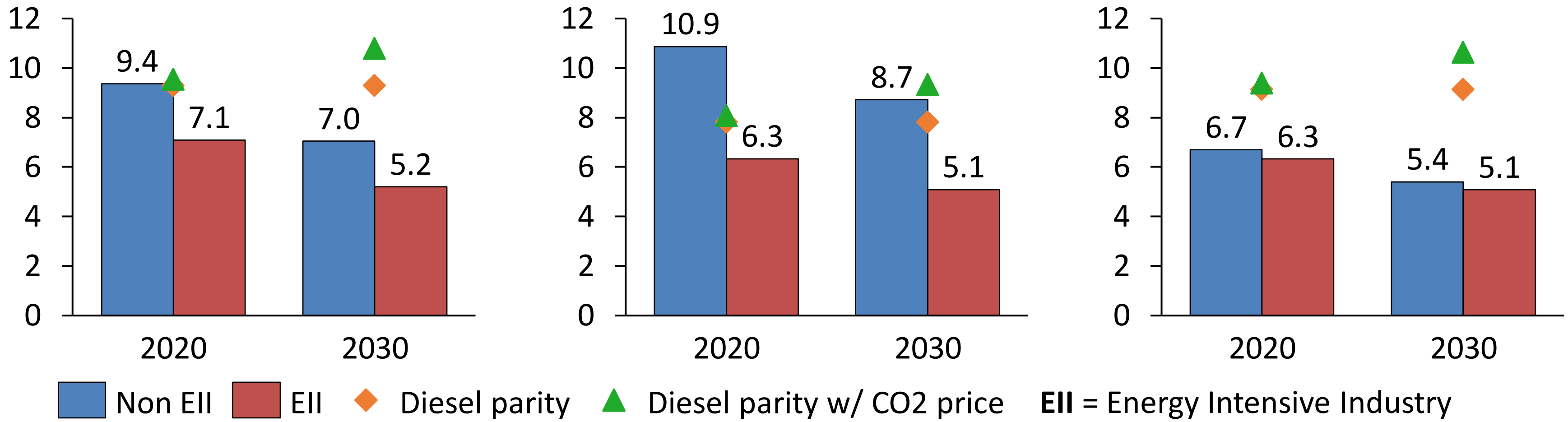
Conclusions and recommendations

Appendix

FCH

Cars: Competition with taxed diesel possible in 2020; increases towards 2030

Cost cp. to taxed Diesel GB [€/kg] | **Cost cp. to taxed Diesel Germany [€/kg]** | **Cost cp. to taxed Diesel France [€/kg]**



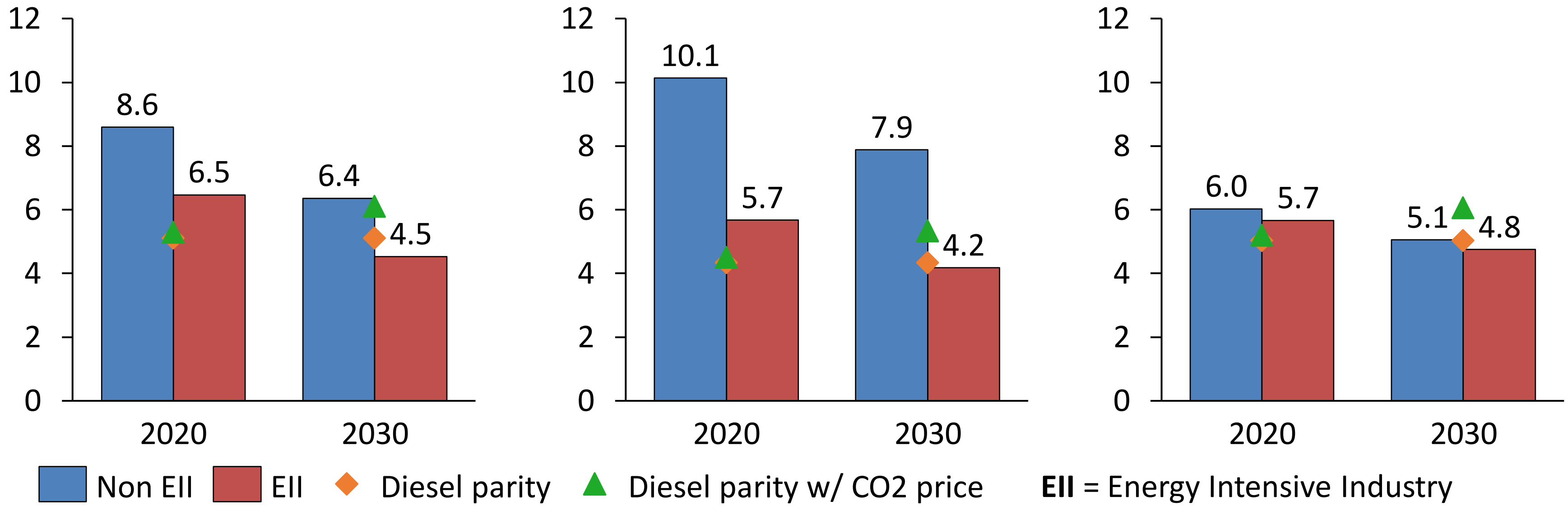
- **Parity prices** with **taxed** Diesel range between **€7.8/kg** (DE) and **€9.3/kg** (GB) due to differences in fuel taxes[1].
- **Hydrogen can** already **compete** with taxed Diesel in FR in 2020, and both in FR and GB in 2030.
- Imposing a carbon tax on Diesel increases parity prices significantly in 2030.
- Hydrogen **cost** are **higher in DE and GB** than in FR due to **policy levies** on electricity to finance renewable electricity.
- **Energy intensive industry (EII)** is exempted from several fees and levies (cp. appendix).
- These exemptions are more significant in DE and GB than in FR. As a result, hydrogen cost are **very similar** in all countries if electrolysis is available for EII exemptions.

1) Assuming a Diesel consumption of 5.0l/100km and a FCEV H_2 consumption of 0.8kg/100km in 2020, reducing to 0.7kg/100km in 2030 and 4.3l/100km respectively in 2030. Based on fuel costs only, difference of purchase price of vehicle not included in analysis.

Busses: Competition with taxed diesel possible in 2030

Hydrogen Mobility Europe

Cost cp. to taxed Diesel GB [€/kg] | **Cost cp. to taxed Diesel Germany [€/kg]** | **Cost cp. to taxed Diesel France [€/kg]**



- **Parity prices** with **taxed** Diesel range between **€4.3/kg** (DE) and **€5.1/kg** (GB) due to differences in fuel taxes[1].
- **Hydrogen cannot compete** with taxed Diesel in **2020**.
- Parity prices based on Diesel prices excl. VAT. Some countries provide subsidies for Diesel buses (e.g. BSOG in GB), but such subsidies are expected to be phased out.
- With EII status, hydrogen can compete with Diesel in 2030 in all countries, while without EII status, hydrogen can only compete in France.

1) Assuming a Diesel consumption of 33.0l/100km and a FCEV H_2 consumption of 8kg/100km in 2020, reducing to 7.1kg/100km in 2030 and 29.3l/100km respectively in 2030. Based on fuel costs only, difference of purchase price of vehicle not included in analysis.

