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TITLE: A COMPARATIVE LIFE CYCLE ASSESSMENT OF ENERGY STORAGE SYSTEMS: LITHIUM-ION BATTERY AND HYDROGEN ENERGY STORAGE SYSTEM

TÍTULO: ACL EN SISTEMAS DE ALMACENAMIENTO DE ENERGÍA: BATERÍA IONES DE LITIO Y SISTEMA DE HIDRÓGENO

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ABSTRACT

Currently, electricity demand is increasing and would continue growing in the future. The primary electricity generation power plants in the world are based on fossil fuels. To fulfill this increasing demand, there has been a prolific increase in electricity production which causes a direct or indirect harmful impact on primary sources available worldwide. The emissions generated from the fossil-fuel-based electricity generation plants can be controlled by replacing them with renewable energy sources, but the environmental impacts associated with the supporting energy storage systems must not be ignored in this scenario. This study is conducted to assess the environmental effects associated with energy storage systems by doing a comparative life cycle assessment, in which only two energy storage systems are considered: lithium-ion battery and hydrogen energy storage system. The functional unit was chosen as one vehicle-kilometer. The cradle-to-grave approach was selected from which the EOL phase is excluded. LCI for both product systems is based on secondary data sources. The openLCA sustainability software version 1.3 and the ECOINVENT database are used to execute the work. The ReCiPe endpoint level LCIA method is selected to evaluate the results. The results obtained depicted that lithium-ion battery has shown inferior results compared to hydrogen energy storage system. The hydrogen energy storage system showed less environmental impact than the lithium-ion battery system. Solar and wind energy sources led to better results than the grid mix when all the three electricity sources are supplied during the use phase of two product systems.

Keywords: Lithium-ion and Hydrogen Batteries; LCA for sustainability; electrolyze; PEM; ReCiPe.

RESUMEN

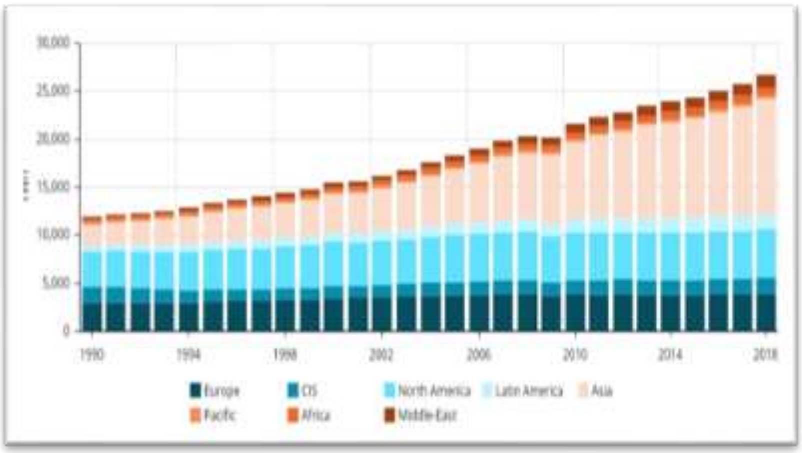
Actualmente, la demanda de electricidad aumenta día a día y continuará creciendo en el futuro. Las principales centrales eléctricas de generación de electricidad del mundo se basan en combustibles fósiles. Para satisfacer esta creciente demanda, se ha producido un prolífico aumento en la producción de electricidad con un impacto nocivo directo o indirecto sobre las fuentes primarias disponibles en todo el mundo. Las emisiones generadas por las plantas de generación de electricidad a base de combustibles fósiles se pueden controlar reemplazándolas por fuentes de energía renovables, pero, los impactos ambientales asociados con los sistemas de almacenamiento de energía de apoyo también deben contabilizarse en este escenario. Para evaluar efectos ambientales asociados con los sistemas de almacenamiento de energía mediante una evaluación comparativa del ciclo de vida se realizó este estudio, en el que solo se consideran dos sistemas de almacenamiento de energía: la batería de iones de litio y el sistema de almacenamiento de energía de hidrógeno. La unidad funcional fue un vehículo-kilómetro. Para ejecutar el trabajo se utiliza el software de sostenibilidad openLCA versión 1.3 y la base de datos ECOINVENT y se utiliza el método ReCiPe. Los resultados derivados del análisis muestran que la batería de iones de litio ha mostrado resultados inferiores en comparación con el sistema de almacenamiento de energía de hidrógeno. Las fuentes de energía solar y eólica dieron mejores resultados que la combinación de la red cuando las tres fuentes de electricidad se suministran durante la fase de uso de dos sistemas de productos.

Palabras clave: baterías de Iones de litio e hidrógeno; ACL para la sostenibilidad; electrolizador; PEM; ReCiPe.

