Future production costs of green hydrogen

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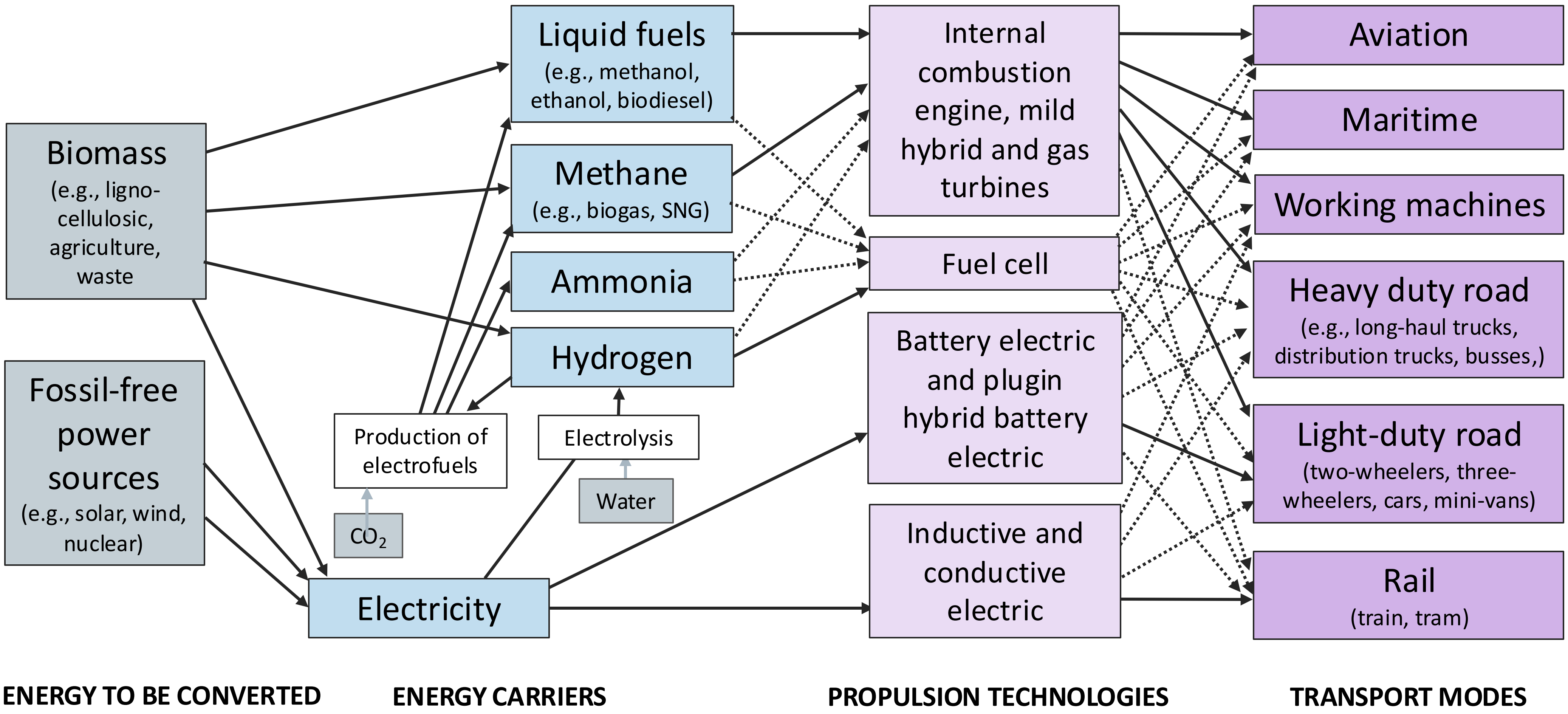
Various types of fuels and vehicle technology options

which are differently well suited for the different transport modes, where the dashed arrows indicate pathways that currently are more complex or less mature.



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Review of electrofuel feasibility: Cost and environmental impact

