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Water footprint of the manufacturing of a traction lithium ion battery pack

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Executive Summary

Mining and refining activities are known to have an impact on water quality. The number of different metals and the quantity present in a lithium-ion battery raises questions on the impact on water footprint of the manufacturing of an electric vehicle. This life cycle assessment study therefore assesses the impact on water quality (eutrophication, toxicity and acidification) and on water scarcity of the manufacturing of a NCA traction battery. This paper presents a cradle-to-gate study that also focuses on the influence of impact assessment methods on water scarcity results.

The impact on freshwater eutrophication and ecotoxicity is driven by the presence of precious metal in the electronic components of the module housing. The impact on water scarcity is between 28 m^3 and 1800 m^3 per pack, depending on the method used for the assessment. The direct use of water during the cell manufacturing is the main contributor to water scarcity for five out of six impact assessment methods. Ecoscarcity 2013 method shows a result slightly different than the other impact assessment methods due to the high relative difference in the characterization factors for countries with different hydrologic profiles. This finding raises the question of the use of global datasets from generic databases for water footprint assessment.

1 Introduction

Global freshwater availability is limited and moreover climate change and economic development influence this availability now and in the future. By 2040, in a "business as usual" scenario, the water stress index, calculated as the ratio between total water withdrawals and available renewable surface water, tends to increase in 92% of the countries [1]. Water scarcity is becoming an environmental concern.

Water footprint has been standardized in an ISO standard [2] and does not only address water scarcity but also all impacts related to water quality, the degradative use of water. Water scarcity looks at a quantity perspective only. Water quality can be assessed thanks to a large number of parameters. The World Health Organization recognizes four aspect categories for drinking water quality: microbial aspects, chemical aspects, radiological aspects and acceptability aspects (taste, odour and appearance) [3]. Boulay et al. [4] listed 136 water quality parameters and showed that few surface water has a good or excellent quality in the world: 26 out of 224 watersheds. In LCA (Life Cycle Assessment), water quality can be assessed through several midpoint indicators: eutrophication, ecotoxicity and acidification.

It has been shown that the impact of a BEV (Battery Electric Vehicle) is lower than other vehicle technologies for different environmental categories such as climate change and respiratory effects [5]. The battery is a key component when assessing the environmental impact of the life cycle of an EV. Li-ion batteries require a high content of several metals such as nickel, cobalt, aluminium and copper. Metal mining and refining have potential impacts on hydrology and water quality [6]. Indeed, mines can be a big local consumer of water, as wet ore processing is generally used. Mining can occur in regions with high water stress index [7] and loose environmental regulations. Nevertheless, previous studies on battery manufacturing mainly focused on impact on climate change, according to the review from Peters et al. [8]. Water quality is sometimes assessed for batteries whether it is ecotoxicity [9–12], eutrophication [10–14] or acidification [9–12, 14]. All these previous studies assessed LFP, NMC, LMO or Lithium-air batteries but NCA batteries are missing.

Water footprint has been evaluated for vehicles [15–17], electricity generation [18–20] and mining [6, 7], but usually what is called water footprint is just a water scarcity assessment that does not include water quality assessment.

Onat et al. [21] assessed the water consumption and withdrawal of EVs in the United States, excluding the manufacturing stage and EoL (end of life) stage. They showed that electricity mix is a key parameter when assessing water withdrawal and water consumption. Water withdrawal of EVs charged with US average electricity mix is driven by the use stage [16]. If BEVs (Battery Electric Vehicles) are charged with solar energy, their water withdrawals can be reduced by up to 85%. When focusing on the manufacturing of batteries, the electricity mix used to power the factory is also a key parameter for the impact on climate change [22, 23].

At our knowledge, only [13] assessed water depletion potential, using ReCiPe 2008, at cell level for laminated and solid state cells but they do not focus on water footprint, they assessed 6 impact categories. They found that refining process of ores are the main contributors to water depletion potential. We are the first, at our knowledge, to assess the water footprint of the manufacturing of a traction battery.

The section 2 presents the goal and scope of the LCA, section 3 presents several water scarcity methods, section 4 presents the inventory, section 5 presents the results of the impact assessment and finally, section 6 concludes this work.

