Received: 13 July 2018 | Revised: 4 October 2018 | Accepted: 15 October 2018
DOI: 10.1002/pip.3089

EU PVSEC PAPER

WILEY PROGRESS IN PHOTOVOLTAICS

Life cycle assessment of PV-battery systems for a cloakroom and club building in Zurich

Philippe Stolz[1] | Rolf Frischknecht[1] | Thomas Kessler[2] | Yvonne Züger[2]

[1] treeze Ltd., Kanzleistrasse 4, 8610 Uster, Switzerland

[2] City of Zurich, Switzerland

Correspondence
Philippe Stolz, treeze Ltd., Kanzleistrasse 4, 8610 Uster, Switzerland.
Email: stolz@treeze.ch

Funding information
Office for Building Engineering of the City of Zurich

Abstract

The Office for Building Engineering of the City of Zurich plans the construction of a cloakroom and club building. The building and the floodlights of the surrounding soccer fields use electricity mainly in the evening. That is why the installation of a photovoltaic (PV) system in combination with a battery storage system is evaluated in the pre-project phase. The environmental footprint of the PV system with multicrystalline silicon modules and of current, future, and second-life lithium-ion batteries is quantified within the life cycle assessment of the building. The self-consumption share of PV electricity increases from 31% to 62% if a 60 kWp PV system is complemented by a 100 kWh battery storage. The complementary grid electricity mix strongly influences the environmental impacts of electricity consumed by the cloakroom and club building. The installation of a PV system and a battery storage leads to a 10% to 17% reduction in greenhouse gas emissions compared with the full coverage of the electricity demand by the average Swiss supply mix. The addition of a current battery system does not yield any further reduction compared with the "PV only" option. With the renewable electricity mix of the City of Zurich, the installation of a PV system and a battery storage leads to higher environmental impacts of the electricity consumed by the cloakroom and club building, irrespective of the type of battery used. A future increase in energy density, production optimisations, and second-life batteries bear a significant potential to reduce the environmental impacts of battery storage systems.

KEYWORDS

battery, building, life cycle assessment, lithium-ion, photovoltaics, self-consumption

1 | INTRODUCTION

The City of Zurich has committed itself to develop towards the 2′000-Watt Society.[1] This vision is based on the premise that the limited worldwide energy resources should be fairly allocated among countries and generations and used in a way that environmental impacts are minimized.[2] To achieve the goals of the 2′000-Watt Society, the City of Zurich strives to reduce the primary energy demand related to energy purposes such as heating, hot water, electricity, and fuels from 3′900 watt per capita (average 2012-2016[3]) to 2′000 watt per capita. In addition, a reduction of the per capita greenhouse gas emissions from an average 4.7 ton CO_2-equivalent (t CO_2-eq) between 2012 and 2016[4] to 1.0 t CO_2-eq per capita in 2050 is pursued. The measures to realise the targeted reduction pathways include, among others, the promotion of energy efficiency and the increased use of renewable energy.[5]

Photovoltaic (PV) systems have one of the highest potentials among renewable electricity generation technologies in Switzerland.[6] The cumulative installed PV capacity has more than doubled between 2013 and 2016.[7] The vast majority of PV systems in Switzerland is decentralised and either mounted on or integrated in buildings.[8] Buildings with PV systems are increasingly equipped with a battery storage system for various reasons. Batteries may be used to increase the share of self-consumed PV electricity and can contribute to the integration of additional PV electricity into the grid by shaving production peaks. Furthermore, a battery storage system can be used as a backup in case of blackouts and may prevent the need for enlarging the connection for power supply.[9]

The combination of a PV system with a battery storage results in an increase of the environmental impacts of building construction. A detailed understanding of the environmental impacts of currently available battery systems is therefore an important prerequisite for the design of buildings with low environmental impacts over their entire life cycle. The rapid development in battery research and in battery applications raises the question as to how the environmental impacts may change in the future. Potential future optimisations in battery manufacturing and the repurposing of traction batteries used in electric vehicles are therefore also taken into consideration in the evaluation of the environmental footprint of batteries used in stationary storage systems.

This study aims to analyse the life cycle environmental impacts of a PV system in combination with a battery storage system using the specific case of a cloakroom and club building that is currently planned by the Office for Building Engineering of the City of Zurich. In the pre-project phase, the installation of a roof-integrated PV system and a battery storage system is evaluated.[10] A battery storage system helps to increase the share of self-consumed PV electricity since the building and the floodlights of the surrounding soccer fields use electricity mainly in the evening. Three types of battery systems are investigated: current lithium-ion (Li-ion) batteries, repurposed (second-life) Li-ion batteries previously used in electric vehicles, and future Li-ion batteries with an increased energy density and environmentally optimized production. The environmental impacts of the PV system and the battery storage systems are quantified by means of life cycle assessment (LCA). The main components and processes contributing to the environmental impacts are identified. The results are then used to calculate the average environmental impacts of the electricity supplied to the cloakroom and club building depending on the presence of a battery storage system and the battery type.