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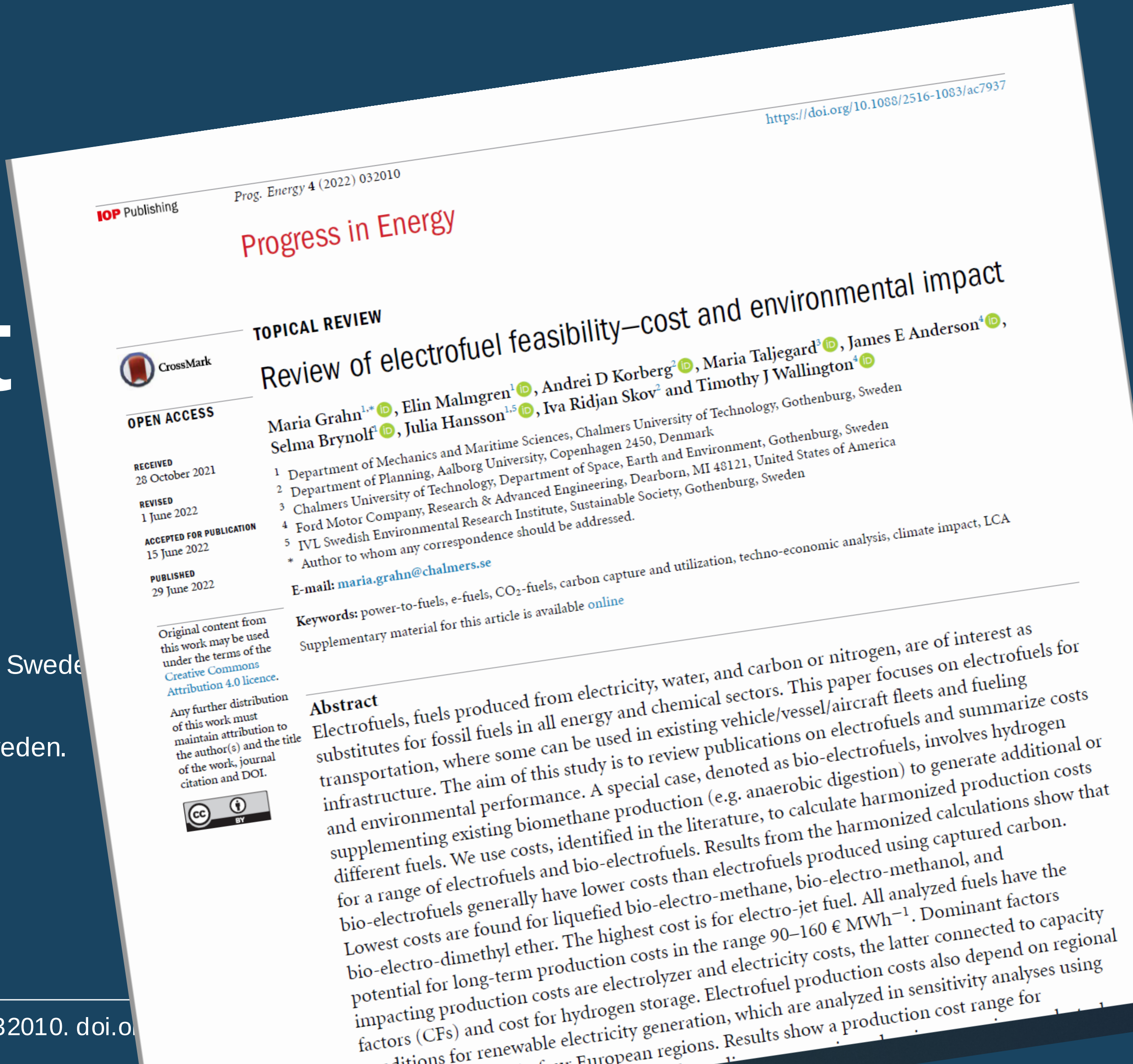
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TOPICAL REVIEW

Review of electrofuel feasibility—cost and environmental impact

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Supplementary material for this article is available online

Abstract

Electrofuels, fuels produced from electricity, water, and carbon or nitrogen, are of interest as substitutes for fossil fuels in all energy and chemical sectors. This paper focuses on electrofuels for transportation, where some can be used in existing vehicle/vessel/aircraft fleets and fueling infrastructure. The aim of this study is to review publications on electrofuels and summarize costs and environmental performance. A special case, denoted as bio-electrofuels, involves hydrogen supplementing existing biomethane production (e.g. anaerobic digestion) to generate additional or different fuels. We use costs, identified in the literature, to calculate harmonized production costs for a range of electrofuels and bio-electrofuels. Results from the harmonized calculations show that bio-electrofuels generally have lower costs than electrofuels produced using captured carbon. Lowest costs are found for liquefied bio-electro-methane, bio-electro-methanol, and bio-electro-dimethyl ether. The highest cost is for electro-jet fuel. All analyzed fuels have the potential for long-term production costs in the range 90–160 € MWh^{-1}. Dominant factors impacting production costs are electrolyzer and electricity costs, the latter connected to capacity factors (CFs) and cost for hydrogen storage. Electrofuel production costs also depend on regional conditions for renewable electricity generation, which are analyzed in sensitivity analyses using … European regions. Results show a production cost range for …