2 Goal and scope

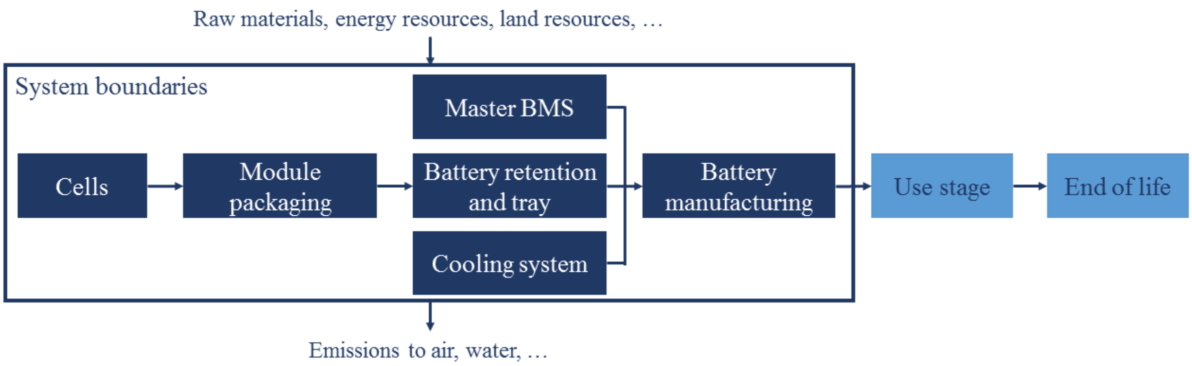

Figure 1: System boundaries

This study focuses on the impacts on water of the manufacturing of a battery pack for EVs. This is a cradle to gate study, as the system boundaries include raw material extraction, the cradle, transformation and battery manufacturing until the factory gate (Figure 1). A cell is composed of electrode pastes on current collectors, a separator, electrolyte and a cylindrical container. Cells are assembled in a module and modules are assembled with a master battery management system and a cooling system in a battery retention and tray.

The functional unit is the "quantified performance of a product system for use as reference unit" [24]. In this paper, the functional unit is a 20 kWh battery pack, at factory gate.

The first goal of this study is to assess the impact on water quality of a traction battery. For water scarcity, several impact assessment methods exist [25]. The second goal is therefore to assess the influence of impact assessment methods on water scarcity results. Six methods will be presented in section 3.

The LCA software used for this study is Simapro 8.5. Freshwater and marine eutrophication (Feu, Meu) are assessed thanks to ReCiPe 2016 Midpoint H [26]. Freshwater ecotoxicity (Fet) is assessed using characterisation factors from USEtox 2.02 (recommended + interim) [27]. Freshwater acidification is based on Impact 2002+ v2.14 [28]. In the ISO standard [2], it is stated that water scarcity should not consist of a volumetric inventory but should include regional characterization factors. In our study, water scarcity is then assessed thanks to six midpoint impact assessment methods that are detailed in section 3.

3 Water scarcity methods

To understand water scarcity methods, some vocabulary is necessary (Figure 2). Water withdrawal is the amount of water which is taken from a water body (surface water, ground water, …). Withdrawal only focuses on the origin of the water and does not consider the destination of the water. Water consumption is the use of water when the release does not come back into the same water body due to evaporation, product integration or discharge into a different water body. For instance, evaporated water for cooling in a power plant is called water consumption.

