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Towards a Life Cycle Sustainability Assessment of Alkaline Water Electrolysis

Jürgen-Friedrich Hake[a], Jan Christian Koj[a]*, Wilhelm Kuckshinrichs[a], Holger Schlör[a], Andrea Schreiber[a], Christina Wulf[a], Petra Zapp[a], Thomas Ketelaer[a]

[a]Forschungszentrum Jülich, Institute of Energy and Climate Research – Systems Analysis and Technology Evaluation (IEK-STE), D-52425 Jülich, Germany

Abstract

This paper compares the sustainability of pressurized alkaline water electrolysis systems operating at different places in Europe (Austria, Germany and Spain). Using a Life Cycle Sustainability Assessment (LCSA) approach, an advanced electrolysis system (6 MW) based on Zirfon membranes is investigated. Results of Life Cycle Assessment, Life Cycle Costing and social Life Cycle Assessment plus subsequent normalizing, weighting, and aggregation in LCSA are assessed. A closer look reveals that the choice of weighting concept has a crucial impact on results. As main outcome, the comparison illustrates that hydrogen production via electrolysis in Germany performs best if weak sustainability (equal weighting of dimensions) is assessed. Using the strong sustainability concept (considering only environmental results) Germany yields worst results mostly due to the environmental impacts of its electricity generation.

Keywords: Life Cycle Sustainability Assessment, hydrogen production, alkaline water electrolysis, Life Cycle Assessment, Life Cycle Costing, Social Life Cycle Assessment

1. Introduction

Hydrogen is an important raw material for the chemical industry. When very pure hydrogen (approx. 99.8 %) is required, it is normally produced by alkaline water electrolysis (AEL). Typical fields of application are the fertilizer industry, food processing and metallurgy. In this study, various sites are selected

* Jan Christian Koj. Tel.:+49 2461 61-4540; fax:+49246161-1560.
E-mail address: j.koj@fz-juelich.de.

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for such a hydrogen plant in the European context. Therefore, hydrogen production by pressurized AEL is analyzed for three locations in Europe, considering different sustainability concepts.

The general sustainability definition by the Brundtland Commission [1] is widely accepted, however, more specific definitions and concepts for the implementation of sustainability differ quite considerably. For example, the concept of weak and strong sustainability [2] leads to very diverse consequences in the rating of dimensions of sustainability. Furthermore, the choice of sustainability indicators depends greatly on the interpretation of what sustainability should include. Ultimately, every choice of indicator results from normative rules and cannot be derived from scientific principles. Any applied weighting only reflects the author's value system. Keeping this in mind, the approach of Life Cycle Sustainability Assessment (LCSA) [3] is used in this paper to assess hydrogen production. This methodology enables the assessment of the three sustainability dimensions from a life cycle perspective by combining the methods of Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and social Life Cycle Assessment (s-LCA). To date few publications about LCSA of hydrogen production exists. While two of these publications [4, 5] clearly focused on methodological aspects of LCSA, this paper presents a first full LCSA case study of hydrogen production via alkaline electrolysis.

2. Goal and Scope

This paper presents a LCSA case study on advanced pressurized AEL plants operating at different places in Europe. A common definition of the scope is necessary in order to implement a consistent application of the three dimensions of LCSAs. This includes the functional unit, consistent system boundaries and a harmonized data framework [3]. Basis system is a pressurized AEL plant with Zirfon-based membranes. It was developed in the EU-funded "ELYGRID" project [6] and achieves a hydrogen output of 118 kg/hr with an electricity consumption of 54 kWh/kg H_2. An outline of the technical system boundary is illustrated in (Fig. 1).

