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Photovoltaic Manufacturing Factories and Industrial Site Environmental Impact Assessment

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Abstract: Life cycle inventories (LCIs) and life cycle assessments (LCAs) of photovoltaic (PV) modules and their components focus on the operations of PV factories, but the factories and industrial site product and construction stages are either not or only partially tackled. This work contributes through the bottom-up, model-based generation of LCIs and LCAs for setting up a vertically integrated 5 GWp/a PV industrial site, including the manufacturing of silicon ingots, wafers, solar cells, and PV modules, on a 50 ha greenfield location. Two comparative LCAs are performed. The first compares the annualized environmental impacts of the developed LCI sets with four existing inventories in the Ecoinvent v3.8 database. The second comparative LCA explores the environmental impact differences concerning the industrial site when using different building systems for the factories. Here, the reference system with a steel structure is compared with two alternative building systems: precast concrete and structural timber. The results show that the wafer, cell, and module factories' annualized environmental impacts with the Ecoinvent LCIs are strongly overestimated. For the ingot factory, the opposite result is identified. The impacts of all four factories show reductions of between 11.7% and 94.3% for 14 of the 15 impact categories. High mean environmental impact shares of 79.0%, 78.2% and 79.2% for the steel, precast concrete and timber structural building systems, respectively, are generated at the product stage. The process and facilities equipment generates 54.2%, 54.4% and 58.2% of the total product and construction stages' mean environmental impact shares. The proposed alternative timber building system reduces the environmental impacts in 14 of the 15 evaluated categories, with reductions ranging from 1.1% to 12.4%.

Keywords: life cycle inventory (LCI); photovoltaics; industrial infrastructure; environmental impact assessment; life cycle assessment (LCA); structural timber; sustainable building materials

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1. Introduction

With the exponential growth of PV installations worldwide, the global PV manufacturing capacity has seen an increase from 30 gigawatts peak per year (GWp/a) in 2010 for both modules and wafers to 400 GWp/a and 500 GWp/a in 2022, respectively [1]. This is a welcome development when it comes to achieving global sustainability goals and enabling the decarbonization of future economies. At the same time, this growth entails an increase in the consumption of resources for production and the consequent environmental impacts. As such, sustainable pathways for manufacturing products along the PV value chain are of high relevance to minimize those impacts for the expected terawatt-scale deployment of PV [2–5].

Research on the environmental impacts of the PV value chain, with respect to its constituent materials, especially the critical raw materials, the efficiencies of the different generations of PV technologies, as well as their subsequent performance in the operational stage, is widely available and published [6–13]. However, there is almost no research or literature related to the environmental impacts of infrastructure developed in the service of the PV manufacturing production chain [14].

In this study, infrastructure refers to the involved lists of process equipment (PE) and facility equipment (FE), civil, structural, and architectural (CSA) components of the process industrial halls and ancillary buildings needed, as well as general services such as internal roads, parking lots, reserved landscaping areas, and basic water and sewage facilities.

In line with the limited availability of dedicated scientific or official publications, the appearance of environmental databases at the turn of the century has encouraged the application of the life cycle assessment (LCA) methodology [15] to quantify potential environmental impacts. The development of the world's most recognized life cycle inventory (LCI) databases, such as GaBi [16] and Ecoinvent [17], is a recent development, meaning that data are now available for a variety of processes and product systems.

Ecoinvent contains four product systems in its database—silicone plant, wafer factory, photovoltaic cell factory, and photovoltaic panel factory—that theoretically fit within the scope of the evaluated infrastructure and have been established as the state-of-the-art reference for this work. As these datasets were integrated into the Ecoinvent database within the years 1999 to 2006, it is the overall objective of this work to generate product systems analogous to the Ecoinvent ones, assess the environmental impact of the infrastructure of the factories that would produce monocrystalline silicon (c-Si) ingots, wafers, passivated emitter back-contact solar cells (PERCs) and PV modules. This is performed for an industrial cluster of 5 GWp/a capacity in Germany, and then the results are compared and potential optimizations of the impacts obtained are identified. This work presents novel bottom-up, model-based LCIs and environmental impact assessments for the product and construction stages of the infrastructure needed to transform solar grade polysilicon into PV modules.

1.1. Reference Processes

The Ecoinvent LCI database accounts for more than 18,000 datasets [17] describing a wide range of processes. Four identified datasets describing the raw data inventories of the infrastructure related to the PV stages under study, production of monocrystalline silicon ingots, silicon wafers, photovoltaic cells and photovoltaic modules, were examined to determine and understand their scope in terms of the building's life cycle stages as defined in the European standard EN 15978 [18]. As an overview, in addition to the materiality of the building construction, these datasets also partially include the process equipment for the PV stage, without including any reference to ancillary buildings or areas and their associated facility equipment. These datasets are used to compare the LCIs and LCAs models generated in this work and their main elements are described below.

1.2. Silicone (A Multiproduct Silicone Factory Is Described in the Ecoinvent Database, Therefore We Do Not Use the Term Silicon in This Section) Plant Construction Scope

Section 5.6.5 of the Ecoinvent report No. 6-XII [19] states that one Cz-silicon crystal grower is made out of 4536 kg of steel and can produce 40 kg monocrystalline silicon per day over 10 years. Nevertheless, Table 5.11 in the report only includes as infrastructure in the dataset "silicone plant", with a coefficient of 1.00E-11 units per 1 kg of Cz-single crystalline silicon. No relation to the crystal growers is suggested. The silicone plant inventory described in the Ecoinvent report No. 8, v2.0 [20] has an output of 1 million metric tons/a of silicone products and a 100-year service life. It considers one single-story hall with a 228 ha footprint, chemical production facilities, pipelines, railways tracks, road network and residual material landfill. The data quality sections of the dataset declare that large differences between different silicone products are envisioned and that a detailed investigation of each specific product must be performed. The source data were gathered between the years 1999 and 2001. The building topology is not specified in the dataset.

1.3. Wafer Factory Construction Scope

The analysis of the Ecoinvent dataset for a silicon wafer factory infrastructure located in Germany, which we refer to as the EI Wafer factory in this paper, is introduced here. The dataset reflects a 1 million wafer/a factory capacity and a 25-year service life. The functional unit is "1 unit factory" of wafer manufacturing. The information contained in the dataset, or model, was gathered between the years 2000 and 2005, mainly through a collaboration by local supplier companies at the time. The capacity of this factory is about a thousand times smaller than the one analyzed in this study.

From the building system perspective, a single-story 110 m^2 footprint industrial hall, based on a mix of 70% structural steel framing and 30% wood construction, is described. Besides the hall, the land use is included, as well as a water supply network provision representing drinking water pipelines. Additionally, the total weight of the Pes is expressed in kilograms of "*metal working machine*" manufactured entirely in the European region (RER). Neither the type of the PE nor any FE or ancillary buildings supporting the process are mentioned. The life cycle stages of the building are addressed: product and construction, as well as the waste management of the main construction components involved in the dismantling of the building at the end of its service life. The use stage of the entire infrastructure is not included in the model.

In terms of the production process, this model includes monocrystalline (sc-Si) and multi-crystalline (mc-Si) silicon wafers, as well as ribbon silicon wafers. The processes considered are wafer sawing, wafer cleaning and packing in plastic foil and polystyrene. No specifications regarding the shares of the wafer types are given.

The sc-silicon columns are sawed into square wafers with a size 156 × 156 mm^2 (0.0243 m^2), thickness of 190 μm and a wafer weight of 466 g/m^2. Similarly, the mc-silicon columns are sawed into wafers with a square size 156 × 156 mm^2 (0.0243 m^2), thickness of 190 μm and a weight of 443 g/m^2. Finally, the ribbon silicon wafers' area is between 120 and 156 mm^2, with a thickness range of 200 to 300 μm, resulting in an average weight of 583 g/m^2.

1.4. Photovoltaic Cell Factory Construction Scope

This dataset describes the raw unit process data of the infrastructure for the construction of a solar cell factory. The data gathered between the years 2000 and 2005 introduce a plant with a production capacity of 100,000 square meter/a (m^2/a) of silicon solar cells, here referred to as the EI PV Cell factory, with a 25-year lifespan. The capacity of this factory is very small in comparison to current production capacities, 238 times smaller than the one analyzed in this study. This dataset includes an estimate of a single-story 1730 m^2 footprint industrial hall, based on structural steel and reinforced concrete components. The land use accounts for the industrial and green areas. Neither ancillary areas, utilities, internal roads, and parking lots nor FE are specified. The PE list is represented by the amount of "*metal working machine*" flow, manufactured entirely in RER. The product life cycle stage is addressed, and a direct estimate of the waste management of the main components is reported as well, with no specification regarding the energy use for demolition purposes. The construction stage is not included in the model, presumably due to its brown field setting in a pre-existing industrial site. Finally, the use stage is outside of its scope.

The production process includes the reception of wafers, etching, doping, printing metallization, anti-reflection coating, testing, and sorting.

1.5. Photovoltaic Panel Factory Construction Scope

The dataset of the PV panel factory, in the following referred to as the EI PV Mod factory, is similar to the silicon wafer factory approach in terms of the flows and unit processes considered. The data gathered between the years 2005 and 2006 describe a customized 799 m^2 single-story hall footprint. The land use is expressed as the industrial area with internal interconnections and the green area. However, services facilities are not specified in this case. With a capacity of 10,000 modules/a and a 25-year lifetime, the factory described depicts a global benchmark process performed for this product system. The underlying capacity represents a very small factory in comparison to current ones, 1597 times smaller than the one considered in this study. The process equipment list is represented as an amount of "*metal working machine*" as well, 33% from RER suppliers and 67% from Rest of the World (RoW) suppliers. Halls are represented by the process "*market for building hall*"—in a global context (GLO) as for the wafer factory model and with similar assumptions for the product, construction, and waste management stages. The use stage is not part of the scope of this dataset. In this case, there is no information related to ancillary buildings or their facility equipment, as in all the previous cases.

The process for the production of the panels is accountable for the cells' stringing arrangement, laminations at the front and the rear, edge insulation, aluminum frame installation as well as the connection box installation.

2. Materials and Methods

To determine the potential environmental impacts of a 5 GWp/a module equivalent capacity industrial site placed in Cologne, Germany, a bottom-up LCA was applied. The scope of the analysis focuses on the creation of inventories of components from the civil, structural, and architectural (CSA) and process disciplines, which are necessary for the construction and set-up of the industrial site. The process analysis considers the reference sequence defined by Brailovsky et al. (2023) for the production of Cz-ingots, monocrystalline wafers, PERC solar cells and PV modules [6]. Two comparative LCAs are conducted, one to compare the annualized environmental impacts between our analogous own models (OMs) with the Ecoinvent (EI) ones, and a second comparison to evaluate the environmental impacts of alternative building systems. Figure 1 illustrates the methods with a simplified flowchart.