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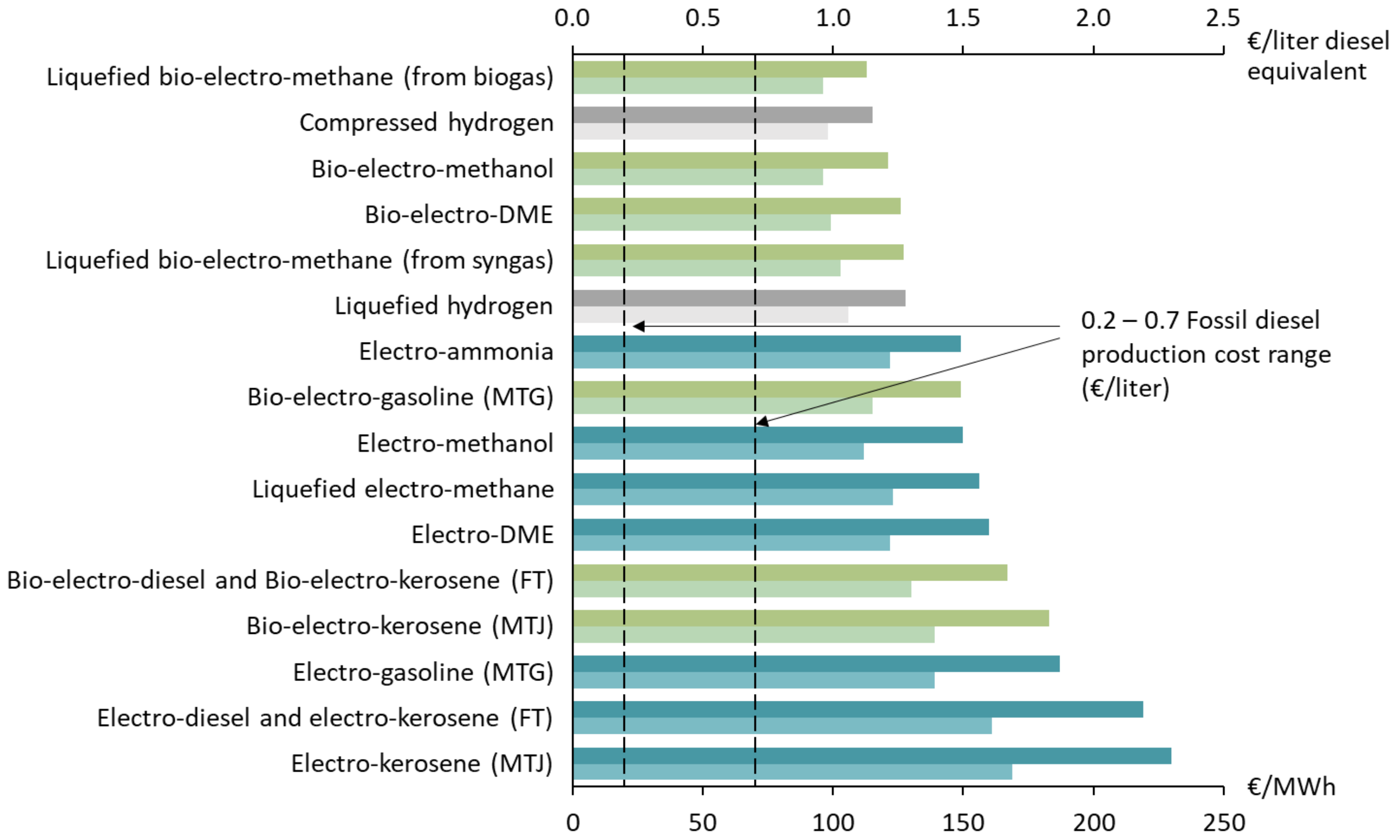
Production costs for electrolytic hydrogen, bio-e-fuels, and e-fuels



Dark colored bars: Near-term cost, approx. 5-10 years in future. **Results 110-230 €/MWh.**

Light colored bars: long-term cost, approx. 20-30 years in future. **Results 90-160 €/MWh.**

Black dotted lines illustrate a range of production costs of fossil gasoline/diesel/kerosene, corresponding to an oil price range of $30–$100/barrel.

Note: no cost for fuel infrastructure nor hydrogen storage, and no revenue for oxygen, are included.

Acronyms used:
DME: dimethyl ether;
MTG: methanol-to-gasoline;
MTJ: methanol-to-jet;
FT: Fischer-Tropsch.

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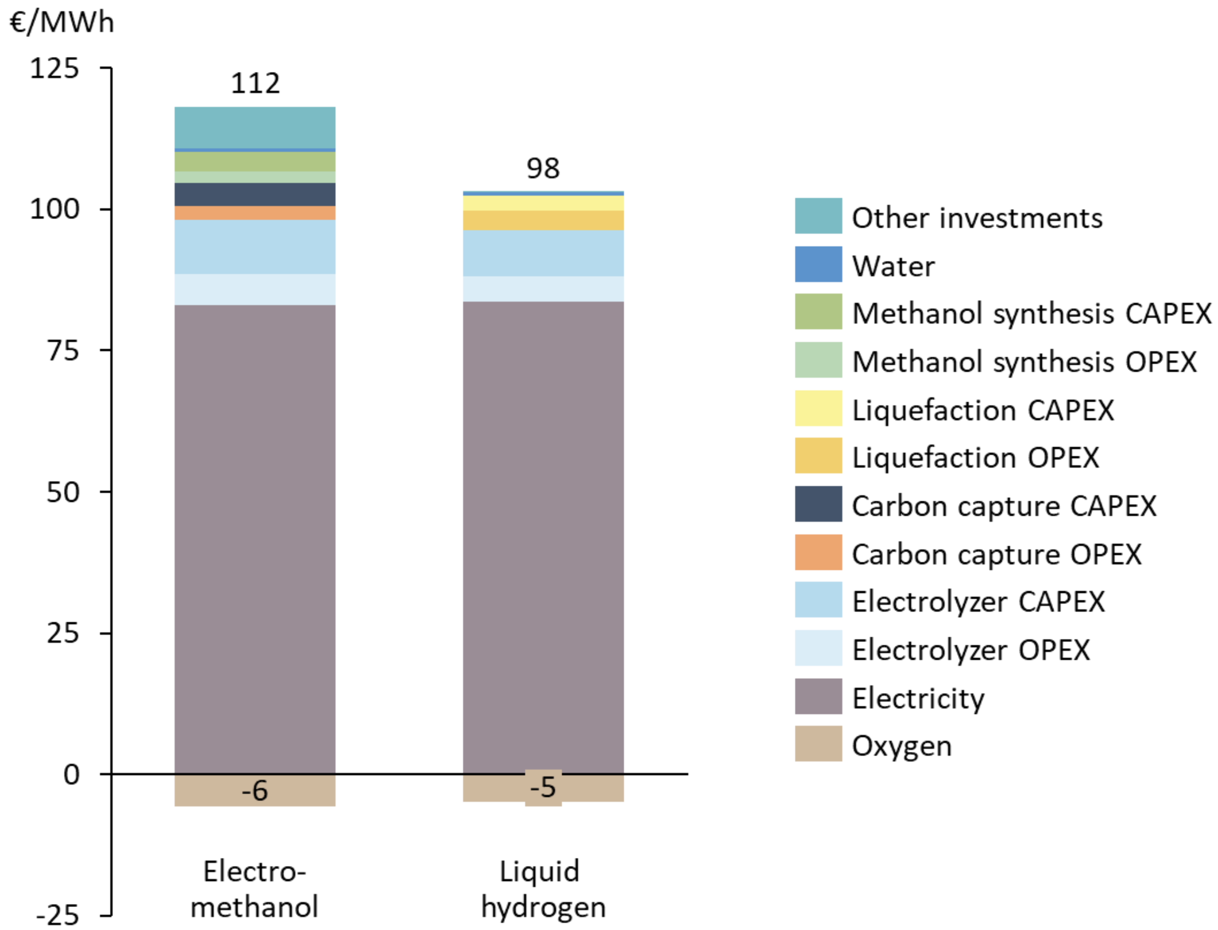
Production costs e-methanol and liquefied electrolytic hydrogen