INTRODUCTION

From the beginning of the 19th century until today, there has been continuous development and progress in electrical engineering. Electricity is considered one of the essential parts of our daily life (Everett, et al., 2012). Nowadays, electricity has become the backbone of modern social and industrial society, and it is at the heart of many modern electronics and electric technologies. Electricity is a secondary energy source that can mainly be produced from conventional sources of energy like fossil fuels and non-conventional energy sources like wind, solar, hydro, etc. (Everett, et al., 2012). Today the total energy production in the world is around 27,644,800 GWh (Enerdata, 2020). In 2018, the electricity produced from coal was around 10159646 GWh, followed by natural gas 6150200 GWh, the highest among all the available energy sources used to produce electricity (IEA, 2021). The CO_2 emissions associated with the coal and natural gas electricity production in 2018 were 3351 Mt and 6876 Mt, respectively. In

2018, 1.7 % of CO_2 emission rose due to electricity production worldwide and around 33.1 Gt of CO_2 emission occurred (IEA, 2021). The total production of electricity for the past three decades at different parts of the world are shown in the figure below.



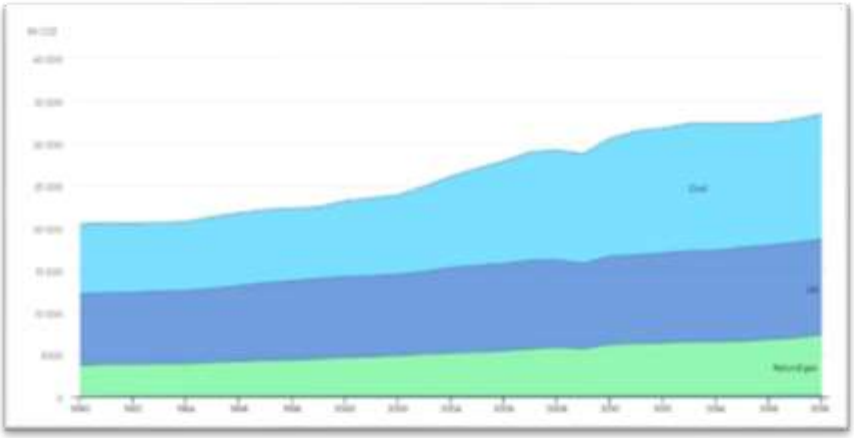
Graph 1. Global electricity production in TWh from year 1990 to 2018

Source: Enerdata (2020)

The above graph explicitly depicts a gradual rise in electricity production from different resources between 1990 and 2018. From 2000 to 2018, there is an increment in global electricity production by 3% every year (Enerdata, 2020). Examining graph 1, in Asia, China and India are major countries in the electricity generation sector. China is the leading country in electricity production with a growth of 4.5% in 2019 along with the rise in thermal and renewable based production (Enerdata, 2020). In Europe, especially in Germany, the economic growth has declined in 1.8% due to the cutback of coal-based power generation in Germany, followed by France due to less hydro-power and nuclear power availability (Enerdata, 2020). In 2019, the global electricity production, which is based on 36% coal-fired power generation, decreased by 3.5%, on the other hand, there is an increase in gas-fired power generation by 3.2%, followed by solar by 24%, wind by 12% and nuclear by 3.6% (Enerdata, 2020)

Graph 2 shows the CO_2 emission occurred during the years from 1990 to 2018 by a different energy production source. Around 33513 Mt CO_2 emission has taken place in

2018, where coal-based electricity production contributed around 44%, followed by oil with 33% and natural gas with 23%, see graph 2.



Graph 2. CO_2 emissions caused by different energy sources from year 1990 to 2018
Source: IEA (2021)

Examining graph 1 and graph 2, we can see that from 1990 to 2018, there has been a continuous rise in electricity production from various energy sources, which simultaneously gave rise to CO_2 emissions. Considering the above-mentioned growth of electricity production, China is the leading country in electricity generation and there was a +2.8% steady rise in CO_2 emissions in 2019 (Enerdata, 2020). On the other hand, a considerable amount of reduction in CO_2 emissions was achieved by India by reducing coal consumption in power plant and increasing usage of hydropower generation and renewable energy. In 2019, 0.2% decrease in CO_2 emissions was measured, which was mainly because of growth in the contribution of renewable energy sources in the power grid mix, the development of energy intensity, and the reduction of CO_2 emission amount per kWh (-3.2%, or 443 gCO_2/kWh) electricity produced (Enerdata, 2020). In many developed countries such as Germany, UK, Turkey, Spain, and Poland in Europe and the USA, a significant drop in CO_2 emissions was registered by -3.9% and -2.4%, respectively (Enerdata, 2020). These reductions occurred because of the shifting of coal-to-gas and the rapid rise in renewable energy. The analysis of the previously available data regarding electricity production and CO_2 emission associated with it proved that coal, oil, and natural gas-based electricity production causes a large amount of CO_2 emission worldwide. Whereas CO_2 emission caused by renewable energy sources is significantly less in comparison. In such a case, to reduce the overall environmental impact associated with electricity production, renewable energy-based electricity generation's contribution needs to be enhanced in the succeeding years.

