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Energy Use and Environmental Impact of Three Lithium-Ion Battery Factories with a Total Annual Capacity of 100 GWh

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Abstract: The rapid evolution of Li-ion battery technologies and manufacturing processes demands a continual update of environmental impact data. The general objective of this paper is to publish up-to-date primary data on battery manufacturing, which is of great importance to the scientific community and decision-makers. The environmental impacts have been calculated and estimated based on publicly available data disclosed under Hungarian government regulations and official decrees. The gate-to-gate energy use, greenhouse gas (GHG) emissions, water consumption, and N-methyl-2-pyrrolidone (NMP) consumption are estimated for three battery factories in Hungary, with a total annual capacity of approximately 100 GWh. The factories use around 30–35 kWh energy per kWh of battery capacity and the associated GHG emissions are around 10 kgCO_2eq per kWh of cell production. The water consumption varies considerably among factories, with one plant using 28 L per kWh and the other two using 56 and 67 L per kWh. The specific consumption of NMP was calculated for two factories, resulting in close values of 0.51–0.56 kg per kWh of cell production. As a new approach, we distinguish between global and local GHG emissions related to battery production. The main component of the latter is carbon dioxide from the combustion of natural gas, but the local transport related to the battery factories is also a source of emissions. Our estimations include not only the consumptions required directly for the manufacturing technology, but also those for social purposes (e.g., heating offices), giving a more complete picture of the factory's environmental impact. We believe that up-to-date primary data are crucial for ensuring transparency and holds significant value for both the scientific community and decision-makers.

Keywords: local emissions; primary data; greenhouse gas (GHG) emissions; water consumption; NMP consumption

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1. Introduction

Reducing greenhouse gas (GHG) emissions from transport is critical to mitigating climate change, as this sector is responsible for around 15% of global GHG emissions [1]. The transition to electric vehicles (EVs) plays a crucial role in the fight against climate change [2–5]. However, in order to achieve significant reductions in GHG emissions, two key conditions must be met: (i) the energy grid that powers EVs should be decarbonized and (ii) the battery cells of EVs must be produced in the most sustainable way possible. As a consequence, several studies have been conducted on the environmental impact of batteries, particularly lithium-ion batteries (LIBs), which are the leading technology for mobile applications. Their sustainability is usually assessed by two interrelated impacts, the energy demand and the GHG emissions (or the CO2-equivalent emissions). Life cycle assessment (LCA) is a standardized methodology for evaluating the environmental impacts associated with all stages of a product's life cycle, from raw material extraction through production, use, and disposal [6–8]. In their review, Peters et al. found an overall total of 79 available LCA studies on LIBs and 34 on electric mobility [9]. However, only 36 of them were identified as meeting their selection criteria (i.e., providing detailed results for LIB production). Moreover, they found that the majority of the studies reviewed did not provide their own original life cycle inventory (LCI) data, but relied on data from previous works. Despite the shared data, the variation in the results is very large, which can be explained by the different assumptions made in the studies regarding key parameters (e.g., lifetime, energy density or the energy required for manufacturing). However, the choice of a top-down or bottom-up approach to battery manufacturing calculations was found to be the main reason for differences in results. The top-down studies start with production data from a factory, whereas studies using the bottom-up approach collect data for each individual activity in a plant. Peters et al. reported [9], that on average, the production of 1 kWh of storage capacity is associated with a cumulative energy demand of 328 kWh and causes GHG emissions of 110 gCO_2eq. A more recent literature review by Degen and Schütte concluded that many LCA studies of LIB cell production rely on three major outdated (10 or more years old) inventories, and consider obsolete or less relevant material chemistries and production technologies [10]. In addition, as they pointed out, the highly cited studies were based on data of uncertain quality. They emphasize the urgent need for up-to-date and high-quality battery manufacturing data (which is exactly the main objective of our present paper). In their review, Tolomeo et al. highlighted the lack of primary data as a critical issue for LCA of Li-ion batteries [11]. Primary data collected from stakeholders in the lithium-ion battery supply chain may be subject to non-disclosure agreements and not easily accessible. They found that only 12% of the papers reviewed used primary data only. In his letter, Kallitsis carried out a meta-analysis of published data on energy use in battery production, applying filtering criteria on production scale (greater than 1 GWh per year) and battery chemistry (lithium nickel cobalt manganese oxide, NCM333 or later) [12]. The energy consumption data reported by the five filtered studies fell within reasonable proximity, specifically in the range of 30–50 kWh per kWhcell. It should be noted that these studies used a gate-to-gate system boundary, which results the energy consumption of the battery cell factories (cf. cradle-to-grave, cradle-to-cradle, and cradle-to-gate system boundaries [13]). In one of the studies filtered by Kallitsis, Kurland estimated the energy consumption of two large-scale battery cell factories using publicly available data, one based on early company estimates and the other calculated from taxes paid on utilities [14].