WP 4: Electrolyser modelling

Executive Summary

Introduction

Techno-economic assumptions

Methodology

Results and discussion

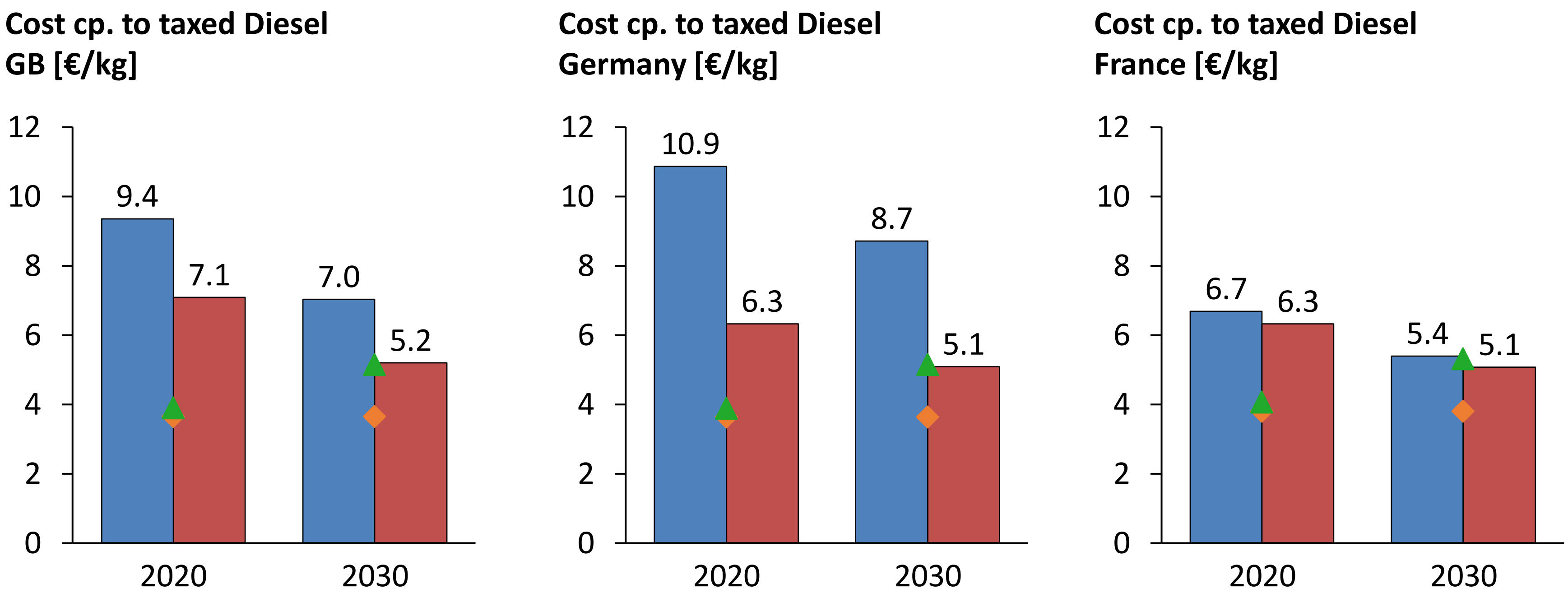
- Competitiveness vs taxed Diesel
- **Competitiveness vs untaxed Diesel**
- Trends and sensitivities

Conclusions and recommendations

Appendix

Cars: Competition with untaxed diesel possible in 2030 given appropriate policy

Hydrogen Mobility Europe

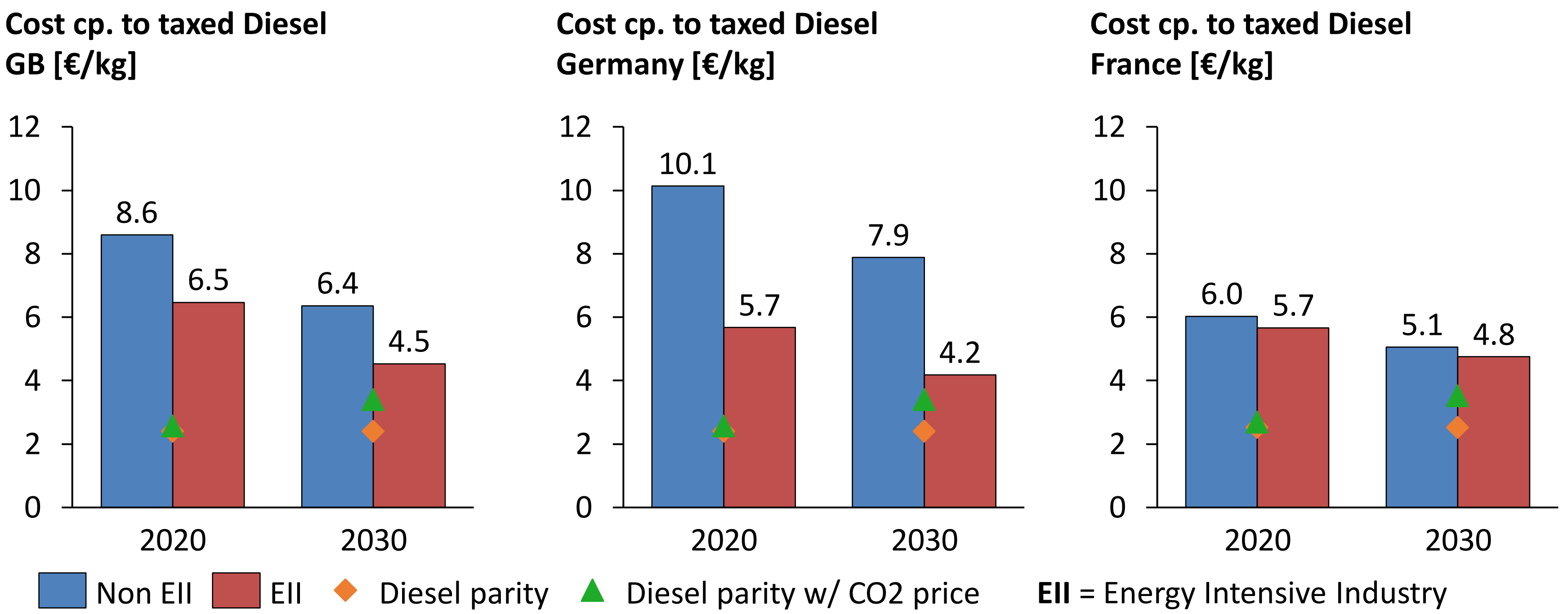


- **Parity prices** with **untaxed** Diesel are similar in all countries ranging between **€3.6/kg** in GB and DE to **€3.8/kg** in FR. In all countries, taxes comprise more than 50% of Diesel price.
- Hydrogen **cannot compete** with untaxed Diesel in **2020** in any country.
- However hydrogen is able to achieve fuel price **parity** with untaxed Diesel **in 2030** if it is exempted from fees and levies (**EII** exemption) and a **carbon tax** is imposed on Diesel (note that carbon costs of hydrogen are already included in the hydrogen electricity costs).

1) Assuming a Diesel consumption of 5.0l/100km and a FCEV H_2 consumption of 0.8kg/100km in 2020, reducing to 0.7kg/100km in 2030 and 4.3l/100km respectively in 2030

Busses: Competition with untaxed diesel not possible up to 2030

Hydrogen Mobility Europe



- **Similar parity prices** with **untaxed** Diesel across countries, ranging between **€2.4/kg** (DE, GB) and **€2.5/kg** (FR) due to differences in fuel taxes[1].
- **Hydrogen cannot compete** with untaxed Diesel in **2020 or 2030**.
- Lower competitiveness of hydrogen for busses than for cars, compared to Diesel, due to lower relative efficiency of H2 busses than rel. efficiency of H2 cars cp. to Diesel.