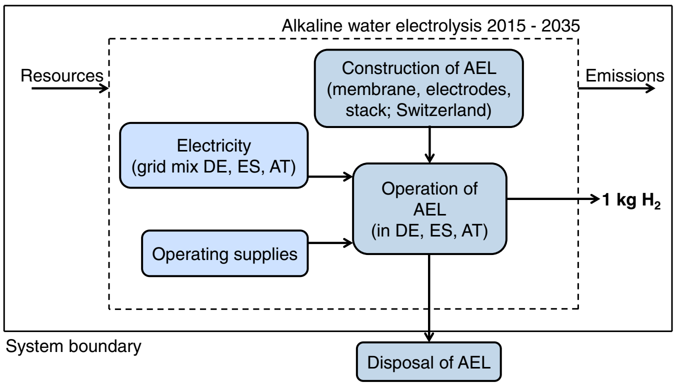

Fig. 1. System boundary of the 6 MW water electrolysis system

In this study, Germany (DE), Spain (ES) and Austria (AT) are the assumed production sites of the AEL system. A time horizon of 20 years is assessed according to the projected lifetime of electrolyzers. Individual components, such as the cell stacks, have to be replaced within this period. For each site, the country-specific electricity grid mix is considered. As the composition of the grid mix will not be constant over the period considered, an arithmetic mean of the predicted grid mix for the years between 2015 and 2035 is used for LCA and LCC [7]. The production of 1 kg H_2 (33 bar, 40 °C, 99.8% purity) is used as consistent reference unit (functional unit) for all cases and all base methods. Hydrogen compression, storage and further use are not considered within the system boundaries. Due to a lack of knowledge about recycling and disposal of the membranes, it was not possible to consider this aspect. Inventory data as framework of all three assessments are mainly taken from "ELYGRID" [6]. This includes the amount of electricity and other operating supplies such as deionized water, potassium hydroxide (KOH) and steam as well as systems engineering of AEL. Data for the auxiliary and construction materials are mainly taken from the LCA database ecoinvent 2.2 [8]. The major source of cost data is [7]. For the social assessment, data are taken from the Social Hotspots Database (SHDB) [9].

3. Method

In the UNEP/SETAC LCSA approach [3], the life cycle thinking perspective is operationalized, ensuring that the three dimensions of sustainability are considered consistently. Basis for the assessment is a separate evaluation for each dimension LCA, LCC and s-LCA according to common standards and guidelines.

While the technical process chains are the same for the evaluations in each dimension, the level of aggregation varies, with LCA considering the most detailed description. Regarding the choice of impact categories for the three dimensions of LCSA, double or even triple counting should be avoided [3]. Therefore no internalization of external (environmental) effects is considered in LCC. Health effects, which are already accounted for in the environmental impact category of human health, are also neglected in s-LCA.

While the LCSA guideline advises that plain results should be presented without weighting and aggregation, the present paper explicitly addresses this topic in the overall evaluation to differentiate between the two sustainability concepts (weak and strong sustainability).

3.1. LCA

This study considers 11 environmental indicators, taking into account the impact categories recommended by the International Reference Life Cycle Data System (ILCD) Handbook [10]. The best known environmental indicator considered is climate change. It refers to the warming of the global climate system, caused by cumulative radiative forcing of greenhouse gases. It is considered to be a global indicator, because impacts do not depend on the location of the emission source. Another prominent indicator of environmental and sustainability assessments is human toxicity. This indicator reflects emissions of toxic substances and the assessment of their damage to human health. A third common indicator, terrestrial acidification, considers regional ecosystem damage. It is caused by base cation leaching. There are several models that describe this effect. In the present study, terrestrial acidification results are expressed in SO_2 equivalents, comprising the effects of NO_x, NH_3 and SO_2 emissions into the air. The indicator depletion of energy resources concerns the safe guard field of resources. Other indicators complete the set.

3.2. LCC

The indicator set for economic assessment comprises 5 indicators. Investment cost focuses on technology-specific aspects avoiding case-dependent considerations of construction times. This is expressed as the present value of all planned investment activities during the lifetime of the facility. It comprises the initial investment cost and stack replacement investment after 10 years of operation. As no market price for investments is available for the AEL plant under consideration, literature data on smaller

AEL capacities [11] and engineering approaches for plant upscaling and investment costs [12] are used.

The levelized cost of energy (LCOE) approach is fundamental for technology cost comparison. Typically, cost covers investment costs, fix and variable O&M cost. For discounting, the real Vanilla WACC (Weighted Average Cost of Capital) concept is used, considering the difference between equity and debt shares for financing the investment. This is important for long-living capital goods such as AEL plants, and it is the more significant the higher the specific investment cost and the difference between expected returns on equity or on debt are. For AEL, electricity costs are also a variable cost component. As one of the main cost drivers for hydrogen generation it is presented separately. According to the electricity generation scenario, the cost (in real terms) of electricity for AEL plant operators is expected to increase over the lifetime of the AEL plant. Therefore, it is defined as present value of the annually recurring specific electricity costs, which is expected to change over the plant lifetime at a constant yearly rate [13] (per present value of physical output, thus resembling a levelized cost concept). It is avoided to reflect on a statistical average electricity price for industry. The AEL plant operator is regarded as a customer actively participating in power markets, thus achieving a lower electricity price. Additionally, variable costs and fix costs are considered as further LCC indicators.