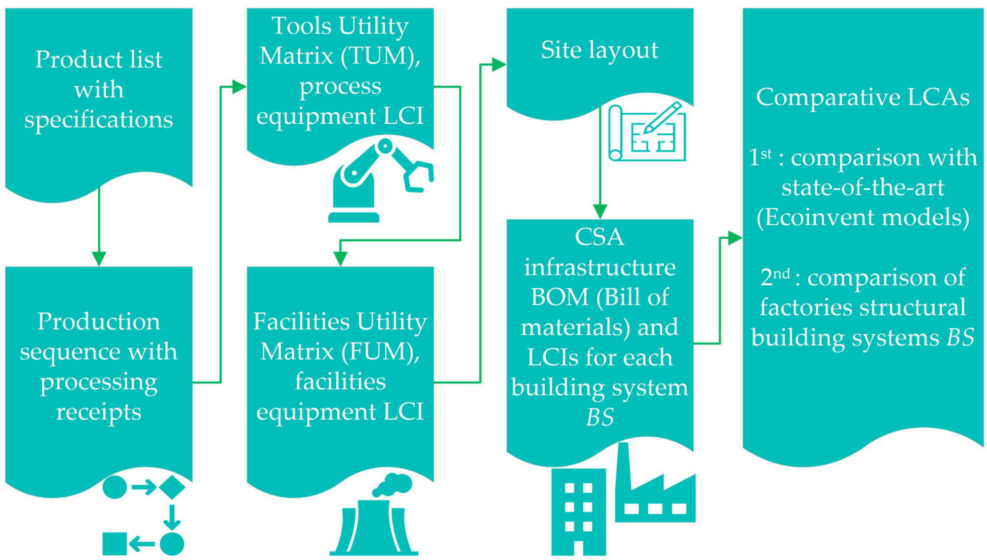

Figure 1. Simplified methods flowchart.

2.1. Functional Unit and System Boundaries

The defined functional unit is in all cases a "one factory unit", analogous to the Ecoinvent datasets (EI models) for all the PV factories.

The life cycle of the buildings is classified into five stages defined in the European standard EN 15978:2011: (1) product, (2) construction, (3) use, (4) end of life, and (5) benefits and loads beyond the system boundary stages [18]. The cradle-to-site system boundary of this work encompasses the product and construction stages for all the buildings defined and analyzed and all the required equipment for their manufacturing operations. The energy, materials, and waste flows generated during the product and construction stages are considered for the preparation of the site, infrastructure construction, and equipping the industrial halls.

2.2. Life Cycle Inventory (LCI)

As a first step, this work identified and categorized four specific Ecoinvent (EI) models as reference models to compare with the herein-developed analogous own models (OMs).

The selected datasets are accountable for a silicon monocrystal factory construction (EI Silicon factory), a silicon wafer factory construction (EI Wafer factory), a PV cell factory construction (EI PV Cell factory), all located in Germany and, a PV panel factory construction (EI PV Mod factory), as described in detail in Section 1.

In a second step, the integration of all the analogous inventories was carried out based on the identification, listing and quantification of the process equipment, facilities equipment and construction components, organized as a bill of materials (BOM) for each factory and the industrial site ancillary facilities, as shown in Figure 1. The Fraunhofer ISE technoeconomic assessment software SCost (Version 6.0) [21] was used to model the selected process sequence from Brailovsky et al. (2023) [6]. A throughput analysis was performed to generate the required tools for each of the production processes. With the quantified tools and their weights, the process equipment LCI for each factory was integrated. Subsequently, by summing up the utility requirements for operating the industrial tools, a Tool Utility Matrix (TUM) was consolidated for each factory. The ancillary services and their equipment were then dimensioned to integrate the Facilities Utility Matrix (FUM), and the facilities equipment LCI for the industrial site was generated. The dimensioning of areas of the industrial site considering a safe distance between operations, storages, and administration halls, as well as required parking and roads network and landscaping zones of the industrial site, took place, and the site masterplan layout was created. Then, the building's structure and envelope were designed by using the site layout, the processes and facilities equipment inventories and their physical dimensions, floor loads, distribution within the buildings and required environmental conditions. This process resulted in the generation of the reference civil, structural, and architectural (CSA) infrastructure BOMs and LCIs for the factories and ancillary buildings and areas. The latter represent the reference scenario of the OMs.

In the next step, all of these reference CSA BOMs and LCIs were modified according to a scenario-based analysis. Considering three primary material types of building systems—steel, precast concrete, and timber—three versions of the BOMs and LCIs were obtained for each of the factories, keeping the amounts and requirements of the process equipment (PE) constant in all cases. In total, 12 inventories were created. Regarding the ancillary buildings and areas, this work only produced BOMs and LCIs based on a structural steel framing system.

For most cases, the elementary flows and unit processes were selected directly from Ecoinvent v3.8 [17]. Only for those cases where data were not available were new unit processes elaborated to obtain a final required component in the inventories. All the required equipment components, both process and facilities machinery, have been considered and modeled as kilograms of "*metal working machine*" elementary flow, in the same way as these elements are treated in the Ecoinvent models.

Equation (1) represents the proposed product and construction stages own model $\mathrm{I_{OM}}(B)$ industrial site inventory as a union of the of civil, structural, and architectural (CSA) components for the factories $F \in \{\text{Ingot; Wafer; Cell; Module}\}$ and related building systems $B \in \{\text{Steel; Precast concrete; Timber; } B_{\mathrm{EI}}(F)\}$ with the required ancillary infrastructure Anc, as well as the required facility equipment FE, and process equipment PE.

$$I_{\mathrm{OM}}(B) = I_{\mathrm{OM,CSA}}(F,B) \cup I_{\mathrm{OM,Anc,CSA}}(\mathrm{Steel}) \cup I_{\mathrm{OM,PE}}(F) \cup I_{\mathrm{OM,FE}} \quad (1)$$

The Ecoinvent building systems per each factory F are denoted by $B_{\mathrm{EI}}(F)$; they are equal to "Steel" for the cell factory $B_{\mathrm{EI}}(\mathrm{Cell})$ and "70% Steel + 30% Timber" for the other three factories $B_{\mathrm{EI}}(\mathrm{Ingot}) = B_{\mathrm{EI}}(\mathrm{Wafer}) = B_{\mathrm{EI}}(\mathrm{Module})$. Figure 2 visualizes the inventory integration.

Similar to Equation (1), Equation (2) represents the integration of the own model inventories per factory and building system $I_{\mathrm{OM}}(F, B_{\mathrm{EI}}(F))$. The Anc components and FE elementary flows are distributed in equal portions of 25% for each of the four factories. The number of factories is denoted by f.

$$I_{\mathrm{OM}}(F, B_{\mathrm{EI}}(F)) = I_{\mathrm{OM,CSA}}(F, B_{\mathrm{EI}}(F)) \cup \frac{I_{\mathrm{OM,Anc,CSA}}(\mathrm{Steel})}{f} \cup I_{\mathrm{OM,PE}}(F) \cup \frac{I_{\mathrm{OM,FE}}}{f} \quad (2)$$

The factories' inventories for the Ecoinvent EI models are represented by Equation (3) and consider the CSA elements for each factory F and the associated PE equipment. These inventories do not include or specify the Anc infrastructure or FE equipment.

$$I_{\mathrm{EI}}(F, B_{\mathrm{EI}}(F)) = I_{\mathrm{EI,CSA}}(F, B_{\mathrm{EI}}(F)) \cup\ I_{\mathrm{EI,PE}}(F) \tag{3}$$

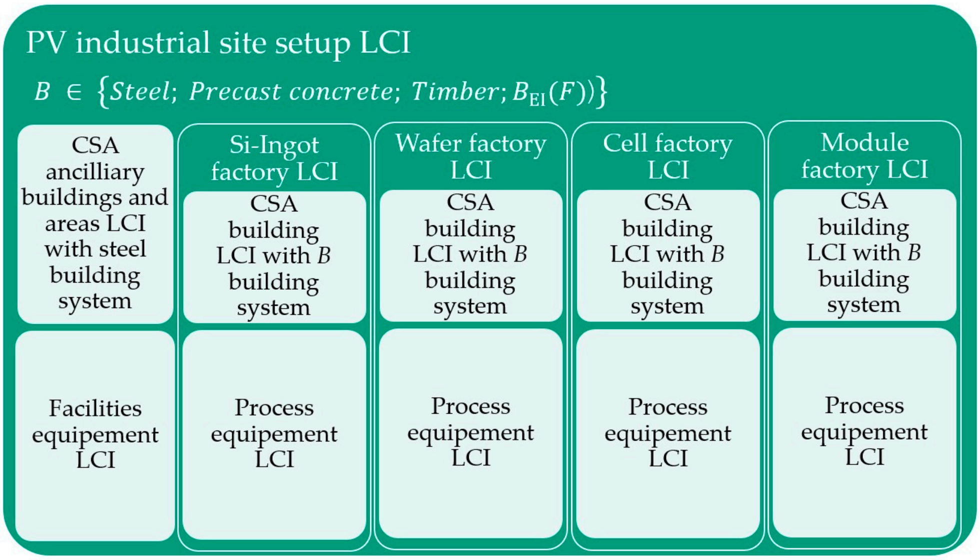

Figure 2. Own model (OM) PV industrial site LCI integration.

2.3. Life Cycle Assessment (LCA)

To estimate the potential environmental impacts of the factories' infrastructure, an LCA applied to a building's life cycle has been conducted following the ISO 14040 [22], ISO 14044 [23] and EN 15978 [18] standards. The models of the LCIs were implemented using Umberto 11 software [24] in combination with the Ecoinvent Version 3.8 database [17] and the system model "allocation, cut-off". The LCIA method applied was the EU Product Environmental Footprint Version 3.0 (PEF) [25], following the EU Commission recommendation on the PV sector. The results are reported for the impact categories $k \in$ {*Freshwater ecotoxicity total*; *Carcinogenic and non-carcinogenic effects*; *Respiratory effects, inorganics*; *Ozone layer depletion*; *Climate change*; *Marine eutrophication*; *Photochemical ozone creation*; *Freshwater eutrophication*; *Minerals and metals use*; *Ionizing radiation*; *Water scarcity, use*; *Fossils use*; *Freshwater and terrestrial acidification*; *Terrestrial eutrophication*; *Land use*} and their indicators.

The 1st comparative LCA is performed to compare the annualized environmental impacts $E_{\mathrm{Annual},k}(F,\ B_{\mathrm{EI}}(F))$ derived from the created $I_{\mathrm{OM}}(F, B_{\mathrm{EI}}(F))$ inventories and the Ecoinvent inventories $I_{\mathrm{EI}}(F, B_{\mathrm{EI}}(F))$. The comparison is performed for each factory F and impact category k, considering the Ecoinvent building systems $B_{\mathrm{EI}}(F)$, as represented by Equation (4).

$$E_{\mathrm{OM,Annual},k}(F,\ B_{\mathrm{EI}}(F)) \neq E_{\mathrm{EI,Annual},k}(F, B_{\mathrm{EI}}(F))\ \forall\, k, F \tag{4}$$

With Equations (5) and (6), the annualized environmental impacts $E_{\mathrm{Annual,k}}(F, B_{\mathrm{EI}}(F))$ are calculated for each inventory element i and summed for all n elements. The impacts are annualized by dividing the inventory subsets by their respective lifetime l in years—$l_{\mathrm{OM,CSA}} = 30, l_{\mathrm{EI,CSA}}(\mathrm{Ingot}) = 100,\ l_{\mathrm{EI,CSA}}(\mathrm{Wafer}) = l_{\mathrm{EI,CSA}}(\mathrm{Cell}) = l_{\mathrm{EI,CSA}}(\mathrm{Module}) = 25,\ l_{\mathrm{OM,FE}} = 20,\ l_{\mathrm{OM,PE}} = l_{\mathrm{EI,PE}} = 10$—to allow the models' comparison. The own models' lifetime l assumptions are based on the authors' PV sector expertise, financial depreciation tables [26] and machinery lifetime data [27].

