LCA of a Net Zero Energy Office Building - The New Technology Park of Bolzano

Marina
Fusco
Researcher
Institute of Renewable Energy
EURAC research
Italy
marina.fusco@eurac.edu

Ulrich Filippi Oberegger, Senior Researcher, Institute of Renewable Energy, EURAC research, Italy, ulrich.filippi@eurac.edu
Roberto Lollini, Group Leader, Institute of Renewable Energy, EURAC research, Italy, roberto.lollini@eurac.edu

Short Summary

We have performed a life cycle assessment of an office building of the planned Technology Park in Bolzano, Italy. The analysis takes into account embodied, operational and transport energy, carbon emissions and other environmental impact factors. Further, we have created two virtual scenarios that show how green choices during building design and operation can potentially reduce total life cycle energy and carbon emissions by 60%. Assessments of this kind are still missing in most design and tendering procedures, and even if they are done, they usually focus only on one single aspect at a time. Such an approach may result in a considerable waste of resources and increase in environmental impact. We have estimated that for Net Zero Energy Buildings embodied energy and transport energy may account for more than 90% of the total life cycle energy. Therefore, we strongly recommend integrating these factors in building design.

Keywords: office building; embodied energy; operational energy; transport energy; green insulation; emissions reduction; sustainable mobility; Net Zero Energy Building

1. Introduction

It is reported that conventional office buildings consume in the range of 250-550 kWh/m^2 per year and that Operational Energy (OE) for these buildings amounts to 80-90% [1]. Therefore, it seems natural to focus on OE. However, in highly efficient buildings such as Net Zero Energy Buildings (NZEB), OE is expected to be low. Therefore, Transport Energy (TE) and Embodied Energy (EE) of such buildings grow in importance. EE is even more important in office buildings that contain large amounts of steel, reinforced concrete and glass. TE can be reduced designing an efficient transport system that connects the building with the surroundings. Also, the building location affects the commuters' habits and therefore the TE.
A comprehensive Life Cycle Assessment (LCA) that includes EE, OE and TE is still rare in procurement, design and tendering procedures for new buildings. A study on residential buildings in line with such an approach has shown that EE and TE together can amount to almost 50% of the total life cycle energy demand in passive houses [2]. Office buildings are a much more complicated system from a construction and technological point of view. In this work we would like to analyse how the impact of different building life stages is transforming in a vision of very low energy demand office buildings.
Our case study is a new office building in the industrial zone of Bolzano, northern Italy. The building has been designed by Claudio Lucchin & Architetti Associati and Chapman Taylor and

denominated “Black Monolith”. Building owner and design teams aspire to reach the targets of total primary energy (PE) consumption less than 60 kWh per square meter per year and net zero energy balance. To reach these targets, a set of energy efficiency solutions has been selected during the integrated design process with the aid of dynamic simulation results. To reduce environmental impact, passive solutions, in particular natural ventilation and daylighting, have been preferred over active solutions. Apart from PV and solar-thermal renewable energy integration, otherwise wasted energy such as heated-up ground water in series with an industrial cooling process has been exploited. The building has been selected as a pilot for the European FP7 project DIRECTION dedicated to the demonstration of innovative, cost-effective and replicable energy efficiency solutions for low energy new buildings [3]. The results obtained in this study are useful to the project and to the building owners to a) better assess the sustainability of the DIRECTION pilots, b) identify the most impacting parts of them, and c) eventually unleash the potential of green alternatives.

2. Methodology

We have taken into account Operational Energy, Embodied Energy and Transport Energy in order to develop three main scenarios of the expected total life cycle energy (LCE) and emissions of the building. The method is replicable in other designs of office buildings.
The LCE is the life cycle energy demand of a building and its users and is therefore the sum of the requirements at building scale (embodied and operational) and at city scale (infrastructure and transport) [2].