As mentioned above, there has been a drastic rise in electricity production and corresponding CO_2 emissions from the last two decades. The leading causes behind these are the rapid growth rate of the world's population, changes in people's living standards, modern luxurious amenities, industrialization, developed modern electric and electronic equipment, etc. To meet this increased demand, humankind needs to rely majorly on fossil fuels-based electricity generation. Generation of electricity by the mean of conventional energy sources, i.e., fossil fuels based, are becoming very inconvenient and destructive concerning social, economic, environmental and health aspects. Concerning the overall climate change and environmental impact, the world is settling on sustainable renewable energy sources such as wind, solar, hydro, etc., which is also supported by many international organizations and programs (Hossain, et al., 2020). As we all know, renewable energy sources produce green and clean electricity, which indirectly causes less environmental impact than conventional fossil fuels-based electricity generation power plants. Nevertheless, RES's experiences the ill effect of the dishonor of irregularity and uncertainty in electricity generation, instability of solar radiation, irregular wind flow and speed, uncertainty in water availability for hydropower system, slower economic growth, changing climate, changing government policies, etc. Wind and solar energy sources are incredibly unpredictable to estimate their generated outputs and play a decisive role in energy generation and transition. However, the problem related to flexibility, demand response, storage, and grids' interconnection will increase substantially in the coming years. All these factors urge to bring more stability and flexibility in the power systems.

To mitigate the fluctuations in power, to boost the flexibility of electric systems used in renewable energy, maintain the steady performance of different renewable sources, store the excess of generated energy, and avoid wastage of energy generated, various energy storage systems must be installed. Thus, the energy stored in the implemented energy storage systems can reconvert the stored energy into electricity or other energy forms. There are different types of energy storages available for various applications and purposes such as pumped hydro, flywheel, lead-acid battery, lithium-ion battery, sensible heat storage, hydrogen energy storage system, etc. Concerning applications, there are many advantages and disadvantages of the above-mentioned energy storages that need to be accounted for. It is an easy and straightforward task to select or compare any of the energy storage systems for any required applications considering or viewing their technical specifications, advantages and disadvantages. However, it is a tough job to select or compare any of the energy storage systems for any applications which are environmentally friendly or cause less environmental impact throughout their entire life cycle, that is, from their production, use and disposal phases; hence, to understand the overall life cycle impact on the environment caused by any energy storage systems and how environmentally sustainable they are to utilize. Therefore, it is necessary to assess the systems and to evaluate the environmental impact associated with them. It can be achieved by conducting a life cycle assessment of energy storage systems. Life cycle assessment (LCA) is an established and internationally recognized methodology used to assess the environmental impact associated with any products or processes or services. This tool evaluates the environmental impact associated with any product system from the extraction of raw materials required to manufacture the products, including the raw material processing stage, the product manufacturing stage, various transportation within the entire product system, the use phase and finally, the disposal phase. There are various LCA approaches available in the study from which one can be chosen to conduct the LCA, such as cradle-to-gate, cradle-to-grave and cradle-to-cradle. LCA methodology consists of four main phases that are linked and

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dependent on each other throughout the entire execution of LCA: Goal and scope definition, Life cycle inventory analysis (LCI), Life cycle impact assessment (LCIA) and Interpretation. The whole LCA study revolves around these phases. This method is based on ISO: 14040 and 14044 described by the International Organization for Standardization. LCA methodology evaluates all the emissions, consumed resources, EIs, human health and natural resources depletion issues associated with defined product system(s) (Hauschild, et al., 2010). It helps many researchers or decision-makers of manufacturing companies improve their respective production technology to avoid wastage of materials and the type of materials used to lessen the EIs associated with them. LCA plays an important role and acts as a robust decision-making tool.

Considering the introduction and methodology described by the author, this paper aims to show the results of a life cycle assessment of energy storage systems. The energy storage systems considered in this article are electrochemical energy storage system – Lithium-ion battery and chemical energy storage system – Hydrogen energy storage. The purpose of the LCA is to evaluate and understand the environmental impact associated with the considered energy storage systems through the cradle-to-grave approach, which is further implemented in electric vehicle and fuel cell vehicle respectively. The interpreted result will help the audience of this thesis understand the LCA tool in a better way. It will make it easy for decision-makers to select the appropriate energy storage systems for required applications to some extent. A detailed description of two defined energy storage systems and LCA conducted are described below.

DEVELOPMENT OF THE WORK

LITERATURE REVIEW

Well-established methodology to evaluate the life cycle assessment of any processes or products or services is defined by International Standards (ISO) in “The new international standards for life cycle assessment: ISO 14040 and 14044 by the author Matthias Finkbeiner, Atsushi Inaba, Reginald B.H. Tan, Kim Christiansen and Hans-

Jürgen Klüppel, published in the International Journal of Life Cycle Assessment in 2006". This paper is an important literature for every practitioner, researcher, student conducting LCA on any products or services before starting their respective study (Finkbeiner, et al., 2006).