2 | METHODOLOGY AND SCOPE

2.1 | PV system

The functional unit of the LCA of the manufacture and disposal of the PV system is 1 kWp maximum power output. The LCA of the PV system comprises the manufacture of the PV modules, the slanted-roof construction, the electric installation, and the inverter. The planned PV system is integrated in the roof of the cloakroom and club building. Since the LCA of the PV system is done as part of a building LCA (not shown in this paper), an allocation of the environmental impacts of the PV system to the functions of electricity generation and weather protection is not needed; 100% of the environmental impacts of the PV system are attributed to electricity in the assessments presented in this paper.

2.2 | Battery storage systems

The functional unit of the LCA of the manufacture and disposal of the battery systems is 1 kWh storage capacity. In the LCA of battery storage systems, the manufacture or repurposing (in case of second-life batteries) of Li-ion batteries including the production of the battery management system, the cooling system, the battery cells, and the packaging is taken into account. The manufacture of electronics for battery control, the wiring, and the system housing are also included.

2.3 | Electricity consumption

The electricity consumed by the cloakroom and club building is assessed using the functional unit of 1 year of electricity consumption. The annual electricity demand may be covered from the grid, the PV system, and the battery system. According to the technical bulletin SIA 2040 of the Swiss Society of Architects and Engineers that sets the rules for building LCAs, the environmental impacts of PV electricity supplied to the grid are subtracted from the impacts of the construction of the PV system using the same environmental intensity.[11] This means that the environmental impacts of the PV system are only accounted for to the degree the PV electricity is self-consumed. The environmental impacts of the battery storage system are fully allocated to the building based on the assumption that the battery is used only by the building itself and does not provide any services to the grid. The analysis in this paper is limited to the electricity consumption of the cloakroom and club building and does not include other parts of building LCAs such as construction, heating energy, and induced mobility.

2.4 | Background data and indicators

The life cycle inventories (LCIs) of the PV system and the battery systems are linked to KBOB life cycle inventory data DQRv2:2016,[12] which is an extensively updated version of ecoinvent data v2.2.[13] The life cycle impact assessment results are shown using the indicator greenhouse gas emissions.[14] The indicators cumulative energy demand[15] and total environmental impacts according to the Swiss ecological scarcity method 2013[16] were also analysed but are not shown here. In general, the results are similar for the three indicators analysed.[17] The analyses were carried out using SimaPro v8.4.0.[18]

3 | LIFE CYCLE INVENTORIES

3.1 | PV system

The planned PV system of the cloakroom and club building is integrated in the roof and has a maximum power output of 60 kWp. It consists of 230 multi-crystalline silicon (multi-Si) framed PV modules with a maximum power output of 161 Wp/m^2.[10] In accordance with the draft Product Environmental Footprint Category Rules for PV Electricity[19] it is assumed that 1% of the modules supplied is rejected and that 2% of the PV modules are defective during the time of operation. The replacement of these modules is accounted for. Generic LCIs are used to model the inverter, the electric installation, and the integrated slanted-roof construction.[20] It is assumed that the life time of the PV system is 25 years and that the inverter is replaced once within this time. The annual yield of the PV modules at the location of the cloakroom and club building is 950 kWh/kW$_p$, including degradation.[10]

3.2 | Battery storage systems

3.2.1 | Current Li-ion batteries

The LCIs of battery storage systems are compiled based on information reported in literature and obtained in expert interviews. Li-ion batteries are characterised by a high energy density, a high efficiency, and a long life time[9] and are frequently used for mobile and stationary applications. There is a variety of Li-ion batteries with the chemical composition of the cathode as the main difference. Changes in the cathode composition are used to influence important features such as the energy and power density, the life time, the operational safety, and the costs.[21,22] Li-ion batteries for stationary applications often have a lithium iron-phosphate ($FePO_4$) cathode, which ensures a long life time and high operational safety.[23]

Very detailed and transparent LCI data of battery production were reported in Ellingsen et al,[24] which are based on primary data from a Norwegian manufacturer of Li-ion batteries with a lithium nickel-cobalt-manganese oxide (NCM) cathode. Due to their high energy density, these batteries are frequently used in electric vehicles. The LCIs based on Ellingsen et al[24] and published in Stolz et al[25] are used for the storage system with current Li-ion batteries since primary data on the production of $LiFePO_4$ batteries were not available. A previous study also revealed that the contribution of the cathode to the total environmental impacts of Li-ion batteries is small.[26]

The analysed LiNCM battery weighs 253 kg and has a storage capacity of 26.6 kWh, which yields an energy density of 105 Wh/kg.[24] The battery cells contribute 60% to the total battery weight and are composed of a $Li(Ni_{0.33}Co_{0.33}Mn_{0.33})O_2$ cathode and an anode based on graphite. The separator is made of a porous polyolefin film, and lithium-hexafluorophosphate is used for the electrolyte. Battery cell production is very energy-intensive with an electricity demand of 22.7 kWh/kg. This electricity is supplied by an Eastern Asian mix since battery cells are mainly produced in that region.[24,25] Besides the battery cells, the LiNCM battery also requires a battery management system, a battery cooling system, and packaging.[24] For Li-ion batteries used in stationary storage systems, the batteries are packed in a housing made of steel, connected to each other with cables and equipped with a control unit.[26]

The storage capacity of Li-ion batteries continually decreases with use and ageing. The life time of Li-ion batteries is uncertain, which is partly due to its dependence on temperature and the depth of discharge. For current batteries, the life time is assumed to be 15 years or 5′000 charging cycles.[9,22,27]

