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Site-Dependent Environmental Impacts of Industrial Hydrogen Production by Alkaline Water Electrolysis

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Abstract: Industrial hydrogen production via alkaline water electrolysis (AEL) is a mature hydrogen production method. One argument in favor of AEL when supplied with renewable energy is its environmental superiority against conventional fossil-based hydrogen production. However, today electricity from the national grid is widely utilized for industrial applications of AEL. Also, the ban on asbestos membranes led to a change in performance patterns, making a detailed assessment necessary. This study presents a comparative Life Cycle Assessment (LCA) using the GaBi software (version 6.115, thinkstep, Leinfelden-Echterdingen, Germany), revealing inventory data and environmental impacts for industrial hydrogen production by latest AELs (6 MW, Zirfon membranes) in three different countries (Austria, Germany and Spain) with corresponding grid mixes. The results confirm the dependence of most environmental effects from the operation phase and specifically the site-dependent electricity mix. Construction of system components and the replacement of cell stacks make a minor contribution. At present, considering the three countries, AEL can be operated in the most environmentally friendly fashion in Austria. Concerning the construction of AEL plants the materials nickel and polytetrafluoroethylene in particular, used for cell manufacturing, revealed significant contributions to the environmental burden.

Keywords: hydrogen production; alkaline water electrolysis; life cycle assessment; Austria; Spain; Germany

1. Introduction

The majority (48%) of hydrogen is produced by reforming of natural gas and refinery gas, as a by-product of chemical production (30%) and coal gasification (18%). Only about 4% of global hydrogen production comes from electrolysis [1]. However, water electrolysis is one of the most proven options for low-carbon hydrogen [2] and plays a key role in mobility, industry or energy storage scenarios today [3].

Due to increasingly requested technical features like a modulating operation mode, many efforts have been made to develop appropriate and efficient water electrolysis technologies in recent years. As recently pointed out by a review study [4], many Life Cycle Assessment (LCA) studies assess environmental impacts of multi-stage hydrogen pathways, ranging from hydrogen production and storage to transport and utilization. Many studies consider hydrogen as a fuel for transport applications. The scope of some of these studies ends at the (re)fueling stations [5,6] while several studies additionally take utilization for fuel cell electric vehicles into account [7–10]. However, there are also several LCA studies focusing solely on the environmental impact assessment of hydrogen production without considering subsequent steps (e.g., [11,12]). The common goal of all these studies is to find the most sustainable option with regard to minimizing resources, emissions and costs [13].

Previous studies have shown that hydrogen production via alkaline water electrolysis (AEL) is very environmentally friendly if it is supplied with renewable energy.

However, at present, AELs for industrial applications are mostly operated by electricity from the grid rather than from renewables. Previous LCA studies [9,12] reveal that the electricity supply is an essential parameter when assessing electrolytic hydrogen production. Hence three different sites of operation with Western European standards and strongly different grid mixes are chosen, to assess the environmental consequences in relation to the choice of production sites. Austria (AT) is chosen as a country with a high share of renewables (70%). Spain (ES), with a considerably high share of fossil fuel based energy production (45%), represents a country with a fossil/nuclear/renewable generation mix. Germany (DE) is considered as a country with an even higher fossil fuel based share (55%) today, but an agreed phase-out of nuclear and an ambitious transformation towards renewable electricity generation in a short time period. Therefore, impacts of changes in generation mix within the lifetime of an electrolyzer technology can be shown. Hence, this choice represents Western European countries with a divergent composition of electricity from the grid and associated emissions profiles, different material flows, and good data availability.

Additionally, the ban on asbestos products, like membranes usually used in electrolyzers regulation (EC) No 1907/2006 [14], forced manufacturers to develop advanced membrane materials, causing changes in performance patterns. Therefore this study considers hydrogen production using a large-scale pressurized 6 MW AEL with a novel Zirfon membrane for the first time. Hence, a second focus is on the update of electrolyzer construction involving detailed inventory data on cell production.

To assess the environmental impacts of the hydrogen production on the different sites a LCA is conducted. Beside climate change further environmental impacts are evaluated widening the scope of environmental performance assessment of AELs compared to most other former LCAs.

The combination of these assessments of advanced AELs and the dependence on site selection can be used as part of a multi-criteria decision making process to support environmentally friendly and sustainable hydrogen production in the future.

2. Method

To conduct a consistent and comprehensive environmental impact assessment, LCA is used as an approved method. According to ISO 14040 [15] and 14044 [16] LCA is typically composed of four stages:

- Goal and scope definition,
- Inventory analysis (LCI),
- Impact assessment (LCIA),
- and interpretation.

For hydrogen systems the FC-HyGuide guidance [15] interprets the ISO standards specifically. In goal and scope definition the considered systems and their functions are described and system boundaries are defined. During inventory all inputs into and outputs from the systems are evaluated. Although the selection of inputs and outputs shall be as representative and transparent as possible, most former LCAs of electrolysis present little or no data for the LCI. This study fills this gap by including detailed LCI information for advanced AELs. In the subsequent LCIA the gathered and aggregated inputs and outputs of the entire system are categorized and allocated to environmental impact categories. To get a broader picture of the environmental performance other environmental impacts than climate change are assessed also. To reach this, the International Reference Life Cycle Data System (ILCD) guidelines [16] recommended by the European Commission, Joint Research Centre, Institute for Environment and Sustainability are applied. Only impacts which are at least characterized as "recommended but in need of some improvements" are considered.

For the assessment the GaBi software (version 6.115, thinkstep, Leinfelden-Echterdingen, Germany) [17] is used. Data for the AEL are adapted from an European research project [12,18] developing advanced 6 MW AELs. Most of upstream process data (e.g., transport, energy supply, auxiliary material) are taken from the ecoinvent 3.1 database and GaBi 6.115 [17,19]. In this study an additional normalization is conducted to facilitate the interpretation of the findings. Normalization means that for each calculated environmental impact a benchmarking against the known overall effect of a reference system is conducted. Consequently each environmental impact category is translated into relative contributions, making different units comparable. The normalization is realized with the Product Environmental Footprint (PEF) method [20] version 1.09 and taking into account EU-27 as reference system [21].