$$E_{\mathrm{OM,Annual},k}(F, B_{\mathrm{EI}}(F)) = \sum_{i=1}^{i=n} C_{\mathrm{LCIA},i,k} \times I_{\mathrm{OM},i}(F, B_{\mathrm{EI}}(F)) \times \begin{pmatrix} 1/l_{\mathrm{OM,CSA}} & ,\ I_{\mathrm{OM},i} \in I_{\mathrm{OM,CSA}}(F, B_{\mathrm{EI}}(F)) \\ 1/l_{\mathrm{OM,FE}} & ,\ I_{\mathrm{OM},i} \in I_{\mathrm{OM,FE}} \\ 1/l_{\mathrm{OM,PE}} & ,\ I_{\mathrm{OM},i} \in I_{\mathrm{OM,PE}}(F) \end{pmatrix} \tag{5}$$

$$E_{\text{EI,Annual},k}(F, B_{\text{EI}}(F)) = S_{\text{PSF}}(F) \times \sum_{i=1}^{i=n} C_{\text{LCIA},i,k} \times I_{\text{EI},i}(F, B_{\text{EI}}(F)) \times \begin{pmatrix} 1/\, l_{\text{EI,CSA}}(F) & , I_{\text{EI},i} \in\ I_{\text{EI,CSA}}(F, B_{\text{EI}}(F)) \\ 1/l_{\text{EI,PE}} & , I_{\text{EI},i} \in I_{\text{EI,PE}}(F) \end{pmatrix} \quad (6)$$

Respectively, with Equation (7), the process scaling factors $S_{\text{PSF}}(F)$ are calculated by dividing the annual production $P_{\text{OM,Annual}}(F)$ of each factory in this study by the corresponding $P_{\text{EI,Annual}}(F)$ from the Ecoinvent factories. The $C_{\text{LCIA},i,k}$, environmental impact coefficients are taken from the Ecoinvent v3.8 database.

$$S_{\text{PSF}}(F) = \frac{P_{\text{OM,Annual}}(F)}{P_{\text{EI, Annual}}(F)} \quad (7)$$

The 2nd comparative LCA is performed for the calculation of the environmental impacts E for the construction of the whole industrial site. Here, the site environmental impacts $E_{\text{OM},k}(B)$ for each category k are compared for each analyzed factory building system $B \in \{\text{Steel; Precast concrete; Timber}\}$ as represented by Equation (8). Equation (9) is used for their calculation.

$$E_{\text{OM},k}(\text{Steel}) \neq E_{\text{OM},k}(\text{Precast concrete}) \neq E_{\text{OM},k}(\text{Timber}) \; \forall\, k \quad (8)$$

$$E_{\text{OM},k}(B) = \sum_{i=1}^{i=n} C_{\text{LCIA},i,k} \times I_{\text{OM},i}(B) \quad (9)$$

3. Proposed Production Factories and Facilities LCIs

Using a greenfield project approach, we developed a preliminary layout for an integrated PV industrial site based on the estimated annual production for each factory F. The footprints of the factories F, road networks, ancillary areas, and buildings Anc had been estimated. The facilities' equipment FE and process equipment PE requirements, dimensions and handling spaces were used for the building footprint estimations. The inventories' integration sequence per engineering discipline is described in Sections 3.1 and 3.2.

3.1. Process and Facilities Equipment LCIs

The industrial site is dimensioned to produce 25,902 metric tons/a of Cz-ingots, 24,631,830 m^2/a wafers, 23,678,425 m^2/a PERC solar cells and 25,500,741 m^2/a PV modules—bifacial selective emitter 60-cell p-type M2 Cz PERC glass and backsheet modules with an aluminum frame—, which are equivalent to an aligned module factory output of 5 GWp/a. The reference products and process sequence with 35 processes defined by Brailovsky et al. (2023) [6] have been considered.

The site dimensioning considers the required equipment footprints, consumables storage space, logistics and services operations, utilities, and building and facilities requirements. The main material flows that take place along the site are of water, wastewater, PV modules, solar glass, aluminum frames, module packaging materials, encapsulants, backsheets, polysilicon chunks and crucibles. A storage capacity of 30 days is considered for consumables and final products, with 24 h storage defined for municipal water. An electrical substation of 100 MVA is placed on site. In total, for the 5 GWp/a polysilicon to module production facility, 3467 process equipment tools have been quantified for the 4 factories and 1070 facilities equipment tools for the facilities of the industrial site. The weights of the equipment per factory and facilities are reported in Figure 3. The facilities and Si-ingot factory represent almost a third each from the total equipment weights. The highest total weight of the process equipment comes from the Cz pullers, the PV module laminators, and the furnaces for the solar cell passivation steps. The highest total weight of the facilities equipment belongs to the heating, ventilation, and air-conditioning (HVAC) system and the effluent treatment plant (EFP). See Appendix A for more details.

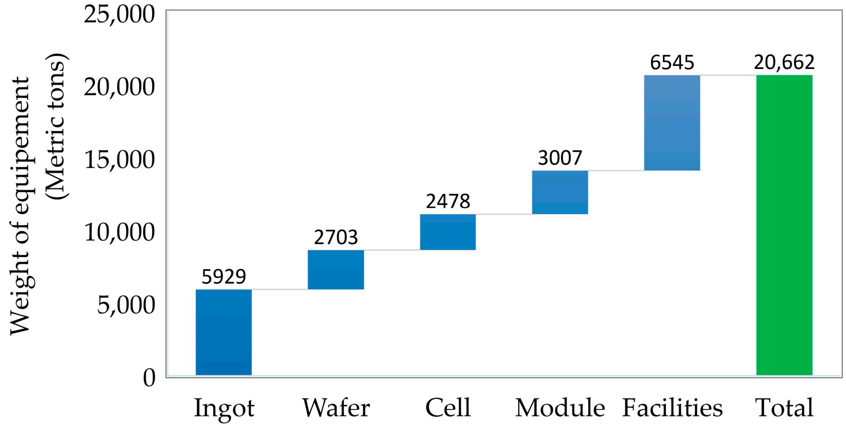

Figure 3. Process and facilities equipment LCI.

3.2. Civil, Structural and Architectural LCIs

3.2.1. Industrial Site Location

The city of Cologne in Germany has been selected as the location for the industrial site modeling. The effect of site conditions on the quantification of construction materials is evaluated at a predesign level. German snow and wind load maps [28], as well as a seismic activity zoning map [29], are important sources for the CSA predesign. The process and facilities equipment does not affect the estimated calculation of the structure weights per m^2, since they have all been assumed to be directly supported on the floor without the assistance of bridge cranes. It is assumed that the site has a soil with proper bearing capacity, and that soil improvement is not needed.

3.2.2. Building Systems

The most traditional materials used worldwide for primary structural components in the building sector are structural steel and structural concrete or precast concrete [30,31]. In addition to these, structural timber is frequently found as a framing material in the residential and commercial sectors.

Table 1 describes the main constructive components quantified, i.e., the foundations, floor slabs, framings, siding, roofing, and ceiling solutions, for each of the analyzed building systems.

Table 1. Building systems' description.

Building Component	**Building Systems**		
	Steel	**Precast Concrete**	**Timber**
Building hall	Hot-rolled structural steel framing, based on wide flange columns and lattice trusses beams. Purlins, wall grits and bracing elements made of steel.	Prefabricated structural concrete portal frames, including purlins and secondary columns and grits. Bracing system of metallic bars or cables.	Structural timber or glue-laminated timber framing. Purlins, secondary pillars, girts, bracing elements made of wood.
Siding and roofing	Double-skin steel-faced sandwich panels with an insulation core.	Double-skin steel-faced sandwich panels with an insulation core.	Roofing same as for steel and precast concrete halls. Siding up to 7 m made of plasterboard panels with insulation. Siding from 7 to 15 m same as for steel and precast concrete halls.
Foundations	Cast-in-place reinforced concrete with normal compressive strength.		
Slab on grade	Normal reinforced concrete, with an epoxy-coating layer on the top.		
False ceiling	Metallic false ceiling in manufacturing and ancillary areas.		

3.2.3. Civil Design Basis

In the context of this paper, the civil discipline is responsible for the land use quantification, massive and local earthworks, roads design as well as the perimeter fencing of the project site. Occupation and transformation of land have been considered for the proportional terrain of each factory.

Massive earthworks tasks are estimated to prepare the operational platform surface with an assumed regular rectangle configuration.

The main assumptions of the design are a 3% natural slope of the terrain, 45 degrees cut and fill slopes, 25 cm clean up and natural ground with bushes excavation using mechanical equipment. The massive filling material is assumed to be reclaimed and selected soil from the site's excavation. Local excavations and backfilling volumes are estimated based on the concrete volume considered for the building's foundations.

The backfilling material is set as a mix between 50% recovered soil from the local excavation tasks and 50% externally supplied as a classified crushed or round gravel.

It is assumed that the site's soil-bearing capacity is enough to provide proper support for the light industrial halls and floor-standing pieces of equipment.

The roads have been considered in the same way as in the Ecoinvent models, as applied to the planned surface for all the internal logistic operations.

3.2.4. Structural Design Basis

The structural discipline is responsible for all the structural elements required to form process and ancillary buildings and areas, including foundations, concrete slabs, primary structure, secondary structural elements and miscellaneous items such as handrails.

A range of 12 to 15 m between vertical structural components (columns) has been assumed. Together with the predefined heights of each factory, the resulting mean values of the design ratios are as follows: 80 kg/m^2 of structural steel in the case of metallic frame-based halls, 0.4 m^3/m^2 of precast concrete for a concrete-based frame hall and 0.08 m^3/m^2 of structural timber in the case of a wooden frame-based primary structure.

Regarding the construction method for the primary structure alternatives, we have considered precast concrete, which is 100% prefabricated at a workshop, an 80% preassembled structural steel, and an in situ wooden frames construction.

In all cases, the foundations and slab-on grades follow a traditional cast in situ construction method.

3.2.5. Architectural Design Basis

The addressed and quantified architectural components of the process and ancillary buildings are the claddings, windows, internal and external doors, locksmith, and non-structural room dividers.

Double-skin steel-faced sandwich panels and plaster board panel with an insulation core are considered as siding and roofing solutions, depending on the building system evaluated. The floor finishing layer in the process areas is an epoxy coating. In the administrative areas, laminated wooden products are used as the floor.

Double glazing and PVC framing for windows are considered, with a general criterion of 10% of openings in all the facades. Metallic external doors and wooden interior doors are included.

3.2.6. Site Master Plan

With the factories and facilities halls' dimensions and a material flow analysis, an efficient site master plan layout is generated. A minimum clearance distance between the buildings' outer walls of 28 m is set for operational safety. A two-way road network of 6.4 km is traced on site; each track is 4 m wide, which results in a road footprint of 51,272 m^2. A 28 m wide perimetric landscape surrounds the industrial site for noise mitigation, rainwater infiltration and aesthetics. Figure 4 presents the resulting master plan with an area footprint of almost 50 ha. The factories' consumables enter the site through the material gate, and materials are then delivered to the *Central consumable storage*, *Chemical storage*, and *Gas yard*. The materials required for production are supplied to the corresponding factories. The finished PV modules are stored in the *Product area*. The personnel enter the factory via the *Plant entry*. The *Gas yard* and *Chemical storage* are located close to the wafer and cell factories, where most of the gases and chemicals are required. The *Central Utilities Building* provides compressed dry air (CDA), ventilation and conditioned air (HVAC), process-cooling water (PCW), ultrapure water (UPW), process wastewater treatment and facility management and control systems to all the factories. The *Effluent Treatment Plant (ETP)* manages the domestic and industrial sewage. The electrical *Substation* provides power to the whole industrial site. The emergency response team (*ERT-Fire response*) prevents and attends any sort of emergency at the industrial site. The two-story *administrative building* provides working and meeting space for the site personnel.