Component costs, using base values (long-term) from the literature review.

A potential revenue for selling oxygen at 50 EUR/tO_2 is included.

Neither costs for fuel infrastructure, nor cost for hydrogen storage, are included.

CAPEX: capital expenditures
OPEX: operational expenditures

Insights
- The cost for electricity dominates, followed by the costs for the electrolyzer.
- Selling by-products as oxygen benefit the business opportunities.

Data used generating results on previous 2 slides

Near-term: approx. 5-10 years.
Long-term: approx. 20-30 years.
Costs represent €2019.

Electrolysis	Unit	Near-term	Long-term
CAPEX electrolyzer (near-term: an average of AEL and PEMEL, long-term: an average of AEL, PEMEL and SOEL)	€/kW_{el}	900	500
OPEX (including replacement of the stack)	share of CAPEX	0.04	0.04
Conversion efficiency	$H_{2,LHV}$/electricity input	65%	74%
Demand for water (assuming 2X stoichiometric demand)	ton/MWh_{H2}	0.54	0.54
Cost for deionized water	€/ton_{water}	1	1
Bio-e-fuel processes[a)]	**Unit**	**Near-term**	**Long-term**
CAPEX gasification (including gas cleaning)	€/$kW_{dry\ biomass}$	1250	1150
Conversion efficiency	$GJ_{Syngas}/GJ_{Input\ biomass}$	77%	83%
Biomass feedstock	€/$GJ_{biomass}$	7	7
CAPEX biogas plant (anaerobic digestion)	€/kW_{biogas}	1900	1650
Biogas substrate feedstock	€/$GJ_{biogas\ substrate}$	1.2	1.2
Fuel synthesis	**Unit**	**Near-term**	**Long-term**
CAPEX synthesis reactor and conversion efficiency in parentheses			
Hydrogen to methane	€/kW_{CH4}	450 (83%)	250 (83%)
Hydrogen to methanol	€/kW_{MeOH}	700 (84%)	300 (84%)
Hydrogen to DME	€/kW_{DME}	700 (81%)	300 (81%)
Methanol to gasoline	€/$kW_{Gasoline}$	600 (88%)	300 (88%)
Methanol to jet fuel[b)]	€/$kW_{Jet\text{-}fuel}$	1000 (74%)	500 (74%)
Hydrogen to Fischer-Tropsch liquids[c)]	€/$kW_{fuel\ liquids}$	1600 (66%)	750 (66%)
Ammonia synthesis (including ASU)	€/kW_{NH3}	1400 (79%)	850 (79%)
OPEX	share of CAPEX	0.04	0.04
Other[d)]	**Unit**	**Near-term**	**Long-term**
Cost for CO_2 capture (point source)[e)]	€/ton_{CO2}	50	25
Electricity price[f)]	€/MWh_{el}	50	50
Hydrogen liquefaction	€/kW_{fuel}	0.30	0.17
Other investments (costs for installation, unexpected costs, etc)	factor multiplied to CAPEX	1.5	1.5
Capacity factor for electrolyzers (in base case assumed to operate without H_2 storage)	share of max capacity	0.70	0.70
Interest rate		0.05	0.05
System life time	years	25	25

a) Bio-e-fuels production costs are built up by costs for gasification/anaerobic digestion, biomass feedstock/biogas substrate, electrolyzer, electricity, fuel synthesis and eventual liquefaction.

b) Although one can expect the two processes MTG and MTJ to be similar, there is currently very little information in the literature. The MTJ process is still in test and demonstration scale and therefore near-term (as well as long-term) costs, and efficiencies, are very uncertain.