3. Goal and Scope

The aim of this assessment is to reveal insights into the environmental performance of a projected pressurized 6 MW AEL operating in different countries, using electricity from the respective national grid. In order to implement a consistent comparison a definition of the scope is necessary. This includes the functional unit, consistent system boundaries and impact categories to be investigated.

3.1. Technical Scope

The basis is a projected pressurized 6 MW AEL, which is not in commercial operation yet. Information is gathered by upscaling operation and material data of commercially available 3.5 MW AELs and scientific experiences with a smaller advanced AEL pilot during an European research project [12,18], considering recent technology advancements. Beside the electrolyzer itself the system includes auxiliary system components in its Balance of Plant (BOP). This includes

- tanks,
- heat exchangers,
- pumps,
- power electronics/inverter,
- and a potassium hydroxide filter.

The assessment of AEL operation contains the necessary electricity and deionized water supply, the cycles of potassium hydroxide solution (KOH) and cooling water. A KOH solution with a concentration of 25% w/w is used. A 10-year usage of this KOH solution is assumed before it must be disposed and replaced by a new solution. During this operation time the KOH solution can be circulated without conditioning. Additionally, deionized water is used for system operation. For the production of 1 kg of hydrogen the amount of around 10 L deionized water is required. Oxygen is co-generated to hydrogen in the electrolysis process. Despite the technical feasibility of further utilization of oxygen it is not assessed as a by-product of AEL in this study as the majority of applications vent it into the air today. Furthermore, hydrogen purification, compression, and storage are not included into the system boundaries. Further assumptions are an availability of approximately 95% (8300 h: nearly full-time operation) and five run-ups per year as simplification. Process steam is used during run-up to heat up the systems and nitrogen is used for cleaning purposes.

The centerpieces of electrolyzers are the cells. The investigated 6 MW AEL includes four cell stacks consisting of 139 cells each. A cell is composed of electrodes, a membrane, a cell frame and a gasket as shown in Figure 1. The cells have a diameter of 1.6 m.

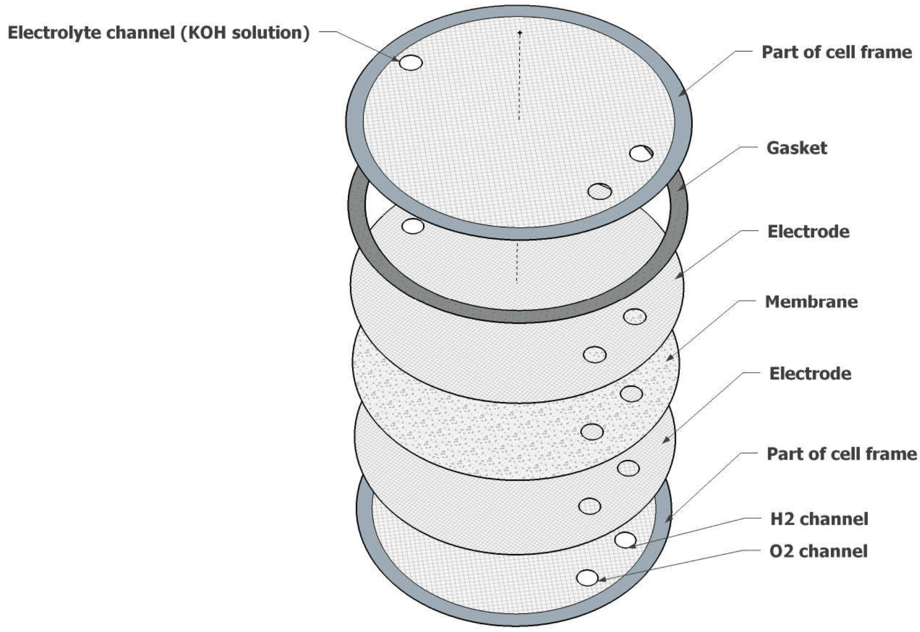

Figure 1. Alkaline electrolysis cell set-up (based on [22]).

Inside the cells electrolysis is enabled by an electric current between the electrodes and a circulating aqueous KOH solution. Migration of ions and the separation of both electrolysis products, hydrogen and oxygen, is enabled by the membrane. Recent AELs like the considered one are using polymer-based membranes (here Zirfon-based) after former asbestos membranes have been banned by regulation (EC) No 1907/2006 (also known as REACH) [14].

Table 1 points out main characteristics of the assessed AEL technology.

Table 1. Alkaline electrolysis technical characteristics (based on [12]).

Parameter	Unit	Value
Electrolyte	–	Aqueous KOH solution (25% w/w KOH)
Membrane type	–	Zirfon
Capacity	MW	6.0
Hydrogen production rate	kg H_2/h	118
Electricity-to-hydrogen efficiency	%	65.7
Hydrogen purity	%	99.8
System lifetime	a	20
Stack lifetime	a	10
Stacks per AEL system	pcs	4
Annual operation	h/a	8300
Operating pressure	bar	33
Operating temperature	°C	85
Hydrogen output temperature	°C	40

In the assessment two life cycle stages (construction and operation) are considered. As no final data, how Zirfon membranes are going to be disposed is available yet, the end of life stage is not considered within this study.

3.2. Spatial Scope

The assessed regions of AEL operation are Germany, Spain, and Austria. As a key objective of this study environmental differences of these three sites of operation are evaluated. Today, electricity generation in Austria is already mainly based on renewable energy technologies, i.e., hydro power.