2.1 Embodied Energy

We have evaluated the EE of the construction materials with the online tool “SBS Building Sustainability” (SBS) developed at the Fraunhofer Institute for Building Physics [4]. The tool integrates the European Sustainable Construction Database (ESUCO) and GaBi data [5] for less common materials.
As reported by the SBS online tool, the life cycle inventory is based on data collections from industry and on a literature research. A deviation margin of 10% is added to the results since they have not undergone independent review. The environmental profile contains the expenditures from "cradle to gate".
We have inserted the following constructive elements into SBS:

- Building envelope: major contributory elements and materials of façade and roof
- Load-bearing structure: concrete beams, pilasters, main walls, stairs and ramps
- Main party walls for services and technical rooms
- Floor slabs

For each material, the Life Cycle Inventory (LCI) of SBS takes into account the following impact factors: Primary Energy (PE), Global Warming Potential (GWP), Abiotic Depletion Potential (ADP), Acidification Potential (AP), Photochemical Ozone Creation Potential (POCP), Eutrophication Potential (EP) and Ozone Depletion Potential (ODP).
The load-bearing structure has an important impact on environment due to the considerable bulk of material. The subdivision of the indoor spaces of the Black Monolith has been kept flexible by request of building owner and future tenants. Nevertheless, main party walls have been considered as they are a common part of office buildings.
At the time of writing, bids have not been reviewed completely. Only the tendering documents with minimum equipment performance requirements have been available to us, but no information on specific brands or products. As the materials and their production chain may vary completely from one product to another, we have decided to exclude HVAC&R, lighting and renewable energy production systems from the analysis.
We have considered the following life cycle phases: production, operation, reuse/replacement and recycling/disposal taking into account a suitable lifespan for each material and a 50 years lifespan for the whole building. We haven’t considered a longer lifespan as construction materials and building system technologies change rapidly. However, the emissions distribution in the atmos-

phere changes considerably over much longer time periods [6,7]. Therefore, we have chosen a lifespan of 100 years for the emissions estimation.
SBS computes the maintenance and replacement cycles automatically according to the lifetime of the building.
First, we have performed a LCA of the actual building design as specified in the tendering documents. The building structure is of reinforced concrete. The EPS- and XPS-insulated envelope is a combination of glazed curtain walls and aluminium panels.
Next, we have chosen five claimed as greener insulation materials in order to reduce the EE and environmental impact of the façade: cotton fleece, expanded cork, hemp fibre fleece, natural rubber foam and mineral wool. We have varied the insulation thickness in order to keep the thermal transmittance of the building envelope constant. Finally, we have substituted the aluminium envelope with a wooden construction.
Based on the results, we have chosen the following three envelope variants:

- XPS- and EPS-insulated aluminium envelope
- XPS- and EPS-insulated wooden envelope
- Hemp fibre-insulated wooden envelope

2.2 Operational Energy

In SBS, the user can choose from generic equipment such as different kinds of heat pumps, boilers, chillers, etc. As the equipment and energy efficiency measures for the Black Monolith cannot be mapped in sufficient detail to the types available in SBS, we have computed the OE with a dynamic simulation model developed in TRNSYS. In the OE calculation, the PV field energy production has been subtracted from the thermal and electrical loads for HVAC&R and lighting.
We have calculated the OE for two cases. In the first case we have considered only the PV field on the roof of the Black Monolith (estimated MWh/year: 264). In the second case we have considered also the planned PV field on the roof of an adjacent historical industrial building (estimated MWh/year: 450) located on the same lot.

2.3 Transport Energy

Life cycle transport energy of a building is the energy demand associated with commuting and is mainly determined by the annual travel distances and energy intensities (energy consumed per unit of distance) of the transport modes used by the commuters [2,8].
We have compared three transport configurations: the as it is case, a case based on expected changes in Bolzano in the 20 years and a case going beyond.
The first strategy corresponds to the actual transport situation. We have combined the commuting behaviour of the roughly 40 employees at the Institute for Renewable Energy of EURAC research, Bolzano, Italy in 2013 with statistical data on transport modalities in the municipality of Bolzano shown in Table 1 [9]. We expect the near-future commuting behaviour of the roughly 300 employees working at the Black Monolith to be very similar as our offices are only 1 km away from the construction site and the future tenants will be involved mainly in RTD activities.

