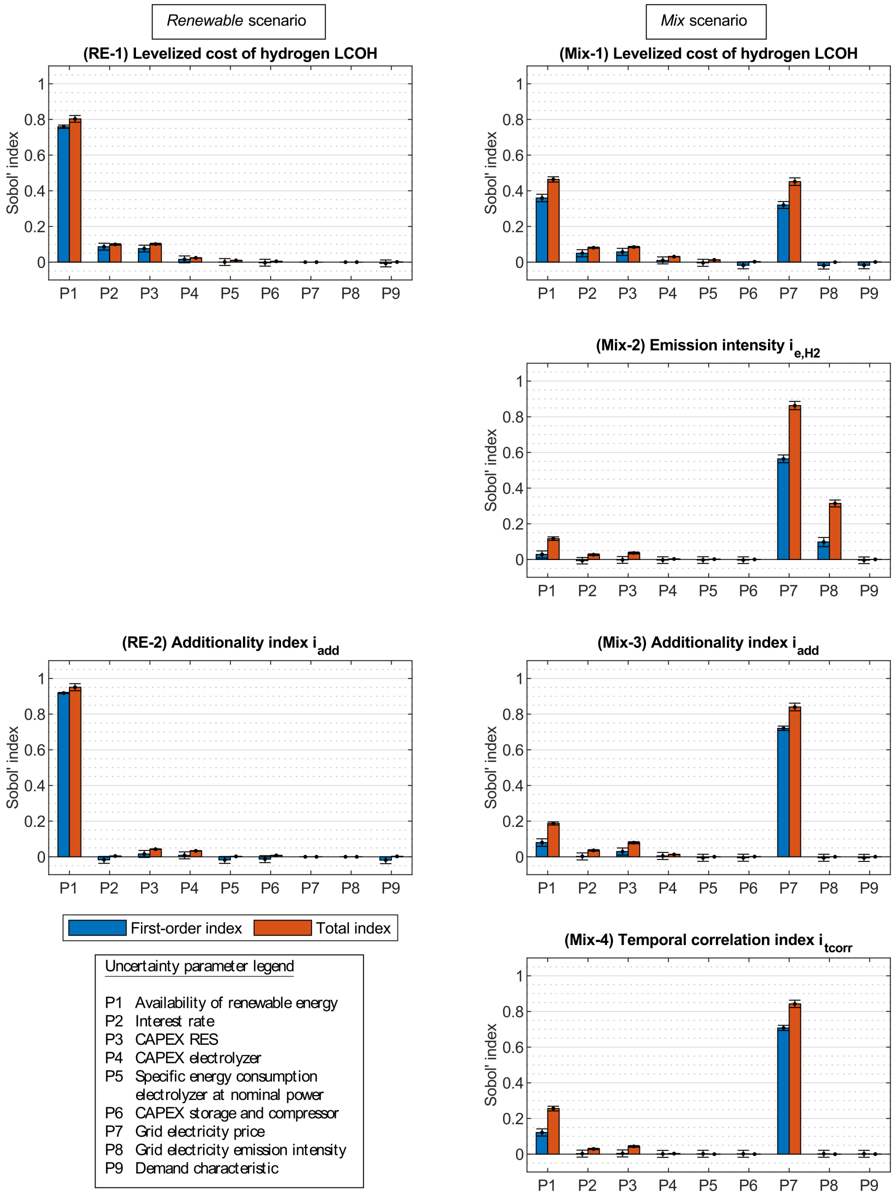
# Cost and competitiveness of green hydrogen in Europe: Effects of the European Union regulatory framework - Supplementary information

## Supplementary Note 1

Supp. Figure 1 shows the results of the variable importance analysis. (RE-1) and (RE-2) in the left column show the results of the *Mix* scenario and (Mix-1) to (Mix-4) in the right column show the results of the *Renewable* scenario. The variance-based variable importance measures calculated here are first-order and total Sobol' indices, with the former indicating the exclusive contribution of the uncertainty of the respective input variable on the uncertainty of the model output and the latter additionally including contributions from combinatorial effects with other uncertain input variables [1]. Hereby, a high first-order index indicates a high contribution of the uncertainty of the respective input variable and a low index indicates a low contribution.