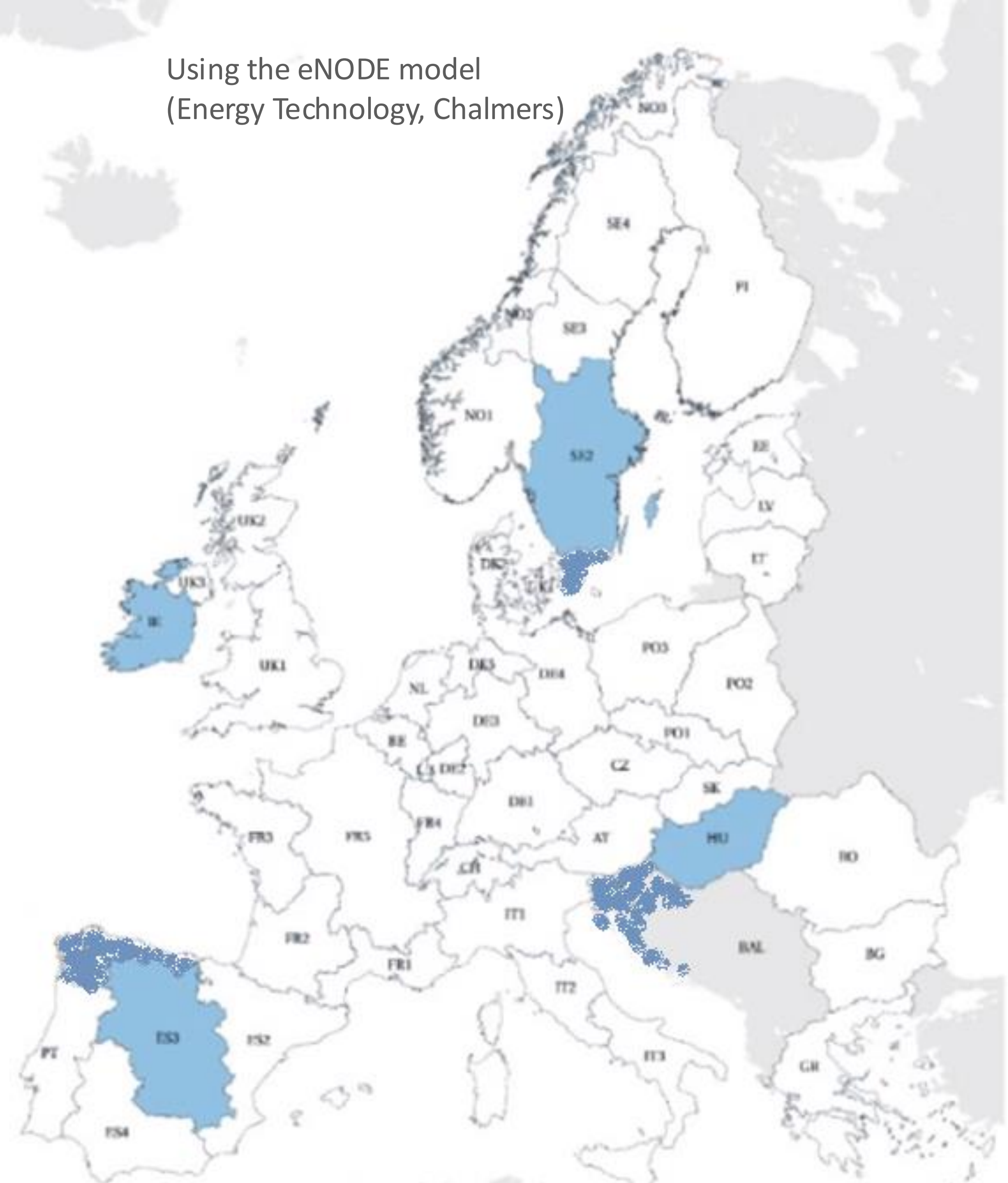
c) We assume a production efficiency from H_2 to FT liquids of 73%, and that 90% of this output can be a commercialized fuel after upgrading (of any type). For simplicity reasons we assume all commercial FT liquids being diesel and jet fuels (and thereby disregard from that a certain share of the commercial FT products are gasoline, feedstock for chemicals and other products.

d) We do not include cost for carbon transport or storage, essentially assuming that carbon is captured close to the e-fuel production site and the rate of capture exactly matches the demand. This is a simplifying assumption that deserves further scrutiny in future assessments.

e) Cost for CO_2 capture is very uncertain, but the contribution from this cost factor to the production cost is relatively small and therefore the uncertainties are less critical.

f) Future electricity prices are uncertain and depend on different factors such as the future demand for electricity, the share of variable renewable power sources, potential phase out of nuclear power, the integration with other energy sectors. From running the eNODE model under different scenarios, we find that all studied regions show an average electricity price of approximately 50 €/MWh by both 2030 and 2050, which we have assumed in our base case calculations. The effect of different electricity prices is explored in our sensitivity analyses.

Using the eNODE model
(Energy Technology, Chalmers)



Different conditions for renewable electricity in Europe

Four regions in Europe have been chosen:

1. Hungary-Croatia-Slovenia (relatively poor conditions for wind, hydro and solar generation),
2. Ireland (good wind conditions),
3. western Spain, (good solar conditions),
4. southern Sweden, (access to large reservoir of hydro power and good wind conditions).

Grahn et al (2022) Review of electrofuel feasibility: Cost and environmental impact. *Progress in Energy 4 (3)* 032010. doi.org/10.1088/2516-1083/ac7937.