Table 1: Current commuting modality in Bolzano

Commuting type	Average commuting distance	Means of transport	Use percentage
Urban 65%	8 km/day	Bike Car Train Bus Motorcycle Foot	37% 29% 13% 10% 7% 4%
Extra urban 20%	50 km/day	Train Car Bus	75% 23% 2%
Extra provincial 15%	120 km/day	Train Car	75% 25%

The second strategy follows the Urban Mobility Plan 2020 for the municipality of Bolzano [10]. Compared to the previous as is solution, the bus transfers and 14% of the car transfers are substituted with tram transfers.
The third strategy envisages a transport based purely on electric vehicles: 71% train, 25% shared electric cars and 4% tram.
We have computed the TE for all three strategies using the following formula:

$$LCTE = \sum_{tm=1}^{TM} TD_{tm} \cdot DEI_{tm} \quad (1)$$

In Equation 1, LCTE denotes the life cycle transport energy demand of the building tenants. TD_{tm} denotes the total yearly travel distance of all users that use the transport mode tm and DEI_{tm} denotes the yearly direct energy intensity (energy dedicated only to propulsion per unit of distance) of the travel mode tm. We have taken the DEI_{tm} values from the literature [11].
Finally, we have calculated carbon emissions for all three strategies with the same formula where we have substituted energy intensity with carbon intensity (CO_2-equivalent emissions per unit of distance) [12].

2.4 Comprehensive scenarios

From the EE, OE and TE reduction strategies detailed above, we have developed three comprehensive scenarios listed in Table 2 that consist of meaningful combinations of the considered design factors: a) envelope construction, b) integration of RE production into the calculation of OE, and c) transport strategy. We have compared these scenarios with respect to total life cycle energy demand (LCE).

Table 2: Comprehensive scenarios for the LCE analysis

Scenario	EE	OE	TE
1 (as it is)	XPS- and EPS-insulated aluminium envelope	PV field on the roof of the Black Monolith only	As it is
2	XPS- and EPS-insulated wooden envelope	PV field on the roofs of the Black Monolith and the adjacent historical industrial building	Urban Mobility Plan for Bolzano (PUM 2020)
3	Hemp fibre-insulated wooden envelope	PV field on the roofs of the Black Monolith and the adjacent historical industrial building	Only electric vehicles

3. Results

In order to be able to compare the impact of OE, EE and TE, we have normalized the energy figures to kWh per year and the CO_2-equivalent emissions to kg/tons per year. Tables 3 and 4 report the overall energy and carbon demands for the three scenarios.

Table 3: Shares of OE, EE and TE in the total LCE for the three scenarios

Scenario no.	EE [kWh/year]	OE [kWh/year]	TE [kWh/year]	Total PE [kWh/year]
1	303,000	482,000	330,000	1,110,000
2	275,000	41,300	332,000	649,000
3	245,000	41,300	208,000	495,000

Scenario 1 is the as it is situation. The OE amounts to 38.5 kWh/(m^2 year). The PV field on the roof of the Black Monolith is estimated to produce 49.7 kWh/(m^2 year). Therefore, without renewable energy production, the OE would amount to 88.2 kWh/(m^2 year). OE, EE and TE share 43%, 27% and 30% of the total LCE, respectively. If TE is not considered, OE amounts to 61% and EE to 39% of the total LCE. 50% of the CO_2-eq. emissions are due to transport ("transport carbon"), 36% are due to building operation and 14% are due to "embodied carbon", that is, CO_2-eq. emissions caused by raw materials extraction, production processes and recycling.