The first-order Sobol' indices for the *Renewable* scenario, depicted in (RE-1) and (RE-2) in Supp. Figure 1, show that the uncertainty in the LCOH and in the additionality index result mainly from the uncertain availability of renewables, indicated as P1 in Supp. Figure 1, that differs between the different possible locations in Europe. Even under consideration of combinatorial effects, the uncertainty in availability of renewables (P1) mainly determines the resulting LCOH and additionality index in the *Renewable* scenario.

The LCOH in the *Mix* scenario also shows a high dependency on the uncertainty of availability of renewables (P1), with the uncertainty of grid electricity prices (P7) having a similarly large impact in this scenario, as shown in Supp. Figure 1 (Mix-1). The uncertainty of all renewable indices in the *Mix* scenario is mainly influenced by the uncertainty in GEP (P7) (see Supp. Figure 1 (Mix-2) to (Mix-4)). Whereby, the influence on the emission intensity of hydrogen is notably higher in combination with the uncertainty of emission intensity of grid electricity (P8) (see Supp. Figure 1 (Mix-2)). Also worth mentioning is the impact of the uncertainty of availability of renewables (P1) on the additionality and the temporal correlation index (see Supp. Figure 1 (Mix-3) and (Mix-4)) in the *Mix* scenario.




**Supp. Figure 1** Results of the variable importance analysis. (RE-1) and (RE-2): Results of the *Renewable* scenario. The impact of the input parameters' uncertainty on the emission intensity $i_{e,H2}$ is excluded because it is zero under all circumstances due to the calculation method presented in section *Methods*. Similar applies to the temporal correlation index which is, independently from the uncertainty of all input parameters, always one. (Mix-1)-(Mix-4): Results of the *Mix* scenario.

Supp. Table 1 shows the uncertain optimization input parameters and their respective range of uncertainty that are used in the performed variable importance analysis.

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**Supp. Table 1** Uncertain input parameters.

| Input parameter | Uncertainty range | Unit | Reference |
|---|---|---|---|
| Availability of renewable energy at different locations | [1811, 4767] | Potential full load hours | [2–4] |
| Interest rate | RES: [4, 9]<br>Hydrogen production plant: [6, 11] | %<br>% | [5–9] |
| CAPEX RES | Wind: [1070, 2077]<br>PV: [530, 1097] | €/kW<br>€/kW | [5, 10, 11] |
| CAPEX electrolyzer | [650, 1710] | €/kW | [12–17] |
| Specific energy consumption of electrolyzer plant at nominal power | [49, 56] | kWh/kg | [13, 15, 18–22] |
| CAPEX storage and compressor | Storage: [462, 684]<br>Compressor: [500, 568] | €/kg<br>€/kW | [7, 9, 23, 24] |
| Grid electricity price | [0.02, 0.58] | €/kWh | [25–32] |
| Emission intensity of grid electricity | [0.01476, 0.74376] | $kgCO_2eq/kWh$ | [33] |
| Demand profiles | [8760, 313] | Full load hours | see text below |

The uncertainty in location within Europe reflects on the potential yield of the onshore wind turbine and the utility-scale photovoltaic. It is represented by capacity factor time series in 20 different European locations on NUTS3 level that are characterized by the sum of increasing potential full load hours. The time series are generated by using the coastdat-2 COSMO-CLM reanalysis [2] as weather data and applying it to reference plant models [3, 4]. For onshore wind power locations with average wind speeds above 6 m/s, the Vestas V117/3450 is used as reference plant. For lower average wind speeds the Vestas V126/3450 is used. For utility-scale photovoltaic, frameless monocrystalline Solitek modules with an optimal tilt angle depending on the latitude of the location and a south orientation are used. In order to balance weather phenomenons of extreme weather years, capacity factor time series averaged over four years, are used.

The uncertainty range for industrial grid electricity prices in the European Union is oriented on historical data [25] and electricity price developments in the recent months [26–31].