1) Assuming a Diesel consumption of 33.0l/100km and a FCEV H_2 consumption of 8kg/100km in 2020, reducing to 7.1kg/100km in 2030 and 29.3l/100km respectively in 2030

WP 4: Electrolyser modelling

Hydrogen Mobility Europe

Executive Summary

Introduction

Techno-economic assumptions

Methodology

Results and discussion

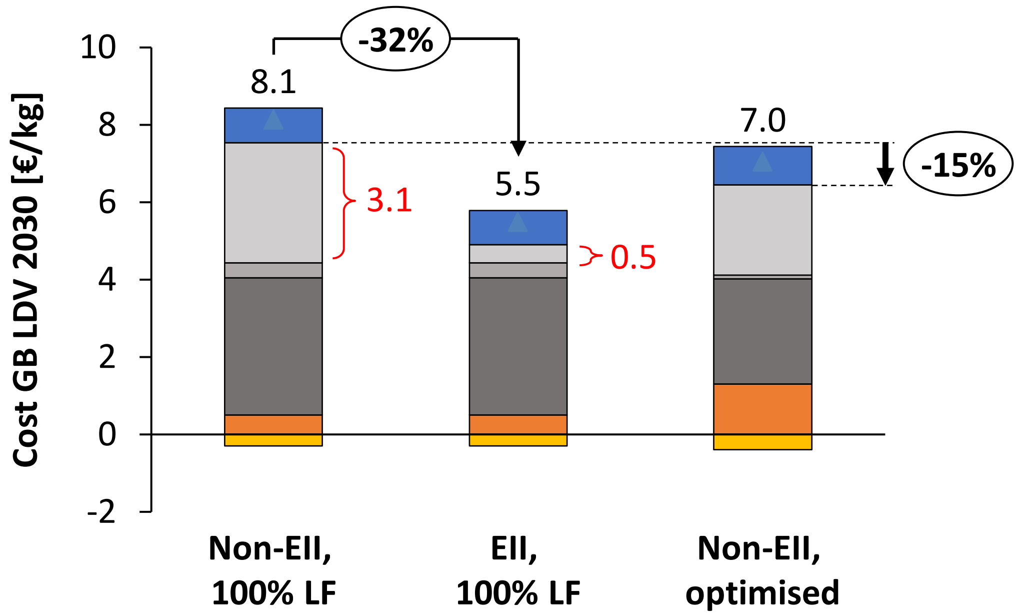
- Competitiveness vs taxed Diesel
- Competitiveness vs untaxed Diesel
- **Trends and sensitivities**

Conclusions and recommendations

Appendix

Grid fees and green levies are a significant component of the cost of green hydrogen

Hydrogen Mobility Europe

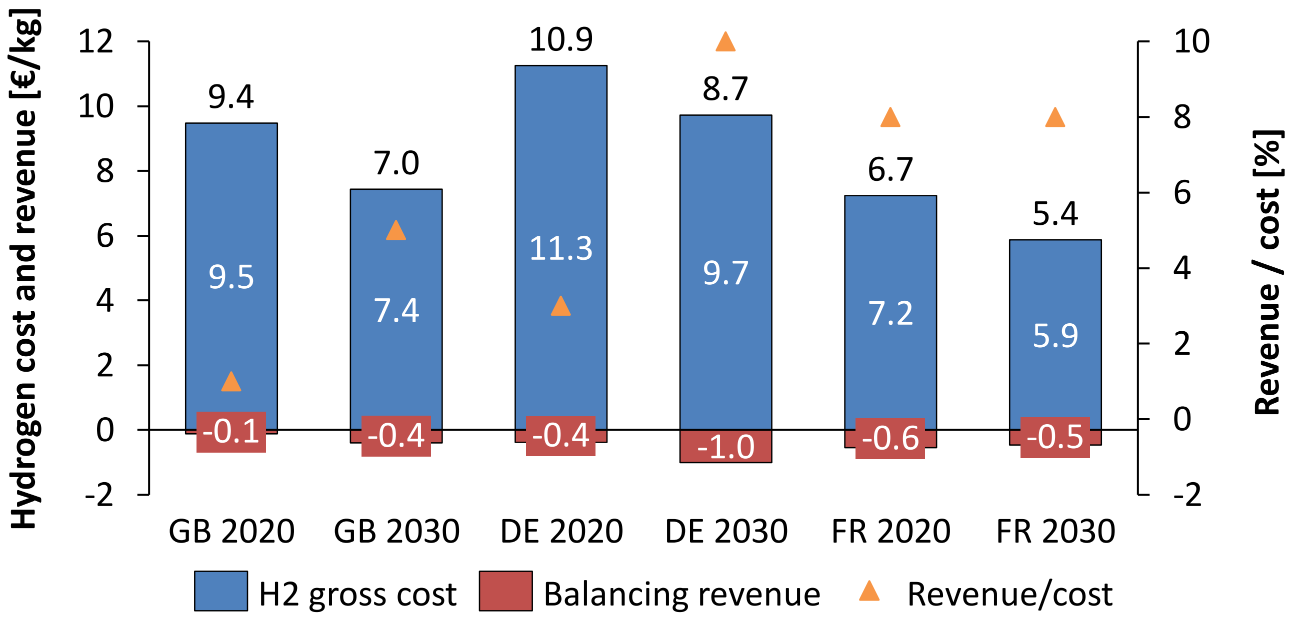


EII = Energy Intensive Industry
LF = Load Factor

- Policy levies comprise more than 40% of industrial electricity prices in GB.
- 80% of these levies are for green policies such as the Renewable Obligation and Contracts for Difference.
- Reduction of levies by up to 85% available to **energy intensive industry** (EII), similar reductions available in DE. In FR, electrolysis already exempted from levies; EII status only reduces grid fees and the difference between EII and Non-EII costs are not as high as in GB and DE.
- In 2030, such a reduction would have a **higher impact** on the hydrogen cost **than operational optimisation** of the electrolyser to utilise low price periods.
- Operational optimisation: 12% reduction; EII status: 32% reduction
- In terms of **realistic policy**, it may be problematic if grid connected electrolysers are economically viable only through being exempted from contributing to decarbonisation of electricity

FCH

Electricity balancing services can improve the business case of hydrogen marginally