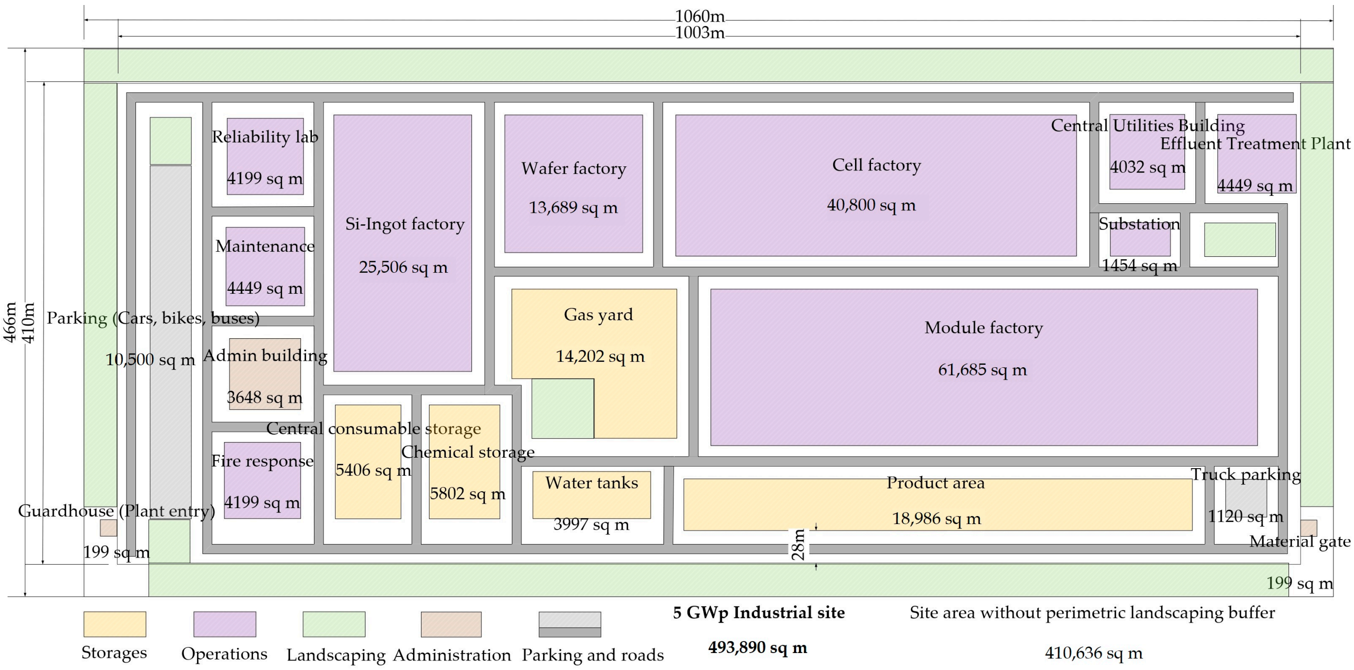

Figure 4. Site master plan layout of the 5 GWp/a fully integrated PV industrial site.

3.3. LCI Model Organization

The inflows, outflows, and unit processes used have been classified according to a construction component categorization criterion, as based on the nature of the tasks and the building's life cycle stages.

Following the EN15804 structure, the product stage components include the following items:

- material supply for massive and local earthworks as backfilling,
- concrete in situ supply for foundations and slab-on grades and reinforcing steel bars,
- structure manufacturing, structural steel, precast concrete and structural timber for building framing,
- siding and roofing solutions for enclosed halls, both metal-skin sandwich panels and plasterboard panel manufacturing,
- miscellaneous manufacturing department accountable for false ceilings, floor finishing, internal room dividers, doors, and windows,
- services supply, including drinking water network, sewage grid and reinforced concrete for electromechanical services support, and
- process equipment PE and facility equipment FE manufacture.

The construction stage components include the following works: earthwork execution, efforts for cut and fill of the operational platform, local excavations and backfills to place the underground concrete elements, structural elements erection, siding, and roofing installation, miscellaneous and services installation, and the process equipment PE and the facility equipment FE installation items before pre-commissioning. The transport of all the construction elements from the supplier's gate to the project site and the empty runs back to the corresponding warehouses or designated facilities are also allocated within this stage. The LCIs for the product and construction stages of the 5 GWp/a industrial site for the steel, precast concrete and timber building systems are reported per factory and for the ancillary buildings in the Supplementary Materials.

4. Results

The results of both comparative LCAs are presented in this section. For the first comparative LCA, the annualized environmental impact per category and factory $E_{\text{Annual},k}(F,\ B_{\text{EI}}(F))$ are presented for the proposed inventories' OMs and for the Ecoinvent ones EI, using in both cases the Ecoinvent building systems $B_{\text{EI}}(F)$. For the second comparative assessment, the industrial site setup environmental impacts $E_{\text{OM},k}(B)$ derived from the proposed inventories' OMs are reported for each building system $B \in \{\text{Steel};\ \text{Precast concrete};\ \text{Timber}\}$.

4.1. Comparison of Proposed Models with Ecoinvent Ones—First Comparative LCA—

In Table 2, the process-scaling factors per factory $S_{\text{PSF}}(F)$ used to scale the Ecoinvent datasets to the case study capacities are shown. The $S_{\text{PSF}}(\text{Wafer})$, $S_{\text{PSF}}(\text{Cell})$ and $S_{\text{PSF}}(\text{Module})$ values show that the analysed 5 GWp/a industrial site has a much higher capacity than the state-of-the-art factories within the Ecoinvent references by two to three orders of magnitude. On the contrary, the $S_{\text{PSF}}(\text{Ingot})$ reflects a two orders of magnitude smaller capacity for the case study factory.

Table 2. Process-scaling factors for the Ecoinvent factories models.

Factory (*F*)	Annual Production EI $P_{\text{EI,Annual}}(F)$	Produced Goods	Annual Production Case Study $P_{\text{OM,Annual}}(F)$	Process Scaling Factor $S_{PSF}(F)$
	[kg/year]		[kg/year]	
Si-ingot	1,000,000,000	Cz Ingots	25,902,594	0.03
	[m^2/year]		[m^2/year]	
Wafer	24,300	Wafers	24,631,830	1014
Cell	100,000	Cells	23,678,426	237
Module	15,970	Modules	25,500,741	1597

The resulting $E_{\text{Annual},k}(F,\ B_{\text{EI}}(F))$ are reported in Table 3. The percentual differences $\frac{E_{\text{EI,Annual},k}(F,\ B_{\text{EI}}(F)) - E_{\text{OM,Annual},k}(F,\ B_{\text{EI}}(F))}{E_{\text{OM,Annual},k}(F,\ B_{\text{EI}}(F))} \times 100\%$ are visualized in Figure 5. For the wafer, cell, and module factories, the EI annualized environmental impacts are strongly overestimated for most impact categories, which reflects the technology and productivity evolution over the last two decades, both in terms of the process equipment capacities and the construction techniques. For the categories *freshwater and terrestrial eutrophication*, *land use* and *respiratory effects*, overestimations of more than one order of magnitude are found for the module factory, which is also observed for the wafer factory freshwater eutrophication.

For the ingot factory, the opposite behavior is identified, showing an underestimation when using the Ecoinvent datasets in comparison to the results of this work. This unexpected outcome is explained by the very long Ecoinvent lifetime assumption $l_{\text{EI,CSA}}(\text{Ingot})$ of 100 years for this factory, 3.33 times longer than $l_{\text{OM,CSA}} = 30$, and due to the absence of a specific equipment-related inventory—e.g., Cz pullers, diamond wire saws—in this dataset.

The overall impacts of all four factories with the OMs show reductions of between 11.7% and 94.3% for 14 of the 15 impact categories. Only for the category *Minerals and metals use* is an increment of 19.2% observed.

Table 3. Annualized environmental impacts of the Ecoinvent building systems.

Category Units	Module OM	Module EI	Cell OM	Cell EI	Wafer OM	Wafer EI	Ingot OM	Ingot EI
Freshwater ecotoxicity CTUe	2.73E+08	9.75E+08	2.33E+08	4.05E+08	2.45E+08	7.57E+08	4.71E+08	1.33E+07
Carcinogenic and non-carcinogenic effects CTUh	3.90E-01	1.03E+00	3.33E-01	4.85E-01	3.37E-01	9.98E-01	6.41E-01	1.18E-02
Respiratory effects, inorganics Disease incidences	3.15E-01	3.57E+00	2.62E-01	1.23E+00	2.28E-01	8.46E-01	4.38E-01	5.59E-02
Ozone layer depletion kg CFC-11-Eq	3.17E-01	3.09E-01	2.62E-01	8.75E-01	2.05E-01	1.11E-01	3.64E-01	5.75E-03
Climate change kg CO_2-Eq	3.67E+06	2.37E+07	3.08E+06	1.31E+07	2.66E+06	7.76E+06	4.98E+06	4.00E+05
Marine eutrophication kg N-Eq	4.83E+03	3.47E+04	4.03E+03	1.52E+04	3.48E+03	1.06E+04	6.47E+03	6.03E+02
Photochemical ozone creation kg NMVOC-Eq	1.80E+04	1.14E+05	1.51E+04	5.82E+04	1.30E+04	3.90E+04	2.43E+04	2.00E+03
Freshwater eutrophication kg P-Eq	2.16E+02	8.56E+03	1.84E+02	4.61E+02	1.75E+02	6.65E+03	3.30E+02	1.38E+02
Minerals and metals kg Sb-Eq	5.47E+02	8.43E+02	4.70E+02	4.09E+02	4.97E+02	8.00E+02	9.47E+02	1.25E+01
Ionizing radiation kBq U235-Eq	1.57E+05	8.76E+05	1.27E+05	3.58E+05	1.04E+05	4.42E+05	1.87E+05	2.16E+04
Water scarcity m^3 world-Eq	1.42E+06	6.70E+06	1.19E+06	4.03E+06	1.05E+06	2.81E+06	1.97E+06	1.21E+05
Fossils MJ	4.44E+07	2.43E+08	3.72E+07	1.25E+08	3.18E+07	8.68E+07	5.86E+07	4.29E+06
Freshwater and terrestrial acidification mol H+-Eq	3.70E+04	2.39E+05	3.14E+04	6.83E+04	3.08E+04	9.60E+04	5.82E+04	3.45E+03
Terrestrial eutrophication mol N-Eq	5.50E+04	7.48E+05	4.60E+04	1.68E+05	4.04E+04	1.50E+05	7.52E+04	1.15E+04
Land use points	7.30E+07	1.12E+09	5.75E+07	2.47E+08	4.83E+07	1.93E+08	6.78E+07	2.35E+07