Information about different energy storages systems and their real-life applications are gathered by the author from the literature "Energy storage technologies and real-life applications – A state of the art review, written by Mathew Aneke and Meihong Wang which was published in Applied Energy journal in the year 2016". This reviewed literature is based on various aspects and technologies relevant to the energy storage systems and their future livelihood is also predicted. Hampering challenges regarding the utilization of energy storages systems on a commercial basis are also foregrounded. This literature helped the author to choose the energy storage systems for the thesis to some extent and drove to understand and think broadly to work on the real problems relevant to energy storage technologies (Aneke & Wang, 2016).

Notter and coauthors in the paper had described the environmental impact of Lithium-ion Batteries (LIB) based on Electric mobility in details. Battery-powered Electric Vehicles (BEV) are playing a vital role in future mobility scenarios replacing conventional vehicles in many aspects. The Lithium-ion battery Life Cycle Assessment (LCA) (from its production, use, and disposal phase) is carried out in this paper to check the environmental burdens associated with the Lithium-ion battery. The LCA conducted on lithium-ion battery based on BEV in the paper is compared with the environmental impact concerned with Internal Combustion Engine Vehicle (ICEV). The reference flow in correspondence with FU is one vehicle-kilometer. The system approach encompasses cradle-to-grave with no cut-off limits. Ecoinvent version 2.01 database is used to acquire materials and processes for background processes. Supporting Information document is also provided by the author of the paper, which contains all the inputs and outputs flows of the system boundary processes along with infrastructure, electricity, or energy utilization and the assumptions for transport distances (Notter, et al., 2010a)

Bareiß and others published a paper about the LCA of hydrogen from proton exchange membrane water electrolysis in future energy systems, provided the information about life cycle assessment. Detailed LCI was provided in the paper only for PEM electrolysis technology. The LCA conducted on PEM was compared with another hydrogen production technology based on natural gas and steam feedstock called steam methane reforming (SMR). The author showed that producing hydrogen through the PEM electrolysis method could reduce the CO_2 emissions by 75% only when electricity generated from renewable energy resources is used in the electrolysis method. To analyze the requirements of energy by the system in future, an energy model was built by the author. SimaPro software is used to execute the LCA. The data required for background processes is acquired from the ecoinvent v3.3 database. The author presented the results for different impact categories for the year 2017 and 2050 (baseload). The difference between the cumulative energy demand for both renewable and non-renewable energy are shown in the paper by author (Bareiß, et al., 2019).

METHODOLOGY

LCA methodology is used to evaluate the environmental impact associated with the two defined product systems, i.e., lithium-ion battery and hydrogen energy storage system and to carry out a comparative analysis based on their LCA results and to answer the research questions. Different life cycle approaches such as cradle-to-gate, cradle-to-grave and cradle-to-cradle in LCA methodology are chosen according to the aim and objectives of the research work. The LCA methodology depends on four main phases.

1. Goal and Scope definition
2. Life Cycle Inventory Analysis (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation

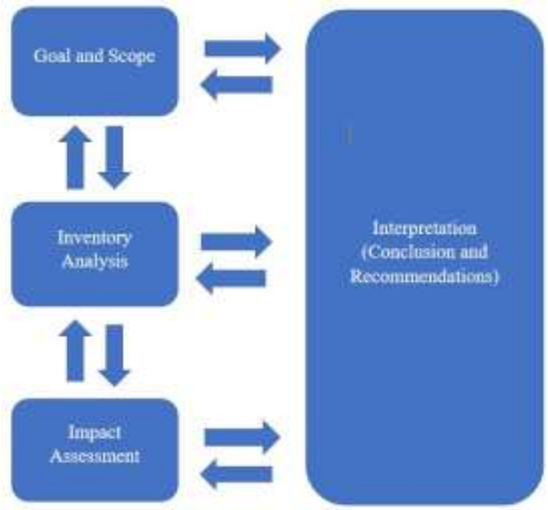

Figure 1. Life Cycle Assessment phases

Source: (Hauschild, et al., 2010)