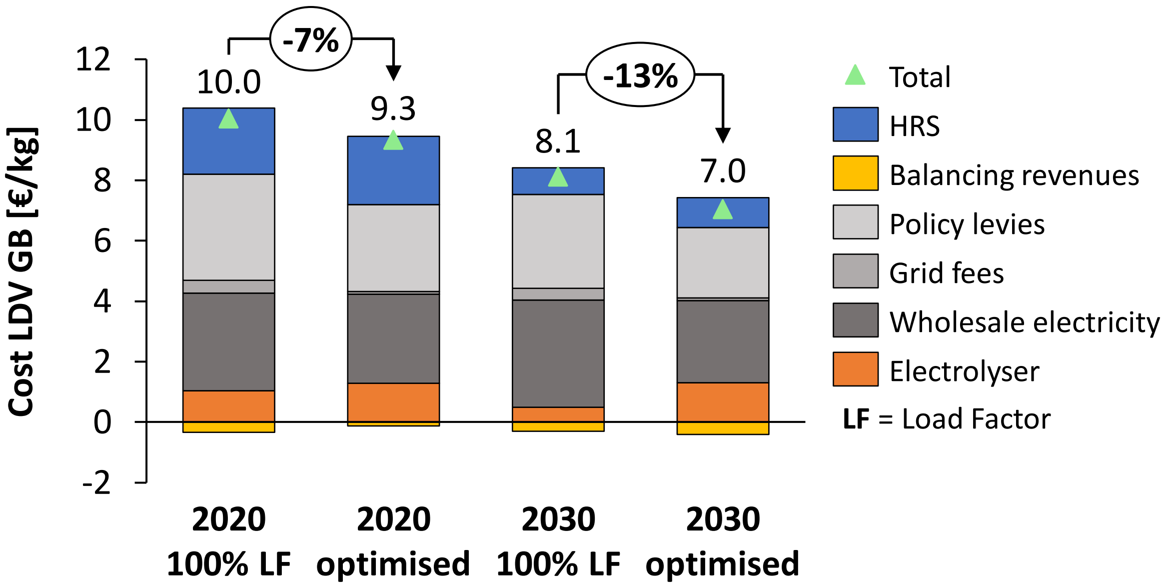


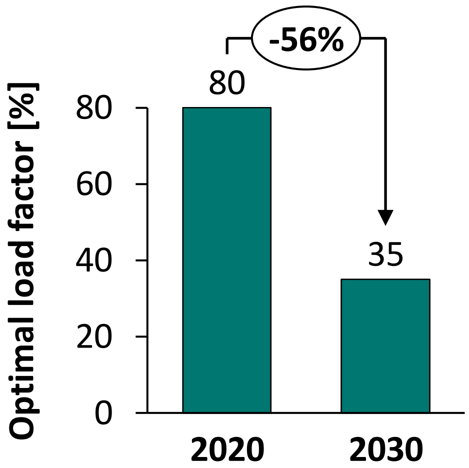
- Providing **balancing services** can help to **improve the business case** but is not a material revenue stream.
- Balancing revenues **reduce** the **cost** of hydrogen by **1-10%** across countries[1].
- Revenues increase in GB and DE in 2030, as a **lower** electrolyser **load fac**tor is used, and thus **more capacity** can be offered to provide balancing services.
- While balancing services might provide valuable **additional revenue** in particular cases, they should not be a main pillar of a general business case due to the **finite market** size and competition from **alternative supply technologies** such as batteries reducing value (cp. Appendix).

1) Shown results are for LDV, and no EII exemption

Flexible, grid responsive electrolyser operation is becoming more economic in future grids

Hydrogen Mobility Europe



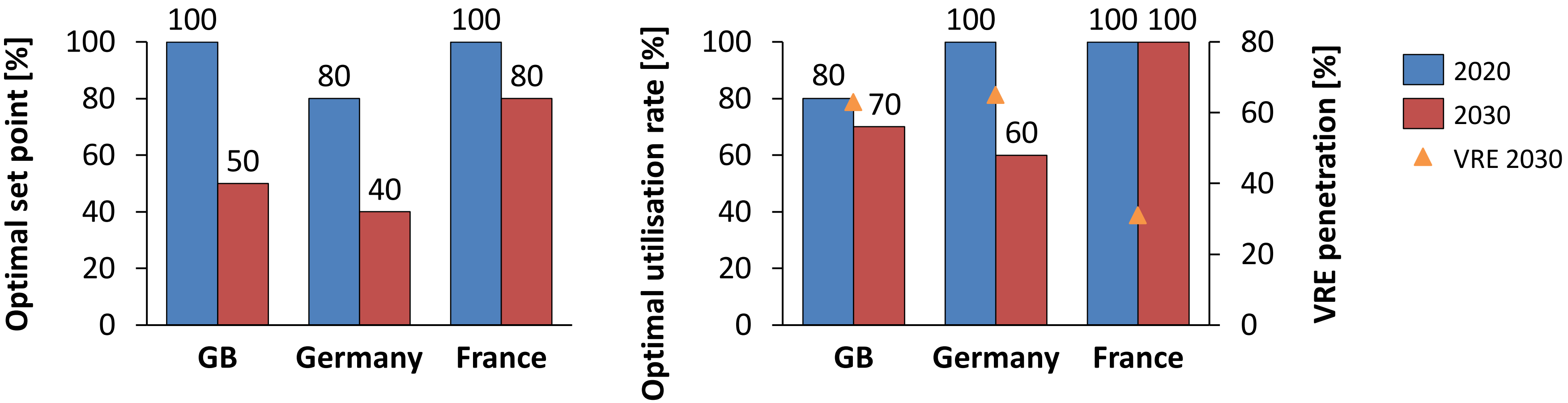


- The relative **impact of operational optimisation increases** up to 2030: while optimisation leads to a 7% cost reduction in 2020, in 2030 optimisation enables a 13% reduction.
- The optimal **load factor decreases**: while in 2020 H2 costs are minimised when using an 80% load factor, in 2030 costs are minimal when a 35% load factor is used.
- In 2030, optimisation enables a 23% reduction of wholesale electricity cost vs. 8% in 2020[1].
- **Reduced specific electrolyser CAPEX** allow to oversize electrolysers at lower cost in 2030 than in 2020.
- HRS cost based on 100% utilisation. Due to low numbers of H2 vehicles, **average utilisation** across a fleet of HRS up to 2030 is likely to be significantly **lower**, leading to **higher cost per kg**.

FCH

1) Note that wholesale electricity cost increase from 2020 to 2030 in the case of a 100% load factor due to increasing average wholesale prices

Optimal set points and optimal utilization rates both decrease for future installations



- The **load factor** of the electrolyser in a particular model run is the **product of** the electrolyser **set point** (% of rated MW capacity, at which the electrolyser is run) and its **utilization rate** (% of annual hours in which electrolyser is run)**.**
- The **optimal set point** is **decreasing** from 2020 to 2030 due to the higher efficiency of the electrolyser at a lower set point, increasing electricity prices and decreasing electrolyser CAPEX (left graph[1]). The **optimal utilization rate** is **decreasing** due to increased volatility of electricity prices caused by high VRE penetration (right graph[2]).
- In 2020, the utilization rate in DE and FR is 100% vs 80% in the UK (right). This is due to the fact that **more components** of the electricity price are **dynamic in the UK** than in FR and DE. In spite of implying higher CAPEX, running at a lower set point of 80% is economic in Germany, du to the high German electricity retail price (left).
- In 2030, utilization rate in DE and the UK decreases due to higher wholesale price volatility and lower specific electrolyser CAPEX. In FR the utilization rate stays at 100% due to low overall electricity prices as well as lower wholesale price fluctuation compared to DE and GB (caused by high share of nuclear power).

1) Both graphs are for a LDV HRS, Non-EII electricity costs
2) VRE penetration measured as VRE generation divided by total electricity consumption

Total H2 cost (€/kg) for set point / utilization rate combinations GB

LDV_GB_2020

Set point	Utilisation rate 100%	90%	80%	70%	60%	50%
100%	10.03	9.40	9.36	9.58	9.91	10.42
90%	10.02	9.41	9.38	9.62	9.95	10.46
80%	10.02	9.44	9.44	9.64	9.98	10.52
70%	10.07	9.51	9.47	9.69	10.05	10.63
60%	10.16	9.61	9.54	9.78	10.17	10.80
50%	10.34	9.71	9.68	9.95	10.39	11.08

- Lower set points become more economic as average electricity prices rise;
- Lower utilisation rates become economic as wholesale price volatility increases

LDV_GB_2030

Set point	Utilisation rate 100%	90%	80%	70%	60%	50%
100%	8.12	7.51	7.31	7.27	7.30	7.43
90%	8.05	7.46	7.27	7.24	7.24	7.37
80%	8.00	7.42	7.24	7.17	7.18	7.32
70%	7.96	7.40	7.18	7.11	7.13	7.28
60%	7.94	7.37	7.13	7.06	7.10	7.26
50%	7.97	7.31	7.09	7.04	7.09	7.27

Total H2 cost (€/kg) for set point / utilization rate combinations Germany

Hydrogen Mobility Europe

LDV_DE_2020

Set point \ Utilisation rate	100%	90%	80%	70%	60%	50%
100%	10.90	11.01	11.17	11.35	11.69	12.13
90%	10.87	10.99	11.16	11.36	11.72	12.10
80%	10.87	11.00	11.18	11.41	11.73	12.10
70%	10.90	[illegible]	11.25	11.45	11.74	12.14
60%	10.98	[illegible]	11.29	11.48	11.79	12.24
50%	11.09	[illegible]	11.35	11.57	11.93	12.43

- Lower set points become more economic as average electricity prices rise;
- Lower utilisation rates become economic as wholesale price volatility increases