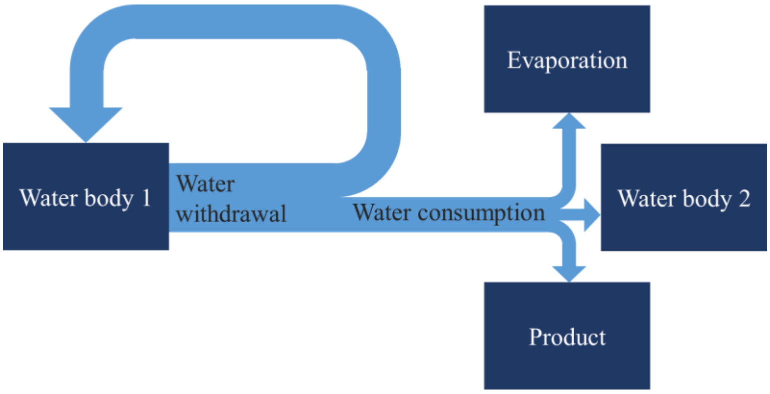

Figure 2: Water flows

Methods use either withdrawal-to-availability ratio [29, 30] or consumption-to-availability ratio [31, 32] or demand-to-availability ratio [33]. The oldest methods include withdrawal-to-availability ratio, later were developed methods using consumption-to-availability ratio, assuming that water that is released in the same water body does not have impact on water scarcity. Note that Loubet et al. [34] showed that there can be however a local impact.

Characterisation factors are based on the same model for several methods for water availability [29–31, 33]: the WaterGAP model that includes freshwater flows, storage, withdrawals and uses for more than 11000 water basins worldwide [35]. This model has been developed by the Center for Environmental Systems Research at the University of Kassel. This model includes annual average for the period 1961-1990, which does not show monthly and yearly variability.

The Water Stress Index (WSI) by Pfister et al. [29], as one of the oldest methods, uses the water withdrawal-to-availability ratio, which was determined using the WaterGAP2 model. This may be one of the most used index in the literature [6]. Expert judgement is used to define moderate and severe water stress (thresholds of 20 and 40% for the withdrawal-to-availability ratio, respectively). This method also accounts for inter- and intra-annual precipitation variability. The characterisation factors range from -1 to 1 and describes the portion of water consumption that deprives other users of freshwater.

Swiss ecoscarcity [30] is based on the distance-to-target principle. This method is a LCIA method that not only focuses on water resources but includes 19 impact categories. Results are shown in points. The targets are based on Swiss political targets for pollution emission. This method uses WaterGAP model for water availability. The span of the characterisation factors is the highest above all the methods: from 0 to 20,000,000.

Water Accounting and Vulnerability Evaluation (WAVE) method by Berger et al. [31] assesses the risk of ground and surface water depletion and is based on consumption-to-availability ratio. This method includes a model of atmospheric evaporation recycling effects. WAVE also considers absolute scarcity by means of aridity: arid regions have a water depletion index set to the maximum even though the local water consumption is 0. Characterisation factors amplitude lies between -1 and 1.

Hoekstra et al. [32] propose a method based on consumption-to-availability ratio, for ground and surface water on a monthly basis. For water flows, they assessed 405 river basins for the period 1996-2005 [36], which may lead to some missing characterization factors. They presume that risks to ecological health and ecosystem services is increased as soon as water depletion is beyond 20% of a river's natural flow.

In ReCiPe 2016 [26], characterisation factors are equal to 1 for the midpoint indicator, if the inventory reports water consumption. As a consequence, this method does not characterise water scarcity as the characterisation factors for water consumption is not regionalised. This method does not correspond to the definition of ISO 14046 for water scarcity assessment method but is used here as it shows the water consumption inventory.

Later, demand-to-availability concept has been discussed by the Water Use in Life Cycle Assessment (WULCA), a working group of the UNEP-SETAC Life Cycle Initiative. Ecosystem and human consumption are considered as demand. Demand-to-availability ratio measures the potential to deprive other users of water. Available water remaining (AWARE) [33] is a consensus method developed by the WULCA working group on a water scarcity. Water availability is retrieved from WaterGAP model. Human demand accounts for domestic, industrial, agricultural, livestock, and energy production sectors for the year 2010, and is also found in WaterGAP. Pastor et al.'s model [37] is used for the ecosystem demand but it is not site specific and the authors of the method recognize that this is one of the main limitations. Terrestrial and groundwater-dependent ecosystems demand is not included.