Fossil electricity generation has a clearly higher share in the electricity mix of Spain and Germany. While the electricity generation in Spain is characterized by high efficient fossil power plants (especially combined-cycle plants) Germany's electricity mix today is characterized by a broad range of fossil, nuclear and renewable energy technologies. Consequently, the spatial consideration of AEL operation in these countries and their electricity generation structures represents and demonstrates a broad spectrum of environmental aspects. Due to their minor relevance concerning environmental impacts and for simplification non country-specific but European datasets are used to represent the further operating supplies (deionized water, potassium hydroxide, steam, nitrogen). While the operation takes place in the three countries considered, it is assumed that the AELs for all cases are produced in Switzerland.

3.3. Electricity Supply

The electricity supply and its assessment are of distinctive importance for this LCA. The AEL technology requires considerable amounts of electricity. Former LCA studies (e.g., [9,12]) show that it is an essential parameter when assessing electrolytic hydrogen production. For the assessed industrial hydrogen production via AEL electricity supply from the grid is of particular importance and profoundly assessed in this study. Thus, country-specific electricity generation and emission profiles are taken into account. The composition and the development of the different electricity mixes are described here in more detail. For the operation a time horizon of 20 years is considered, beginning with 2015 as base year, and ending in 2035 (final year). It is chosen pursuant to the projected lifetime of AELs. The electricity supply in the chosen countries is supposed to change significantly over this time horizon as projected in an EU study by Capros et al. [23]. The EU study contains consistent electricity projections for EU member states till 2050. Thus, basic information for the development of electricity mixes for this LCA study are taken from [23]. As the electricity mix subdivision in this EU study is not completely compatible to the used LCA datasets additional assumptions are used. The EU study merges several energy carriers as "solids" or "biomass-wastes". Sequentially, there is no direct transparency about shares of different coal types as well as about the breakdown of solid biomass, biogas, and waste. A more itemized electricity mix statistic is published by Eurostat [24]. As it contains appropriate data about the percentage of hard coal, lignite and different biomass fuels these data are used to precise the shares within "solids". Percentages about solid biomass, biogas, and waste are used to break down shares within "biomass-wastes". As there are no forecasts given for the percentage data within [24] it is assumed as simplification that these shares are also valid for the assessment period. Figure 2 points out the applied temporal development of the grid mixes in the countries considered.

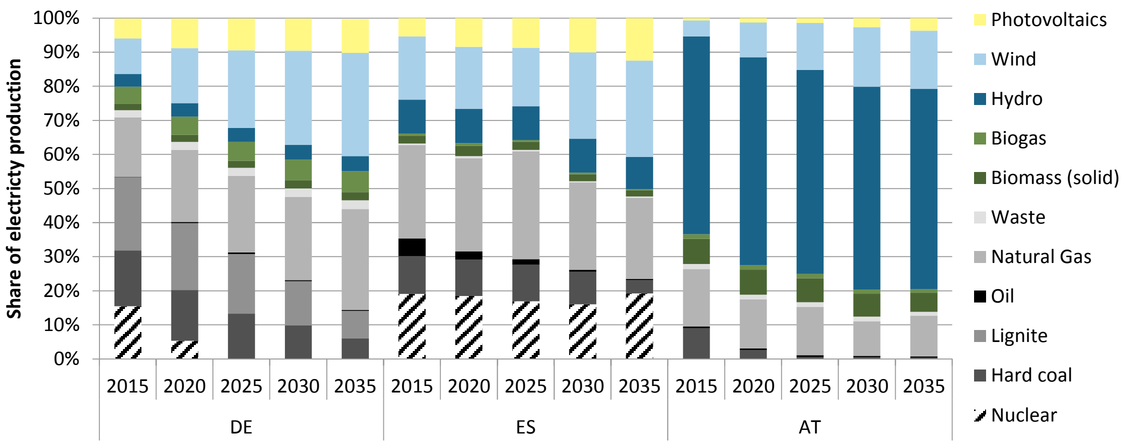

Figure 2. Projected structural change of electricity mixes in Austria, Spain and Germany.

Figure 2 shows generation mixes for the assessed countries in five year steps. Austria predominantly uses hydro power and other renewable energy sources. In contrast, Germany has high shares of fossil and nuclear electricity generation in its 2015 mix. The share of fossil fuels for Spain lies between the values for Germany and Austria. As a result of the transformation processes towards more sustainable electricity systems the electricity sectors in the analysed countries will change during the period under consideration (2015–2035) [25]. A relevant change of the electricity supply structure in Germany will be the phase out of nuclear power plants and a reduction of lignite and hard coal use. A decrease of fossil fuel usage is also projected for Spain and Austria. There will be substitutions by solar and wind power in all three countries. Due to the significance of the transformation process on industrial AEL operation, special attention is paid to environmental effects of the changing electricity mix structures over time by an additional analysis in the result Section 5.2.

3.4. Functional Unit and Environmental Effects Considered

As a functional unit, the production of 1 kg hydrogen (33 bar, 40 °C, 99.8% purity) is chosen.

To obtain high-quality results, only midpoint impact categories, which are characterized by the ILCD guidelines [16] as "recommended and satisfactory" or at least "recommended but in need of some improvements" (level I and II), are considered. Table 2 lists these impact categories.

Table 2. Overview of investigated ILCD impact categories (based on [16]).

Impact Category	Abbreviation	Unit	Level
Acidification	AP	Mole of H+-eqv.	Midpoint
Climate change	GWP	kg CO_2-eqv.	Midpoint
Eutrophication freshwater	EP fw	kg P-eqv.	Midpoint
Eutrophication marine	EP sw	kg N-eqv.	Midpoint
Eutrophication terrestrial	EP ter	Mole of N-eqv.	Midpoint
Ozone depletion	ODP	kg CFC-11-eqv. [1]	Midpoint
Particulate matter/Respiratory inorganics	PM	kg $PM_{2.5}$-eqv.	Midpoint
Photochemical ozone formation	POCP	kg NMVOC-eqv. [2]	Midpoint
Depletion of abiotic resources	RDP abiotic	kg Sb-eqv.	Midpoint

[1] CFC-11 = trichlorofluoromethane; [2] NMVOC = non-methane volatile organic compound.