LDV_DE_2030

Set point \ Utilisation rate	100%	90%	80%	70%	60%	50%	40%
100%	9.44	9.41	9.33	9.23	9.23	9.28	9.22
90%	9.35	9.32	9.26	9.17	9.19	9.17	9.11
80%	9.27	9.25	9.20	[illegible]	9.09	9.06	9.01
70%	9.21	9.20	9.16	[illegible]	8.98	8.95	8.92
60%	9.17	9.17	9.07	8.95	8.88	8.86	8.83
50%	9.13	9.06	8.96	8.85	8.79	8.78	8.77
40%	9.02	8.96	8.87	8.77	8.72	8.73	8.74

FCH

Total H2 cost (€/kg) for set point / utilization rate combinations France

Hydrogen Mobility Europe

LDV_FR_2020

Utilisation rate

Set point	100%	90%	80%	70%	60%	50%
100%	6.69	6.83	7.02	7.25	7.63	8.08
90%	6.73	6.88	7.08	7.33	7.74	8.13
80%	6.79	6.95	7.17	7.44	7.85	8.20
70%	6.89	7.06	7.31	7.63	7.94	8.32
60%	7.04	7.23	7.54	7.74	8.07	8.50
50%	7.28	7.50	7.68	7.91	8.29	8.78

- Lower set points become more economic as average electricity prices rise;
- Wholesale price volatility does not increase sufficiently to justify lower utilisation rates

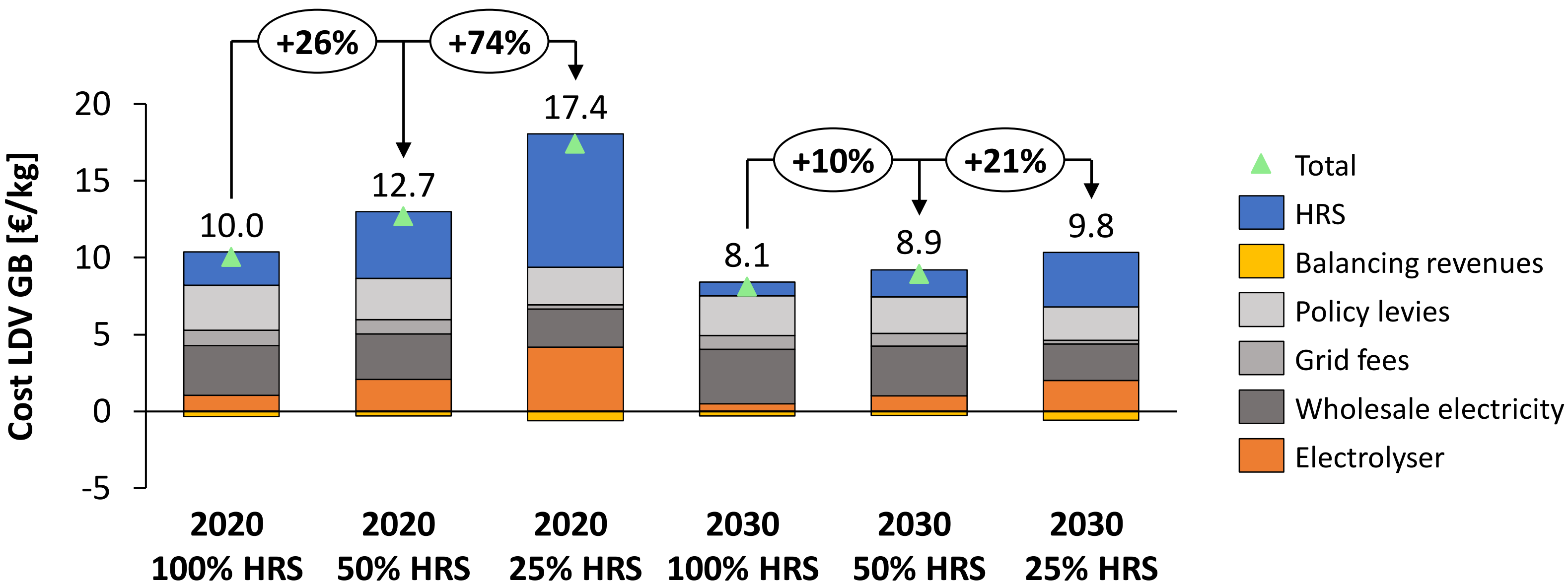
LDV_FR_2030

Utilisation e

Set point	100%	90%	80%	70%	60%	50%
100%	5.43	5.48	5.56	5.63	5.82	6.12
90%	5.41	5.46	5.55	5.63	5.83	6.07
80%	5.40	5.46	5.55	5.64	5.89	6.02
70%	5.40	5.47	5.58	5.74	5.84	5.98
60%	5.44	5.51	5.67	5.70	5.81	5.95
50%	5.51	5.61	5.64	5.67	5.79	5.95

FCH

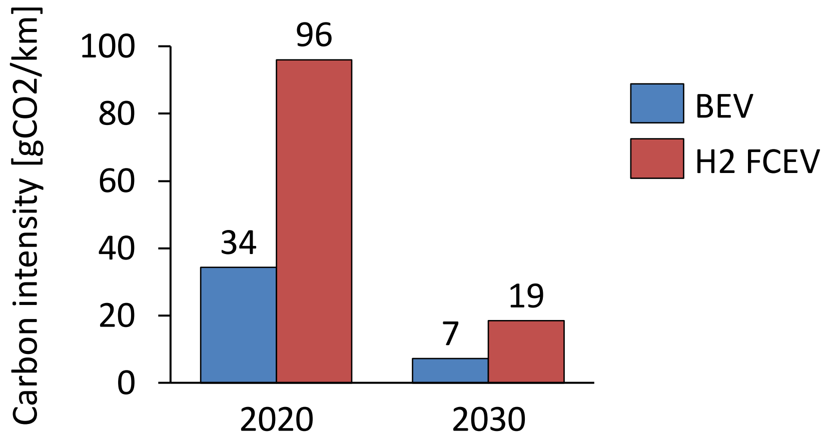
Lower utilization rates of HRS can make electrolyser and HRS dominate costs



- Hydrogen costs shown so far are based on a 100% utilization rate of the HRS.
- **Reduction of HRS utilization** leads to an increase of CAPEX and fixed OPEX of HRS and electrolyser per kg of H2 produced.
- Above graph compares H2 cost based on 100% utilization rate of the HRS and 100% load factor of electrolyser to H2 cost based on **50% and 25% utilization rate of the HRS**[1].
- A **25% utilization rate** makes **HRS** and **electrolyser dominate costs.**
- **In 2020**, it leads to a **74% cost increase**, **in 2030** it leads to a **21% increase** due to lower specific cost of the HRS and the electrolyser in 2030.

1) Above results are for a LDV HRS in GB with non-EII electricity cost. Assuming electrolyser run at 50% set point and 100% (50%) utilization rate in case of 50% (25%) utilization rate of HRS, leading to lower electricity cost due to higher efficiency (and flexibility). Note that currently HRS can have utilization rates significantly lower than 25% due to low penetration of H2 FCEVs.