The ten demand profiles used to represent the uncertainty in demand characteristic are synthetically generated and range from constant to intra-weekly and intra-daily changing profiles. The average daily demand is equal for all profiles and is 10,000 kg$H_2$. Seasonal or monthly changing profiles are excluded because the European Commission identifies the industrial sector (relatively constant profiles) and the mobility sector (intra-daily and intra-weekly changing profiles) as main application sectors for green hydrogen [34]. The demand profiles are sorted from low fluctuation to high fluctuation indicated by the number of full load hours of each profile. The full load hours $n_{\mathrm{FLH},i}$ of the profile $d_{\mathrm{H_2prof},i}$ are calculated by dividing the annual sum of the demand profile by its maximum hourly demand:

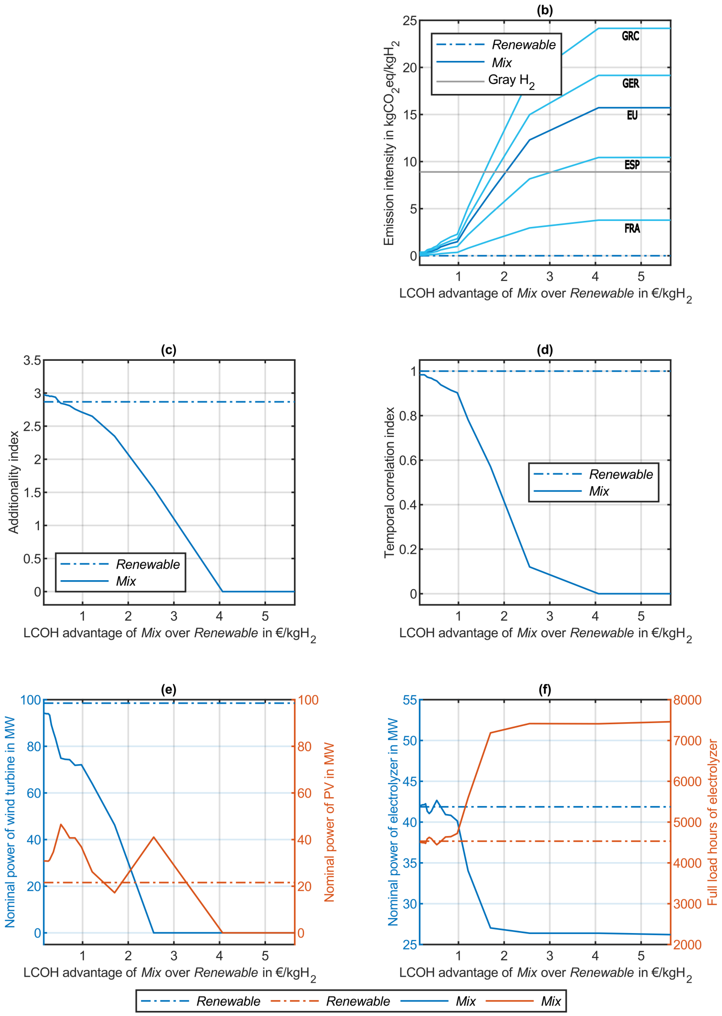
$$n_{FLH,i} = \frac{\mathrm{sum}(d_{\mathrm{H_2prof},i})}{\max(d_{\mathrm{H_2prof},i})} \tag{1}$$

Thereby, a low amount of full load hours indicates that the maximal hourly demand appears relatively rarely and deviates strongly from the average hourly demand, whereas a high amount characterizes a relatively even demand profile. Details of the demand profile generation (Respective full load hours in brackets):