ILCD midpoint categories, as implemented in the GaBi 6 software are used. The used system model from ecoinvent is "Allocation, cut-off by classification" as integrated in GaBi.

4. Life Cycle Inventory

In the LCI all material and energy inputs and outputs for the entire AEL life cycle are calculated. As no direct emissions during hydrogen production by alkaline water electrolysis occur, it is strongly dependent on the upstream-processes of the electrolyzer construction and operation material and energy inputs. Table 3 points out relevant inputs of the cell stack construction per AEL and 20 years as well as inputs for operation.

Steel is the main input during AEL construction. The majority of steel is used as cell stack framework. Further steel is required for the cell frames of each single cell. Nickel is assumed to be a constituent of anodes and cathodes as well as component of the cell frames. Copper is solely utilized for manufacturing of the cell stack framework. Aluminum is considered as constituent of the Raney nickel cathodes. For Raney nickel cathodes also carbon monoxide is required within the manufacturing process. Zirconium oxide, polyphenelene sulfide, polysulfones, and N-Methyl-2-pyrrolidone are necessary to depict the membrane production. Polytetrafluoroethylene, graphite, acrylonitrile butadiene styrene and aramid fibers and small amounts of lubricating oil are assumed constituents for gasket manufacturing. Inputs into aramid fibers are aniline, acetic anhydride, terephtalic acid, nitric acid, and hydrochloric acid. Besides the described inputs to construction of cells and cell stack frameworks there are additional inputs for the BOP construction. Heat exchangers yield a total mass of around 3900 kg. Furthermore, the considered AELs involve some tanks or reservoirs:

- KOH tank (approx. 4000 kg),
- water tank (31,200 L),
- gas separator (4970 kg).

Highly detailed data concerning power electronics as further BOP components are not available. As a rough assumption an inverter unit (2.5 MW < 5000 kg) is used. Finally, a steel KOH filter with a mass of 145 kg is considered as BOP and construction component.

Table 3. Main material and energy inputs.

Cell Stack Construction—per AEL		
Cell Stack Framework		
Copper	t	2.0
Unalloyed steel	t	200
Cells		
Nickel	t	19
Aluminum	kg	450
Calendered rigid plastic	kg	780
Polytetrafluoroethylene	kg	78
Acrylonitrile butadiene styrene	kg	160
Polyphenylene sulfide	kg	340
Polysulfones	kg	260
N-Methyl-2-pyrrolidone	t	1.3
Aniline	kg	49
Acetic anhydride	kg	54
Terephthalic acid	kg	88
Nitric acid	kg	33
Hydrochloric acid	kg	130
Graphite	kg	430
Lubricating oil	kg	0.48
Zirconium oxide	t	1.1
Carbon monoxide	kg	150
Decarbonized water	t	11
Deionized water	t	86
Electricity	GJ	36
Heat	GJ	88
Steam	MJ	700
Industrial machine production	kg	0.16
Plaster mixing	kg	780
Operation—per Functional Unit		
Electricity	MJ/kg H_2	180
Deionized water	kg/kg H_2	10
Nitrogen	g/kg H_2	0.29
Potassium hydroxide	g/kg H_2	1.9
Steam	kg/kg H_2	0.11

5. Life Cycle Impact Assessment

Within this section environmental impacts of AELs are calculated. At first, environmental impacts caused by different sites of operation and life cycle stages are displayed in Section 5.1. Also impacts related to the electricity supply of AEL and to their construction phase are pointed out. Subsequently, the development of environmental impacts over time, especially focused to effects of the transformation process of the country-specific electricity systems, is presented in Section 5.2.

5.1. Environmental Impacts—Spatial Comparison and Life Cycle Stages

A detailed assessment of impacts caused by different life cycle stages can be seen in Figure 3, distinguished between the different operation places.

Figure 3 points out dominating contributions of the operation phase for the majority of environmental impact categories. The operation phase is further subdivided into electricity and further operation supplies. Compared to the impacts caused by the electricity mix impacts of other supplies are of little account and are consequently not assessed in more detail. The construction phase is important for some environmental effects. ODP is the only impact category clearly dominated by impacts of the AEL construction. In other impact categories (RDP, PM, EP fw, AP) the construction phase contributes noticeably. In the remaining four impact categories (GWP, EP ter and sw, and POCP) the electricity generation almost exclusively determines the results.

The environmental comparison of different sites of operation in Europe reveals clear tendencies. Austria shows the lowest environmental impacts in eight of nine categories. Only in impact category EP fw does it not show the best environmental performance. For this impact category the operation in Spain is most favorable. EP fw impacts are caused by phosphorous compounds, which in Austria are mainly emitted by electricity generation from biomass (biogas and solid biomass). On the other hand, Germany yields worst results in seven out of nine impact categories. This is mainly driven by the comparatively high shares of coal (hard coal and lignite) and biogas within the German electricity grid mix in comparison to Austria and Spain. Electricity generation from coal shows particular impacts on the GWP results while biogas clearly dominates EP fw values. Results of AEL operation in Spain are usually ranked on the intermediate position between Austria and Germany. Only concerning PM and ODP impacts Spain ranks on the last position. The electricity generation by hard coal and natural gas power plants goes along with highest contributions to the PM results. ODP impacts for all three countries are primarily evoked by the construction phase. Additionally, higher ODP values of Spain are mainly evoked by the persisting nuclear electricity production in Spain.

5.1.1. Environmental Impacts Caused by Electricity Supply (Operation Phase)

Figure 4 shows the impacts of the electricity mix for four impact categories in more detail. The illustrated impact categories are selected due to relevance concerning environmental issues (GWP), exceptional results (RDP abiotic) or to represent the results of a group of indicators (e.g., EP fw as one example to illustrate impacts caused by eutrophication).