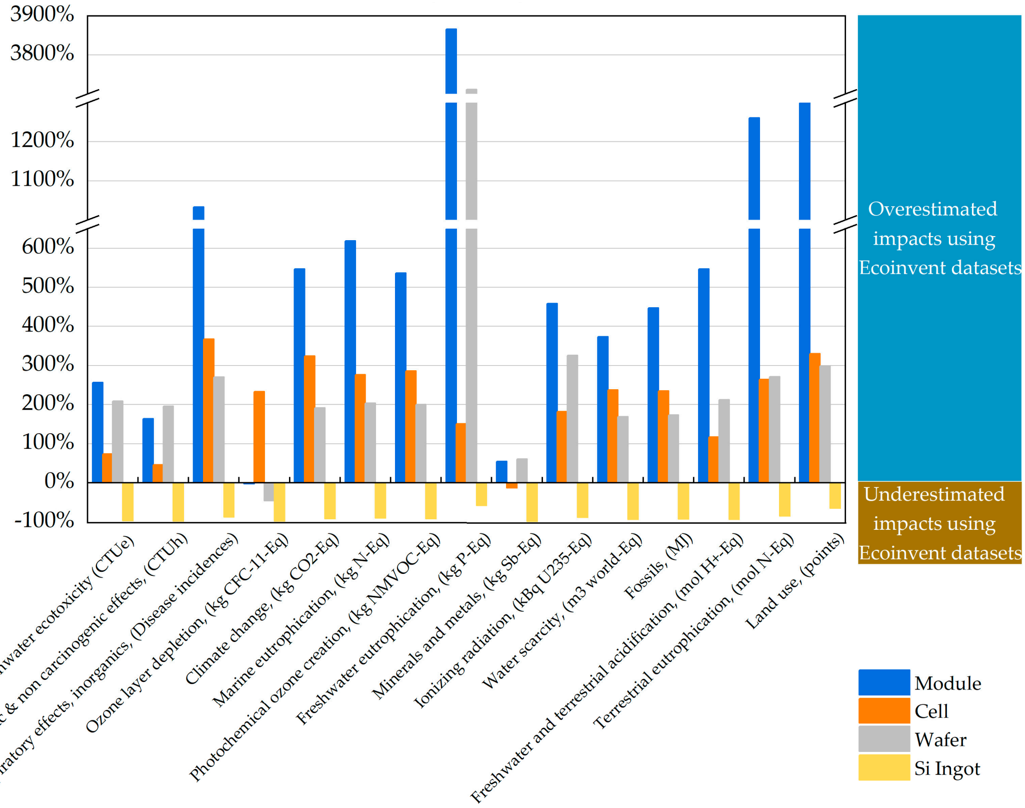

Figure 5. Annualized environmental impact differences per category and factory (Ecoinvent own model).

To further compare both inventory datasets, Figure 6 presents their impact shares per factory. The EI shares reveal the modeling approach differences between the factories; the inventories are based on data gathered from a small set of companies and with different system boundaries, as described in Section 1. For the proposed OM inventories, considering the Ecoinvent building systems, the shares have a homogenous distribution along all the impact categories due to the systematic modeling approach used for all the factories. The widest share shown by the ingot factory reflects the higher process equipment PE requirements for this factory.

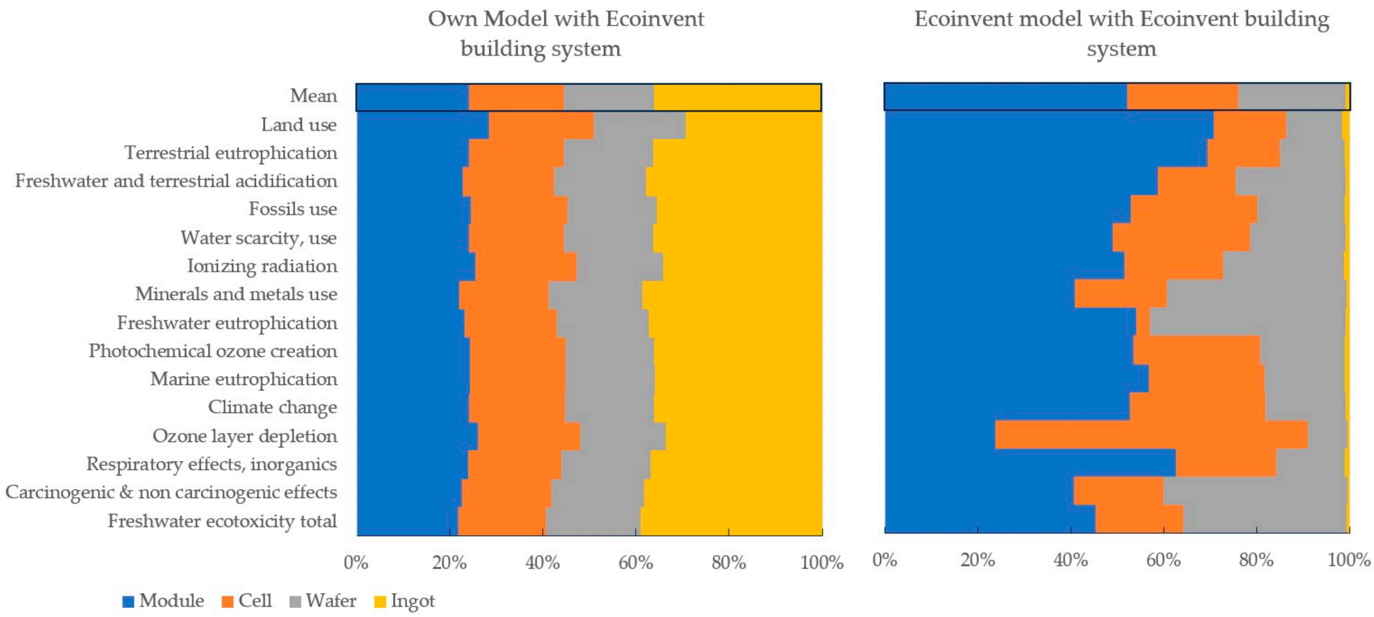

Figure 6. Annualized environmental impact shares per factory and category.

4.2. Industrial Site Setup Environmental Impacts per Building System—Second Comparative LCA—

The environmental impacts $E_{\mathrm{OM},k}(B)$ for each building system $B \in \{Steel;\ Precast\ concrete;\ Timber\}$ are reported in Figure 7. The results are aggregated by the life cycle stage, CSA components, and process and facilities equipment. In Appendix B, the results are detailed for all the items introduced in Section 3.3. At the product stage, the most impactful are the process equipment PE and facility equipment FE manufacturing, the production of the steel and precast concrete structural frames, and the concrete in situ supply. The mean environmental impact shares of the product stage are 79.0%, 78.2% and 79.2% for the steel, precast concrete, and timber structural building systems, respectively. The PE and FE equipment amounts are modeled with the inventory dataset "*metal working machine production, unspecified*". Within this dataset, the exchanges "*metal working, average for steel product manufacturing*" and "*copper cathode*" have the highest impacts.

At the construction stage, the mean environmental impact shares are 21.0%, 21.8% and 20.8% for the steel, precast concrete and timber structural building systems, respectively. Most of the *Land use* impacts are generated in this stage. Furthermore, the construction stage impacts are dominated by the earthworks execution for all the building systems B. Overall, the CSA components generate most of the *Land use* and *Ozone layer depletion* impacts. The amount of equipment drives the impacts for the categories *Freshwater ecotoxicity*, *Carcinogenic and non-carcinogenic effects*, *Freshwater eutrophication*, *Minerals and metals use*, *Water scarcity*, and *Freshwater and terrestrial acidification*. The impact categories for the department earthworks execution are dominated by the transportation of the excavated soil to a landfill site and of the gravel supply to the industrial site, as well as by the use of construction machinery for the preparation of the site and the electricity demand. The department earthworks execution has the highest influence on the impact category *Land use* due to the *Occupation and Transformation* items of the industrial use within this department.

Building system	Stage	Component	Freshwater ecotoxicity total (CTUe)	Carcinogenic & non carcinogenic effects (CTUh)	Respiratory effects, inorganics (Disease incidences)	Ozone layer depletion (kg CFC-11-Eq)	Climate change (kg CO2-Eq)	Marine eutrophication (kg N-Eq)	Photochemical ozone creation (kg NMVOC-Eq)	Freshwater eutrophication (kg P-Eq)	Minerals and metals use (kg Sb-Eq)	Ionizing radiation (kBq U235-Eq)	Water scarcity, use (m3 world-Eq)	Fossils use (MJ)	Freshwater and terrestrial acidification (mol H+-Eq)	Terrestrial eutrophication (mol N-Eq)	Land use (points)
Steel	Product	All	1.61E+10	2.22E+01	1.59E+01	1.28E+01	2.11E+08	2.32E+05	9.33E+05	1.30E+04	3.01E+04	7.15E+06	9.14E+07	2.39E+09	2.00E+06	2.65E+06	1.13E+09
	Construction	All	4.83E+08	4.38E-01	3.68E+00	1.02E+01	4.71E+07	9.18E+04	2.83E+05	4.16E+02	9.48E+01	2.91E+06	2.72E+06	6.68E+08	2.49E+05	1.01E+06	4.73E+09
	Both	CSA	3.38E+09	4.02E+00	1.01E+01	1.60E+01	1.43E+08	1.78E+05	6.57E+05	4.37E+03	1.57E+03	5.56E+06	4.39E+07	1.69E+09	6.50E+05	1.92E+06	5.06E+09
		PE + FE	1.32E+10	1.86E+01	9.47E+00	7.03E+00	1.14E+08	1.46E+05	5.59E+05	9.07E+03	2.86E+04	4.50E+06	5.02E+07	1.37E+09	1.60E+06	1.74E+06	8.07E+08
		All	1.66E+10	2.27E+01	1.96E+01	2.30E+01	2.58E+08	3.24E+05	1.22E+06	1.34E+04	3.02E+04	1.01E+07	9.41E+07	3.06E+09	2.25E+06	3.66E+06	5.86E+09
Precast concrete	Product	All	1.59E+10	2.20E+01	1.55E+01	1.25E+01	2.11E+08	2.34E+05	9.19E+05	1.27E+04	2.99E+04	7.00E+06	8.83E+07	2.32E+09	1.99E+06	2.66E+06	1.15E+09
	Construction	All	5.24E+08	4.86E-01	4.04E+00	1.09E+01	4.99E+07	9.57E+04	2.96E+05	4.31E+02	1.05E+02	3.10E+06	2.92E+06	7.12E+08	2.61E+05	1.05E+06	4.79E+09
	Both	CSA	3.22E+09	3.84E+00	1.01E+01	1.64E+01	1.47E+08	1.84E+05	6.56E+05	4.10E+03	1.38E+03	5.60E+06	4.10E+07	1.66E+09	6.49E+05	1.97E+06	5.13E+09
		PE + FE	1.32E+10	1.86E+01	9.47E+00	7.03E+00	1.14E+08	1.46E+05	5.59E+05	9.07E+03	2.86E+04	4.50E+06	5.02E+07	1.37E+09	1.60E+06	1.74E+06	8.07E+08
		All	1.64E+10	2.25E+01	1.96E+01	2.35E+01	2.61E+08	3.30E+05	1.22E+06	1.32E+04	3.00E+04	1.01E+07	9.12E+07	3.03E+09	2.25E+06	3.71E+06	5.94E+09
Timber	Product	All	1.53E+10	2.13E+01	1.45E+01	1.11E+01	1.82E+08	2.11E+05	8.21E+05	1.19E+04	2.98E+04	6.42E+06	7.98E+07	2.09E+09	1.89E+06	2.42E+06	2.25E+09
	Construction	All	4.62E+08	4.18E-01	3.49E+00	9.77E+00	4.51E+07	8.76E+04	2.69E+05	4.02E+02	9.18E+01	2.77E+06	2.63E+06	6.38E+08	2.38E+05	9.63E+05	4.71E+09
	Both	CSA	2.59E+09	3.12E+00	8.53E+00	1.38E+01	1.13E+08	1.53E+05	5.32E+05	3.23E+03	1.25E+03	4.70E+06	3.23E+07	1.36E+09	5.31E+05	1.64E+06	6.16E+09
		PE + FE	1.32E+10	1.86E+01	9.47E+00	7.03E+00	1.14E+08	1.46E+05	5.59E+05	9.07E+03	2.86E+04	4.50E+06	5.02E+07	1.37E+09	1.60E+06	1.74E+06	8.07E+08
		All	1.58E+10	2.18E+01	1.80E+01	2.09E+01	2.27E+08	2.99E+05	1.09E+06	1.23E+04	2.98E+04	9.20E+06	8.25E+07	2.72E+09	2.13E+06	3.38E+06	6.96E+09

PE:Process Equipment, FE:Facilities Equipment, CSA: Civil, Structural, and Architectural components
The coloured bars are used to better visualise the magnitude of the environmental impacts, and each building system has a different colour to facilitate the comparison

Figure 7. Environmental impacts for the 5 GWp/a industrial site setup.