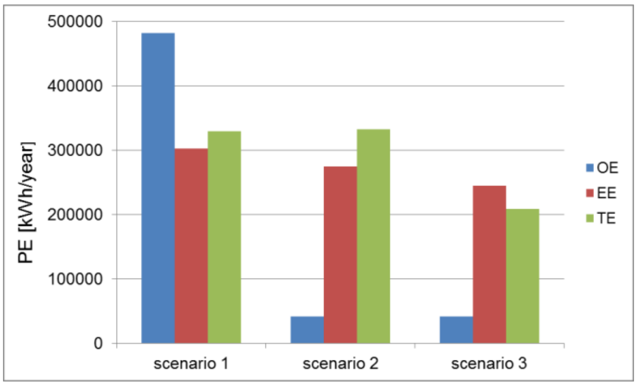

Fig. 1: OE, EE and TE shares in LCE for the three scenarios listed in Table 2

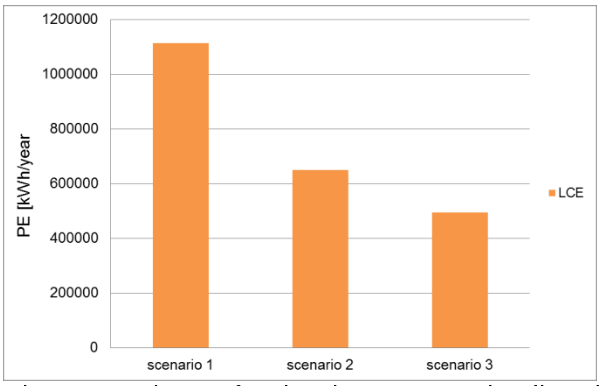

Fig. 2: Total LCE for the three scenarios listed in Table 2

Scenario 2 represents an intermediate solution. OE, EE and TE share 6%, 43% and 51% of the total LCE, respectively. The high shares of TE and EE are due to the use of cars and EPS and XPS as envelope insulation materials. If TE is not considered, EE amounts to 87% and OE to 13% of the total LCE.
Although the PE consumption due to transport is different from that in Scenario 1 by less than 1%, the CO_2-eq. emissions are reduced by 38% thanks to the Urban Mobility Plan for Bolzano. Transport is mainly responsible for carbon emissions (72% of the total carbon emissions), while embodied carbon amounts to 28%. The carbon emissions during the operational phase are lower than 1% as the electricity produced by the PV field enters the OE calculation as avoided carbon emissions. In practice, the electricity produced will be auto-consumed or fed to the grid.
The very low figures for OE in scenarios 2 and 3 are due to the applied conversion factors that profusely rewards the avoided emissions. That is, it is more a calculation effect than an actual zero emission phase.

Table 4: Shares of embodied, operational and transport emissions in tons CO_2-eq. for the scenarios listed in Table 2

Scenario no.	Embodied carbon	Operational carbon	Transport carbon	Tot.CO_2-eq
1	48,000	126,000	177,000	351,000
2	42,000	Less than 1, see text	109,000	152,000
3	38,000	Less than 1, see text	104,000	142,000

In Scenario 3, EE amounts to 50%, OE to 8% and TE to 42% of the total LCE. If TE is not considered, EE amounts to 86% and OE to 14% of the total LCE.
The CO_2-eq. emissions are 73% caused by transport (“transport carbon”). “Embodied carbon” amounts to 27%. For the same reason as in Scenario 2, the CO_2-eq. emissions during the operational phase are lower than 1%.

All other environmental impact factors assessed are listed in Table 5.

Table 5: Values of the other environmental impact factors on EE assessed for the scenarios listed in Table 2

Scenario no.	PE [kWh/m^2 year]	GWP [kg CO_2-eq]	ADP [kg Sb-eq]	AP [kg SO_2-eq]	POCP [kg ethene-eq]	EP [kg phosphate -eq]	ODP [kg R11-eq]
1	24.0	3.87	0.0286	0.0258	0.00255	0.00153	2.27 E-7
2	22.0	3.39	0.0262	0.0241	0.00243	0.00144	1.80 E-7
3	19.6	3.04	0.0225	0.0230	0.00192	0.00134	1.71 E-7
DGNB benchmark values	41.9	9.40		0.037	0.0042	0.0047	5.30 E-7

The results listed in Table 5 show that substituting the aluminium envelope with a wooden envelope reduces environmental impact by 5-12% in almost all impact categories except for the ODP which decreases by 21%.
In changing synthetic polymer insulation (XPS and EPS) with hemp fibre insulation, the highest decrease is in POCP (21%) followed by ADP (14%), whereas the other impact categories decrease by 5-10%.
The values relative to the main impact categories listed in Table 5 are all lower than the benchmark values reported by the Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council, DGNB) [13]. The values – reported in Table 6 for the convenience of the reader – are taken from a German national research project [14] in which “typical” buildings in Germany have been evaluated in order to derive benchmarks on the basis of mean values and develop an understanding of the relations between a building and its environmental impacts. The values are referred to educational, office, hotel and residential buildings in a reference study period of 50 years.