3.2.2 | Future Li-ion batteries

The LCI of the future battery system is based on the LCI of current battery systems[24,25] and modified in relevant aspects. Future Li-ion batteries are projected to reach an energy density, which is approximately twice as high compared with today's batteries.[9,21,22,28] This increase is taken into account by assuming an energy density of future Li-ion batteries of 210 Wh/kg. There is also intensive research on new materials to be used in electrodes and electrolytes.[29] For instance, the graphite-based anodes are expected to be increasingly blended with silicon in order to enhance the capacity, and some of the cobalt and manganese contained in the cathode is expected to be replaced by nickel (shift from $Ni_{0.33}Co_{0.33}Mn_{0.33}$ to $Ni_{0.6}Co_{0.2}Mn_{0.2}$ or $Ni_{0.8}Co_{0.1}Mn_{0.1}$).[22,30] However, LCIs for the future development of these components are not available, and a preliminary analysis of current batteries revealed a minor contribution of the anode, the cathode, and the electrolyte to the environmental impacts. These potential changes in materials are therefore neglected in the LCA of future Li-ion battery storage systems.

Instead, it is assumed that battery manufacturers will focus on the most important materials and processes in order to reduce the environmental impacts of future Li-ion batteries. The electricity demand of battery cell production and the copper used in the anode were found to be particularly relevant for the environmental footprint of the battery. Production optimisations in these areas are taken into account in the LCIs of future Li-ion batteries manufactured by environmentally conscious companies. A reduction in the electricity demand of future battery cell production to 15.0 kWh/kg was reported to be achievable in the medium term.[28] It is assumed that this electricity demand will be covered by large-scale open ground PV systems with multi-Si modules. The improvement of the module conversion efficiency is approximated by a PV installation located in Spain, where the annual yield is about 20% higher compared with the location of important Asian battery producers.[31] For the production of anodes used in future Li-ion batteries, it is assumed that only secondary copper is used, which causes significantly lower environmental impacts compared with the production mix of primary copper. The housing, cabling, and electronics required for stationary storage systems with future Li-ion batteries decrease as the energy intensity of the batteries increases. The demand of these components is therefore reduced by a factor of two.

The life time of future Li-ion batteries is projected at approximately 10′000 charging cycles or up to 25 years.[9,27,32] In the present study, a life time of 20 years is assumed for storage systems with future Li-ion batteries.

3.2.3 | Second-life Li-ion batteries

Stationary storage systems with repurposed Li-ion batteries are an alternative to the recycling of the materials in used traction batteries. Electric vehicles usually have stronger requirements regarding the energy density, so batteries are changed when they reach about 70% to 80% of the initial capacity. Some of these batteries may be suited for a second use in stationary storage systems. However, there are several logistic, technical, and economic challenges of sorting and repurposing used batteries.[33-35] An ongoing pilot project tried to overcome these difficulties by only using batteries that were previously used in electric scooters of the Swiss Post.[36] Primary data from this project are used to compile an LCI of second-life Li-ion batteries.

The effort of sorting the used batteries from electric scooters is negligible since only one type of batteries is collected. Each battery is equipped with a newly developed electronic print, which allows the individual management of each battery cell. The possibility to bypass cells that are defective or have a low storage capacity substantially facilitates the testing of the used batteries.[36] After their first use in electric scooters, the batteries retain an economic value. The production efforts of Li-ion batteries therefore need to be allocated to the two use phases, which is done according to their economic value based on current prices. According to this allocation key, the second use of the Li-ion batteries in stationary storage systems bears one seventh of the environmental impacts of the initial battery production. The price paid for the used batteries from electric scooters may significantly change in the future, which would affect the share of environmental impacts of battery production to be allocated to the second use. The battery production is modelled using the LCIs of current Li-ion batteries.[24,25]

The energy density of the second-life battery system is 84 Wh/kg (approximately 80% of the capacity of new batteries[33-35]). Performance tests of the second-life Li-ion batteries developed in the pilot project[36] are being carried out, but results were not available to the time this study was carried out. It is assumed that the stationary storage system with second-life Li-ion batteries is operated for 10 years.

3.3 | Electricity consumption of the cloakroom and club building

Different options are considered in the LCA of the yearly electricity consumption of the cloakroom and club building: (1) grid supply only (no PV system and no battery storage); (2) 60 kWp PV system without battery storage; and (3) 60 kWp PV system and 100 kWh battery storage. The last option is further divided into three alternatives: (3a) current Li-ion battery; (3b) future Li-ion battery; and (3c) second-life Li-ion battery. The projected electricity demand of the planned cloakroom and club building is 106 MWh/a. The consumption profile exhibits a distinctive evening peak, which is mainly caused by the electricity demand of the floodlights used for the surrounding soccer fields (see Figure 1).

The annual electricity demand of the planned building is covered from the grid, the PV system (options 2 and 3), and the battery system (option 3). The self-consumption share of PV electricity in option 2 is estimated at 31%, and the self-sufficiency share is 18%. The self-consumption share and the self-sufficiency share increase to 62% and 35%, respectively, if the 60 kWp PV system is complemented by a 100 kWh battery storage (option 3). Hence, even with a battery storage system, almost two thirds of the yearly electricity demand are covered by the grid. The grid electricity is modelled using two different mixes, namely the Swiss supply mix and the renewable electricity mix of the Zurich City Administration.