Overall, for the product and construction stages together, the process and facilities equipment have mean environmental impact shares of 54.2%, 54.4% and 58.2%, respectively, for the steel, precast concrete and timber structural building systems. The remaining shares correspond to the CSA components. At this point, it is relevant to recall that the process equipment and facilities equipment have shorter lifetimes than the CSA components, which implies larger impact shares in an annualized comparison.

The environmental impact differences between the building systems are visualized in Figure 8. The reference case for the comparison is the steel-based frame structure due to its predominance in the industrial market [14], which was also reflected in the configuration of the Ecoinvent datasets. The blue and green bars show negative values when the impacts of the precast concrete and structural timber solutions, respectively, are lower than those of the steel one. The differences per category in Figure 8a show that in 14 out of 15 categories the use of structural timber leads to lower environmental impacts. Reductions of between 1.1% and 12.4% are obtained, and only the *Land use* impact increases. The reductions are mainly gained at the product stage. For the precast concrete structure, slight reductions of between 0.05% and 3.1% are observed along nine impact categories, although six categories reflect increments in the range of 0.5% to 2.1%.

The median differences per construction components in Figure 8b reflect the specific levers of the impact changes. The structural timber system impacts have important reductions in the structure and concrete in situ supply and execution. The concrete and backfilling materials requirements are smaller as the underground components' dimensions are adapted to the lighter above-ground structure. For the precast concrete system, the impacts shift due to a higher usage of concrete and lower use of steel.

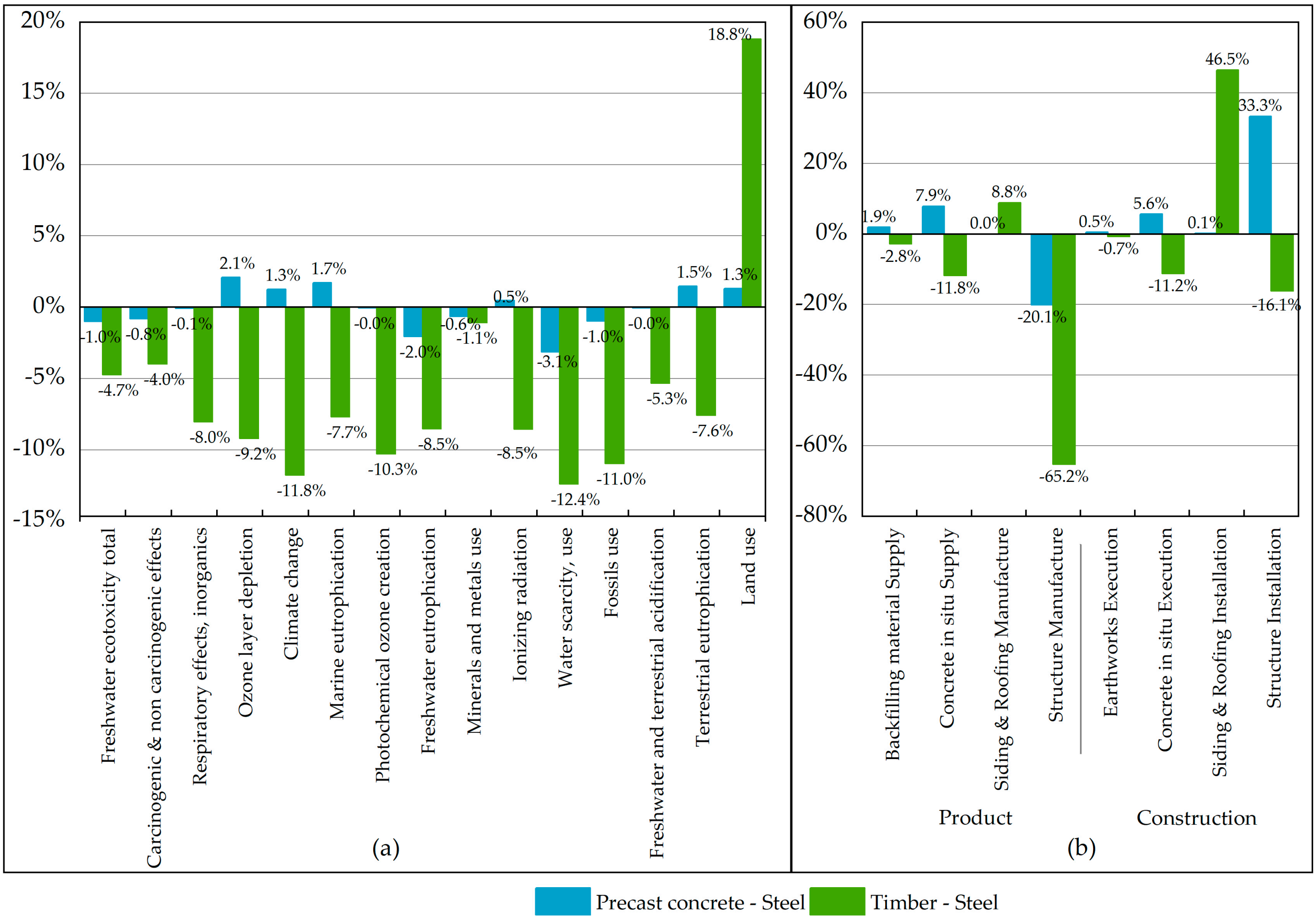

Figure 8. Environmental impact differences of the industrial site for different building systems. (**a**) Differences per category. (**b**) Median differences per construction component.

5. Discussion

Our analysis required multiple assumptions and interpretations, which create certain limitations. The details of the assumptions are set out throughout the report, especially in the Methodology section; nevertheless, they are briefly summarized as follows. Under the assumption of quantifying the bill of materials and linking it to the Ecoinvent flows and processes, for some cases it was not possible to reflect their final composition due to the lack of full suppliers' data or equivalent processes in the database, especially for composite or prefabricated products such as cladding panels and floor finishings.

Other sources of uncertainty in the assumptions are (i) the distances considered for the transport of building materials and components, which are provided in the Supplementary Materials and have been calculated based on supply mainly within the European region, and (ii) the performance rates of the building machinery used. We highlight that these assumptions have been applied across all the inventories generated and evaluated, and this is reflected in the consistency of the results.

Another source of variability is the intended use of the site. The impact depends heavily on whether the site is already suitable for industrial use or whether the land use type first needs to be transformed, e.g., from grassland or forest. Different ecosystem services will be lost or reduced as the site's land is transformed and occupied.

As stated in Section 1, the reference cases in this work are the Ecoinvent models. However, a search of other references for LCAs of industrial buildings was performed as well. The main findings of this literature review are that previous LCAs of buildings have focused on investigating the energy consumption and embodied carbon of commercial and residential buildings under different building systems [14,32–34]. Very few studies addressed industrial facilities or focus on specific building components, such as cladding or insulation alternatives. No previous works were found wherein the PEF methodology was applied to buildings and infrastructure. Considering these limitations, this study is compared to previous ones in terms of the buildings' specific initial embodied energy in GJ/m^2. Cole and Kernan (1996) studied office buildings framed with steel, conventional concrete and wood in Canada, and they reported initial embodied energies of 4.8, 4.5 and 4.3 GJ/m^2, respectively; the transport of building materials was not accounted for [32]. Aye et al. (2012) analyzed the embodied energy of an eight-story residential building made of steel, conventional concrete and timber framing, and they stated consumptions of 14.4, 9.6 and 10.5 GJ/m^2, respectively; the study did not consider the scope of the civil discipline, foundations or slabs-on grade [33]. Rodrigues et al. (2018) [34] studied an industrial building under construction in Portugal and reported an initial embodied energy of 4.9 GJ/m^2; the building system and materials were not specified and the transport of materials to the site was not considered.

In the proposed OM inventories in this work, a gross building area of 14.2 ha is quantified for all the factories on the industrial site. This results in an initial embodied energy of 10.01, 9.95 and 7.55 GJ/m^2, respectively, for the steel, precast concrete, and timber building systems. These results are of the same order of magnitude as those in the reviewed literature, with differences arising because each study has its own specific application, scope, boundary system, site conditions, design ratios and modeling assumptions. Cole and Kernan (1996) [32] and Aye et al. (2012) [33] also identified the benefits of the timber structural frame in comparison to the steel one. Aye et al.(2012) [33] stated that the conventional concrete system was slightly less energy-intensive than the timber system, but as the foundations, floor slabs and civil scope were not evaluated, there is room for uncertainty. In our inventories, we consider that the dimensions of the underground components can be reduced when using a timber structural frame due to its lighter weight. Rodrigues et al. (2018) [34] found that 96% of the energy is consumed in the product stage and just 4% in the construction stage. In our work, ranges of 47%–57% and 43%–53% are calculated for the latter, considering the set of proposed building systems. Again, these differences are due to a variety of factors, including the site conditions, system boundaries, volume ratios per m^2 of floor area, materials and their treatment, differences in architectural components, transport distances and modes, modeling dataset selection and assumptions.

In sector-specific LCA studies of PV module production, the infrastructure components have been identified as important sources of impacts for the categories *Land use* and *Resource use, minerals and metals* [8,35]; however, the specific impact quantities were not disclosed. Herceg et al. (2021) reported that infrastructure components are not considered in the GaBi database [35], which represents a critical underestimation of the environmental impacts when using this database in comparison to the Ecoinvent one. Nevertheless, the results presented in this work show that the environmental impacts of infrastructure are also underestimated for the ingot factory, and overestimated for the wafer, cell and module factories, when using the Ecoinvent datasets. Future studies should assess and report the environmental impact category shares of the product and construction stages for the full life cycle of the industrial sites, at least for the product, construction, and use stages. As a first insight, Müller et al. (2021) [36] reported a global-warming potential of 580 kgCO_2- Eq per kWp of glass-backsheet PV modules produced in Germany. Our calculated annualized polysilicon to module infrastructure *climate change* impact reported in Table 3 represents 8.89 and 2.85 kgCO_2- Eq per kWp (1.5% and 0.5% share) for the Ecoinvent factories EI model and own model OM, respectively. For other impact categories like the *Land use* and *Resource use, minerals and metals*, higher shares for the infrastructure are expected. Also, shorter lifetimes for process and facilities equipment will lead to higher shares.