As shown by Figure 4 GWP is primarily caused by fossil fuels for all three countries. In Germany electricity generation by coal power plants (lignite and hard coal) dominates the results. In contrast the biggest single contribution to GWP in Austria and Spain is from natural gas electricity generation. Impacts due to renewable electricity generation have minor relevance concerning the GWP results. On the other hand the results for EP fw are completely the opposite, as a consequence of its source in phosphorous compounds. This category is unambiguously produced by biomass-based (biogas and solid biomass) electricity generation for all three countries. A more differentiated structure of the impacts is given for RDP abiotic. This category describes the depletion of mineral resources. For all three countries there is a notable share of photovoltaic electricity generation, contributing to the impacts in a range of 40–65%. The comprehensive electricity generation in Austria by hydro power stations leads to a notable share of around 30% of RDP abiotic aroused by ferrous alloys required for construction of these power stations. AP is mainly provoked by fossil fuels for Germany and Spain. Only Austria shows in consequence of the lower fossil fuel based electricity generation a dominating contribution of biomass electricity generation to the AP impacts.

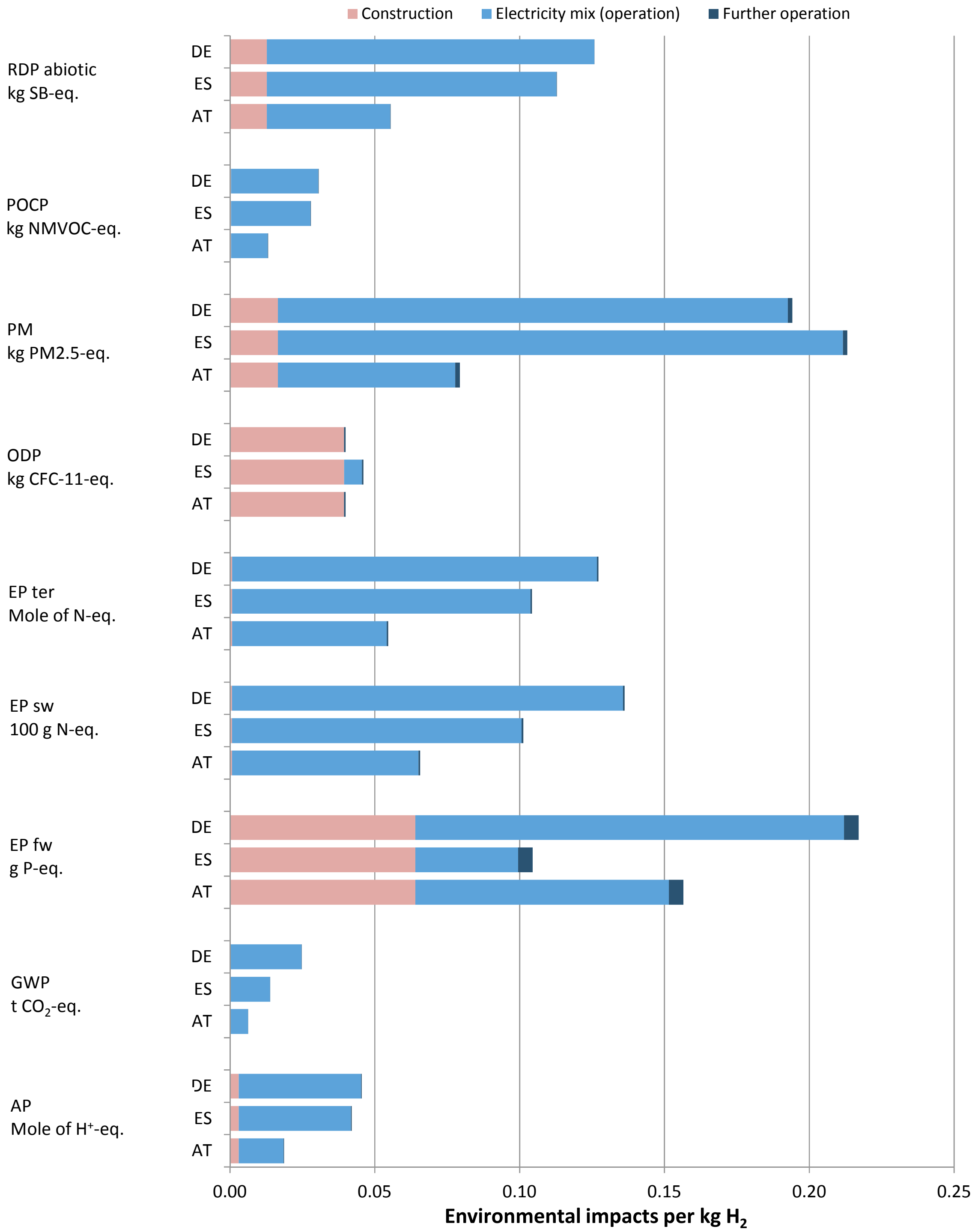

Figure 3. Share of life cycle stages on the impact categories at different sites of operation.