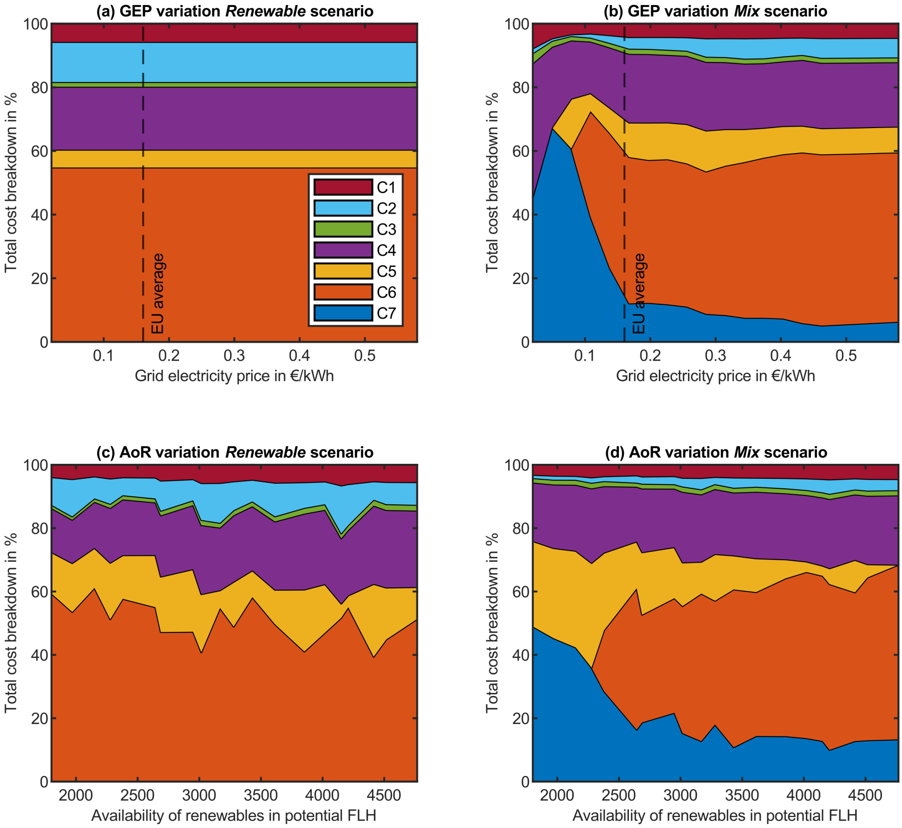
1. Continuous (8760)
2. Continuous with week-weekend shift: Hourly demand on weekdays is twice as high as the demand on weekends (7512)
3. Continuous with day-night shift: Hourly demand between 6 A.M. and 6 P.M. is twice as high as the demand during the nighttime (6570)
4. Continuous with night-day shift: Hourly demand between 6 P.M. and 6 A.M. is twice as high as the demand during the daytime (6570)
5. Continuous with week-weekend and day-night shift: Average daily demand on weekdays is twice as high as on the weekend and the hourly demand between 6 A.M. and 6 P.M. is twice as high as the demand during the nighttime (5634)
6. Non-continuous with an even distribution of the average daily demand over the 7th, 13th and 19th hour of each day (1095)
7. Non-continuous with an even distribution of the average daily demand over the 7th and 13th hour of each day (730)
8. Non-continuous with an demand twice as high at the 7th hour of each day in comparison to the 13th hour of each day (547.5)
9. Non-continuous with the total average daily demand at the 7th hour of each day (365)
10. Non-continuous with week-weekend shift: A single daily demand at the 7th hour of each day with a demand on weekdays being twice as high as on the weekend (313)

All uncertain input parameters are assumed to be uniformly distributed over their range of uncertainty. The chosen number of samples for the variable importance analysis is 10,000, resulting in 110,000 solved optimization problems per scenario. The relatively low complexity of the linear optimization problem allows to perform this computational demanding variable importance analysis [35].