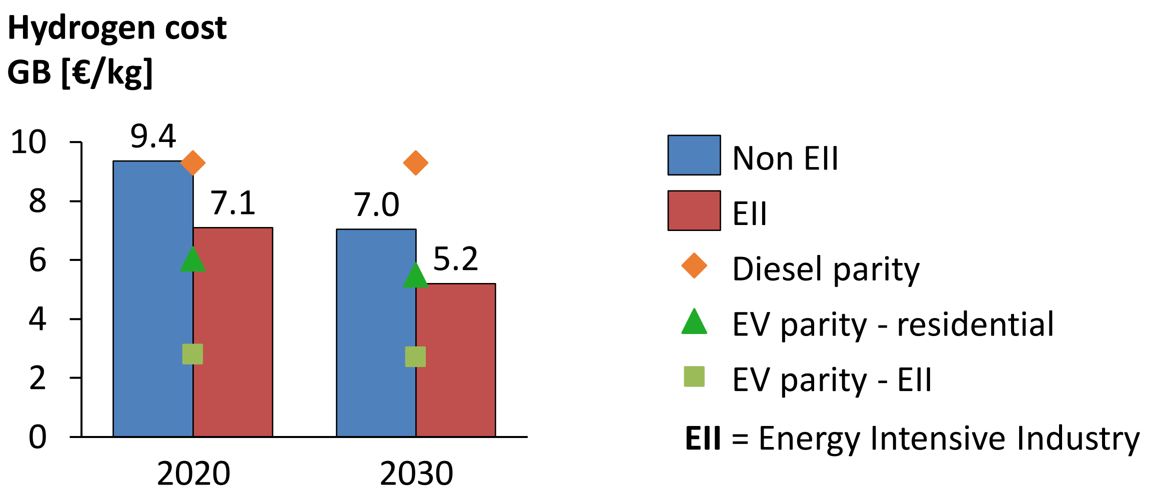
Reduction of green levies for electrolysis will depend on assessment of alternatives



- Reduction of policy levies for electrolysis will pose the question if such a reduction should also apply to battery electric vehicles (BEVs) as an alternative route for decarbonisation of transport.
- Due to the **higher consumption of electricity per km** of FCEVs cp. to BEVs, the carbon intensity of FCEVs per km is higher than those of BEVs, in the case of grid connected electrolysers (cp. figure above[1]).
- **Reduction of policy levies for electrolysis** is therefore **uncertain** and are likely to be restricted to segments where electrification is not an option.
- In its **Hydrogen Strategy**, the German government has declared it intends to free electrolysers of the renewable energy surcharge, which comprises almost 50% of the electricity price paid by electrolysers currently.
- However it is not clear if this will apply to H2 produced for cars and if similar reductions will be available in other European countries.

1) Assuming 200gCO_2/kWh grid carbon intensity in 2020, 50gCO_2/kWh in 2030, 17kWh/100km BEV electricity consumption in 2020, 15kWh/100km in 2030, 60kWh/kg electrolyser electricity consumption in 2020, 53kWh/kg in 2030, 0.8kg/100km FCEV electricity consumption in 2020, 0.7kg/100km in 2030.
2) https://www.cleanenergywire.org/factsheets/germanys-national-hydrogen-strategy

Cars: Competition with electric vehicles remains challenging



- The above shows H2 prices corresponding to fuel parity with EVs[1] in 2020 and 2030 along with the modelled hydrogen cost in GB, both for the case of **LDVs**.
- Assumed EV fuel costs include electricity cost as well as the cost of an EV home charger.
- In **2020 H2 FCEVs cannot achieve fuel parity** with EVs.
- In **2030 H2 FCEVs** could achieve **fuel parity given levy reductions** for electrolysers and assuming **EVs pay residential prices** for electricity.
- Residential prices are much higher than industrial prices with reductions assumed for electrolysers.
- For **EV electricity costs based on industrial electricity prices** with levy reductions, **EV parity prices** are **much lower** (€2.8/kg and €2.7/kg in 2020 and 2030 respectively) and **H2 FCEVs could not achieve parity in either 2020 or 2030**.
- Electricity **levy reductions** for electrolysers providing H2 to LDV FCEVs are **uncertain** due to the alternative of electric vehicles (cp. previous slide).

1) Cp. appendix for EV fuel cost assumptions

Executive Summary

Introduction

Techno-economic assumptions

Methodology

Results and discussion

Conclusions and recommendations

Appendix

CONCLUSIONS

Hydrogen Mobility Europe

- **Cars:** Competition with taxed diesel possible in 2020 in GB and FR given high utilization of refueling stations; increases towards 2030.
- **Busses:** Competition with taxed diesel possible in 2030 given exemption from policy levies.
- Competition with **electric vehicles (EVs)** only possible given exemption from levies for electrolysers and full residential electricity prices paid by EVs.
- In **2030**, **oversizing** the electrolyser offers **cost savings** due to increased **volatility** of electricity prices, higher **efficiency** of electrolysers at lower set points, and reduced electrolyser CAPEX.
- This development is **more pronounced in DE and GB**, which are expected to have higher average electricity prices as well as higher electricity price volatility (due to high renewable penetration) than FR.
- **Exemption from policy levies** as currently available in DE, GB and FR for energy intensive industries would help to **improve** the electrolyser **business case** significantly.
- **Balancing services** can provide a secondary revenue stream for electrolysers but are not expected to be the main pillar of a business model.
- **Reducing the HRS utilization** rate from 100% to 25% would make **HRS and electrolyser dominate green hydrogen cost** (instead of electricity). It would lead to a 74% cost increase of hydrogen cost in 2020 in GB, vs. 21% in 2030 due to expected CAPEX reductions of electrolysers and HRS.

FCH

FURTHER WORK

- Model **RES collocation** of electrolysers: allows avoiding policy levies and grid fees, will require transport of H2 to HRS
- Refinement of **HRS cost** modelling
- Analysis of impact of **multiday hydrogen storage**
- Further development of **electricity prices modelling s**uch as accounting for generator bidding strategies and refined representation of the value of flexibility.

Hydrogen Mobility Europe

Executive Summary

Introduction

Techno-economic assumptions

Methodology

Results and discussion

Conclusions and recommendations

Appendix

Assumptions on vehicle fuel consumption

Hydrogen Mobility Europe

Quantity	Unit	Year	Value	Notes and source
LDV Diesel consumption	l/100km	2020	5	(ADAC, 2019 a), (DfT, 2019)
LDV Diesel consumption	l/100km	2030	4.3	Assuming same efficiency improvement as for H2 FCEVs in (FCHJU, 2018)
HDV Diesel consumption	l/100km	2020	33	(BMVI, 2015)
HDV Diesel consumption	l/100km	2030	29.3	Assuming same efficiency improvement as for H2 FCEVs in (FCHJU, 2018)
LDV H2 consumption	kg/100km	2020	0.8	(Toyota, 2019)
LDV H2 consumption	kg/100km	2030	0.7	Assuming same efficiency improvement as for H2 FCEVs in (FCHJU, 2018)
HDV H2 consumption	kg/100km	2020	8	(FCHJU, 2018)
HDV H2 consumption	kg/100km	2030	7.1	(FCHJU, 2018)

Assumptions on vehicle fuel consumption

Quantity	Unit	Country	Year	Value	Notes and source
Diesel retail price LDV (w/o carbon cost)	€/l	France	2020 & 2030	1.46	(Fuels Europe, 2019)
Diesel retail price LDV (w/o carbon cost)	€/l	Germany	2020 & 2030	1.25	(ADAC, 2019 b)
Diesel retail price LDV (w/o carbon cost)	€/l	UK	2020 & 2030	1.48	(AA, 2019)
Fuel duty on Diesel	€/l	France	2020 & 2030	0.61	(EU Commission, 2020)
Fuel duty on Diesel	€/l	Germany	2020 & 2030	0.47	(EU Commission, 2020)
Fuel duty on Diesel	€/l	UK	2020 & 2030	0.65	(HMT, 2020)
VAT on Diesel	%	France	2020 & 2030	20%	(EU Commission, 2020)
VAT on Diesel	%	Germany	2020 & 2030	19%	(EU Commission, 2020)
VAT on Diesel	%	UK	2020 & 2030	20%	(HMT, 2020 a)
Carbon price	€/tCO2	DE, FR, UK	2020	16	(HMT, 2020 b)
Carbon price	€/tCO2	DE, FR, UK	2030	91	(HMT, 2020 b)

Prices have been converted from £ to €, using an exchange rate of 1.130081 €/£ (avg. exchange rate in 2018, https://www.ofx.com/en-gb/forex-news/historical-exchange-rates/yearly-average-rates/)