We do not attempt to question the civil, structural, and architectural configuration of the industrial buildings reported in the Ecoinvent datasets. We understood and accepted from the outset of our analysis that the inventoried data represented the best available information from specific factories and a limited number of suppliers who provided information to

Ecoinvent in the early 2000s. This is indeed valuable, as it is not easy to find information from private industries in databases. However, two decades after the data collection, there is no doubt that the use of building materials has been optimized as a result of a more efficient definition of space use and the benefits of current construction methods.

The above, combined with the tremendously higher productivity levels of photovoltaic production equipment in the industrial facilities and thus the significant increase in PV products produced per square meter of factory building, has resulted in potential environmental impacts that are rather far from those that Ecoinvent provides. With the support of the present work, we strongly recommend the use of the proposed OM inventories—provided as Supplementary Materials—for the environmental assessment of PV-related infrastructure for ingot, wafer, cell, and module factories.

6. Conclusions

The two comparative LCAs presented in this work have shown significant differences in the environmental impacts, both between the Ecoinvent models and those generated for this work and between the three building systems analyzed.

The proposed OM inventories provide highly valuable datasets for the research community and industry, as they update the state-of-the-art in PV infrastructure modeling. Their bottom-up integration is also a novel approach to quantifying the impacts of industries where limited information or data have been made publicly available.

From the results reported for the industrial site environmental impacts $E_{\mathrm{OM},k}(B)$, the high relevance of the product stage for the equipment (PE and FE), steel, concrete and insulation material manufacturing should be highlighted. For the equipment, the relevance of the copper-mining impacts is to be emphasized; further research should explore the representativeness and up-to-dateness of the "*metal working machine*" and "*copper, cathode*" datasets for diverse industries to avoid associated limitations. The refining of copper and steel and the production of concrete are strongly influenced by the electricity and fuel mix, and by the shares of primary and secondary materials (recycling content) at the production sites. The proposed structural timber framing system helps to significantly reduce the environmental impacts of the CSA components. The use of environmentally friendly cladding insulation materials should also be considered.

During the construction stage, the main environmental impacts are caused by earthworks and most of the *Land use* impacts take place. The operation of construction machinery and the transportation of filling material and wasted soil to and from the project site are the specific sources of these impacts. They occur locally at the area of influence of the production site, which should be monitored by local environmental protection authorities. The physical conditions of the site—i.e., terrain slope, soil-bearing capacity—, transport distances, means of transportation and degree of modernization of the transportation fleet have a strong influence on these impacts, and they limit the extrapolation of the results.

Finally, in comparing the results with those of previous studies, it is noted that it is neither easy nor fair to make judgments, except under quite similar conditions, due to the different reference units, system boundaries, site conditions, data availability, assessment methodologies applied, and assumptions in general. Each study has its individual purpose and value, but all the studies share an interest in highlighting the issues associated with resource use and subsequent environmental impacts, and in providing recommendations for the development of further research. This paper is no exception and, based on the limitations identified, offers an invitation for further studies of the same scope. With regards to process and facilities equipment, the importance of dedicated research reflecting the state-of-the-art situation is emphasized.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en17112540/s1, File S1: The LCIs for the ancillary buildings and support areas, and for each factory considering the three analyzed building system.

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Data Availability Statement: The authors declare that the data supporting the findings of this study are available within the paper, its appendices, and the Supplementary Materials.

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Appendix A. Facilities Equipment LCI

Facility	Main Equipment	Tools Quantity (Units)	Area (m^2)	Weight (Metric Tons)	Source
Electrical substation	10-MVA containerized substations	10	1444	441	[37,38]
Central Utility Building:					
Compressed dry air (CDA) production units (compressors and filters)	9 units of 2700 m^3/h compressors	41	172	71	[39,40]
Exhaust systems (vacuum generators, filters and scrubbers)		403	223	76.1	[41,42]
HVAC and cleanroom systems (ventilators, filters, chillers)			False ceiling area of production buildings	2498	[43]
Process-cooling water (PCW) (electrical chillers)	Industrial chillers with 43 kW of cooling capacity	54	456	43	[44]
Ultrapure water (UPW) production units (pre-treatment, RO)	20.5 m^3/h containerized UPW system	8	465	152	[45]
Wastewater treatment (collection tanks, UF/RO, F-precipitation and sedimentation, neutra)		166	933	463	[46–49]
Facility Management and Control System (FMCS) (Servers, UPS)		145	693	116	[50]
Cooling tower (PCW pullers)/ adiabatic cooling	Adiabatic coolers with 397 tons of cooling capacity	32	1311	174	[51]
Effluent Treatment Plant	100 KLD sewage treatment plant (Packaged model/Civil model)	71	4473	2219	[52]
Water tanks (tanks for 24 h storage, pumps)	500 m^3 tanks	15	4066	218	[49]
Chemical storage (tanks for 30 days storage, pumps)	20 m^3 tanks	125	5814	73	[49]
Total		1070	15,355	6545	