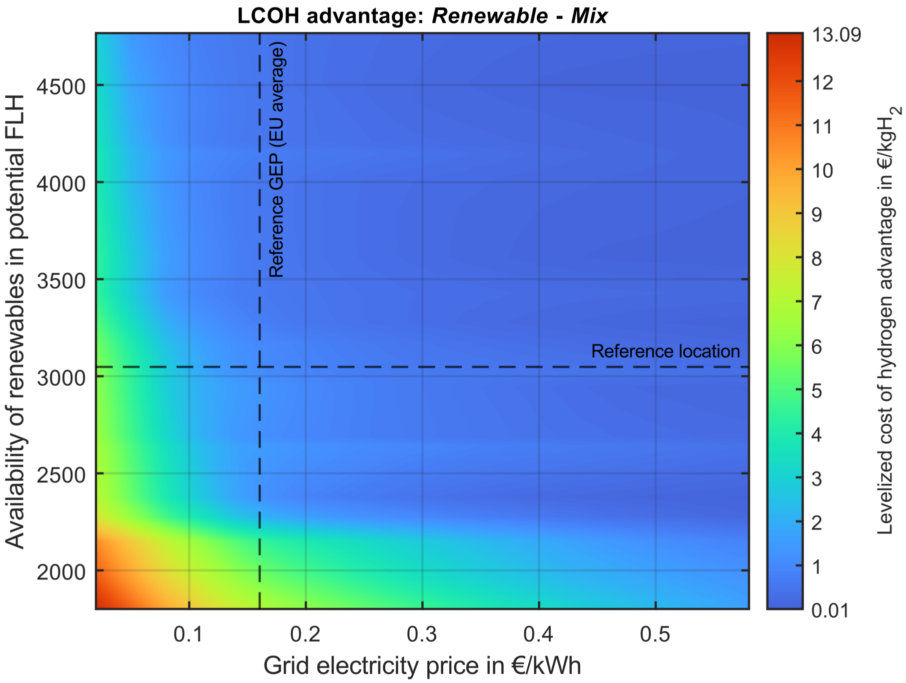
# Supplementary Note 2



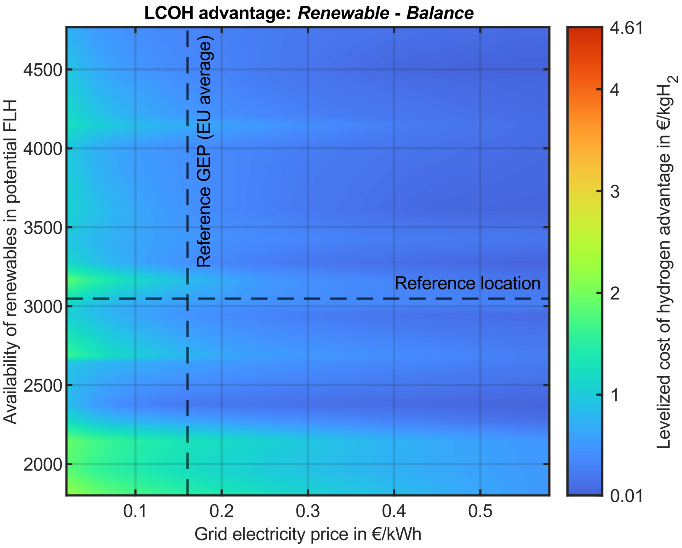

**Supp. Figure 2** Alternative visualisation of results of the optimal design and operation for varying grid electricity prices: All results are plotted as a function of the LCOH advantage of the *Mix* scenario over the *Renewable* scenario. (b)-(d) show the economical and renewable indices for the *Renewable* (dash-dotted line) and the *Mix* scenario (solid line). For reasons of comparability an additional line is included in (b): the emission intensity of gray hydrogen. (e) displays the added nominal power of renewable energy sources and (f) the nominal electrolyzer power and the full load hours (FLH) of the electrolyzer in both scenarios. The chosen location for this analysis has a medium availability of renewables, which is represented by the potential yield for onshore wind and utility-scale photovoltaic in potential FLH. It is 1980 potential FLH for wind onshore and 1036 potential FLH for utility-scale PV. The emission intensities of grid electricity for Greece, Germany, Spain and France can be found in the DA II [33]. The covered hydrogen demand is 10 tons per day on average. All further technical and economical assumptions are summarized in Supplementary Note 3.