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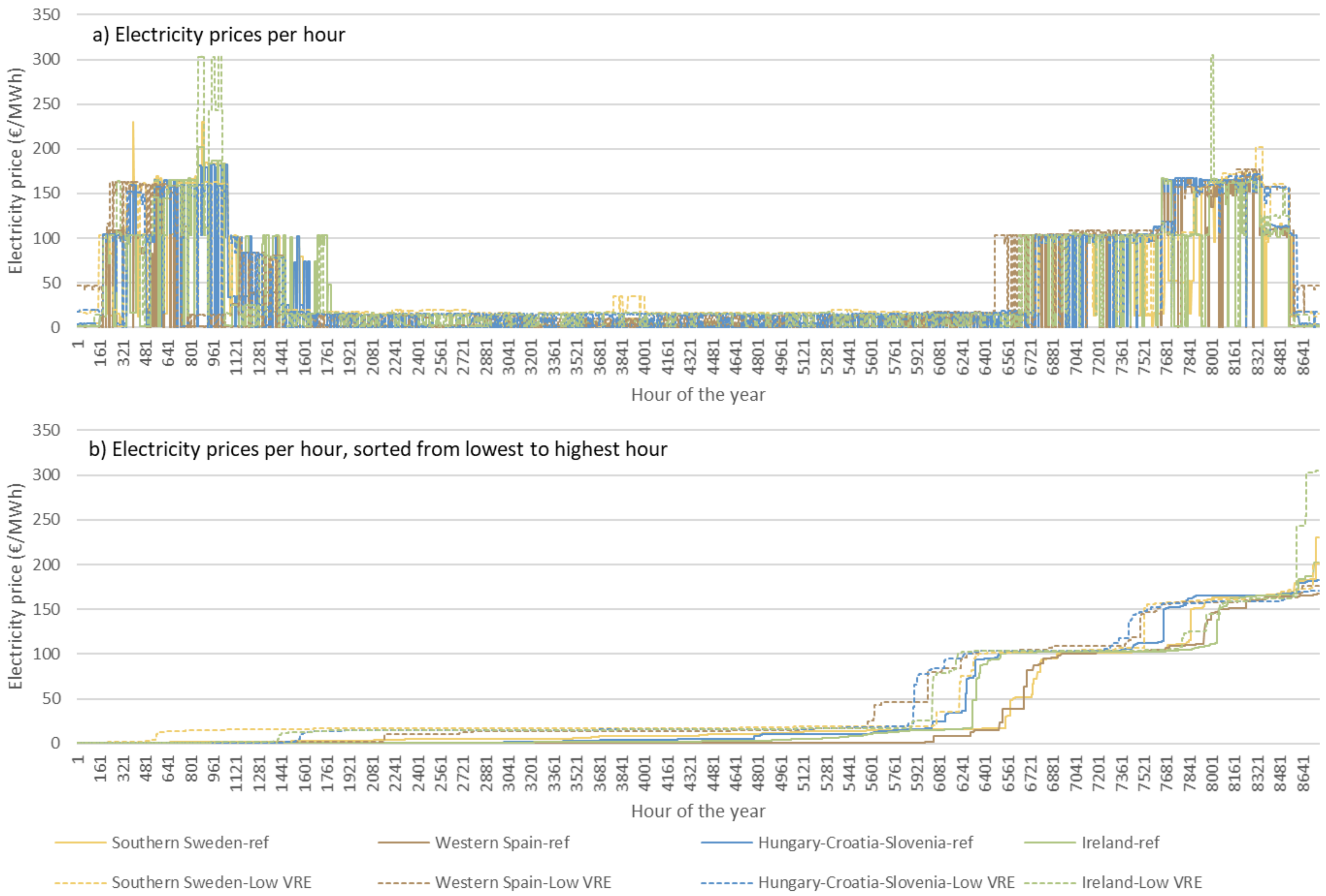
Modeled electricity prices for the 4 regions, 2050



In Case ”Low VRE” we assume there will be low acceptance for electricity generated from solar and wind, in combination with a large demand for hydrogen, which will lead to higher electricity prices compare to the reference scenario.

General reflections

- All four regions show lower electricity prices during summer than winter.
- All regions have potential to generate electricity prices below 50 €/MWh for more than half of the hours per year, but remaining hours the prices are much higher, up to 300 €/MWh.
- The high demand for H2 in Case Low VRE can to some extent represent a society utilizing low electricity prices (demand side management).

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Using the eNODE model (Energy Technology, Chalmers)