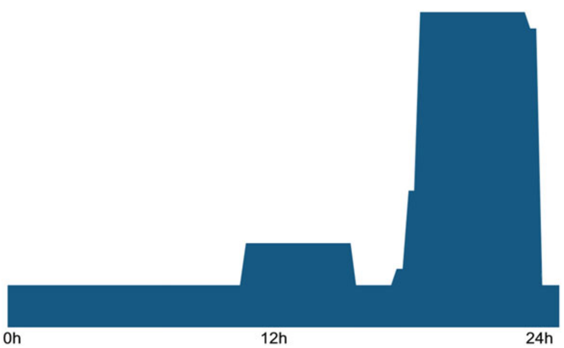

FIGURE 1 Forecast electricity consumption profile during a typical day of the cloakroom and club building that is currently planned by the City of Zurich [Colour figure can be viewed at wileyonlinelibrary.com]

4 | RESULTS AND DISCUSSION

4.1 | PV system

The greenhouse gas emissions of the PV system planned for the cloakroom and club building are shown in Figure 2 and compared with a similar roof-integrated PV system with multi-Si modules based on a generic LCI of KBOB life cycle inventory data DQRv2:2016.[12] The results are normalised to the functional unit of 1 kWp maximum power output. The difference in the greenhouse gas emissions of the two PV systems is very small, which is mainly due to the use of generic LCI data and default assumptions for the PV system of the planned cloakroom and club building. The multi-Si PV modules foreseen for this building have a higher conversion efficiency (16.1%) compared with the assumed efficiency in the LCI of multi-Si PV modules in KBOB life cycle inventory data DQRv2:2016 (14.7%).[12,37] However, the lower environmental impacts due to the higher module conversion efficiency are largely compensated by the aluminium frame that is foreseen for the modules of the cloakroom and club building but not included in the generic LCI.

The supply of the PV modules contributes approximately 79% to the total greenhouse gas emissions of the planned PV system of the cloakroom and club building. The shares of the roof-integrated substructure, the inverter, and the electric installation are 9%, 8%, and 3%, respectively. The greenhouse gas emissions caused by the transport of the PV modules and the BOS component and by the construction of the PV system are negligible.

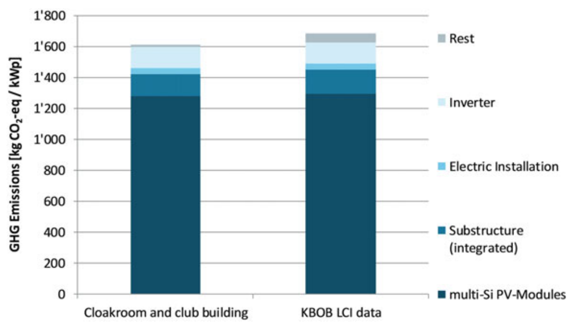

FIGURE 2 Greenhouse gas emissions in kg CO_2-eq/kWp of the roof-integrated PV system with multi-crystalline silicon modules for the planned cloakroom and club building. The greenhouse gas emissions of a similar PV system using a generic dataset from the KBOB life cycle inventory data DQRv2:2016 are shown for comparison. The contributions of the most important components are shown separately [Colour figure can be viewed at wileyonlinelibrary.com]

4.2 | Battery storage systems

The greenhouse gas emissions of battery systems with current, future, and second-life Li-ion batteries per kWh storage capacity are depicted in Figure 3. The contributions of the most relevant materials and processes are shown separately. The greenhouse gas emissions of the storage system with current LiNCM batteries (185 kgCO_2-eq/kWh) are significantly higher than the greenhouse gas emissions of storage systems with future and second-life LiNCM batteries (49.4 kgCO_2-eq/kWh and 80.6 kgCO_2-eq/kWh, respectively).

The manufacture of the Li-ion batteries contributes 79% to the greenhouse gas emissions of current battery storage systems. The electricity demand of Li-ion battery cell production (48%) is by far the most relevant process for the greenhouse gas emission of current battery systems, followed by the cathode (9%) and the anode (5%). The remaining processes and components of current Li-ion battery manufacturing include for instance the battery cooling system, the packaging, and the electricity demand of battery assembly. The housing, electronics, and cabling used for the stationary storage system and the transport of the battery system to the place of installation contribute 21% to the total greenhouse gas emissions of battery systems with current LiNCM batteries.