In this paper, we assess and report on the main environmental impacts of three battery factories in Hungary, with a total annual capacity of approximately 100 GWh, based on publicly available data disclosed under Hungarian government regulations and official decrees Hungary aims to become one of Europe's battery manufacturing centers and a key player in the global battery revolution [15]. (The Supplementary Materials file presents tables and graphs on Hungary's energy consumption, water consumption, greenhouse gas emissions and CO_2 emissions compared to the EU countries.) It is worth, therefore, assessing not only the global environmental impacts, but the local impacts as well. Accordingly, we also calculate local environmental impacts such as CO_2 emissions (including those caused by increased traffic), local electricity demand and water consumption. We believe that published up-to-date primary data can be of great importance to the scientific community and decision-makers, and furthermore, to the best of our knowledge, the local approach is missing from the literature.

2. Methods

The gate-to-gate system boundary was used in our top-down study to assess the environmental impact of the battery factories. Our estimate only includes impacts directly related to factory production and doesn't consider, for example, extracting minerals and waste disposal or recycling. We have filtered available data and criteria in order to perform a meta-analysis environmental impact assessment (e.g., as part of a policy study or industry trend analysis), that does not require a detailed LCA inventory, according to above mentioned Kallitsis [12] and Kurland [14]. We searched for primary data that had been published by the factories themselves on public websites. In Hungary, governmental decrees regulate the disclosure of environmental permits and annual energy reports. We used the published primary data [16–19] and the standard emission factors [20–22] in our calculations. In the latter case, we had to be very cautious because, for example, the emission factor of the combusted gas is different for local and global emissions, as will be detailed later. The most relevant parts of the referenced documents available only in Hungarian [16–19] are compiled and translated in the Supplementary_Information. The primary data provided by CATL are future estimates as the plant is currently under construction and is scheduled to start production in 2025. The same is true for the SK Innovation's plant that has started operations this year (2024). This uncertainty can be addressed by monitoring the environmental impact of factories once they have started production.

3. Environmental Impact of GWh-Scale Battery Cell Production

The gate-to-gate system boundary was used in our top-down study to assess the environmental impact of the battery factories. We searched for primary data that had been published by the factories themselves on public websites. Fortunately, in Hungary, government decrees regulate the disclosure of environmental permits and annual energy reports. We used the published primary data and the standard emission factors in our calculations. In the latter case, we had to be very cautious because, for example, the emission factor of the combusted gas is different for local and global emissions, as will be detailed later. The main environmental impacts of three battery factories in Hungary are compiled in Table 1, and the details of the calculations and graphs presenting the main data are provided in Supplementary Materials Battery factories impact.

Table 1. The environmental impacts of three battery factories in Hungary (WSF stands for water scarcity footprint).

		CATL	Samsung	SK Innovation
Capacity	GWh/year	40	26	30
Natural gas consumption	m^3/year	90,000,000	25,926,560	93,590,640
Electricity use	GWh/year	533	497	N/A
Energy consumption	kWh/kWh_{prod}	34.6	28.3	29.4 *
Local CO_2 emission	ton/year	181,655	56,007	182,162
Global CO_2 emission	ton/year	437,860	259,628	N/A
Global CO_2 emission	kg/kWh	10.95	9.92	N/A
Water consumption	L/kWh	27.9	55.7	67.0
WSF	L/kWh	32.4	64.8	78.0
NMP use	ton/year	2000 **	14,477	13,150
NMP use	kg/kWh		0.557	0.506

* Calculation from natural gas consumption only. ** NMP is recovered within the factory.