Assumptions on hydrogen storage cost

Hydrogen Mobility Europe

Quantity	Unit	Year	Value	Notes and source
LDV H2 storage CAPEX	€/kg	2020	2,000	(New Bus Fuel, 2017)
LDV H2 storage CAPEX	€/kg	2030	1,200	Assuming the same cost reduction 2020-2030 as for HRS in (FCHJU, 2018)
HDV H2 storage CAPEX	€/kg	2020	1,350	(New Bus Fuel, 2017)
HDV H2 storage CAPEX	€/kg	2030	836	Assuming the same cost reduction 2020-2030 as for HRS in (FCHJU, 2018)

- In addition to the CAPEX, fixed **OPEX** of **5% of CAPEX** per year are assumed
- The HRS cost target by the FCHJU, which we are using as HRS cost estimate, includes the cost of on site storage
- We assume that storage cost in addition to the storage cost included in the HRS cost estimate are only incurred if the storage size exceeds the storage size required for a 100% load factor of the electrolyser

Assumptions on EV fuel cost

Quantity	Unit	Year	Value	Notes and source
Residential electricity price GB	£/kWh	2020	0.203	(BEIS, 2019 a)
Residential electricity price GB	£/kWh	2030	0.199	(BEIS, 2019 a)
EV electricity consumption	kWh/100km	2020	17.2	EE modelling
EV electricity consumption	kWh/100km	2030	14.7	EE modelling
EV charger – installed cost	£/EV	2020	750	(Spirit Energy, 2020)
EV charger – installed cost	£/EV	2030	450	Assume same cost reduction as for HRS CAPEX in (FCHJU, 2018)

Further assumptions

- A mileage of 12,000 km/EV is assumed[1].
- An exchange rate of 1.1301 € per 1 £ is applied to convert £ to €[2].
- A 10 year lifetime of an EV charger is assumed[3].

1) https://www.mein-autolexikon.de/magazin/tipps-und-tricks-fuer-autofahrer/fahrleistung-bundesland-fahrzeugalter-geschlecht-alter.html
2) 2018 avg. exchange rate acc. to: https://www.ofx.com/en-gb/forex-news/historical-exchange-rates/yearly-average-rates/
3) https://www.evconnect.com/blog/maintenance-for-ev-charging-stations-what-to-know-about-ev-charger-repair/

Assumptions on balancing services (1/3)

General assumptions

- Three different kinds of balancing services are modelled:
  - **positive** balancing (increasing generation or reducing demand)
  - **negative** balancing (reducing generation or increasing demand)
  - **symmetric** balancing (providing equal amounts of positive and negative balancing).
- The same prices are assumed in 2020 and 2030.
- In the case of **symmetric** balancing availability payments per MW refer to MW flexibility provided in **upward as well as downward** direction
- In the case of **positive / negative** balancing, payments per MW refer to MW flexibility provided in **either upward or downward** direction

UK assumptions

- **UK prices** and service windows are based on current (2018/2019) prices and windows (EFA blocks) for Firm Frequency Response (**FFR**), which providers can offer as positive, negative as well as symmetric service. No utilisation payments are assumed as currently this is merely required by providers even though the possibility for such payments exists.
- It is assumed a service in a particular daily window has to be offered for one week. Currently, monthly FFR auctions are held, with weekly trials being deployed.

Assumptions on balancing services (2/3)

DE and FR assumptions

- **DE and FR prices** and service windows for the **symmetric** balancing service are based on current (2018/2019) prices and windows for Frequency Containment Reserve (**FCR**), which is procured in daily auctions as 24h symmetric service (window length 24h) jointly held by TSOs from DE, FR, AT, DK, CH, BE, NL. Only availability is remunerated, utilisation is not remunerated.
- **DE prices** and service windows for **positive and negative** balancing are based on current (2018/2019) prices and windows for positive and negative Secondary Control Reserve (**SCR,** automatic Frequency Restoration Reserve, **aFRR**, in ENTSO-E terminology) in Germany, procured in daily auctions of 4h windows. The wholesale price is subtracted and added to pSCR and nSCR utilisation payments to account for the fact that these utilisations will need to be offset through subsequent changes in the electrolyser consumption profile.
- **FR prices** and service windows for **positive and negative** balancing are based on current (2018/2019) prices and windows for **aFRR** in FR, provided by CNR. As in the case of Germany, the wholesale price is subtracted and added to pSCR and nSCR utilisation payments to account for the fact that these utilisations will need to be offset through subsequent changes in the electrolyser consumption profile.
- It is assumed that aFRR will be procured as an asymmetric service in France as this is required by the Electricity Balancing Guideline (Article 32.3).

Assumptions on balancing services (3/3)

Quantity	Balancing service	Unit	GB	DE	FR
Availability payment	Symmetric	€/MW/h	11	13	13
	Positive	€/MW/h	6	4	9
	Negative	€/MW/h	6	4	9
Utilisation payment	Symmetric	€/MWh	0	0	0
	Positive	€/MWh	0	35	0
	Negative	€/MWh	0	54	0
Utilisation rate	Symmetric		5%	N/A	N/A
	Positive		5%	7%	7%
	Negative		5%	6%	6%
Window length	Symmetric	h	4	24	24
	Positive	h	4	4	4
	Negative	h	4	4	4

Assumptions on electricity wholesale prices

Hydrogen Mobility Europe

- Wholesale electricity prices in the 2020 model run are based on 2018 wholesale market data in all three countries.
- Wholesale electricity prices in 2030 are based on prices as modelled in the EE dispatch model for future power system scenarios.
- The following describes assumptions taken on grid fees and policy levies. The same assumptions were used for 2020 and 2030.

FCH

Assumptions on grid fees and policy levies GB

Grid fees

- DUoS, based on UKPN Eastern Power Networks schedule of charges (2019 V2.0), cp. table below
- Capacity charge: £40.80/MVA/day, based on UKPN EPB schedule of charges (2019 V2.0)
- BSUoS: based on average Apr 2018 – Mar 2019 of SF data published by National Grid: £3.09/MWh
- TNUoS: based on average 2018/2019 tariff as published by National Grid: 46,170£/MW/y

Policy levies

- Green levies (levies to fund the support schemes Renewable Obligation Certificates, Feed in Tariffs, Contracts for Difference as well as the Climate Change levy) adding up to £37.95/MWh in 2018/2019
- Capacity Market levy: total CM costs are spread across the gross demand in the so called peak period, referring to 4-7pm in November until February, corresponding to £94.3/MWh in this period.

	Red (4-7pm)	Amber (7am-4pm, 7pm-11pm)	Green (0-7am, 11pm-0am)
DUoS charge (p/kWh)	57.11	1.62	1.14

Assumptions on grid fees and policy levies Germany

Grid fees

- Electrolysers are exempt from grid fees in Germany[1].