Goal and Scope Definition – The goal definition in the LCA methodology describes the purpose of the research work. It is the first phase component of LCA and provides much clear information about the respective research work. Goal definition narrates the path to all the other remaining phases and acts as a decisive aspect. It outlines the framework and delivers the guidelines for the scope definition and life cycle inventory work. The goal of the study is to perform comparative LCA of two product systems, i.e., lithium-ion battery and hydrogen energy storage system and carry out a comparative assessment of the results considering different impact categories that are environmentally oriented and answer the mentioned research questions. The functional unit chosen for the study is one kilometer vehicle driven in Europe, and the corresponding reference flow is one vehicle-kilometer. Cradle-to-grave LCA approach was considered by the author for both defined product systems in the study. EOL phase is excluded from the study. Attributional LCI modelling framework is selected. Considering the definition of allocation procedure, in this thesis, no allocation was considered by the author. For each defined product system, no allocation or partition is performed. The quality of the collected data plays an important role throughout the entire LCA study. This thesis is based on the data obtained from secondary sources. No primary data is used. In the absence of any data, assumptions have been made to fill in the gaps of absent data. Proxies of many materials have also been made with other materials having similar chemical properties while performing LCA on software. Ecoinvent database is used to acquire data for all the background processes for both systems. Software used for executing LCA work is open LCA sustainability software version 1.3. The systems are produced as per kg basis, i.e., 1kg of lithium-ion battery and 1kg of the electrolyzer. Balance of plant (BOP) is not considered for both systems. The assembly of all the different components for both systems are considered in the European region. The use phase of both systems, i.e., use phase of electric vehicle and fuel cell vehicle, are considered in Switzerland. Therefore, electricity sources (grid mix/ wind/ solar energy) used to charge electric vehicles and produce hydrogen gas are also taken from Switzerland's electricity grid and UCTE grid. Drive train parts such as electric motor, gearbox, controller, cooling system, cables, charger for the electric vehicle, fuel cell, battery, etc., are only inventory components considered for both vehicles. On site hydrogen production is considered via containerized and portable PEM electrolyzer. No secondary materials are used to manufacture the components for both systems.

Life Cycle Inventory - The lithium-ion battery chemistry considered for this thesis is lithium-manganese-oxide (LMO). The inventory for lithium-manganese-oxide battery is based on Notter, et al., (2010a) and the corresponding supporting information document Notter, et al., (2010b). In the study, the author has considered the PEM electrolyzer. The inventory collected for the PEM electrolyzer is taken from Lundberg (2019) and Bareiß, et al., (2019).

Life Cycle Impact Assessment - The authors have selected the ReCiPe Endpoint (E,A) method to evaluate the environmental impact associated with the defined product systems. The ReCiPe method provides results at both levels: midpoint and endpoint.

However, the author has only considered the impact category indicators at the endpoint level for the long term, i.e., damage caused to ecosystem quality, human health and resources.

Interpretation - The LCA interpretation phase aimed to provide a full explanation of the final resulting outcome, conclusion and recommendations. It also interprets the results and provides the answers to the predefined research questions, which intends to respect the goal and scope definition of the conducted LCA. The interpretation aims to serve two different fundamental purposes: to improve the LCI model and to provide robust conclusions and recommendations (Hauschild, et al., 2010). The results of the study and interpretation is described below.

RESULTS

In this section, the overall results of the LCA study are presented. The results for the two defined research questions are presented separately. These results are further grouped into three characterization factors, i.e., impact on ecosystem quality, human health and resources, and their total. The considered characterization factors and impact categories included in the ReCiPe endpoint method are shown below.

Table 1. Characterization factors and impact categories considered from ReCiPe endpoint method

Characterization factors	Impact categories
Ecosystem Quality	Climate change, acidification, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, agricultural, urban and natural land occupation, eutrophication
Human health	Climate change, ozone layer depletion, ionizing radiation, human toxicity, particulate matter formation, photochemical oxidation
Resources	Fossil depletion and metal depletion

Source: Author

On the next four pages are nine tables that summarize the results obtained with the OpenLCA software when processing the inventory data for the two electricity storage systems. The information obtained, which is displayed according to the two scientific questions, is analyzed and discussed in the subsequent section.