3.1. CATL, Debrecen, Hungary

Contemporary Amperex Technology Co., Limited, Ningde, China (CATL), the world's largest battery manufacturer, is building its largest European battery factory in Debrecen, our university city. The investment has been announced as a factory complex with a capacity of 100 GWh, and the first plant, currently under construction, scheduled to start production in 2025 with a capacity of 40 GWh per year. CATL's Debrecen plant will produce lithium nickel manganese cobalt oxide (NMC) cells, which is the most widely used cathode chemistry today. Rising cobalt prices and the environmental and ethical concerns associated with cobalt are leading to a shift towards chemistries with higher nickel and lower-cobalt ratios [23]. Accordingly, NMC811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$), the state of the art chemistry today will be used in the new CATL's factory. The following data, estimates and calculations have been made on the basis of the publicly available Uniform Environmental Permit issued in 2024 and written in Hungarian [16].

3.1.1. Energy Use

The energy demand of battery manufacturing was calculated from the projected annual natural gas and electricity consumption of 90,000,000 m^3 and 533 GWh, respectively. These figures include not only the consumption directly required for the manufacturing technology, but also consumption for social purposes (e.g., heating offices), giving a more complete picture of the factory's environmental impact. The average calorific value of the natural gas distributed in Hungary, which is used in our calculations, is 34 MJ m^{-3} (9.44 kWh m^{-3}). The sum of the two types of energy gives 34.6 kWh/kWh_{prod} of energy demand for battery production.

3.1.2. Greenhouse Gas (GHG) Emissions

We assessed both the local and global GHG emissions of the factory. At the gate-to-gate boundary, the majority of the emissions from battery production are associated with the energy demand of manufacturing. The carbon dioxide equivalent (CO_{2eq}) of the GHG emissions was calculated using Equation (1) and (2) for the local and global scope, respectively.

$$CO_{2eq,local} = E_{gas} \times \varepsilon_{gas,local} + CO_{2eq,loc\_traffic} \quad (1)$$

$$CO_{2eq,global} = E_{gas} \times \varepsilon_{gas,global} + E_{elect} \times \varepsilon_{elect} + CO_{2eq,glob\_traffic} \quad (2)$$

where E_{gas} is the energy from the combustion of natural gas, E_{elect} is the electricity consumed (both in kWh), $\varepsilon_{gas,local}$ = 0.202 $kgCO_{2eq}/kWh$ is the IPCC (Intergovernmental Panel on Climate Change) standard default emission factor for natural gas for stationary combustion [20], $\varepsilon_{gas,global}$ = 0.240 $kgCO_{2eq}/kWh$ is the CoM (Covenant of Mayors) LCA default emission factor, calculated by adding supply chain emissions (e.g., methane leakage) to the standard emission factor [21], ε_{elect} is the emission factor of electricity, and $CO_{2eq,loc\_traffic}$ and $CO_{2eq,glob\_traffic}$ are the CO_2 emissions of the local and global traffic generated by the battery factory. The emission factor of electricity depends on the carbon intensity of the regionally-available electricity supply mix. For 2023, ε_{elect} = 0.3226 $kgCO_{2eq}/kWh$ was provided by the Hungarian electricity supplier MVM Next Energy Trading Ltd. [22]. The increase in traffic due to the operation of the factory was estimated in the Uniform Environmental Permit at 1291 cars/day and 350 trucks/day [16]. $CO_{2eq,loc\_traffic}$ was calculated over 330 working days using estimates of 1000 gCO_{2eq}/km and 200 gCO_{2eq}/km for trucks and cars, respectively, and multiplying by an average distance of 50 km. The local GHG emissions for the three factories studied are illustrated in Figure 1. For $CO_{2eq,glob\_traffic}$, the average distance travelled by trucks was estimated to be 500 km. For the local GHG emissions $CO_{2eq,local}$ = 181,655 $tCO_{2eq}/year$, corresponding to 4.54 $kgCO_{2eq}/kWh_{prod}$, was obtained. CATL is committed to achieving carbon neutrality in its core operations by 2025 and across the battery value chain by 2035, as announced at the 20th Shanghai International Automotive Industry Exhibition on 18 April 2023 [24]. For the global GHG emission $CO_{2eq,global}$ = 437,860 tCO_{2eq}/year corresponding to 10.95 $kgCO_{2eq}/kWh_{prod}$, was calculated. The calculation schemes for local and global GHG emissions of the CATL plant in Debrecen, Hungary are shown in Figure S1a and Figure S1b, respectively, in Supplementary_Information.