3.3. s-LCA

For the s-LCA, 23 indicators are selected, capturing central human rights issues such as risk that a country lacks or does not enforce the right to strike, and tolerates child labor, forced labor and corruption. Selected indicators reflect violations of central UN standards for human rights.

Corruption undermines the development of the state's authority and its institutions, as stated by Transparency International [14]. The right to strike is based on the right of freedom of association, which is guaranteed by Articles 20 and 23 of the Universal Declaration of Human Rights. In 1989, the United Nations Convention on the Rights of the Child guaranteed children the right to be protected against economic exploitation ensuring that they can enjoy an appropriate childhood. The international labour organisation (ILO) defines forced labor as involuntary work which is carried out under threat of punishment. These and the other social indicators considered cover five social impact categories: "labor rights and decent work", "health and safety", "human rights", "governance" and "local community" impacts [15].

The SHDB does not only include base data on social impacts, e.g. statistics about corruption, but also the methodology to convert the different indicators into a single score. Base data is classified into different risk levels from low to very high for every assessed sector, e.g. electricity generation, and country. Every sector is characterized by a worker hours model. The activity variable of this model is worker hours. The amount of worker hours required for the analyzed system is multiplied by the risk level of the sector analyzed. Results are termed risk points (RP), which can be summed up for all impact categories.

3.4. Normalization, weighting and aggregation within LCSA

The 39 indicators selected have different units and are not directly applicable for sustainability assessment. In this respect, LCSA can also be interpreted as a multi-criteria assessment (MCA) problem to which MCA methodologies can contribute. Based on the indicator set, the chosen assessment approach needs 3 further steps:

(1) normalization of results: enables a methodologically reliable comparison of indicators with different units

(2) weighting of indicators: defines the relative importance of indicators based on a normative foundation or value concept, which has to be made transparent
(3) aggregation: final assessment by aggregation to an index, while an interpretation of sophisticated information by the performance matrix is also possible.

The max-min approach is used to normalize indicators and yielding ranking results ($u(x_k)$) between 0 (poor performance) and 1 (best performance). For example, lower emissions, lower costs or lower social risks lead to better performance. The calculation is based on single indicator results (x_i) located within a range between x_{min} (highest absolute value / worst indicator performance) and x_{max} (lowest absolute value / best indicator performance).

$$u(x_k) = \frac{x_k - x_{min}}{x_{max} - x_{min}} \quad (1)$$

With respect to weighting, 6 different approaches are selected, where (1)-(4) refer to different sustainability concepts, focusing on weak sustainability (WSuS) and strong sustainability (SSuS), and (5)-(6) are competing concepts. Weak or strong sustainability is interpreted according to the underlying capital concept: total human capital equals natural, economic and social capital. In view of the fact that for sustainability total capital should at least remain constant or rather improve, weak and strong substitutability concepts allow or prevent partial substitution of one dimension by the other. The following weighting approaches are chosen:

(1) equal indicator weighting per pillar and equal weighting of pillars (WSuS), which in the case of a different number of indicators per pillar implicitly results in unequal weighting of indicators across pillars
(2) equal weighting of all indicators (WSuS), which in the case of a different number of indicators per pillar implicitly results in unequal weighting of pillars
(3) attributing higher weightings to selected indicators (WSuS), demonstrated here by focusing on climate change, levelized cost of hydrogen, and risk of total child labor
(4) environment indicators only (SSuS), assigning zero weight to economic and social indicators
(5) economic indicators only, assigning zero weight to ecological and social indicators
(6) social indicators only, assigning zero weight to ecological and economic indicators.

A multi-attribute value method for aggregating the individual indicators in the form of a weighted sum is used, consistent with the OECD approach for technology evaluations [16].