Appendix B. Environmental Impacts of the 5 GWp/a Industrial Site Setup

Building system	Stage	Component	Freshwater ecotoxicity total (CTUe)	Carcinogenic & non carcinogenic effects (CTUh)	Respiratory effects, inorganics (Disease incidences)	Ozone layer depletion (kg CFC-11-Eq)	Climate change (kg CO2-Eq)	Marine eutrophication (kg N-Eq)	Photochemical ozone creation (kg NMVOC-Eq)	Freshwater eutrophication (kg P-Eq)	Minerals and metals use (kg Sb-Eq)	Ionizing radiation (kBq U235-Eq)	Water scarcity, use (m3 world-Eq)	Fossils use (MJ)	Freshwater and terrestrial acidification (mol H+-Eq)	Terrestrial eutrophication (mol N-Eq)	Land use (points)
Steel	Product	Backfilling material supply	5.65E+06	5.85E-03	4.45E-02	3.19E-02	2.41E+05	5.95E+02	1.90E+03	5.56E+00	5.14E+00	3.41E+04	1.10E+06	3.62E+06	2.11E+03	8.11E+03	7.41E+06
		Concrete in situ supply	7.73E+08	7.97E-01	2.06E+00	1.70E+00	3.91E+07	3.25E+04	1.40E+05	1.20E+03	2.12E+02	9.41E+05	1.18E+07	3.05E+08	1.35E+05	3.64E+05	1.14E+08
		Miscelaneous manufacture	4.43E+08	4.42E-01	6.31E-01	6.51E-01	8.04E+06	9.82E+03	3.32E+04	4.44E+02	5.99E+02	2.51E+05	4.15E+06	1.04E+08	5.05E+04	1.01E+05	4.36E+07
		Services supply	5.04E+07	2.20E-01	4.45E-01	1.84E-01	2.36E+06	2.42E+03	9.62E+03	6.75E+01	1.20E+01	5.56E+04	6.25E+05	2.94E+07	9.70E+03	2.70E+04	1.13E+07
		Siding & roofing manufacture	6.38E+08	1.04E+00	9.42E-01	1.43E+00	1.29E+07	1.64E+04	5.20E+04	6.60E+02	1.77E+02	4.53E+05	8.47E+06	2.05E+08	6.59E+04	1.27E+05	3.71E+07
		Structural steel manufacture	1.01E+09	1.11E+00	2.52E+00	2.31E+00	3.64E+07	3.01E+04	1.55E+05	1.60E+03	4.80E+02	1.07E+06	1.52E+07	4.17E+08	1.54E+05	3.46E+05	1.26E+08
		PE manufacture	8.99E+09	1.27E+01	6.32E+00	4.41E+00	7.62E+07	9.60E+04	3.70E+05	6.18E+03	1.95E+04	2.96E+06	3.42E+07	9.08E+08	1.08E+06	1.15E+06	5.39E+08
		FE manufacture	4.17E+09	5.89E+00	2.93E+00	2.04E+00	3.53E+07	4.45E+04	1.72E+05	2.87E+03	9.06E+03	1.37E+06	1.59E+07	4.21E+08	5.02E+05	5.31E+05	2.50E+08
	Construction	Earthworks execution	2.96E+08	2.88E-01	2.18E+00	5.97E+00	2.68E+07	4.90E+04	1.52E+05	2.31E+02	7.07E+01	1.69E+06	1.62E+06	3.87E+08	1.37E+05	5.40E+05	4.64E+09
		Miscelaneous & services installation	5.61E+06	5.46E-03	5.56E-02	9.28E-02	4.72E+05	1.18E+03	3.56E+03	6.28E+00	1.82E+00	2.75E+04	6.38E+04	6.37E+06	3.41E+03	1.25E+04	3.20E+06
		Concrete in situ execution	7.71E+07	5.47E-02	6.12E-01	1.86E+00	8.87E+06	1.88E+04	5.72E+04	7.44E+01	7.68E+00	5.21E+05	4.28E+05	1.22E+08	4.82E+04	2.07E+05	2.86E+07
		Siding & roofing installation	5.07E+06	4.81E-03	3.99E-02	1.02E-01	4.77E+05	1.01E+03	3.10E+03	3.83E+00	1.03E+00	3.04E+04	3.24E+04	6.77E+06	2.70E+03	1.11E+04	3.37E+06
		Structural steel installation	7.21E+07	5.90E-02	5.76E-01	1.62E+00	7.84E+06	1.62E+04	4.94E+04	8.10E+01	8.50E+00	4.74E+05	4.35E+05	1.08E+08	4.22E+04	1.78E+05	3.80E+07
		PE installation	1.90E+07	1.77E-02	1.52E-01	3.92E-01	1.81E+06	3.82E+03	1.18E+04	1.36E+01	3.47E+00	1.10E+05	9.72E+04	2.55E+07	1.05E+04	4.21E+04	1.25E+07
		FE installation	8.80E+06	8.21E-03	7.04E-02	1.82E-01	8.40E+05	1.77E+03	5.45E+03	6.29E+00	1.61E+00	5.10E+04	4.51E+04	1.18E+07	4.86E+03	1.95E+04	5.81E+06
	Both	CSA	3.38E+09	4.02E+00	1.01E+01	1.60E+01	1.43E+08	1.78E+05	6.57E+05	4.37E+03	1.57E+03	5.56E+06	4.39E+07	1.69E+09	6.50E+05	1.92E+06	5.06E+09
		PE	9.01E+09	1.27E+01	6.47E+00	4.80E+00	7.80E+07	9.98E+04	3.82E+05	6.20E+03	1.95E+04	3.07E+06	3.43E+07	9.33E+08	1.09E+06	1.19E+06	5.52E+08
		FE	4.18E+09	5.90E+00	3.00E+00	2.23E+00	3.62E+07	4.63E+04	1.77E+05	2.87E+03	9.06E+03	1.42E+06	1.59E+07	4.33E+08	5.07E+05	5.51E+05	2.56E+08
		All	1.66E+10	2.27E+01	1.96E+01	2.30E+01	2.58E+08	3.24E+05	1.22E+06	1.34E+04	3.02E+04	1.01E+07	9.41E+07	3.06E+09	2.25E+06	3.66E+06	5.86E+09
Precast concrete	Product	Backfilling material supply	5.76E+06	5.96E-03	4.53E-02	3.25E-02	2.46E+05	6.07E+02	1.93E+03	5.67E+00	5.24E+00	3.48E+04	1.12E+06	3.69E+06	2.15E+03	8.26E+03	7.55E+06
		Concrete in situ supply	8.37E+08	8.65E-01	2.23E+00	1.83E+00	4.21E+07	3.50E+04	1.51E+05	1.30E+03	2.28E+02	1.01E+06	1.28E+07	3.29E+08	1.45E+05	3.92E+05	1.23E+08
		Miscelaneous manufacture	4.43E+08	4.42E-01	6.31E-01	6.51E-01	8.04E+06	9.82E+03	3.32E+04	4.44E+02	5.99E+02	2.51E+05	4.15E+06	1.04E+08	5.05E+04	1.01E+05	4.36E+07
		Services supply	5.04E+07	2.20E-01	4.45E-01	1.84E-01	2.36E+06	2.42E+03	9.62E+03	6.75E+01	1.20E+01	5.56E+04	6.25E+05	2.94E+07	9.70E+03	2.70E+04	1.13E+07
		Siding & roofing manufacture	6.38E+08	1.04E+00	9.42E-01	1.43E+00	1.29E+07	1.64E+04	5.20E+04	6.60E+02	1.77E+02	4.53E+05	8.47E+06	2.05E+08	6.59E+04	1.27E+05	3.71E+07
		Structural steel manufacture	2.90E+08	3.25E-01	7.12E-01	7.37E-01	1.07E+07	8.67E+03	4.44E+04	4.64E+02	1.39E+02	3.30E+05	4.45E+06	1.26E+08	4.53E+04	9.95E+04	3.64E+07
		Precast concrete manufacture	4.55E+08	4.85E-01	1.26E+00	1.21E+00	2.32E+07	2.05E+04	8.56E+04	7.46E+02	1.22E+02	5.29E+05	6.57E+06	1.92E+08	8.46E+04	2.29E+05	9.74E+07
		PE manufacture	8.99E+09	1.27E+01	6.32E+00	4.41E+00	7.62E+07	9.60E+04	3.70E+05	6.18E+03	1.95E+04	2.96E+06	3.42E+07	9.08E+08	1.08E+06	1.15E+06	5.39E+08
		FE manufacture	4.17E+09	5.89E+00	2.93E+00	2.04E+00	3.53E+07	4.45E+04	1.72E+05	2.87E+03	9.06E+03	1.37E+06	1.59E+07	4.21E+08	5.02E+05	5.31E+05	2.50E+08
	Construction	Earthworks execution	2.97E+08	2.89E-01	2.19E+00	6.00E+00	2.69E+07	4.93E+04	1.53E+05	2.31E+02	7.11E+01	1.70E+06	1.63E+06	3.89E+08	1.37E+05	5.42E+05	4.64E+09
		Miscelaneous & services installation	5.61E+06	5.46E-03	5.56E-02	9.28E-02	4.72E+05	1.18E+03	3.56E+03	6.28E+00	1.82E+00	2.75E+04	6.38E+04	6.37E+06	3.41E+03	1.25E+04	3.20E+06
		Concrete in situ execution	8.13E+07	5.78E-02	6.43E-01	1.97E+00	9.44E+06	2.00E+04	6.06E+04	7.61E+01	7.97E+00	5.51E+05	4.48E+05	1.29E+08	5.11E+04	2.20E+05	2.68E+07
		Siding & roofing installation	5.08E+06	4.82E-03	4.00E-02	1.03E-01	4.77E+05	1.01E+03	3.10E+03	3.83E+00	1.04E+00	3.04E+04	3.24E+04	6.78E+06	2.70E+03	1.11E+04	3.39E+06
		Structural steel installation	1.93E+07	1.56E-02	1.58E-01	4.47E-01	2.10E+06	4.44E+03	1.36E+04	1.19E+01	2.19E+00	1.28E+05	1.08E+05	2.89E+07	1.15E+04	4.88E+04	1.02E+07
		Precast concrete installation	8.79E+07	8.71E-02	7.40E-01	1.76E+00	7.84E+06	1.42E+04	4.50E+04	8.16E+01	1.61E+01	5.02E+05	4.93E+05	1.15E+08	3.98E+04	1.56E+05	8.85E+07
		PE installation	1.90E+07	1.77E-02	1.52E-01	3.92E-01	1.81E+06	3.82E+03	1.18E+04	1.36E+01	3.47E+00	1.10E+05	9.72E+04	2.55E+07	1.05E+04	4.21E+04	1.25E+07
		FE installation	8.80E+06	8.21E-03	7.04E-02	1.82E-01	8.40E+05	1.77E+03	5.45E+03	6.29E+00	1.61E+00	5.10E+04	4.51E+04	1.18E+07	4.86E+03	1.95E+04	5.81E+06
	Both	CSA	3.22E+09	3.84E+00	1.01E+01	1.64E+01	1.47E+08	1.84E+05	6.56E+05	4.10E+03	1.38E+03	5.60E+06	4.10E+07	1.66E+09	6.49E+05	1.97E+06	5.13E+09
		PE	9.01E+09	1.27E+01	6.47E+00	4.80E+00	7.80E+07	9.98E+04	3.82E+05	6.20E+03	1.95E+04	3.07E+06	3.43E+07	9.33E+08	1.09E+06	1.19E+06	5.52E+08
		FE	4.18E+09	5.90E+00	3.00E+00	2.23E+00	3.62E+07	4.63E+04	1.77E+05	2.87E+03	9.06E+03	1.42E+06	1.59E+07	4.33E+08	5.07E+05	5.51E+05	2.56E+08
		All	1.64E+10	2.25E+01	1.96E+01	2.35E+01	2.61E+08	3.30E+05	1.22E+06	1.32E+04	3.00E+04	1.01E+07	9.12E+07	3.03E+09	2.25E+06	3.71E+06	5.94E+09
Timber	Product	Backfilling material supply	5.49E+06	5.69E-03	4.32E-02	3.10E-02	2.35E+05	5.79E+02	1.84E+03	5.40E+00	5.00E+00	3.32E+04	1.07E+06	3.52E+06	2.05E+03	7.88E+03	7.20E+06
		Concrete in situ supply	6.77E+08	6.96E-01	1.80E+00	1.51E+00	3.47E+07	2.87E+04	1.23E+05	1.05E+03	1.88E+02	8.40E+05	1.04E+07	2.68E+08	1.19E+05	3.22E+05	1.02E+08
		Miscelaneous manufacture	4.43E+08	4.42E-01	6.31E-01	6.51E-01	8.04E+06	9.82E+03	3.32E+04	4.44E+02	5.99E+02	2.51E+05	4.15E+06	1.04E+08	5.05E+04	1.01E+05	4.36E+07
		Services supply	5.04E+07	2.20E-01	4.45E-01	1.84E-01	2.36E+06	2.42E+03	9.62E+03	6.75E+01	1.20E+01	5.56E+04	6.25E+05	2.94E+07	9.70E+03	2.70E+04	1.13E+07
		Siding & roofing manufacture	6.60E+08	1.03E+00	1.03E+00	1.47E+00	1.40E+07	1.78E+04	5.67E+04	7.09E+02	2.22E+02	4.93E+05	8.85E+06	2.18E+08	7.43E+04	1.51E+05	4.34E+07
		Structural steel manufacture	2.82E+08	3.08E-01	7.01E-01	6.44E-01	1.01E+07	8.37E+03	4.32E+04	4.45E+02	1.34E+02	2.99E+05	4.22E+06	1.16E+08	4.29E+04	9.63E+04	3.51E+07
		Structural timber manufacture	4.21E+07	3.25E-02	6.06E-01	1.61E-01	1.21E+06	3.32E+03	1.20E+04	1.23E+02	4.91E+00	1.15E+05	5.00E+05	1.90E+07	9.69E+03	3.67E+04	1.22E+09
		PE manufacture	8.99E+09	1.27E+01	6.32E+00	4.41E+00	7.62E+07	9.60E+04	3.70E+05	6.18E+03	1.95E+04	2.96E+06	3.42E+07	9.08E+08	1.08E+06	1.15E+06	5.39E+08
		FE manufacture	4.17E+09	5.89E+00	2.93E+00	2.04E+00	3.53E+07	4.45E+04	1.72E+05	2.87E+03	9.06E+03	1.37E+06	1.59E+07	4.21E+08	5.02E+05	5.31E+05	2.50E+08
	Construction	Earthworks execution	2.94E+08	2.86E-01	2.16E+00	5.93E+00	2.66E+07	4.87E+04	1.51E+05	2.29E+02	7.02E+01	1.68E+06	1.61E+06	3.84E+08	1.36E+05	5.36E+05	4.64E+09
		Miscelaneous & services installation	5.61E+06	5.46E-03	5.56E-02	9.28E-02	4.72E+05	1.18E+03	3.56E+03	6.28E+00	1.82E+00	2.75E+04	6.38E+04	6.37E+06	3.41E+03	1.25E+04	3.20E+06
		Concrete in situ execution	6.88E+07	4.88E-02	5.44E-01	1.64E+00	7.90E+06	1.67E+04	5.08E+04	7.05E+01	6.97E+00	4.62E+05	3.89E+05	1.09E+08	4.28E+04	1.84E+05	2.44E+07
		Siding & roofing installation	8.98E+06	8.74E-03	5.84E-02	1.34E-01	6.89E+05	1.40E+03	4.17E+03	1.13E+01	2.38E+00	4.09E+04	1.15E+05	9.46E+06	4.58E+03	1.45E+04	6.79E+06
		Structural steel installation	1.67E+07	1.37E-02	1.37E-01	3.82E-01	1.79E+06	3.79E+03	1.16E+04	1.05E+01	2.02E+00	1.10E+05	9.50E+04	2.47E+07	9.84E+03	4.16E+04	9.08E+06
		Structural timber installation	4.10E+07	2.99E-02	3.15E-01	1.02E+00	5.00E+06	1.03E+04	3.11E+04	5.41E+01	3.35E+00	2.88E+05	2.15E+05	6.72E+07	2.62E+04	1.13E+05	1.05E+07
		PE installation	1.90E+07	1.77E-02	1.52E-01	3.92E-01	1.81E+06	3.82E+03	1.18E+04	1.36E+01	3.47E+00	1.10E+05	9.72E+04	2.55E+07	1.05E+04	4.21E+04	1.25E+07
		FE installation	8.80E+06	8.21E-03	7.04E-02	1.82E-01	8.40E+05	1.77E+03	5.45E+03	6.29E+00	1.61E+00	5.10E+04	4.51E+04	1.18E+07	4.86E+03	1.95E+04	5.81E+06
	Both	CSA	2.59E+09	3.12E+00	8.53E+00	1.38E+01	1.13E+08	1.53E+05	5.32E+05	3.23E+03	1.25E+03	4.70E+06	3.23E+07	1.36E+09	5.31E+05	1.64E+06	6.16E+09
		PE	9.01E+09	1.27E+01	6.47E+00	4.80E+00	7.80E+07	9.98E+04	3.82E+05	6.20E+03	1.95E+04	3.07E+06	3.43E+07	9.33E+08	1.09E+06	1.19E+06	5.52E+08
		FE	4.18E+09	5.90E+00	3.00E+00	2.23E+00	3.62E+07	4.63E+04	1.77E+05	2.87E+03	9.06E+03	1.42E+06	1.59E+07	4.33E+08	5.07E+05	5.51E+05	2.56E+08
		All	1.58E+10	2.18E+01	1.80E+01	2.09E+01	2.27E+08	2.99E+05	1.09E+06	1.23E+04	2.98E+04	9.20E+06	8.25E+07	2.72E+09	2.13E+06	3.38E+06	6.96E+09

PE:Process Equipment, FE:Facilities Equipment, CSA: Civil, Structural, and Architectural components
The coloured bars are used to better visualise the magnitude of the environmental impacts, and each building system has a different colour to facilitate the comparison

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