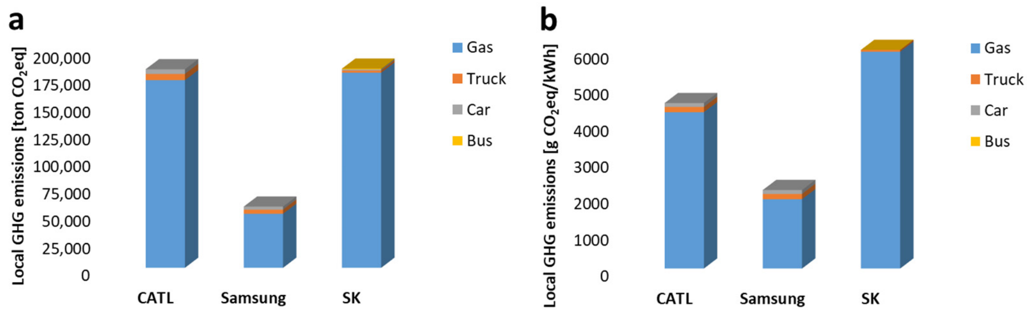

Figure 1. Local greenhouse gas (GHG) emissions of three Li-ion battery factories in Hungary, (CATL in Debrecen, Samsung SDI in Göd, and SK Innovation in Iváncsa): (**a**) in total, and (**b**) specific per kWh battery production.

3.1.3. Water Consumption

In addition to energy use and GHG emissions, the water consumption associated with battery production can be significant, but is often overlooked in LCA's [25]. The Available Water Remaining (AWARE) method recommended by the Water Use in LCA (WULCA) working group was used to calculate the water scarcity footprint (WSF) of the battery factories [26]. AWARE is based on quantifying the relative amount of water available per area once the needs of humans and aquatic ecosystems have been met. The resulting characterization factor (CF) ranges between 0.1 and 100 and can be used to calculate WSF as WSF = Water consumption × CF. For example, Andalusia, in Spain, and County Leitrim, in Ireland, have CF values of 55 and 0.43, respectively, indicating the amount of water available. The AWARE factor for Hungary is very favorable, i.e., rather low, with a CF of 1.164 [26]. CATL has accurately reported its water use, which can also be an important and useful source of data for the scientific community. The average water consumption is estimated to be 3378 m^3/day, resulting in the specific water consumption of 27.9 L/kWh_{prod} and WSF of 32.4 L/kWh_{prod} (calculated over 330 working days).

3.2. Samsung SDI, Göd, Hungary

In Göd, near Budapest, Hungary's first battery factory has been in production since 2018. The plant's publicly available Uniform Environmental Permit does not explicitly disclose its production capacity in GWh/year, but only in tons/year [17]. Using the average energy density of the Li-ion batteries (200 Wh/kg), the annual capacity of 130,900 tons in 2023 gives a production of 26 GWh/year, which is close to the value estimated by S&P Global (29 GWh/year) [27]. The plant currently produces lithium-ion battery cells using two different chemistries, mainly NMC and to a lesser extent NCA (lithium nickel cobalt aluminum oxide).