4. Results

For each dimension, the various indicators are assessed for the three countries considered by using the methods described. In the performance matrix (Tab. 1) the results are listed and the best and worst performing AEL sites for individual indicators are depicted. This matrix clearly shows the challenges for technology assessment: no site performs best or worst in all indicators and how indicators should be compared across the full set, keeping in mind the different indicator units (physical, monetary, risk) and spread of indicator values. AEL operation in Austria achieves the best environmental impacts in 7 out of 11 categories including the lowest climate change. In a further four categories, Spain shows the best environmental performance. In contrast, Germany is placed worst in the environmental ranking for most categories. Results for the levelized cost of hydrogen and electricity cost indicators in absolute terms reveal a slight advantage for Germany, and for investment and fix O&M for Spain. In the case of investment and fix O&M, the advantage for Spain is due to the relatively lower average wage level [17]. For variable O&M costs (except electricity), there is no difference between the 3 sites. Results in terms of the social indicators show a clear advantage for Germany. Most of the impacts for Austria are caused by electricity supply, especially by natural gas imported from Uzbekistan used for power plants. The majority of impacts for Spain are related to natural gas imports from Algeria.

	Indicator	Unit	DE	AU	ES
Environment	Climate change	kg CO_2 eq/kg H_2	23.68	7.52	13.08
	Ozone depletion	kg CFC-11 eq/kg H_2	5.21E-09	5.15E-09	11.9E-09
	Terrestrial acidification	kg SO_2 eq/kg H_2	0.03	0.01	0.03
	Freshwater eutrophication	kg P eq/ kg H_2	14.8E-05	9.05E-05	3.77E-05
	Marine eutrophication	kg N eq/ kg H_2	4.00E-03	3.00E-03	2.00E-03
	Human toxicity	kg 1.4-DB eq/kg H_2	0.73	0.27	0.31
	Photochemical oxidant formation	kg NMVOC eq/kg H_2	0.03	0.01	0.03
	Particulate matter	kg PM_{10} eq/kg H_2	0.01	0.00	0.01
	Agricultural land occupation	m^2yr/ kg H_2	1.30	0.73	0.27
	Depletion of energy resources	kg oil eq/kg H_2	6.13	2.23	4.02
	Metal depletion	kg Fe eq/kg H_2	0.31	0.28	0.28
Economy	Investment cost (PV)	$€_{2015}$/ kg H_2	0.42	0.41	0.40
	Levelized cost of hydrogen	$€_{2015}$/ kg H_2	4.63	5.38	5.55
	Variable O&M (excl. electricity)	$€c_{2015}$/ kg H_2	0.10	0.10	0.10
	Electricity cost (PV)	$€_{2015}$/ kg H_2	3.71	4.49	4.72
	Fix O&M	$€c_{2015}$/ kg H_2	0.25	0.24	0.20
Society	Characterization of commercial labour	RP/kg H_2	0.01	0.02	0.01
	… Heidelberg Barometer1	RP/kg H_2	1.15	1.61	1.65
	… indigenous population	RP/kg H_2	0.64	0.94	1.42
	Overall risk of corruption	RP/kg H_2	1.08	3.35	2.70
	… of gender inequality	RP/kg H_2	0.75	2.01	1.30
	Risk of excessive working time	RP/kg H_2	0.93	1.33	0.78
	… fatal injury	RP/kg H_2	0.85	2.59	3.48
	… workplace noise exposure	RP/kg H_2	0.97	3.31	2.06
	… forced labour	RP/kg H_2	0.93	3.16	1.88
	… fragility in the legal system	RP/kg H_2	0.43	0.74	1.02
	… low life expectancy	RP/kg H_2	0.20	0.44	0.68
	… mortality from communicable diseases	RP/kg H_2	0.34	1.22	1.24
	… no access to an improved sanitation	RP/kg H_2	0.64	0.87	0.84
	… no access to an improved drinking water	RP/kg H_2	1.39	3.88	2.62
	Risk of sector wage being lower than minimum wage	RP/kg H_2	0.59	0.73	1.11
	… total child labour in country	RP/kg H_2	1.66	1.45	3.02
	… of unemployment in country	RP/kg H_2	0.84	2.62	1.52
	… of wages being under $ 2 per day	RP/kg H_2	0.79	3.53	0.47
	Risk that a country lacks the right of strike	RP/kg H_2	1.45	4.08	0.72
	… children do not attend school	RP/kg H_2	0.20	0.69	0.57
	… country does not provide adequate labour laws	RP/kg H_2	0.50	1.52	0.73
	… migrant workers are treated unfairly	RP/kg H_2	1.29	2.07	2.45
	… there are too few hospital beds …	RP/kg H_2	0.65	1.04	1.39