Electricity prices and hydrogen storage cost depending on capacity factor, 2050

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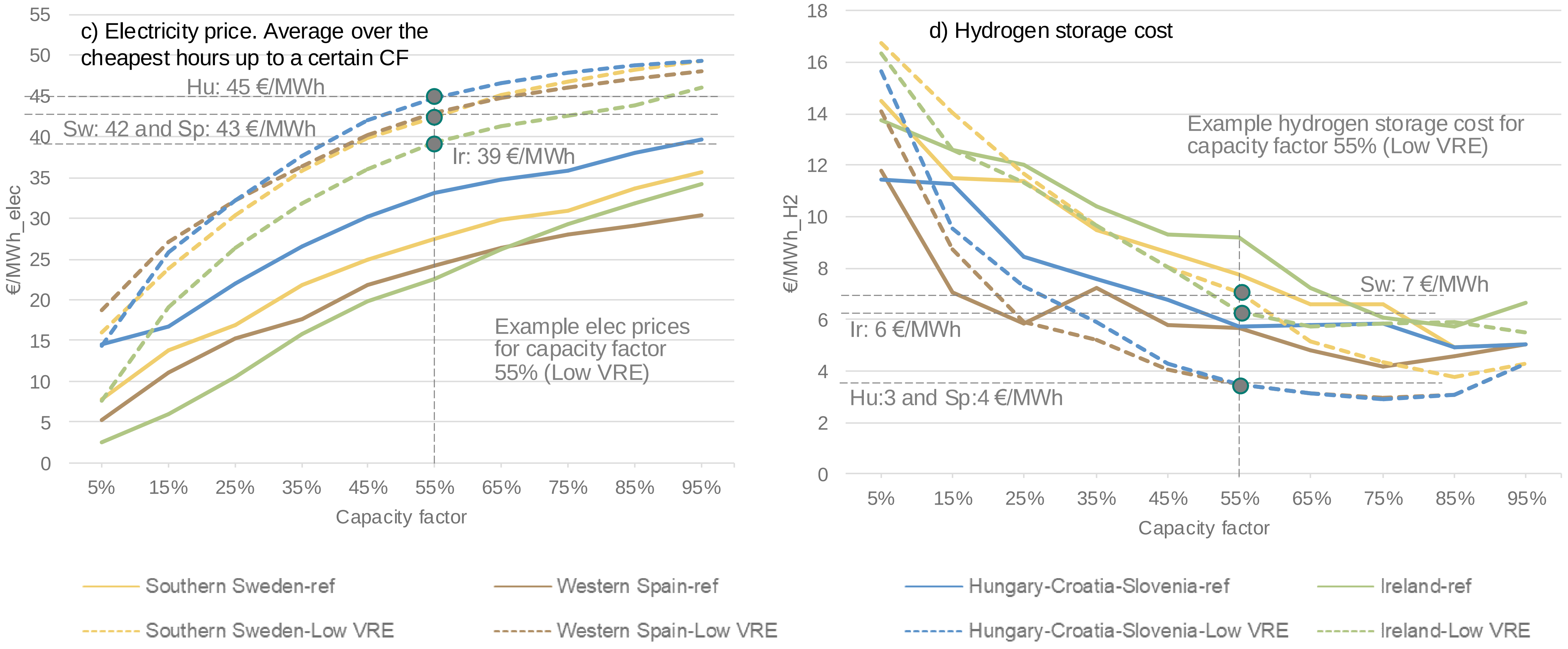
Plots are produced using the European energy systems model eNODE

Case: Low VRE



Average electricity prices for year 2050 starting at the lowest electricity price, for capacity factors 5%, 15% up till 95% of the hours of the year.

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Production cost liquefied electrolytic hydrogen

depending on capacity factor and electrolyzer investment cost, 2050, Low VRE case

Hungary-Croatia-Slovenia

Western Spain

Ireland

Southern Sweden

Electrolyser CAPEX (€/kWelec)										
900	407	175	135	122	115	111	109	107	106	106
750	350	156	124	114	109	106	105	103	103	103
600	293	137	112	106	103	101	100	100	99	100
450	236	118	101	98	96	96	96	96	96	97
300	179	99	90	89	90	91	91	92	93	94
150	122	80	78	81	84	85	87	88	89	91
Capacity factor (%)	5	15	25	35	45	55	65	75	85	95
Electricity price (€/MWh)	16	24	30	36	40	42	45	47	48	49
Hydrogen storage (€/MWh$_{H2}$)	17	14	12	10	8	7	5	4	4	4

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Production cost liquefied electrolytic hydrogen

depending on capacity factor and electrolyzer investment cost, 2050, Low VRE case

Hungary-Croatia-Slovenia

Electrolyser CAPEX (€/kWelec)										
900	473	197	148	131	123	118	115	112	111	110
750	416	178	137	123	117	113	110	108	107	107
600	359	159	125	115	110	108	106	105	104	104
450	302	140	114	107	104	103	102	101	101	101
300	245	121	103	98	98	97	97	97	97	98
150	188	102	91	90	91	92	93	93	94	95
Capacity factor (%)	5	15	25	35	45	55	65	75	85	95
Electricity price (€/MWh)	14	26	32	38	42	45	47	48	49	49
Hydrogen storage (€/MWh$_{H2}$)	16	10	7	6	4	3	3	3	3	4

Western Spain

Electrolyser CAPEX (€/kWelec)										
900	408	175	133	118	112	109	106	104	104	104
750	351	156	121	110	106	103	102	101	100	101
600	294	137	110	102	99	98	97	97	97	98
450	237	118	99	94	93	93	93	93	94	95
300	180	99	87	86	87	88	89	89	90	92
150	123	80	76	77	80	83	84	85	87	89
Capacity factor (%)	5	15	25	35	45	55	65	75	85	95
Electricity price (€/MWh)	19	27	32	36	40	43	45	46	47	48
Hydrogen storage (€/MWh$_{H2}$)	14	9	6	5	4	4	3	3	3	4

Using long-term values from the literature review and electricity prices as well as hydrogen storage costs from the eNODE model.