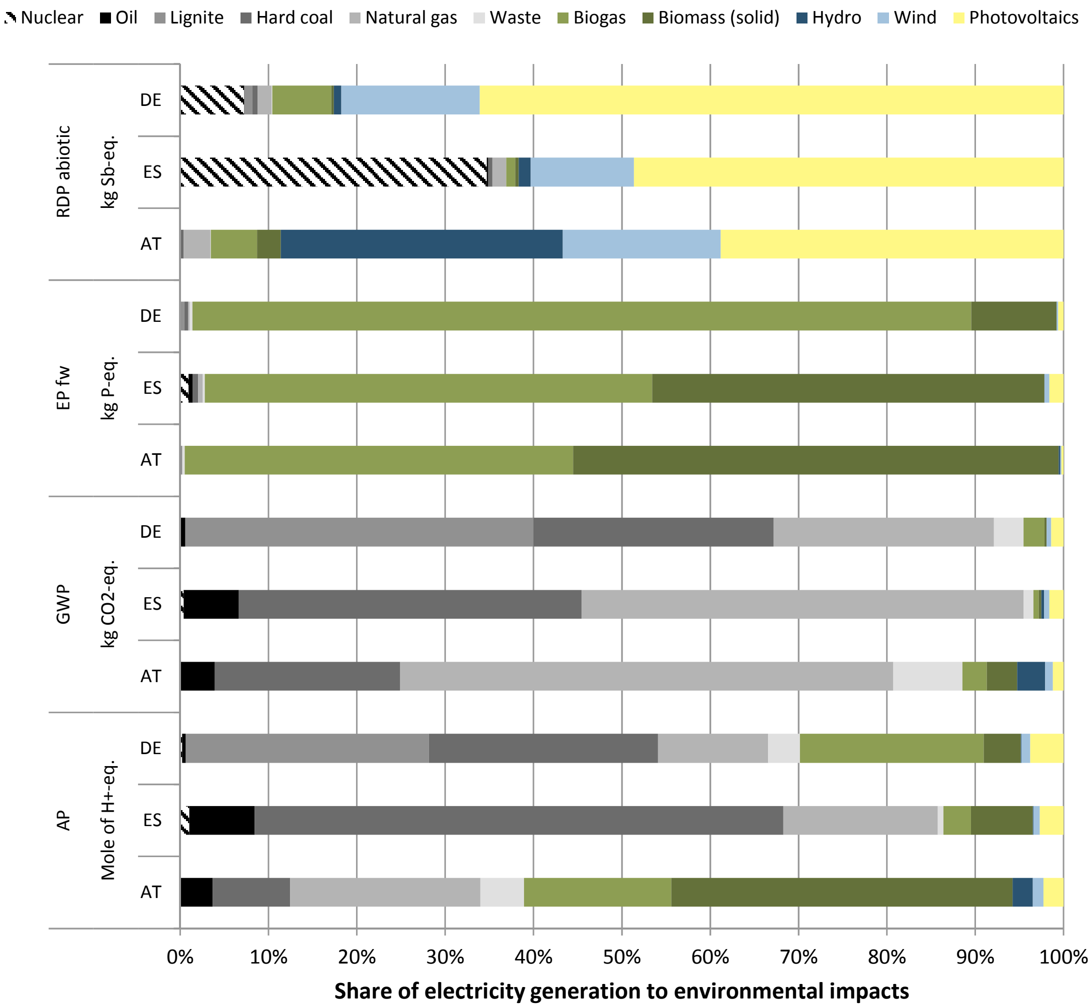

Figure 4. Contributions to environmental impacts of electricity grid mixes.

5.1.2. Environmental Impacts Caused by the Construction Phase

While the operation phase is obviously dominated by the electricity grid mix, impacts of the construction phase are more differentiated and assessed subsequently. Figure 5 shows a subdivision of contributions within the construction phase.

As described in Section 3.1 the electrolyzer consists mainly of cells (anode, cathode, frame, membrane, and gasket), the stack framework and BOP components. As illustrated by Figure 5, cell components cause most environmental impacts during the construction phase.

The gasket production has a significant impact on ODP. This is mainly due to the utilization of polytetrafluorethylene within the gasket production processes. Otherwise, electrodes (anodes and cathodes) dominate most environmental impact categories. Their impacts are mainly affected by their high nickel content. Concerning environmental impacts of nickel emissions of nitrogen and phosphorous compounds within up-stream processes are relevant. Additionally, Nickel contributes significantly to the impacts of cell frames. Low contributions to the construction-related impacts are given by the membranes. The stack framework provokes shares between 25% and 30% for the categories GWP and RDP abiotic. GWP impacts mainly go along with the large amount of required steel and upstream production processes. In contrast, the copper within the stack framework reveals higher influence on the RDP abiotic impacts. Compared to the cells and the stack framework environmental contributions caused by the BOP are comparatively low. Main source of these impacts is caused by an inverter here considered as BOP component.