3.2.1. Energy Use

The energy use of the factory was determined based on the publicly available Annual energy report submitted to the Hungarian Energy and Public Utility Regulatory Authority [18]. The report provides the composition of the energy used by the plant (the ratio of natural gas to electricity) and the total CO_2 emissions of the energy used. By solving a simple linear equation, as detailed in the Supplementary Information Battery factories impact, Samsung_energy sheet, the total annual energy consumption of the factory was determined to be 741.66 GWh, while the annual natural gas and electricity consumption were calculated to be approximately 26,000,000 m^3 and 497 GWh, respectively. At a capacity of 26 GWh/year, the energy required for battery production is 28.3 kWh/kWh_{prod}.

3.2.2. Greenhouse Gas (GHG) Emissions

The traffic generated by the factory has not been disclosed, but has been estimated on the basis of data provided by CATL in proportion to the capacity of the two plants. Using equation 1 and 2 and the method described below them, we have estimated the local and global emissions. Due to the lower ratio of natural gas consumption, the total local GHG emissions are lower than those of CATL, but the total global GHG emissions of 9.92 kg/kWh_{prod} are very close to those of CATL (10.95 kg/kWh_{prod}).

3.2.3. Water Consumption

The Samsung factory in Göd is located next to the Danube. This plant also accurately reported its annual water withdrawals, which were 1,458,927 m^3 in 2022. This corresponds to a specific water consumption of 55.7 L per kWh and a WSF of 64.9 L per kWh.

3.3. SK Innovation, Iváncsa, Hungary

South Korea's SK Innovation has built a 30 GWh battery plant south of Budapest alongside the Danube producing NMC811 LIBs, which—although it has not been officially announced—started operations this year (2024). The environmental impact of the factory can also be calculated or estimated on the basis of the publicly available Uniform Environmental Permit reported in 2023 [19].

3.3.1. Energy Use

We have not found data on the electricity consumption of the factory, so we only report the consumption of natural gas, around 93,600,000 m^3 per year, which is used to generate heat. The combustion of natural gas as an energy source alone results in 29.4 kWh/kWhprod of energy required for battery production. The actual energy demand is higher, of course, because of the electricity consumption.

3.3.2. Greenhouse Gas (GHG) Emissions

The factory reported an estimation of the traffic increase; therefore, the local GHG emissions can be calculated using equation 1, giving $CO_{2eq,local}$ = 182,162 tCO_{2eq}/year for the local GHG emissions, equivalent to 6.07 $kgCO_{2eq}/kWh_{prod}$ (The bus emissions were calculated using 600 gCO_{2eq}/km). Of course, natural gas combustion (178,466 tCO_{2eq}/year) accounts for the majority of local emissions.

3.3.3. Water Consumption

The total water consumption (including social) is reported in the Uniform Environmental Permit as 5200–6982 m^3/day. This corresponds to an average specific water consumption of 67.0 L per kWh and a WSF of 78.0 L per kWh.

3.4. N-Methyl-2-Pyrrolidone (NMP) Consumption

N-methyl-2-pyrrolidone (NMP) is the most commonly used solvent for cathode slurry preparation. Although NMP does not contribute significantly to any of the common impact and emission categories, the environmental, health and safety reasons associated with it make the estimation of the consumed NMP important [28]. In addition, the specific NMP requirement for LIB production is important for the development of LCI data and LCA studies. After the production of electrode materials, the used NMP is recovered and recycled, both for cost efficiency and to protect the environment by reducing waste. As shown in Table 1, there is a large difference between CATL's annual NMP consumption and that of the other two plants. This is because CATL plans to recover NMP within the factory, while the Samsung and SK Innovation plants use an external company. As seen in Table 1, approximately 0.5 kg NMP is used for producing 1 kWh of cell capacity.