Worst indicator performance (red)
Best indicator performance (yellow)

Tab. 1. Performance matrix

Based on the performance matrix and the approaches for normalization, weighting and aggregation, different sustainability approaches are considered and compared (Fig. 2). Variation across the 6 different weighting approaches in terms of assigning sustainability is significant. However, the results are rather robust. In 4 out of the 6 cases the AEL site in Germany performs best and Austria worst. Nevertheless, in the equal indicator weight per weighting approach (1) the difference between the three sites is quite small. Only if environmental indicators are regarded solely (4) Austria shows best results followed by Spain. Additionally, the performance of Spain is equal to Germany if only economic indicators are regarded.

Considering the weak sustainability concept, AEL in Germany performs best irrespective of the chosen weighting procedure. For (4), Germany achieves worst results, because in all environmental indicators except one it performs worst, mostly due to its electricity generation. Choice and weighting of individual indicators has a crucial effect on the results. As an example the share of economic indicators for approaches (1) and (3) for Spain varies significantly. Limitation of the economic dimension on only one indicator (3) provokes a rather small share of the economic dimension on results for Spain. However, consideration of all economic indicators with equal weights (1) affects a clearly higher contribution on the entire results for Spain. Thus, outcomes of technology sustainability assessment are to a large extent determined by normative foundations resulting in different weighting of indicators.

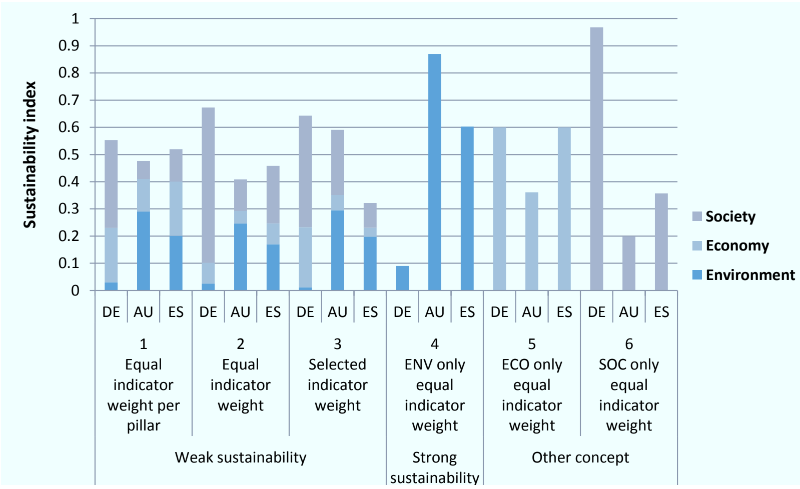

Fig. 2. LCSA results for different weighting approaches

5. Discussion and Conclusions

This paper shows results of a first LCSA case study for alkaline water electrolysis. Three AEL locations in Europe were analyzed using different weighting approaches. The comparison of results revealed a rather robust advantageous sustainability performance of AEL in Germany irrespective of the chosen sustainability approach. Only the weighting approach with exclusive consideration of environmental indicators (strong sustainability concept) depicts entirely different results of AEL operation in Germany for the three pillars. While the AEL site in Germany shows clear advantages regarding most social and economic indicators, its environmental performance is the worst. Results reveal that the choice of location for AEL plants has an influence on their overall sustainability. The spatial scope of industrial nations located in Europe could be extended in a further step considering emerging markets for hydrogen production outside Europe. This would include other economic structures leading to different social results. The selection of indicators covers multiple aspects of sustainability. However, this selection shows a link to future research. As long as sustainability definitions and concepts are still in the process of being developed, sustainability assessments should try to adapt to the latest trends.

Copyright

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Biography Prof. Jürgen-Friedrich Hake

Prof. Jürgen-Friedrich Hake is Head of the Institute of Energy and Climate Research - Systems Analysis and Technology Evaluation (STE) at Forschungszentrum Juelich and Professor for Energy Policy and Energy Economy at Aachen University of Applied Sciences in Germany.