It is obvious that regionalized characterisation factors are necessary to include hydrological conditions. All of these methods include a geographic dimension except ReCiPe [26]: at watershed level, country level, … but only country specific characterization factors are implemented in Simapro. It is nevertheless reasonable to wonder if countries are homogeneous when it comes to water stress. Simapro does not include monthly characterisation factors even though they are available for several methods. Battery manufacturing is however not a seasonal product, annual average can be used to assess water scarcity. In case of an agricultural product for instance, taking into consideration production seasons may be important.

For more details on other methods, Boulay et al. reviewed ten methods on water use [38] as Table 1 shows.

Table 1 : Water footprint methods

Method	Impact
Swiss ecoscarcity 2006 version [39]	Scarcity
Pfister WSI [29]	Scarcity
Blue water scarcity [40]	Scarcity
Boulay [41]	Scarcity, availability, human health
Pfister [29]	Human health
Veolia [42]	Availability
Motoshita, domestic [43]	Human health
Motoshita, agricultural [44]	Human health

4 Life cycle inventory

The pack assessed contains Samsung Li-Ion 21700 cylindrical cells –model INR21700-48G. The inventory for these cells have been retrieved using the following techniques:

- Electrochemical characterization for the harvested electrodes

- X-ray fluorescence (Cary Eclipse, VARIAN) and X-ray diffraction for electrodes (D8 ADVANCE, BRUKER)
- Thermogravimetric analysis for positive electrode (Q500, TA INSTRUMENTS)
- Fourier-transform infrared spectroscopy for separator (FT/IR-4000, JASCO)

Energy demand for cell manufacturing in literature can vary up to one order of magnitude[8]. The average energy consumption found in literature [10, 12–14, 45–51] is 16.7 kWh/kg$_{cell}$. The manufacturing yields originate from the BatPac 3.1 model [52]. The cathode active material is $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ modelled according to [53]. The precursors are nickel sulphate (modelled based on [54]), cobalt sulphate (modelled according to [12]), aluminium sulphate (dataset from Ecoinvent 3.4) and lithium hydroxide (dataset from Ecoinvent 3.4).

The module assessed is a prototype module used to develop and validate modelling techniques in the HiFi Elements European research project. The module packaging is therefore not mass optimized as would a pack manufactured at industrial scale. 36 cells are grouped in a module. Each module has a slave BMS (Battery Management System), cooling plate, busbars, cell spacers, screws, wires and sensors.

Each pack is composed of 32 modules, reaching 20 kWh. The pack housings, cooling system and master BMS are modelled according to [10], scaled to energy capacity. This scaling may over estimate thermal management components. Table 2 shows the inventory of the battery pack. Ecoinvent 3.4 has been used as a database for the background data.

Table 2: Inventory of the battery pack

Material/Energy	Input	Output	Unit
Module packaging	66.2		kg
Battery retention	6.66		kg
Battery tray	18.2		kg
master BMS	6.38		kg
Cooling system wo coolant	7.41		kg
Cell, NCA-G	78.3		kg
Electricity, medium voltage	0.088		kWh
Heat, waste		0.088	kWh
Battery pack		183	kg

The battery pack is assumed to be manufactured in Korea which electricity mix modelled in Ecoinvent is mainly based on hard coal (36%), nuclear power (32%) and natural gas (25%).

5 Water footprint impact assessment

5.1 Impact on freshwater quality

Degradative water use is assessed thanks to four impact categories: freshwater eutrophication (FEu), marine eutrophication (Meu), freshwater ecotoxicity (FEt) and aquatic acidification (see Figure 3).

5.1.1 Eutrophication

The impact on FEu is driven by the presence of gold in the integrated circuit of the slave BMS and sensors of the module packaging, even though gold needed for the manufacturing of the pack only represents less than 0.01% of the battery mass. Gold mining is responsible for 66% of this impact. This metal is mainly mined with silver or copper. In mining, wastes are often responsible for the biggest environmental issues. In this study, sulfidic tailings cause 80% of the impact on FEu. Tailings are a waste produced during ore refining. Tailings contain large quantities of metals and moreover the quantity of tailing can reach 351kg per kg of metallic copper [55]. Sulfidic tailings are a result of processing a sulphide ore. In that case, sulphides are oxidized in sulfuric acid. Impacts on eutrophication, toxicity and acidification of sulfidic tailings are due to tailings impoundment leachate.