3.1 Conclusions and discussion

We have performed a LCA of a planned office building located in the industrial zone of Bolzano, Italy. In addition, we have created two virtual scenarios that show how primary energy and emissions could be reduced by 60%. We have put emphasis on a holistic approach that takes into account the primary energy consumed and produced during each life cycle phase of the building, from extraction of raw materials to deconstruction and recycling. We have also estimated the transport energy and shown that it may account for 50% of the total LCE. By substituting the current transport network with a network based on electric vehicles (shared cars, buses, trams and trains) supplied by renewable energy sources such as PV, PE savings due to transport of up to 60% may be achieved.
The shares of EE and OE reported for Scenario 1 are typical for efficient new office buildings. Good Net Zero Energy Buildings are able to reduce OE to a minimum and may have EE and OE shares similar to those reported for Scenario 2 or 3.
We conclude that, once a complete and accurate building materials, components and systems inventory will be available, a comprehensive LCA that takes into account OE, EE, TE, carbon emissions and environmental impact factors such as GWP, AP, ADP, etc. should be part of every integrated design and tendering procedure for highly energy efficient and sustainable new office buildings. It may even make sense to request a report of the LCA from bidders and to review it carefully during the bids evaluation process. Scenarios 2 and 3 demonstrate the potential and the importance of mobility plans tailored to the commuters’ needs. In Bolzano, a number of cycling

lanes cross the industrial zone. A comprehensive cycling network connecting the building with other hot spots of the city promotes sustainable mobility and improves the quality of life of the workers.

3.2 Limits of the analysis

We have considered only the main building components. Fasteners, screws, cables, etc. have not been included in the assessment. We have had to leave out lighting and building equipment of the EE assessment due to lack of detailed information on the production chains, types and amounts of materials, but we have considered the thermal and electrical loads of these systems in the TRNSYS model and hence in the calculation of OE and carbon emissions. However, we do think that the active building systems play a role in EE assessment. We are awaiting the start of the construction works to be able to integrate reliable information on these systems in the EE evaluation.
We have selected all materials from the ESUCO database without editing their predefined impact factors. Therefore, production, maintenance and recycling processes are in line with the European average. We have made this design choice not only due to lack of information on how materials will be procured during construction, but also to ensure comparability with the LCAs of the other building demonstrators chosen for the DIRECTION project.
The SBS tool does not include transportation in the process cycles assessment. Transportation of materials may lead to a 10% increase in emissions [13] [15]. The tool hasn't any option to recycle the glazing. It is supposed that the glass is simply crushed and thrown into a landfill.
We have focused ourselves on the optimization of insulation and envelope only, without working on the building structure. We have made this choice mainly because the design of the Black Monolith was already at an advanced stage when we started with the LCA, and an analysis of more substantial interventions would have been of no practical use. However, although it may be a good idea to choose green insulation materials in most cases, the insulation is probably not the main element to focus on. The LCA optimization potential of the insulation may be marginal against an optimization of the building structure and the fenestration-wall ratio.
The assessment is based exclusively on an environmental point of view. For example, from an economic point of view, green insulation may be discouraged or prohibitive.
In the assessment of the TE, we haven't considered indirect transport energy intensities. Direct transport energy denotes only the energy used for the propulsion of a vehicle. Indirect energy includes: construction, operation, maintenance and demolition of infrastructure for transport; manufacturing, service and scrapping of vehicles; fuel production for the transport sector. Indirect transport energy may amount to 10-30% of total transport energy [11].

3.3 Acknowledgement

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