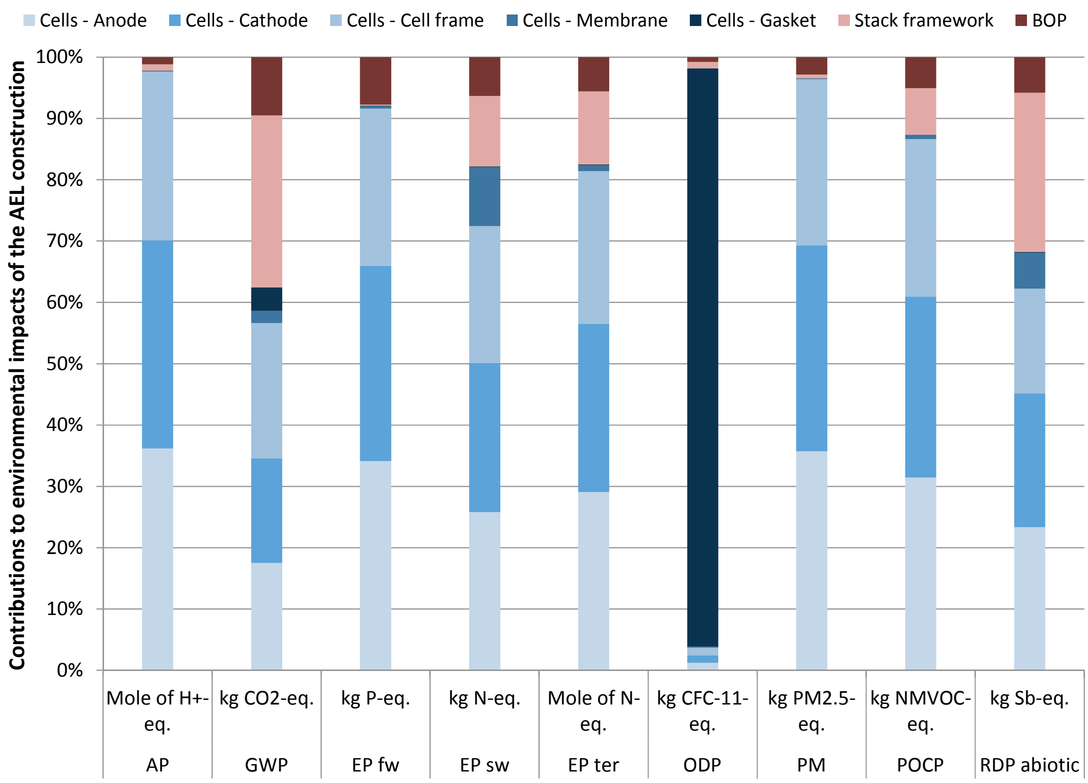

Figure 5. Relative contributions to environmental impacts of the construction phase.

5.2. Environmental Impacts of Electricity System Transformations and Stack Replacement

The electricity supply has been identified as the main driver for most environmental impacts. Due to significant changes (Section 3.4) in the country-specific electricity mix structures in consequence of system transformations their impacts are assessed in more detail. Figure 6 points out how environmental impacts change over the entire operation life time of 20 years for Germany, exemplarily. Construction is subdivided into two steps, initial construction of the complete electrolyzer and one stack replacement in the middle of the operation phase. Operation is subdivided into four time steps, with five years duration each.

Figure 6 reveals a dynamic development of environmental impacts over time. The utilization of electricity from the grid leads to a significant decrease of most environmental impacts from 2015 to 2035. In most categories environmental impacts are between 5 and 15% lower in the last period compared to the starting period. Only exceptions are EP fw and RDP abiotic. An increase of RDP abiotic impacts is expected due to the increasing use of photovoltaics and wind and accompanying needs of mineral resources. Due to the use of photovoltaic and wind power datasets from databases a detailed description of single processes of these technologies is not possible, as they are provided in an aggregated form only. However, a former study [26] on energy technologies emphasizes the relevance of critical mineral resources use, especially indium or selenium for photovoltaics and neodymium for wind power. Increasing EP fw impacts go along with the expected further extension of bio-energy based electricity generation. Most of the tendencies illustrated in Figure 6 are similar to those of Spain and Austria. Photovoltaic and wind-based electricity generation are also expected to increase in these countries, consequently forcing RDP impacts to increase. A comparatively high expected growth of photovoltaic electricity generation in Austria results in an ODP impact increase over time. Further literature [27] points out the responsibility of chlorinated plastic in the photovoltaic panels for ODP impacts. Still, all ODP impacts accompanying the AEL operation are negligible low compared to those of the gasket production.

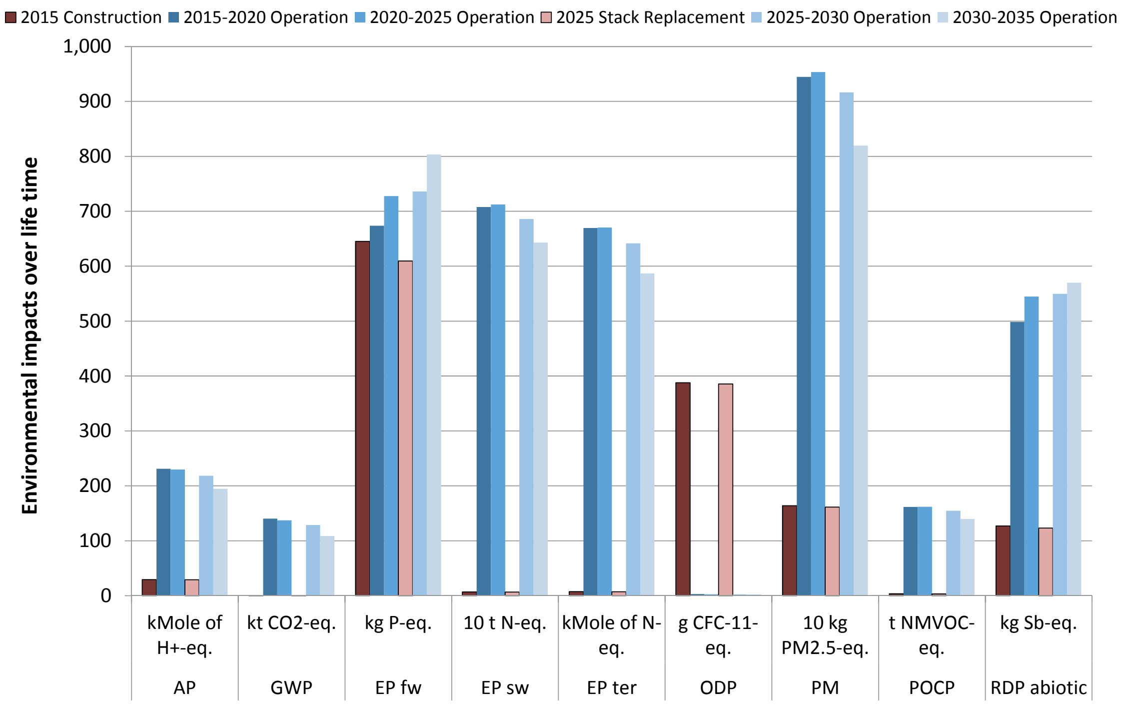

Figure 6. Environmental impacts of life cycle stages related to hydrogen production over 20 years (Germany).

6. Discussion and Conclusions

This environmental assessment set out with the aim of assessing the site-dependent environmental impacts of improved AELs within a European context. The results of this study deliver detailed insights on the environmental status of hydrogen production via alkaline water electrolysis.