A review of previous LCA studies of current Li-ion traction batteries was recently published in Ellingsen et al.[38] It was found that the greenhouse gas emissions of battery production greatly vary between the analysed studies and that the most important sources of difference are the energy demand of cell manufacture and pack assembly as well as the input of cell materials and other battery components. The electrode materials (eg, lithium nickel-cobalt-manganese oxide [NCM] cathode or lithium iron phosphate [$FePO_4$] cathode) have a lower influence on the greenhouse gas emissions of battery production.[38] The greenhouse gas emissions of the storage system with current LiNCM batteries modelled in this study amount to 185 kgCO_2-eq/kWh and are therefore about in the middle of the range of previous publications, which spans from 38 to 356 kgCO_2-eq/kWh.[38] Only one study was found that quantified the environmental impacts of a stationary battery storage system used in a hybrid power plant consisting of a wind park, a PV system, and several diesel generators.[39] The greenhouse gas emissions of the production of the analysed battery with a lithium nickel cobalt oxide cathode and a lithium titanate anode amount to approximately 290 kgCO_2-eq/kWh and are therefore significantly higher compared with the present study. The different LCI of battery production results in higher contributions of the cathode, the anode, and other components. In contrast, the greenhouse gas emissions caused by the electricity demand of cell production are of minor importance.[39]

Future Li-ion batteries are assumed to have an energy density, which is twice as high compared with current Li-ion batteries. In addition, process optimisations in the electricity demand of battery cell production, the electricity mix, and in the supply of copper for the anode are taken into account. The magnitude of the change in greenhouse gas emissions due to the higher energy density and the process optimisations is similar. The share of future LiNCM battery production in the total greenhouse gas emissions amounts to 60%, whereby the cathode (17%), the anode (9%), and the remaining battery components including assembly (20%) are particularly relevant. The electricity demand of future battery cell production contributes 3% to the total greenhouse gas emissions of the battery storage system analysed. The housing, electronics, cabling, and transport cause about 40% of the greenhouse gas emissions of storage systems with future LiNCM batteries.

In a previous study, the greenhouse gas emissions caused by future LiNCM battery production were estimated at 60 kgCO_2-eq/kWh.[28] The LCI of future LiNCM battery production presented in Section 3.2.2 is partly based on Cox and Bauer,[28] in particular regarding the improvement in energy density and the electricity consumption of future cell production. The difference in greenhouse gas emissions between this and the previous study is mainly due to our assumption that the electricity used in the production of future battery cells is generated by large-scale PV systems rather than being supplied by the Eastern Asian electricity mix.

The greenhouse gas emissions of the storage system with repurposed Li-ion batteries are approximately 56% lower than the emissions of the current battery system. The main reason for this difference is that the reused batteries in a stationary storage system bear only one seventh of the environmental impacts of battery manufacturing based on the economic allocation using current prices. The share of battery manufacturing in the total greenhouse gas emissions of storage systems with second-life Li-ion batteries is 32%. The printed wiring board and the energy required for repurposing of used batteries contribute 19% to the greenhouse gas emissions. The remaining 49% of the total greenhouse gas emissions of storage systems with repurposed LiNCM batteries are caused by the housing, electronics, cabling, and transport.

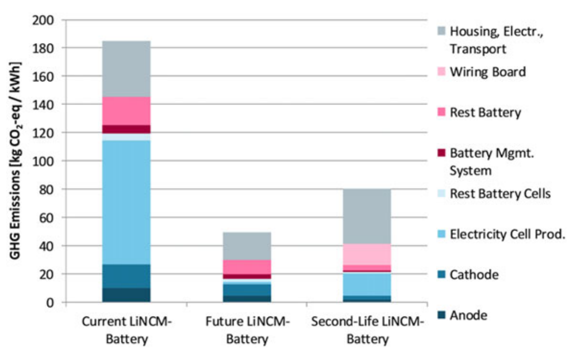

FIGURE 3 Greenhouse gas emissions in kg CO_2-eq/kWh of storage systems with current, future, and second-life lithium-ion batteries with a nickel-cobalt-manganese (NCM) cathode. The contributions of the most important components and processes are shown separately [Colour figure can be viewed at wileyonlinelibrary.com]

4.3 | Electricity consumption of the cloakroom and club building

The greenhouse gas emissions of the different options to cover the yearly electricity demand of the planned cloakroom and club building are shown in Figures 4 and 5. It becomes evident that the results strongly depend on the grid electricity mix used to model the share of electricity demand not supplied by the PV system and the battery storage system.

With the Swiss electricity supply mix, the difference in greenhouse gas emissions of the five options to cover the electricity

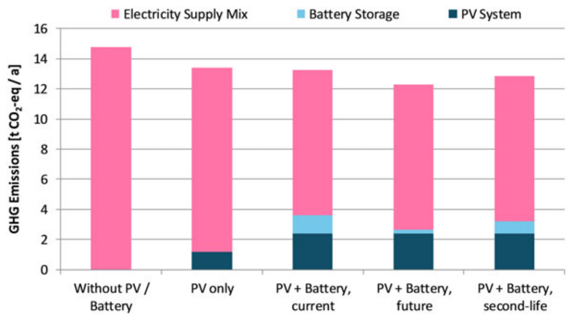

FIGURE 4 Greenhouse gas emissions in t CO_2-eq/a of the electricity consumed by the planned cloakroom and club building for the options without PV system and without battery system, with a 60 kWp PV system only (self-consumption share: 31%, self-sufficiency share: 18%) and with a 60 kWp PV system and 100 kWh storage systems using different types of lithium-ion batteries (self-consumption share: 62%, self-sufficiency share: 35%). The electricity supplied from the grid is modelled with the **Swiss supply mix**. The total electricity consumption is projected at 106 MWh/a [Colour figure can be viewed at wileyonlinelibrary.com]