Policy levies

- Assumptions as in table below, based on 2019 data as specified in (BDEW, 2019) and (PWC, 2019)

Levy	Unit	Value
Renewable surcharge	€ct/kWh	6.405
Electricity tax	€ct/kWh	1.537
CHP surcharge	€ct/kWh	0.28
Offshore grid levy	€ct/kWh	0.416
“StromNEV” §19-Umlage	€ct/kWh	0.05
Concession fee	€ct/kWh	0.11
Interruptible loads fee	€ct/kWh	0.011

1) https://www.juris.de/jportal/portal/page/homerl.psml?nid=jpr-NLURADG000519&cmsuri=%2Fjuris%2Fde%2Fnachrichten%2Fzeigenachricht.jsp

Assumptions on grid fees and policy levies France

Grid fees

- Based on 2019 tariffs as published in (RTE, 2019)
- Fixed charge: 16.02 €/kW/y.
- Variable charge:

		Peak	High Season, Peak	High Season, Off-peak	Low Season, Peak	Low Season, Off-peak
Variable charge	€ct/kWh	2.8	2.1	1.31	0.97	0.86

	From month	To month	From hour	To hour
Peak (morning)	December	February	09:00	11:00
Peak (evening)	December	February	18:00	20:00
High Season, Peak[1]	November	March	07:00	23:00
High Season, Off-Peak	November	March	23:00	07:00
Low Season, Peak	April	October	07:00	23:00
High Season, Off-Peak	April	October	23:00	07:00

Policy levies

- Contribution au service public d'électricité (CSPE): €22.5/MWh (PWC, 2019); electrolysers are exempt from the charge, but electricity used for compression (for storage and distribution) is not;
- Capacity market: 17.365 €/kW/y (PWC, 2019);
- Contribution tarifaire d'acheminement (CTA): 10.14% of fixed grid fee, i.e. 1.62 €/kW/y

1) Excluding Peak hours (i.e. Dec – Feb, 9-11h, 18-20h)

Definitions of energy intensive industry in France and Germany

France

- Differentiation between electro – intensive and hyper – electro – intensive businesses (cp. definition below from (PWC, 2019)
- We assume a 50% reduction of grid fees which is available for electro – intensive businesses
- More details can be found in (PWC, 2019)

Electro-intensive and hyper-electro-intensive consumers are defined as follows:

	Power consumed/Value added	Trade-intensity	Annual power consumption
Electro-intensive	>2,5 kWh/€	>4%	>50 GWh
Hyper-electro-intensive	>6 kWh/€	>25%	Not applicable

Germany

- To be eligible a business needs to meet two criteria
  - The business has to belong to a sector which is among a list of sectors available for exemptions.
  - The business' power cost intensity, given by the ratio of the business' power costs to its gross value added, has to be higher than a certain threshold.
- In 2017, only 2,092 of over 45,000 industrial companies in Germany were eligible but those 2,092 companies represented 48% of industrial electricity consumption (PWC, 2019).
- More details in (PWC, 2019) and (BDEW, 2019).
- We assume a reduction of all policy levies by 85% in the case of reduced levies.

Definitions of energy intensive industry in Britain

UK

- To be eligible for policy levy reductions, the business has to pass two “ tests”
- “ Sector level test”: The business must manufacture a product in the UK within an eligible sector.
- “ Business level test”: In order to satisfy the business level test, businesses will need to show that their electricity costs amount to 20% or more of their Gross Value Added (GVA) over a reference period.
- More details can be found in (BEIS, 2019 b).
- We assume an 85% reduction of green levies and CM levy in the case of levy reductions.

EU Law

- It is important to note that reductions of taxes and levies granted to companies must comply with EU competition law. The European Commission provided framework guidance to EU Member States through the Guidelines on State aid for environmental protection and energy 2014-20202 (EU Commission, 2014). This set out which sectors (by 4-digit NACE[1] code) could be eligible for exemption.

1) Nomenclature des Activités Économiques dans la Communauté Européenne, a European industry standard classification system

References

- **AA, 2019;** *UK and overseas petrol and diesel prices September 2019*; https://www.theaa.com/driving-advice/driving-costs/fuel-prices
- **ADAC, 2019 a**; *Diesel: Die sparsamsten Modelle aller Klassen*; https://www.adac.de/rund-ums-fahrzeug/auto-kaufen-verkaufen/autokosten/die-sparsamsten-diesel-aller-klassen/
- **ADAC, 2019 b;** *Benzinpreise im europäischen Ausland;* https://www.adac.de/verkehr/tanken-kraftstoff-antrieb/ausland/spritpreise-ausland/; as accessed on 25/11/19
- **BDEW, 2019**; *Strompreisananalyse Juli 2019*; https://www.bdew.de/media/documents/190723_BDEW-Strompreisanalyse_Juli-2019.pdf
- BEIS, 2019 a; Energy and Emissions Projections; Annex M; https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/802478/Annex-m-price-growth-assumption_16-May-2019.ods
- **BEIS, 2019 b**; Energy Intensive Industries; https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/831384/CFD_RO_FIT_Exemption_Guidance_Revised_Sept_2019.pdf
- **BMVI, 2015,** *Berechnung des Energieverbrauchs und der Treibhausgasemissionen des ÖPNV;* https://www.bmvi.de/SharedDocs/DE/Anlage/G/energieverbrauch-treibhausgasemission-oepnv.pdf?__blob=publicationFile
- **Bundesnetzagentur, 2018**, *Genehmigung des Szenariorahmens 2019-2030*; Scenario C 2030; https://www.netzausbau.de/SharedDocs/Downloads/DE/2030_V19/SR/Szenariorahmen_2019-2030_Genehmigung.pdf;jsessionid=B23297CB39EF44CEE8DBA3E374081275?__blob=publicationFile

References

- **Committee on Climate Change, 2018**, *Reducing UK emissions – 2018 Progress Report to Parliament*; High Renewables scenario; p. 70**;** https://www.theccc.org.uk/publication/reducing-uk-emissions-2018-progress-report-to-parliament/
- **DfT, 2019**; *Energy and environment: data tables (ENV), ENV0103: Average new car fuel consumption: Great Britain;* https://www.gov.uk/government/statistical-data-sets/energy-and-environment-data-tables-env
- **ENTSO-E, 2018**, *Ten Year Development Plan 2018*; Distributed Generation scenario 2030; https://tyndp.entsoe.eu/tyndp2018/
- **EU Commission, 2014**, *Guidelines on State aid for environmental protection and energy 2014-2020*; https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52014XC0628(01)
- **EU Commission, 2020**, *Oil Bulletin Duties and taxes*; as accessed 02/06/20; https://ec.europa.eu/energy/observatory/reports/Oil_Bulletin_Duties_and_taxes.pdf
- **FCHJU, 2018**, *Multi - Annual Work Plan 2014 – 2020*, https://www.fch.europa.eu/sites/default/files/MAWP%20final%20version_endorsed%20GB%2015062018%20%28ID%203712421%29.pdf
- **Fuels Europe, 2019;** *FUEL PRICE BREAKDOWN*; https://www.fuelseurope.eu/knowledge/refining-in-europe/economics-of-refining/fuel-price-breakdown/
- **HMT, 2020 a**; *Tax on shopping and services*; https://www.gov.uk/tax-on-shopping/fuel-duty
- **HMT, 2020 b**, *Green Book supplementary guidance: valuation of energy use and greenhouse gas emissions for appraisal*; table 3; https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

References

- **New Bus Fuel, 2017**, *New Bus ReFuelling for European Hydrogen Bus Depots - Guidance Document on Large Scale Hydrogen Bus Refuelling*; http://newbusfuel.eu/wp-content/uploads/2015/09/NBF_GuidanceDoc_download.pdf
- **PWC, 2019**, *A European comparison of electricity and gas prices for large industrial consumers*; https://www.creg.be/sites/default/files/assets/Publications/Studies/F20190507EN.pdf
- **RTE, 2019**; *TURPE 5: NETWORK TARIFF - UNDERSTANDING THE TARIFF*; https://clients.rte-france.com/htm/an/mediatheque/telecharge/20190701_Plaquette_tarifaire_TURPE_5_CONSO_PROD_EN.pdf
- **Spirit Energy, 2020**; *EV Charging Knowledge Bank: Electric Home Car Charging Points – Costs*; https://www.spiritenergy.co.uk/kb-ev-charging-point-install-prices

ACKNOWLEDGEMENTS

This project has received funding from the **Fuel Cells and Hydrogen 2 Joint Undertaking** under grant agreement No 671438 and No 700350. This Joint Undertaking receives support from the **European Union**'s Horizon 2020 research and innovation programme, **Hydrogen Europe Research** and **Hydrogen Europe**.