It is confirmed that a significant dependence of most environmental results from the operation phase and especially from electricity supply. Construction of the AEL components and the replacement of cell stacks during the life time show a minor contribution to the environmental impacts. In comparison to the electricity supply contributions of further operation, supplies are negligible.

When supplied with electricity from the grid, impacts differ considerably using country-specific electricity mixes or varied timeframes.

As this study has a comparative character the presentation of an additional normalization step is conducted (Figure 7). The normalization results summarize findings of the comparison of AEL operation in Western European countries. Furthermore, the normalization enables a comparison of environmental impact categories with one another.

Currently, there is a clear ranking for AEL operated with grid mix in the assessed countries. AEL operation in Austria yields the strongest results by having the lowest normalized impacts. The second highest impacts are from Spain. The weakest environmental results are from Germany, which reveals the highest normalized environmental impacts. By now the impact category GWP contributes the most to the normalized impacts of AEL. As GWP results are almost exclusively provoked by the country-specific grid mix, they directly reflect the extent of fossil electricity generation. As the current electricity generation by coal in Germany is approximately three times higher than in Austria, the normalized GWP results are also tripled.

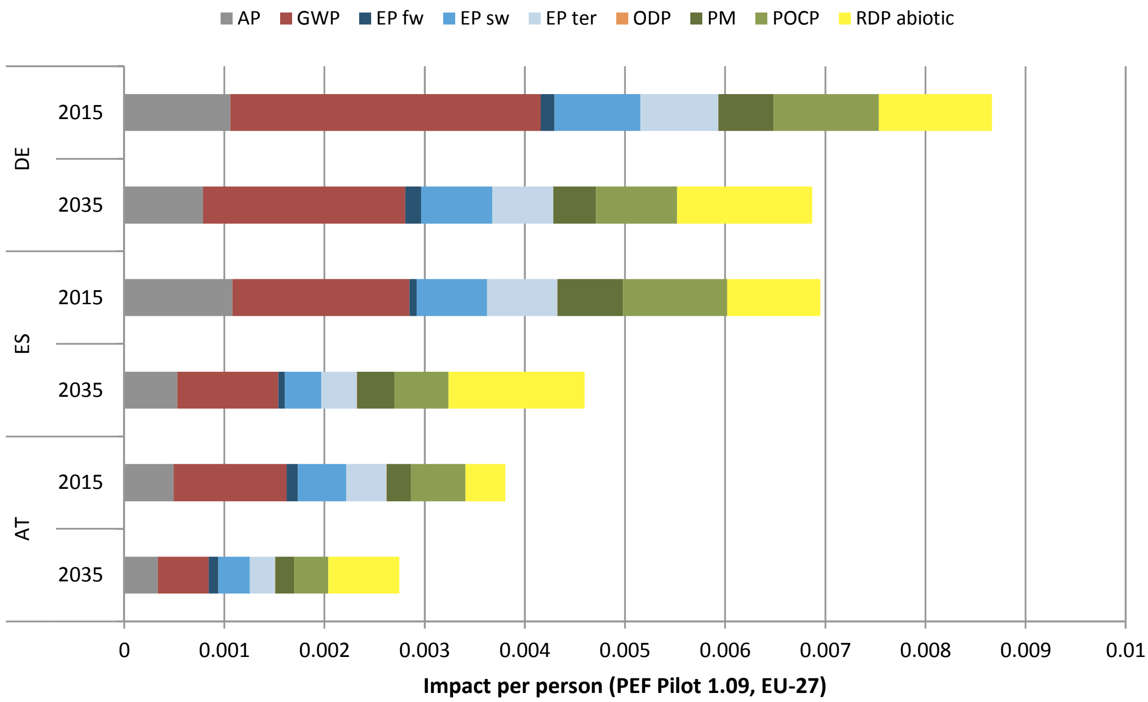

Figure 7. Comparison of normalized environmental impacts based on impacts per functional unit.

Potential for improvement for all considered AEL operation locations is given by the projections for 2035, depicting significant reductions of environmental impacts. Impact reductions range between 21% for Austria and 34% for Spain compared to the base year. The main reason for the overall impact reduction is the decrease of electricity generation based on fossil fuels and the accompanying decrease of GWP impacts. While most environmental impacts are projected to be on a clearly lower level in 2035, RDP abiotic reveals contrary developments. There are increasing RDP abiotic impacts for all three countries consequently provoking more relevant contributions on the total normalized results. The RDP abiotic impacts increase due to an expected growth of electricity generation by wind power and photovoltaics. Further opportunities to improve the environmental performance of AEL for industrial applications will likely occur in consequence of changing framework conditions and research activities. Firstly, the share of renewable energy sources on the electricity supply for these AELs will increase. Secondly, AELs for industrial applications are promising candidates for prospective grid service provision beside hydrogen production, provoking a higher benefit of this technology.

Concerning the construction of AEL plants, the cells exhibited major contributions to environmental impacts. In particular, the cell materials nickel (relevant for electrodes) and polytetrafluoroethylene (used as gasket material) had significant effects on the environmental burden. In consequence of ongoing material research further reductions of the environmental impacts can be expected.

Thus, insights of this study, especially about LCI data and identified environmental challenges, can be used as a basis for prospective LCA studies considering AEL for industrial applications. Further assessments must be conducted if some of the assumed materials are substituted by others or unpredictable breakthroughs in energy consumption occur. Furthermore, different system boundaries, e.g., consideration of hydrogen distribution and utilization for future applications like power-to-hydrogen, can uncover additional knowledge about environmental impacts related to hydrogen. Finally, industrial electrolyzer operators consider additional aspects beside environmental ones. Thus, multi-criterial decision approaches like Life Cycle Sustainability Assessment (LCSA) are necessary to provide operators with many-layered investigations to support decisions like site selection, including costs and social aspects in addition to environmental consequences.

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