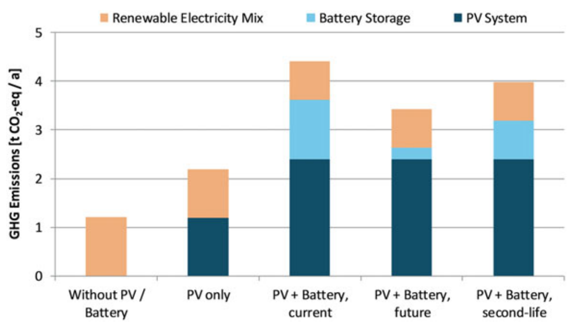

FIGURE 5 Greenhouse gas emissions in t CO_2-eq/a of the electricity consumed by the planned cloakroom and club building for the options without PV system and without battery system, with a 60 kWp PV system only (self-consumption share: 31%, self-sufficiency share: 18%) and with a 60 kWp PV system and 100 kWh storage systems using different types of lithium-ion batteries (self-consumption share: 62%, self-sufficiency share: 35%). The electricity supplied from the grid is modelled with the **renewable electricity mix** used by the Zurich City Administration (ewz Ökopower). The total electricity consumption is projected at 106 MWh/a [Colour figure can be viewed at wileyonlinelibrary.com]

demand of the cloakroom and club building is small (Figure 4). The greenhouse gas emissions amount to 14.8 tCO_2-eq/a if the electricity demand is completely covered by the average Swiss supply mix. These emissions are reduced by about 10% to 13.4 tCO_2-eq/a if a 60 kWp PV system is installed on the planned cloakroom and club building. In this case, 31% of the electricity generated by the PV system are self-consumed by the cloakroom and club building. The electricity demand in this option is covered by 18% PV electricity (self-sufficiency share) and 82% grid electricity. The reduction in greenhouse gas emissions occurs because the emission intensity of electricity generated by the planned PV system is lower compared with the Swiss electricity supply mix.

The complementation of the 60 kWp PV system by a 100 kWh battery storage system leads to a significant increase of the self-consumption share (62%) and the self-sufficiency share (35%). However, the greenhouse gas emissions of electricity consumption are similar to those of the "PV only" option. The greenhouse gas emissions of battery production outweigh the difference in emission intensity of PV electricity and the Swiss supply mix. If future increases in energy density and production optimisations are taken into account for the storage system, the greenhouse gas emissions of the electricity consumption of the cloakroom and club building decrease to 12.3 tCO_2-eq/a (minus 8% compared with the option with a PV system and a storage system with current Li-ion batteries). A further reduction may be achieved by future improvements in the PV module conversion efficiency and the PV module production processes. These developments were not considered in the present study. The greenhouse gas emissions of the option with a PV system and a storage system with second-life Li-ion batteries amount to 12.8 tCO_2-eq/a and are in between the emissions of the options with current and with future battery systems.

The Zurich City Administration uses a renewable electricity mix, which is mainly generated in hydropower plants and contains shares of wind power and PV electricity. If the grid electricity used by the planned cloakroom and club building is supplied by this renewable electricity mix, the absolute greenhouse gas emissions of all options considered are substantially lower (see Figure 5). In this case, the full coverage of the electricity demand by grid electricity is environmentally favourable with greenhouse gas emissions of 1.2 tCO_2-eq/a. Due to the high share of hydropower, the renewable electricity mix used by the Zurich City Administration causes fewer greenhouse gas emissions per kWh than PV electricity. Hence, the installation of a PV system results in an increase of greenhouse gas emissions of electricity consumption to 2.2 tCO_2-eq/a. A storage system with current Li-ion batteries further doubles these emissions (4.4 tCO_2-eq/a) because of the greenhouse gas emissions caused by battery production on the one hand and the higher self-sufficiency share on the other hand. The greenhouse gas emissions of the electricity consumption of the planned cloakroom and club building for the options with a PV system and a storage system with future or second-life Li-ion batteries are 3.4 and 4.0 tCO_2-eq/a, respectively.

5 | CONCLUSION

The cloakroom and club building that is currently planned by the Office for Building Engineering of the City of Zurich was used as a showcase to analyse the environmental footprint of PV-battery systems. The forecast electricity consumption profile of the building is characterised by a distinctive evening peak, which is caused by the floodlights of the surrounding soccer fields. In this case, the complementation of the planned 60 kWp PV system with a 100 kWh battery storage system leads to a significant increase of the self-consumption share of PV electricity from 31% to 62%. However, even with a PV system and a battery storage, approximately two thirds of the electricity consumption are covered with grid electricity. The complementary grid electricity mix strongly influences the environmental impacts of the electricity used by the cloakroom and club building. The installation of a PV system and a battery storage system leads to a 10% to 17% reduction in greenhouse gas emissions compared with the full coverage of the electricity demand by the average Swiss supply mix. The addition of a storage system with current Li-ion batteries does not yield any further reduction compared with the “PV only” option if the complementary electricity supply is covered with the Swiss supply mix. With the renewable electricity mix of the Zurich City Administration, the installation of a PV system and a battery leads to higher environmental impacts of electricity consumed, irrespective of the type of battery used. However, a future increase in energy density, production optimisations and second-life batteries bear a significant potential to reduce the environmental impacts.