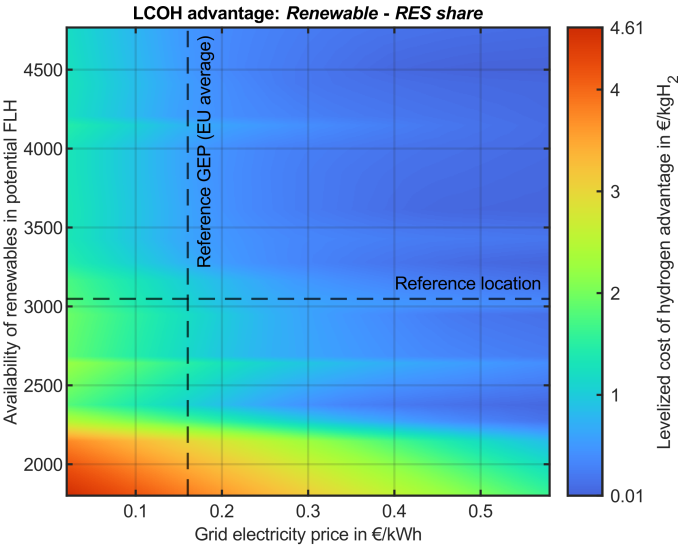



**Supp. Figure 3** (a) and (b): Cost breakdown of the optimal design and operation for varying grid electricity prices in the *Renewable* and the *Mix* scenario. The chosen location for this analysis has a medium availability of renewables (AoR), which is represented by the potential yield for onshore wind and utility-scale photovoltaic in potential full load hours (FLH). It is 1980 potential FLH for wind onshore and 1036 potential FLH for utility-scale PV. (c) and (d): Cost breakdown of the optimal design and operation for increasing AoR in the *Renewable* and the *Mix* scenario. The here displayed increase in AoR is implemented by going through a series of European locations that are sorted by ascending sum of potential FLH. The uneven courses in all graphs reflect the unique characteristics of photovoltaic and wind profiles at the twenty European locations used for this study. The chosen grid electricity price for this analysis is 0.16 €/kWh, which is the EU average for non-household consumers (first half of 2022, [25]). Cost components: C1 Sum of operation and maintenance cost for all components of the hydrogen production plant including water cost, C2 Capital cost for storage, C3 Capital cost for compressor, C4 Capital cost for electrolyzer, C5 Total cost for utility-scale PV, C6 Total cost for onshore wind turbine, C7 Total cost for grid electricity. The covered hydrogen demand is 10 tons per day on average. All further technical and economical assumptions are summarized in the Supplementary Note 3.




**Supp. Figure 4** Range of potential LCOH differences between the *Renewable* and the *Mix* scenario for varying grid electricity prices and an increasing availability of renewables (AoR). The AoR is represented by the sum of the potential yield for onshore wind and utility-scale photovoltaic at the respective location in potential full load hours (FLH). The here displayed increase of AoR is implemented by going through a series of European locations that are sorted by ascending sum of potential FLH. The covered hydrogen demand is 10 tons per day on average. All further technical and economical assumptions are summarized in the Supplementary Note 3.




**Supp. Figure 5** Range of potential LCOH differences between the *Renewable* and the *Balance*, respectively the *RES share* scenario for varying grid electricity prices and an increasing availability of renewables (AoR). The AoR is represented by the sum of the potential yield for onshore wind and utility-scale photovoltaic at the respective location in potential full load hours (FLH). The here displayed increase of AoR is implemented by going through a series of European locations that are sorted by ascending sum of potential FLH. The covered hydrogen demand is 10 tons per day on average. All further technical and economical assumptions are summarized in the Supplementary Note 3.

## Supplementary Note 3

Supp. Table 2, Supp. Table 3 and Supp. Table 4 show the technical and economical parameter assumptions for the parameter studies in section *Effects of the delegated acts supplementing RED II* and section *Effects of the transitional rules.*

**Supp. Table 2** Technical and economical parameter assumptions for the performed parameter studies. The value of the parameters with an uncertainty range in Supp. Table 1 are the mean value of the respective range with exception of the grid energy price, where the average European non-household price in the first half of 2022 is chosen [25], and the emission intensity of the grid electricity, where the unweighted European average was calculated from the annex of the second delegated act [33].