LCA RESULTS COMPARING BOTH STORAGE SYSTEMS

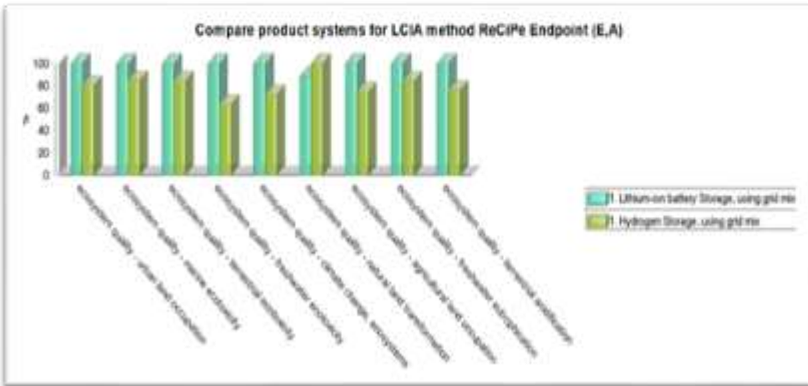

Figure 2. Impact on ecosystem quality. **Source:** Authors

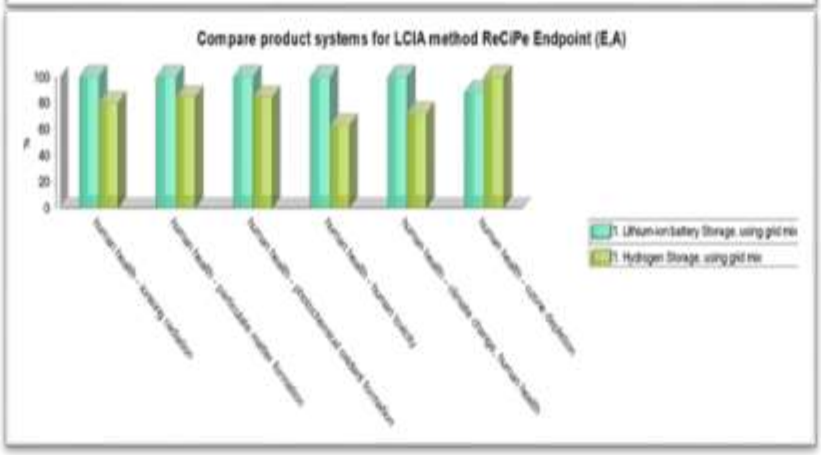

Figure 3. Impact on human health. **Source:** Authors

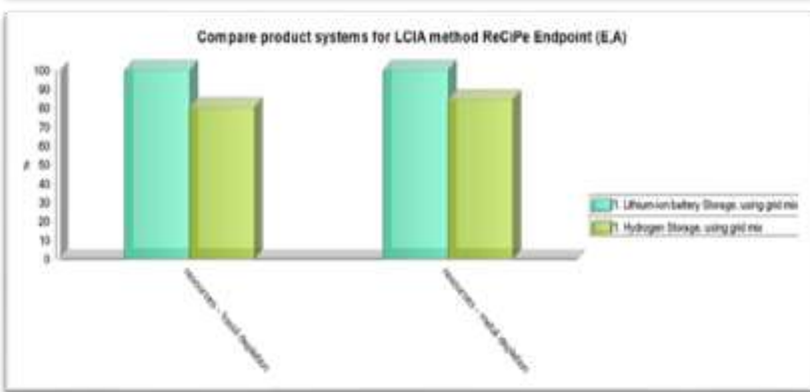

Figure 4. Impact on resources. **Source:** Authors

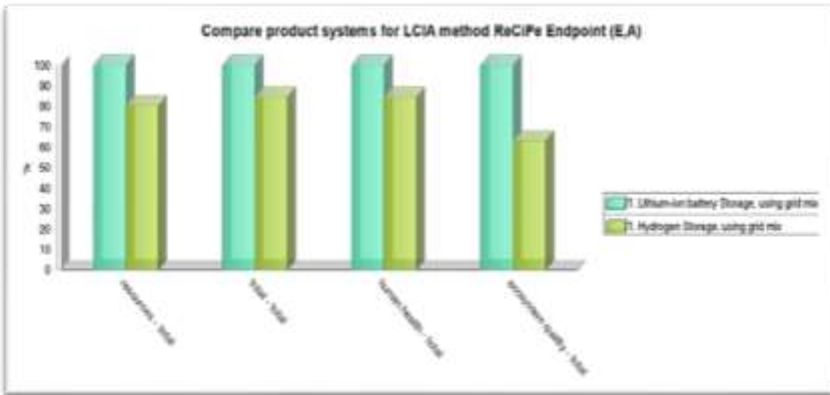

Figure 5. Total impact on environment.
Source: Authors

RESULTS COMPARING BOTH STORAGE SYSTEMS WITH DIFFERENT ENERGY SOURCES

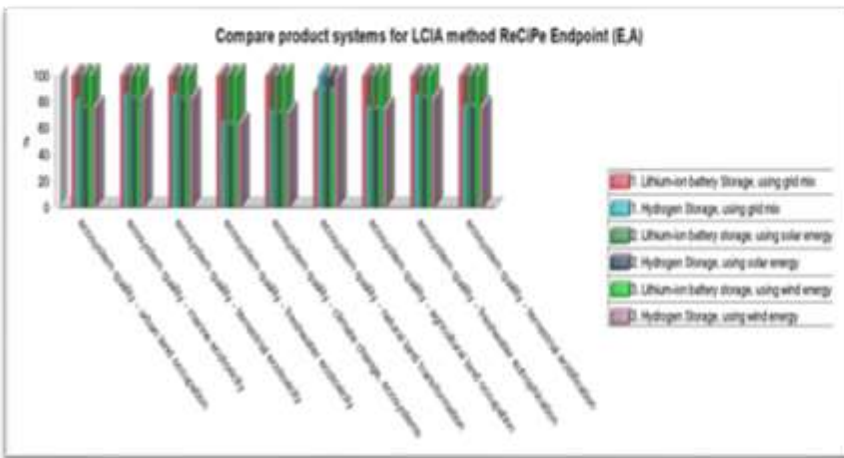

Figure 6. Impact on ecosystem quality.
Source: Authors

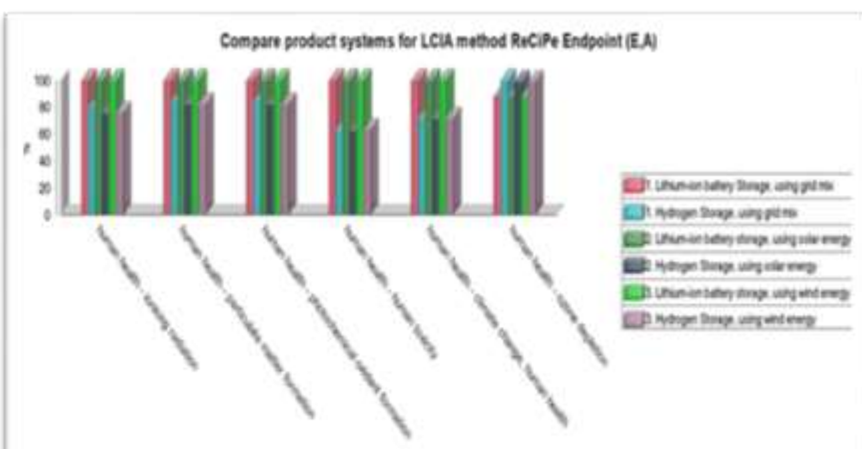

Figure 7. Impact on human health.
Source: Authors

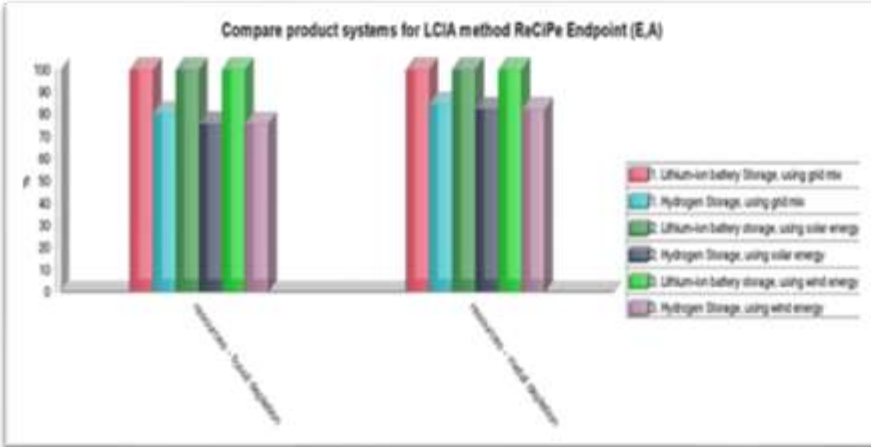

Figure 8. Impact on resources.

Source: Authors

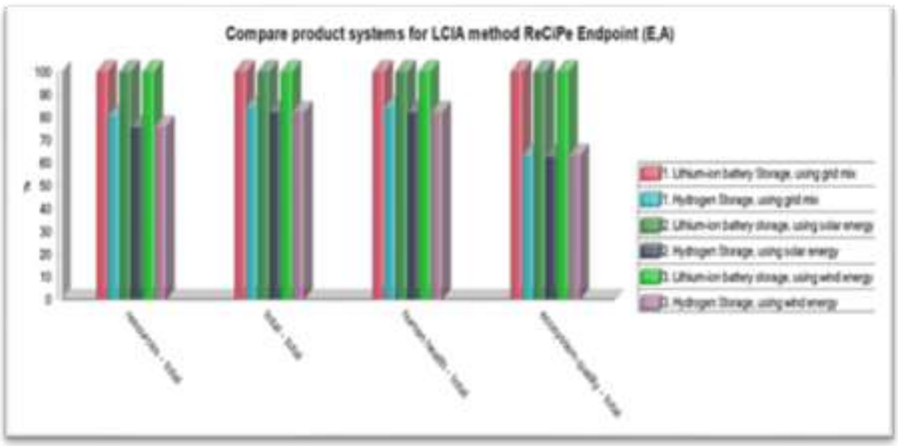

Figure 9. Total impact on environment.

Source: Authors

ANALYSIS OF RESULTS

The interpretation of the results is based on the outcome derived from the conducted LCA study and studied works of literature. To interpret the results, both product systems´ significant aspects need to be considered, such as crucial processes, assumptions made, considered parameter, product flows, elementary flows, etc. These aspects influence the results to a large extent.

In a lithium-ion battery product system, types of material and electricity source used to produce battery pack components such as anode, cathode, separator, solvent, BMS, account to cause a high impact on the environment. Similarly, the production of all these components plays a significant role to influence the results to some extent. Copper contained in the anode and also in all other elements such as cables caused around