The LCIs of the PV system, the storage system with current Li-ion batteries, and the grid electricity mixes are based on reliable and transparent information sources. The data quality of these LCIs is considered as fair. The LCIs of storage systems with future and second-life Li-ion batteries required assumptions on key parameters such as the energy density and the life time. The environmental impacts are very sensitive to changes in these key parameters, which renders the results of the storage systems with future and second-life batteries more uncertain. The LCA of the yearly electricity consumption of the cloakroom and club building is based on a forecast consumption profile and the corresponding self-consumption share and self-sufficiency share. These parameters also have a high influence on the environmental impacts. These uncertainties need to be taken into consideration when interpreting the results, but they are not expected to change the overall conclusions drawn in this paper.

ACKNOWLEDGEMENT

This study was financially supported by the Office for Building Engineering of the City of Zurich.

ORCID

Philippe Stolz http://orcid.org/0000-0003-2647-3159
Rolf Frischknecht http://orcid.org/0000-0001-6376-0355

REFERENCES

1. Stadt Zürich, Gemeindeordnung der Stadt Zürich. 2017.
2. Spreng DT, Semadeni M. *Energie, Umwelt und die 2000 Watt Gesellschaft*. *CEPE working paper Nr. 11*. Zürich: CEPE Centre for Energy Policy and Economics Swiss Federal Institute of Technology; 2001 p. Online Datei. Retrieved from e-collection.ethbib.ethz.ch/show?type=incoll&nr=420.
3. UGZ. *Primärenergiebilanz Stadt Zürich*. *Umwelt- und Gesundheitsschutz Zürich (UGZ)*. Zürich: Stadt Zürich; 2018 https://www.stadt-zuerich.ch/content/dam/stzh/gud/Deutsch/UGZ/Umwelt%20%26%20Energie/Energie%20in%20Zahlen/2000-Watt-Indikatoren/%3e%20Dokumente%20und%20Publikationen/Prim%c3%a4renergiebilanz_Daten.pdf.
4. UGZ. *Treibhausgasemissionen Stadt Zürich*. *Umwelt- und Gesundheitsschutz Zürich (UGZ)*. Zürich: Stadt Zürich; 2018 https://www.stadt-zuerich.ch/content/dam/stzh/gud/Deutsch/UGZ/Umwelt%20%26%20Energie/Energie%20in%20Zahlen/2000-Watt-Indikatoren/%3e%20Dokumente%20und%20Publikationen/Treibhausgasemissionen_Daten.pdf.
5. Gessler R, Volland B. *Roadmap 2000-Watt-Gesellschaft*. Stadt Zürich, Umweltdelegation des Stadtrats: Zürich; 2016.
6. Prognos. *Die Energieperspektiven für die Schweiz bis 2050; Energienachfrage und Elektrizitätsangebot in der Schweiz 2000-2050*. Bern: Bundesamt für Energie, BFE; 2012.
7. IEA-PVPS. *National Survey Report of PV Power Applications in Switzerland 2016*. International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS); 2017.
8. IEA-PVPS, *Trends 2017 in Photovoltaic Applications—Survey Report of Selected IEA Countries between 1992 and 2016*. 2017, PVPS T1-23: 2013, International Energy Agency (IEA) Photovoltaic Power Systems Programme (PVPS). Retrieved from www.iea-pvps.org.
9. Swissolar. *PV-Anlagen mit Batterien*. Zürich: Schweizerischer Fachverband für Sonnenenergie, Swissolar; 2016.
10. Stettler Y. *Garderoben- und Clubgebäude, Zürich Höngg. Projektbeschreibung Photovoltaik Vorprojekt*. Zürich: Basler & Hofmann AG; 2018.
11. SIA. *Merkblatt 2040: SIA-Effizienzpfad Energie*. Zürich: Schweizerischer Ingenieur- und Architektenverein (SIA); 2017:28.
12. KBOB, eco-bau, & IPB, *KBOB Ökobilanzdatenbestand DQRv2:2016; Grundlage für die KBOB-Empfehlung 2009/1:2016: Ökobilanzdaten im Baubereich, Stand 2016*.2016, Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren c/o BBL Bundesamt für Bauten und Logistik. Retrieved from www.ecoinvent.org.
13. ecoinvent Centre. *ecoinvent data v2.2, ecoinvent reports No. 1–25*. Duebendorf, Switzerland: CD-ROM, Swiss Centre for Life Cycle Inventories; 2010 Retrieved from www.ecoinvent.org.
14. IPCC. *The IPCC Fifth Assessment Report—Climate Change 2013: the Physical Science Basis*. Working Group I, IPCC Secretariat; 2013: Geneva, Switzerland.
15. Frischknecht R, Wyss F, Büsser Knöpfel S, Lützkendorf T, Balouktsi M. Cumulative energy demand in LCA: the energy harvested approach. *Int J Life Cycle Assess*. 2015;20(7):957-969. https://doi.org/10.1007/s11367-015-0897-4
16. Frischknecht R, Büsser Knöpfel S. *Swiss Eco-Factors 2013 according to the Ecological Scarcity Method. Methodological fundamentals and their application in Switzerland*. *Environmental studies no. 1330*. Bern: Federal Office for the Environment; 2013 Retrieved from http://www.bafu.admin.ch/publikationen/publikation/01750/index.html?lang=en.
17. Stolz P, Frischknecht R, Kessler T, Züger Y. *Ökobilanz PV-Anlage und Batterie für das Garderoben- und Clubgebäude in Zürich Höngg*. Zürich: Amt für Hochbauten, Fachstelle nachhaltiges Bauen, Stadt Zürich; 2018.
18. PRé Consultants. *SimaPro 8.4.0*. Amersfoort, NL; 2017.
19. Technical Secretariat of the PEF Pilot "Photovoltaic Electricity Generation", *Product Environmental Footprint Category Rules: Production of Photovoltaic Modules used in Photovoltaic Power Systems for Electricity Generation (NACE/CPA class 27.90 “Manufacturing of other electrical equipment”)*. 2016.
20. Frischknecht R, Itten R, Sinha P, de Wild SM, et al. *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems*. 12 International Energy Agency (IEA) PVPS Task; 2015.
21. Helms H, Julius J, Claudia K, Giegrich J, et al. *Weiterentwicklung und vertiefte Analyse der Umweltbilanz von Elektrofahrzeugen*. Umweltbundesamt; 2016.
22. de Haan P, Zah R. *Chancen und Risiken der Elektromobilität in der Schweiz*. Zürich: vdf Hochschulverlag AG; 2013.
23. EnergieSchweiz. *Stationäre Batteriespeicher in Gebäuden (Dokument zur Vernehmlassung)*. Bern: EnergieSchweiz, Bundesamt für Energie BFE; 2018.
24. Ellingsen LA-W, Majeau-Bettez G, Singh B, Kumar Srivastava A, et al. Life cycle assessment of a Lithium-ion battery vehicle pack. *Journal of Industrial Ecology*. 2014;18(1):113-124.
25. Stolz P, Messmer A, Frischknecht R. *Life Cycle Inventories of Road and Non-Road Transport Services*. Uster CH: treeze Ltd.; 2016.
26. Messmer A, Frischknecht R. *Ökobilanz von PV-Batterie-Systemen*. Uster: treeze Ltd.; 2015.
27. EASE/EERA. *European Energy Storage Technology Roadmap. 2017 Update*. Brussels: European Association for Storage of Energy and European Energy Research Alliance; 2017.