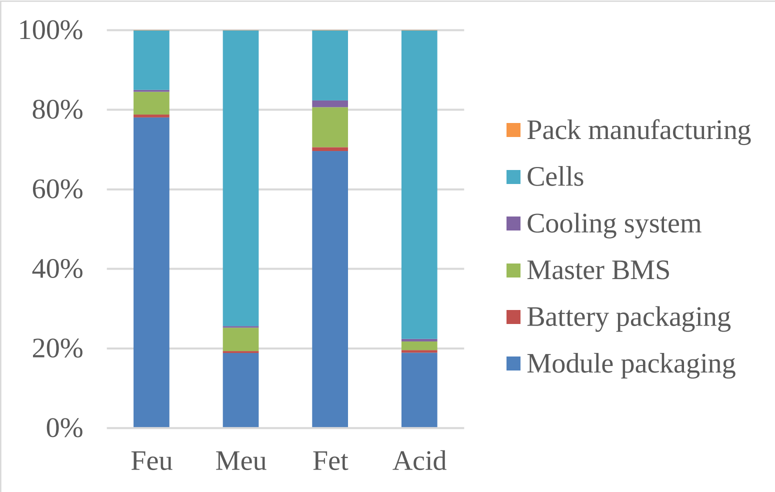

Figure 3: Impact on water quality of the manufacturing of one battery pack. FEu (freshwater eutrophication), Meu (marine eutrophication), FEt (freshwater ecotoxicity) and Acid(aquatic acidification).

Ellingsen et al. [10] also found that the disposal of sulfidic tailings are a major source of freshwater eutrophication. Majeau-Bettez et al. [12] highlighted that electrode substrate and BMS contribute to more than 70% of the impact of a LFP and a NMC battery manufacturing, which is coherent with our finding as copper mining introduces the need of disposal of sulfidic tailings. Lastoskie et al. [13] also highlighted copper as a hotspot for FEu. For Zackrisson et al. [14] the impact on eutrophication of a LFP battery is dominated by the cathode which substrate is a copper sheet.

The impact on FEu is estimated to be 4.26E-2 kg P_{eq}/kg_{pack}, in accordance with [10] that evaluated a NMC battery pack. This result is slightly higher than [12] that evaluated a LFP and a NMC battery pack and almost twice higher than [13]. Our battery is based on a prototype module not mass optimized, the high share of the module packaging is then coherent as the fact that our result is slightly higher than previous studies.

MEu shows a rather different profile than Feu: cells dominate this impact. In marine water, nitrate is the limiting factor for algae growth, while in freshwater, phosphate is the limiting factor. In the cells, the material responsible for the impact on MEu is the cathode active material because of nitrogen oxides emissions from electricity consumption, and diesel and hard coal combustion during nickel mining. The use of nitrogen containing explosives for mining is also a driver of this impact [54].

The impact on MEu of our battery is one order of magnitude lower than [10, 12] which assess batteries with a NMC cathode active material and that use an older dataset for nickel mining, as we updated nickel metal dataset thanks to the Nickel Institute study [54].

5.1.2 Ecotoxicity

Module packaging dominates the impact on FEt. Cells and master BMS are also relevant components for this impact category. As for FEu, gold, present in BMS and sensors, is the material that induces the higher impact. Copper is also relevant. This is coherent with [12] that found that the impact on FEt of the manufacturing of a NMC and a LFP battery is mainly due to the BMS and the electrode substrates. Mining wastes such as sulfidic tailings, hard coal ash and dross from aluminium electrolysis cause more than 84% of the impact on FEt. As previously mentioned, sulfidic tailings release in water several toxic metals. Korean electricity mix is responsible for more than 40% of the impact of the cells on FEt. The first source of electricity in Korea is hard coal that induces a need for treatment of hard coal ashes.

Lithium air cells ecotoxicity is dominated by copper, electricity production and lithium [9]. The NMC battery from [10] impact on FEt is also mainly due to copper current collector because of the disposal of sulfidic tailings.