43% impact (Notter, et al., 2010a). Other materials that are used in anode shows relatively low consequences. In contrast, the cathode contributes the highest share compared to the anode in causing environmental burden. Aluminum foil produces more impact than other materials such as black carbon, binder, etc., that are used to produce cathode. BMS, printed board and wiring, nitrogen, process heat contribute only to a smaller extent to cause EI. Lithium being one of the scarce metal available in the earth crust, lithium contained in the components such as $LiMn_2O_4$ and $LiPF_6$ also causes an impact between 10(EI99 H/A) to 20% (GWP) when assessed with different LCIA methods (Notter, et al., 2010a). Apart from all other contributors to the environmental burden, the energy required for processing and the metal supply are significant contributors. The transportation processes considered in the lithium-ion battery system also causes EI in terms of air pollution by emitting harmful gases such as SO_2, NO_x, etc. These gases cause an adverse impact on human health, ecosystem quality and fossil fuels depletion. Hence, transportation is also one of the main contributors to causing EI. The sensitivity analysis conducted by Notter, et al.,(2010a) on different lithium-ion battery chemistry showed that there are only minor changes in causing EI (Notter, et al., 2010a). The electric vehicle considered within the system boundary also shares a burden on the environment to a small extent because only drive train parts of EV are assumed. The environmental impact caused by the battery used electric vehicle considered in the study contributes to around 7 to 15%, when assessed using CED and EI99 H/A, respectively (Notter, et al., 2010a). In practical, there is no emissions associated with the electric vehicle during its operation phase. The environmental impact associated with the electric vehicle are mainly because of the type of electricity source used to charge the electric vehicle and to a lesser extent due to materials and the kind of electricity sources used to manufacture EV. In the interpretation of the results concerned with the lithium-ion battery, the literature Notter, et al., (2010a) is referred because the LCI data for lithium-ion battery and electric vehicle is referred from Notter, et al (2010a). The results presented above in the 4.4.3 section for both research questions are the outcome of all the above-mentioned significant issues contributing to causing EI.

In the hydrogen energy storage system, the type of materials used to manufacture the electrolyzer and the kind of electricity source used to produce hydrogen causes the highest impact on the environment. The electricity source used to produce hydrogen plays a vital role in increasing or reducing the overall EI contribution. The amount of materials used in the manufacturing of electrolyzer is lower than the materials used to manufacture lithium-ion battery. Therefore, a small amount of EI is caused by the electrolyzer considering its whole life cycle period. In today's scenario, around 29.5 kg of GWP is generated for each kg of hydrogen production (Bareiß, et al., 2019). The transportation factor considered in hydrogen energy storage system caused a small impact on the environment because the transportation of raw materials and the manufactured electrolyzer are considered within the European region. Also, in the study, the author has considered on-site hydrogen production via a containerized electrolyzer. Thus, the extra electricity consumption and transportation needed to compress the produced hydrogen into cylinders and transport those compressed cylinders to the fueling station site is avoided. Hence, these assumptions made by the author regarding hydrogen production showed the hydrogen system results relatively lower compared to the lithium-ion battery system. Similar to the electric vehicle, EI associated with the fuel cell vehicle is also zero. The method and the kind of electricity used to produce hydrogen are the main causes of EI associated with FCV during its use phase. The manufacturing of FCV drivetrain parts is assumed within the system boundary. The impacts related to the manufacturing of FCV is similar to that of the electric vehicle. The results presented above in the 4.4.3 section for both research questions are the outcome of all the above-mentioned significant issues contributing to causing EI.

CONCLUSION AND RECOMMENDATIONS

The lithium-ion battery has caused the highest environmental impact on almost all the impact categories. There are few impact categories, such as natural land transformation, ozone depletion, where lithium-ion battery systems showed lower results compared to the hydrogen energy storage system. The lithium-ion battery had generated the poorer outcome in all impact category indicators throughout its whole life cycle, when only grid mix electricity is used. The hydrogen energy storage system causes less environmental impact, and thus, it seems more environmentally safe to use for a longer time frame. Considering the stated conclusion and long-term time frame circumstances, it is recommended to use a hydrogen energy storage system. The authors also suggest producing hydrogen on site with containerized electrolyzer for avoiding extra electricity and transportation consumption, that is required to compress produced hydrogen into cylinders and to carry compressed hydrogen gas to the fueling station site.

The lithium-ion battery system showed less favorable outcomes for all three electricity sources supplied during its use phase. The similarity between the results has been observed for research questions 1 and 2 for natural land transformation and ozone depletion indicators, where the lithium-ion battery system showed less satisfactory impact results than the hydrogen system. Thus, it can be considered that the lithium-ion battery system, including three electricity sources, causes fewer effects on natural land transformation and ozone depletion for a longer time-frame. Nearly similar, 100% impact results between grid mix, solar and wind electricity sources have been generated when supplied to the hydrogen energy storage system during its use phase in natural land transformation and ozone depletion indicators. Considering all the impact categories' results, the hydrogen energy storage system has shown lower impact than the battery system, including three supplied electricity sources. Therefore, all three provided electricity sources are better suited for the hydrogen energy storage system than the lithium-ion battery system. Specifically, the grid mix electricity source remains out of the comparison window because the grid mix supplied to the hydrogen system generated higher EIs results than solar and wind energy in all the indicators.

The above results, conclusions and recommendations are based on long term time-frame and endpoint level indicators. The results, conclusion and recommendations might be distinct when an additional or different LCIA method is implemented. The author also recommends using other LCIA methods to understand various aspects linked to the product systems' results and might help reduce the environmental impact associated with them.

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