4. Comparison with Previous Studies

It is important to compare our results, which are based on reported and publicly available data, with those of previous publications. Publication date (2019 or newer) and system boundary (gate-to-gate) were the two main filtering criteria used to select the papers for comparison. Together with our results, Table 2 summarizes the environmental data of the selected publications. Kurland's method is the closest to ours [14], however, in contrast to our more comprehensive study, he only estimated the energy consumption of two battery factories. Sun et al. used their own primary data in the LCA study, but lacked transparency regarding the production process and energy mix in China [29]. Dai et al. collected primary industrial data from LIB manufacturers and analyzed the energy use, GHG emissions, and water consumption (among others) with the battery LCA module in the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model [28,30]. Degen et al. determined the energy consumption and associated GHG emissions for each step in the production process and for the process as a whole based on energy consumption data collected from several manufacturers during the design and construction of a research factory in Germany [10]. A cell manufacturing model has been developed by Jinasena et al. to calculate energy and material demands for different battery types, plant capacities, and process steps [31]. In their recent study, Knehr et al. analyzed energy consumption in LIB manufacturing plants using material throughput and equipment specification information at each step of the manufacturing process [32]. An inventory of battery production phases based on data from laboratory disassemble tests has been built by Chen et al., and the energy consumption was measured according to the actual situation of the factory production line, including the consumption of electricity and natural gas [33]. For the sake of interest, we also estimated the specific energy and water consumption using the open-access GREET Battery Module 2023 model [30].

Table 2. Reported environmental impacts of battery factories.

Study	Method	Plant Size GWh/Year	Chemistry	Energy Use kWh/kWh_{prod}	GHG Emissions $kgCO_{2eq}/kWh_{prod}$	Water Use L/kWh_{prod}
Kurland (2020)	Industry report	8		50		
Kurland (2020)	Public data	35		65		
Sun et al. (2020)	Industry data	30	NMC622	30.6	19.01	33.9 *
Dai et al. (2019)	Industry data	2	NMC111	47.2	13.85	55.5
Degen et al. (2022)	Process model	7	NMC622	41.5	10.33	
Jinasena et al. (2021)	Process model	2	NMC333	44.6		
Knehr et al. (2024)	Process model	25	NMC83	40.6 **		
Chen et al. (2022)	Industry data		NMC811		28.11	
This paper, CATL	Industry report	40	NMC811	34.6	10.95	27.9
This paper, Samsung	Industry report	26	NMC #	28.3	9.91	55.7
This paper, SK	Industry report	30	NMC811	29.4 ##		67
This paper, GREET	Process model		NMC811	58.6		52.6

* Used in the electrode material mixing process. ** Production volume 25 GWh/year. # NMC and to a lesser extent NCA. ## Calculation from natural gas consumption only.

As seen in Table 2, the calculations using different methods and battery chemistries give similar results especially for energy and water use. Interestingly, for both energy and water consumption, their relative standard deviations (RSD) are 28%. For GHG emission, the RSD is roughly doubled. This can be explained by differences in the carbon intensity of the electricity mix across countries. As shown in Table 1, approximately 0.5 kg of NMP is used to produce 1 kWh of cell capacity. It is significantly lower than the 4.1 kg/kWh specific NMP use published by Ahmed et al. [34].

5. Conclusions

In this study, based on publicly available data disclosed under Hungarian government regulations and official decrees, we calculated and report on the main environmental impacts of three battery factories in Hungary, with a total annual capacity of approximately 100 GWh. The data on energy and water consumption and GHG emissions from state-of-the-art battery cell production will support strategic decision-making by industrial policy makers and stakeholders in the battery industry. Assessing environmental impact is important not only from a global perspective, but also for the local community. Therefore, as a new approach, we estimated the local GHG emissions and the local water scarcity impacts of the factories. The main local emissions were found to be from the combustion of natural gas, but the growth in local transport is also a source of emissions. The main limitation of the study is that the data of the CATL 'factory are based on future estimations disclosed by the factory itself, because the plant is currently under construction and scheduled to start production in 2025. The same is true for the SK Innovation plant that started operations this year (2024). This can be remedied by monitoring the environmental impacts of factories once they have started production. The objectives of our research have been almost fully achieved, with all major impact categories characterized except electricity use in the SK Innovation factory. To sum up, the environmental impacts (specific energy consumption, greenhouse gas emissions, water consumption) of the factories we studied are slightly below or very close to the values reported in previous studies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments12010024/s1. Supplementary_Information.docx, Battery factories impact.xlsx, Energy_water_gas_emissions.xlsx.

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