This indicator has some limitations that are worth mentioning. Assessing toxicity is rather more complicated than eutrophication, for instance. First of all, the number of characterization factors in the method is much higher. There are 17 and 21 characterization factors for FEu and MEu, respectively while there are more than

25000 for FEt. It is also recognized that uncertainty on those characterization factors is substantial: several order of magnitudes [27]. As a result, this category should mainly be used as a screening category, indicating major sources of pollution but comparison between those sources should be avoided.

In USEtox, there is moreover no characterization factor for lithium, but a review from Shahzad et al. [56] showed that lithium can be toxic for plants. The exact role of lithium in plant toxicity is still unclear. Moreover, plants may accumulate lithium which may expose the rest of the ecosystems and humans [57]. Even if lithium toxicity is low for humans, chronic exposure due to the raise of lithium contamination may lead to health issues [58].

5.1.3 Acidification

Aquatic acidification is driven by the cells and more precisely by nickel mining necessary to produce the cathode active material. The predominance of cathode on this impact has already by underlined by [11] for a NMC battery. As noted by [54], the sulfide ore processing and fossil fuels combustion are responsible of the nickel mining impact on acidification. It is known that acid mine drainage is a major environmental issue for the mining sector.

The terrestrial acidification potential of Ellingsen et al.'s battery is similar to our NCA battery impact on aquatic acidification. The NMC cathode paste is also a significant contributor to this impact, alongside with the copper electrode substrate [10].

The predominance of mining on the impact on freshwater quality has been shown but the degradative water use of mining is site specific [7] because of differences in ore composition and grade, climate and local environmental regulations. For studies including use stage, electricity production for charging the battery is contributing more to eutrophication potential [11, 12] and ecotoxicity [12], but this depends on the electricity mix used.

5.2 Impact on water scarcity

Figure 4 shows the impact on water scarcity of the manufacturing of the battery pack. ReCiPe shows the inventory of water consumption. Decarbonized water used during cell manufacturing is responsible for 59% of the inventoried consumed water. This high direct water use is nevertheless a secondary data [12]. In the cell manufacturing, the cathode active material and Korean electricity mix consume both 8.4% of inventoried water for the pack manufacturing. Water is also consumed for manufacturing of the slave BMS in the module packaging. In electronic components of the slave BMS, water is mainly consumed for electricity production.

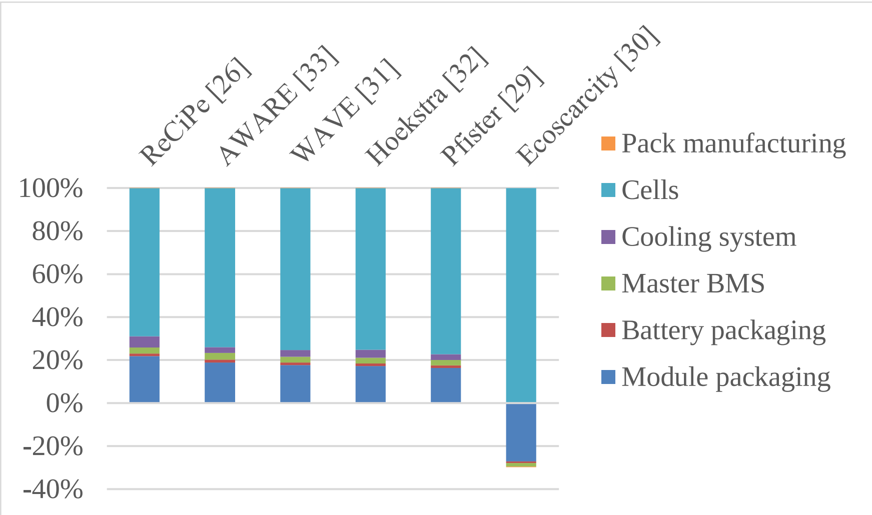

Figure 4: Impact on water scarcity of the manufacturing of one battery pack.