Ireland

Electrolyser CAPEX (€/kWelec)										
900	462	189	142	125	117	112	109	106	105	106
750	405	170	131	117	111	107	104	102	102	103
600	349	151	120	109	104	102	100	99	98	100
450	292	132	108	101	98	96	95	95	95	97
300	235	113	97	93	92	91	91	91	92	94
150	178	94	85	84	85	86	87	87	88	91
Capacity factor (%)	5	15	25	35	45	55	65	75	85	95
Electricity price (€/MWh)	8	19	26	32	36	39	41	42	44	46
Hydrogen storage (€/MWh$_{H2}$)	16	13	11	10	8	6	6	6	6	5

Southern Sweden

Electrolyser CAPEX (€/kWelec)										
900	407	175	135	122	115	111	109	107	106	106
750	350	156	124	114	109	106	105	103	103	103
600	293	137	112	106	103	101	100	100	99	100
450	236	118	101	98	96	96	96	96	96	97
300	179	99	90	89	90	91	91	92	93	94
150	122	80	78	81	84	85	87	88	89	91
Capacity factor (%)	5	15	25	35	45	55	65	75	85	95
Electricity price (€/MWh)	16	24	30	36	40	42	45	47	48	49
Hydrogen storage (€/MWh$_{H2}$)	17	14	12	10	8	7	5	4	4	4

Results (for electrolyzer CAPEX 300–450 €/kW and capacity factors 45–65%):

97–104 €/MWh for Hungary-Croatia-Slovenia

91–98 €/MWh for Ireland

87–93 €/MWh for western Spain

90–96 €/MWh for southern Sweden.

Production cost e-methanol

depending on capacity factor and electrolyzer investment cost, 2050, **Low VRE case**

low acceptance for electricity generated from solar and wind, and large demand for hydrogen (demand side management). Higher elec prices than in the ref case..

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Hungary-Croatia-Slovenia

Electrolyser CAPEX (€/kWelec)										
900	571	235	174	151	140	133	128	125	122	121
750	503	213	160	141	132	127	123	120	118	118
600	435	190	146	132	125	121	118	116	114	114
450	367	167	133	122	117	114	112	111	110	111
300	299	145	119	112	110	108	107	107	106	107
150	231	122	106	102	102	102	102	102	102	103
Capacity factor (%)	5	15	25	35	45	55	65	75	85	95
Electricity price (€/MWh)	14	26	32	38	42	45	47	48	49	49
Hydrogen storage (€/MWh$_{H2}$)	16	10	7	6	4	3	3	3	3	4

Western Spain

Electrolyser CAPEX (€/kWelec)										
900	577	236	172	148	137	130	125	122	120	119
750	509	214	158	138	129	124	120	117	116	116
600	441	191	145	129	122	117	115	113	112	112
450	373	168	131	119	114	111	109	108	108	108
300	305	146	118	109	106	105	104	104	104	105
150	237	123	104	100	99	99	99	99	100	101
Capacity factor (%)	5	15	25	35	45	55	65	75	85	95
Electricity price (€/MWh)	19	27	32	36	40	43	45	46	47	48
Hydrogen storage (€/MWh$_{H2}$)	14	9	6	5	4	4	3	3	3	4

Ireland

Electrolyser CAPEX (€/kWelec)										
900	561	228	169	146	134	127	123	119	117	117
750	493	205	155	136	127	121	117	115	113	114
600	425	182	142	127	119	115	112	110	109	110
450	357	160	128	117	112	109	107	106	105	107
300	289	137	114	107	104	103	102	101	101	103
150	221	114	101	97	97	96	96	97	97	100
Capacity factor (%)	5	15	25	35	45	55	65	75	85	95
Electricity price (€/MWh)	8	19	26	32	36	39	41	42	44	46
Hydrogen storage (€/MWh$_{H2}$)	16	13	11	10	8	6	6	6	6	5

Southern Sweden

Electrolyser CAPEX (€/kWelec)										
900	576	237	176	153	141	133	128	125	122	121
750	508	215	162	143	133	127	123	120	118	118
600	440	192	148	133	126	121	118	116	114	114
450	372	169	135	124	118	115	113	111	110	111
300	304	147	121	114	111	109	107	106	106	107
150	236	124	108	104	103	102	102	102	102	104
Capacity factor (%)	5	15	25	35	45	55	65	75	85	95
Electricity price (€/MWh)	16	24	30	36	40	42	45	47	48	49
Hydrogen storage (€/MWh$_{H2}$)	17	14	12	10	8	7	5	4	4	4

Using long-term values from the literature review and electricity prices as well as hydrogen storage costs from the eNODE model.

Results (for electrolyzer CAPEX 300–450 €/kW and capacity factors 45–65%):

107–117 €/MWh for Hungary-Croatia-Slovenia

107–118 €/MWh for southern Sweden

102–112 €/MWh for Ireland

104–114 €/MWh for western Spain

4-5% higher costs compared to Ireland and western Spain

Main insights

- E-fuel production costs are connected to the conditions for variable renewable electricity systems such as wind, and solar generation.
  - Production costs are lower in regions such as Ireland (good wind conditions), and western Spain (good solar conditions), compared to the two other assessed regions.
- If utilizing varying electricity prices in a smart way, the production cost of liquefied hydrogen and e-methanol can be as low as 58–87 €/MWh and 76–100 €/MWh respectively, assuming an electrolyzer CAPEX of 300–450 €/kW_{elec} combined with capacity factors of 45–65%
  - Future productions cost could, thus, be in the range of 6-10 SEK/liter diesel eq.
  - Electricity prices and electrolyzer CAPEXare two key cost factors.

Från elproduktion med bränsle
till bränsleproduktion med el

AVANCEZ

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