| **Component** | **Parameter** | **Value** | **Unit** | **Reference** |
|---|---|---|---|---|
| Wind turbine onshore | CAPEX | 1573.5 | €/kW | mean value of Supp. Table 1 |
| | OPEX fix | 20 | €/(kW·a) | oriented on [5, 10, 11] |
| | OPEX variable | 0.008 | €/kWh | [10] |
| | Depreciation time | 25 | a | [7, 8, 10] |
| | Interest rate | 6.5 | % | mean value of Supp. Table 1 |
| Photovoltaic utility-scale | CAPEX | 813.5 | €/kW | mean value of Supp. Table 1 |
| | OPEX fix | 13.3 | €/(kW·a) | oriented on [5, 10, 11] |
| | Depreciation time | 30 | a | [7, 10] |
| | Interest rate | 6.5 | % | mean value of Supp. Table 1 |

**Supp. Table 3** Continuation of Table 2.

| Component | Parameter | Value | Unit | Reference |
|---|---|---|---|---|
| PEM electrolyzer (@30bar output) | CAPEX | 1180 | €/kW | mean value of Supp. Table 1 |
| | OPEX fix | 15 | €/(kW·a) | [15] |
| | Depreciation time | 30 | a | oriented on [7, 8, 13, 17, 19] |
| | Interest rate | 8.5 | % | mean value of Supp. Table 1 |
| | Specific energy consumption at nominal load inclusive peripherals | 52.5 | kWh/kg$H_2$ | mean value of Supp. Table 1 |
| | Specific energy consumption peripherals | 3.33 | kWh/kg$H_2$ | own assumption |
| | Decrease of specific energy consumption of stack at part load | 1 | % per 10% load reduction | oriented on [20] |
| | Specific water consumption | 14 | kg$H_2O$/kg$H_2$ | oriented on [7, 20–22, 36] |
| | Water cost | 3.3 | €/kg$H_2O$ | [36] |

**Supp. Table 4** Continuation of Table 3.

| Component | Parameter | Value | Unit | Reference |
|---|---|---|---|---|
| Compressor (@30bar input & 300bar output) | CAPEX | 3090 | €/kW | mean value of Supp. Table 1 |
| | OPEX fix | 4 | % of CAPEX/a | oriented on [9, 23, 24] |
| | Depreciation time | 15 | a | [23, 24] |
| | Interest rate | 8.5 | % | mean value of Supp. Table 1 |
| | $H_2$ losses | 0.5 | % | [23, 24] |
| | Specific energy consumption for isentropic compression | 1.179 | kWh/kg$H_2$ | own calculation according to: [37, 38] |
| | Isentropic efficiency | 80 | % | [39] |
| | Mechanical efficiency | 90 | % | [39] |
| Storage (@300bar) | CAPEX | 573 | €/kg$H_2$ | mean value of Supp. Table 1 |
| | OPEX fix | 2 | % of CAPEX/a | [7, 23] |
| | Depreciation time | 25 | a | oriented on [7, 23, 24] |
| | Interest rate | 8.5 | % | mean value of Supp. Table 1 |
| Grid | Electricity price | 0.16 | €/kWh | [25] |
| | Emission intensity of grid electricity | 0.293 | kg$CO_2$eq/kWh | [33] |

Table 5 shows the technical and economical parameter assumptions for the gray hydrogen calculations shown in section *Effects of the delegated acts supplementing RED II* and section *Effects of the transitional rules.*

**Supp. Table 5** Technical and economical parameter assumptions for the gray hydrogen calculations. To increase comparability with results from the methodology presented in the second delegated act [40], the emission intensity refers exclusively to production related emissions, excluding emissions from construction, decommissioning and waste management.

| **Component** | **Parameter** | **Value** | **Unit** | **Reference** |
|---|---|---|---|---|
| Steam reforming plant | CAPEX | 910 | €/kW | [13] |
| | OPEX fix | 4.7 | % of CAPEX/a | [13] |
| | Depreciation time | 25 | a | [13] |
| | Interest rate | 6.5 | % | mean value of Supp. Table 1 |
| | Efficiency (@LHV) | 0.76 | kWh/kg$H_2$ | [13] |
| | Emission intensity | 8.9 | kg$CO_2$eq/kg$H_2$ | [13] |
| | Price for emission certificates | 90 | €/t$CO_2$eq | [41] |
| | Availability of plant | 95 | % of total time steps per year | [13] |
| | Natural gas price | [0.01, 0.29] | €/kWh | oriented on [42] |

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