The relative contribution analysis (Figure 4) reveals that all methods used find that cells are the main contributor to water scarcity, direct water used during cell manufacturing leads to between 67% and 82% of the impact on water scarcity with Hoesktra et al.'s method and with AWARE method respectively. This finding is in line with the results from ReCiPe. All the methods also point the impact of cathode active material, Korean electricity mix and slave BMS. Electricity production is a background data that is relevant in water scarcity assessment.

The impact on water scarcity assessed thanks to Ecoscarcity has a different profile than the five other scarcity methods. The module packaging, battery packaging, master BMS and pack manufacturing have a negative impact. In LCA, a negative impact is an avoided burden. The reason of this negative impact is the Saudi Arabia electricity production (natural gas, conventional power plant) which is part of the global dataset for electricity production modelled in Ecoinvent 3.4. Even though this dataset is water balanced and shares a small part of electricity production (less than 0.6%), the water output to Saudi Arabia is higher than the water input from Saudi Arabia (Table 3). Saudi Arabia being an arid region, the characterisation factor for water release in a water shed in Saudi Arabia is 1.5E7 higher than for an unspecified region. The reason why this dataset is important for Ecoscarcity and not for other methods is because the relative difference in characterisation factors is higher for Ecoscarcity method than for other methods.

Table 3: Water flows in the Saudi Arabia electricity production, natural gas, conventional power plant from Ecoinvent 3.4 dataset

	Region	Input	Output	Unit
Water (natural origin)	Saudi Arabia	7.52E-02	7.65E-02	m^3
Water, decarbonised	Global	2.62E-03		m^3
Water, to air	Not specified		1.25E-03	m^3
Total		7.78E-02	7.78E-02	m^3

The impact calculated by the different methods shows a high variability, from 28m^3 with Pfister et al.'s method to 1800m^3 with AWARE. The water depletion potential of the batteries assessed thanks to ReCiPe 2008 [13] is between 9m^3 and 74m^3 for a 40kWh battery pack.

It is not possible to compare these results with Ecoscarcity, as the results are presented in points and not in volume. Results for methods [29, 31, 32] are in the same order of magnitude (28-62m^3) as the inventoried consumed water assessed with ReCiPe. On the other hand, the latest method from WULCA [33] leads a completely different result, probably due to the concept of demand-to-availability ratio that this method is the only one to use. In AWARE method, the world average is set as reference flow for characterisation factors. This modelling choice changes the absolute value of the characterisation factors.

6 Conclusion

The water footprint includes assessment of degradative use and consumptive use of water. The impact on water quality is assessed thanks to four indicators: freshwater eutrophication, marine eutrophication, freshwater ecotoxicity and aquatic acidification. The degradation of water quality due to the manufacturing of this battery pack originates from the mining of gold, present in the electronic components, from the production of the cathode active material and from the mining of copper. Mining wastes are a key issue for the impact on water quality.

However, freshwater thermal pollution is not taken into consideration in these indicators even though thermal pollution influences aquatic organisms and solubility of toxic compounds, oxygen and other gases [59]. Raptis et al. [60] developed a method for thermal pollution assessment and used it to assess thermal pollution of thermoelectric power generation. They showed that coal and nuclear power plants are responsible for most of this pollution. Using this method for other systems is difficult due to data unavailability of water discharge temperatures in life cycle inventories and the regional character of the impact assessment method.

The use of several methods for water scarcity does not reveal big differences in relative contribution analysis. The impact on water scarcity is mainly due to the direct use of water in the cell manufacturing. The relative contribution of the components is close to the inventoried consumed water. Electricity production is a background data that seems to have a relevant impact on water scarcity. A data quality assessment on water inventories reveals that increasing quality of these datasets is necessary.

Research is still needed in the assessment of water scarcity at midpoint level. The quantity of water needed for ecosystems is either a normative choice of the authors or assessed for five major type of freshwater ecoregions [37]. Site specific data of watersheds is needed. At endpoint level, the pathway of the impact on human health and ecosystem quality needs more research. Access to water is a human right, therefore further research is needed to include water impact in social LCA.

The results from one method raise the question of the relevance of using global datasets for regionalized impact assessment method. Implementation of watershed characterisation level would also increase the quality of the results, instead of country specific characterisation factors.

7 Acknowledgments

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