28. Cox B, Bauer C. *Environmental assessment of current and future passenger vehicles in Switzerland*. Villigen: Paul Scherrer Institut PSI, commissioned by the Swiss Federal Office for Energy SFOE; 2018.

29. Fraunhofer ISI. *Gesamt-Roadmap Lithium-Ionen-Batterien 2030*. Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung ISI; 2015.

30. Romare M, Dahllöf L. *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries*. Stockholm: IVL Swedish Environmental Research Institute; 2017.

31. Pérez-López P, Gschwind B, Blanc P, Frischknecht R, et al. ENVI-PV: an interactive Web Client for multi-criteria life cycle assessment of photovoltaic systems worldwide. *Progress in Photovoltaics: Research and Applications*. 2016;1-15.

32. EASE/EERA. *European Energy Storage Technology Roadmap towards 2030. Technical Annex*. Brussels: European Association for Storage of Energy and European Energy Research Alliance; 2017.

33. Schaufenster Elektromobilität. *Studie: Second-Life-Konzepte für Lithium-Ionen-Batterien aus Elektrofahrzeugen. Analyse von Nachnutzungsanwendungen, ökonomischen und ökologischen Potenzialen*. Frankfurt am Main: Begleit- und Wirkungsforschung Schaufenster Elektromobilität (BuW); 2016.

34. Neubauer J, Smith K, Wood E, Pesaran A. *Identifying and Overcoming Critical Barriers to Widespread Second Use of PEV Batteries*. Golden, CO.: National Renewable Energy Laboratory NREL; 2015.

35. Reid G, Julve J. *Second Life Batteries as Flexible Storage for RenewableEnergies*. Berlin: Bundesverband Erneuerbare Energie e.V. (BEE); 2016.

36. Sattler M, Hausammann B, Held M. *Stromspeichersystem mit Second-Life Akkumulatoren (SL-Speicher). Jahresbericht vom 26. Juni 2017*. Bern: Bundesamt für Energie BFE; 2017.

37. Stolz P, Frischknecht R, Wyss F, de Wild Scholten M. *PEF screening report of electricity from photovoltaic panels in the context of the EU Product Environmental Footprint Category Rules (PEFCR) Pilots, version 2.0*. Uster, Switzerland: treeze ltd. commissioned by the technical secretariat of the PEF pilot "photovoltaic electricity generation"; 2016.

38. Ellingsen LA-W, Hung CR, Hammer Strømman A. Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. *Transportation Research Part D*. 2017;55:82-90.

39. Stenzel P, Schreiber A, Marx J, Wulf C, Schreieder M, Stephan L. Environmental impacts of electricity generation for Graciosa Island, Azores. *Journal of Energy Storage*. 2018;15:292-303.

How to cite this article: Stolz P, Frischknecht R, Kessler T, Züger Y. Life cycle assessment of PV-battery systems for a cloakroom and club building in Zurich. *Prog Photovolt Res Appl*. 2018;1–8. https://doi.org/10.1002/pip.3089