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EXPLORING LIFECYCLE ZERO ENERGY DEFINITIONS AND CUMULATIVE ENERGY DEMAND OF BUILDINGS[1]

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RESUMO

O conceito de edifícios net zero (balanço neutro de energia) surgiu há alguns anos como uma referência para estabelecer metas e descrever sucesso na busca de redução agressiva do uso de energia em edificações. Como apenas a energia operacional é considerada, as entradas de energia para produção da edificação e incorporadas em outros estágios do ciclo de vida da edificação são negligenciadas. Este artigo tem por objetivo identificar o limite de viabilidade para neutralização da demanda cumulativa de energia (CED) para um edifício de demonstração, através de geração renovável onsite. A motivação é prover uma descrição mais completa do desempenho energético do edifício, pela modelagem detalhada de cada estágio do ciclo de vida e exploração de diferentes cenários para compensação. Os ciclos de produção valeram-se de dados secundários coletados ou adaptados de bases de dados internacionais. Energia secundária operacional foi obtida por simulação utilizando o software EnergyPlus. Componentes renovável e não-renovável de energia foram calculados utilizando o método CED. Simulações para dimensionamento dos arranjos PV foram realizadas utilizando o software Homer Energy. Neutralização da eletricidade operacional total mais a parcela não renovável da CED incorporada nos produtos de construção [NZ(E)B Plus status] foi considerada a meta mais alta possível de ser alcançada para o desenho atual do Living Lab.

Palavras-chave: Avaliação de ciclo de vida. Ciclo de vida de edificações. *NZEB. CED.*

ABSTRACT

The Net Zero concept emerged some years ago as an exciting - and challenging - reference to establish goals and describe success towards aggressive energy use reduction. As only the building operation is considered, the energy input to deliver the building and its components or involved in any other building lifecycle stage is not accounted for. This paper aims at exploring energy compensation scenarios beyond operation stage to identify the feasibility threshold for compensating the cumulative energy demand (CED) over a demo building's lifecycle, and at providing a more meaningful energy performance description by detailed CED modelling in every lifecycle stage. Production cycle modelling used secondary data collected or adapted from SimaPro 7.3 built-in datasets. Operational energy consumption was simulated using Energy Plus software. Renewable and non-renewable embodied energy

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components were calculated using the CED method. Homer Energy software simulations supported sizing of different PV arrays. Raw material supply and product manufacturing (43%) and the use stage (52%) clearly dominate lifecycle CED. Neutralization of the total operational electricity plus the non-renewable CED embodied in building products - NZ(E)B Plus status - w as the highest achievable goal allowed by the current Living Lab design.

Keywords*: Net zero energy. Lifecycle assessment. Building life cycle. NZEB. CED.*

1 INTRODUCTION

This paper has the International Energy Agency (IEA) Annex57 as backdrop, which investigates embodied energy and CO_{2eq} in building construction. The Net Zero concept emerged some years ago as an exciting - and challenging - reference to establish goals and describe success towards aggressive energy use reduction. As only the building operation is considered, the energy input to deliver the building and its components or involved in any other building lifecycle stage is not accounted for. NZ concept also depend on distributed renewable energy generation. From all renewable energy sources, photovoltaic (PV) energy currently shows the fastest growth rate. Considered as one of the cleanest sources of energy available, PV's environmental impacts are basically restricted to manufacturing and disposal (Fthenakis; Kim, 2011). From literature reviewed, this embodied impact fraction is seldom acknowledged in neutralization calculations.

The past decades have focused on increasing operational energy efficiency levels. As top operational performance became mainstream, focus has shifted to the proportional share of (grey) energy embodied in the products stage and in end of life processes. Existing databases and much of the literature provide data for the embodied impacts in product stage. In fact, there seems to be a consistent shortage of data across the construction sector on the energy used during all lifecycle stages (Moncaster; Song, 2012).

Description of transport to site is a big grey area and demands continuous and close interaction with logistics and transport sectors. Prediction of energy use during standard site operations becomes a fundamental part of the whole life embodied energy equation, which has been hampered by a lack of general data on energy intensity of construction equipment and activities, as well as on energy savings related to optimized site management operations. Finally, a clear understanding of the service life of individual components is necessary to support calculations of maintenance, repair, replacement and refurbishment as part of the use stage. There is also limited data on the energy used by demolition, reuse and recycling processes at the end of life of a building.

This paper aims at exploring energy compensation scenarios beyond operation stage to identify the feasibility threshold for compensating the cumulative energy demand (CED) over a demo building's lifecycle, and at providing a more meaningful energy performance description by detailed CED modelling in every lifecycle stage.

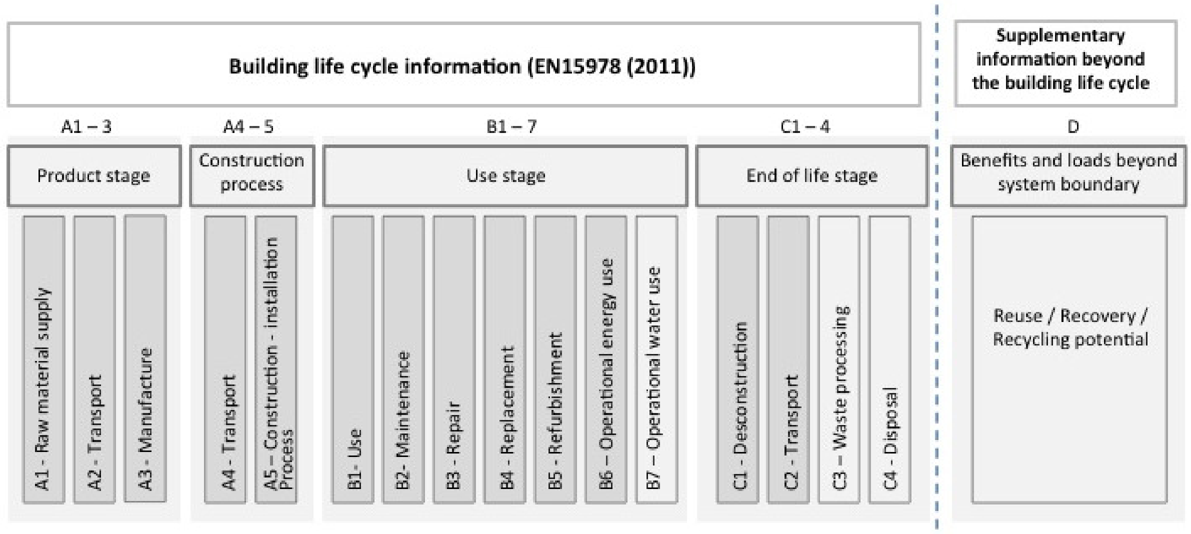
2 PURPOSE AND METHODOLOGICAL APPROACH

2.1 Overview

This research was developed in four main parts: (i) modeling production cycles of building products used in the selected case study; (ii) detailed modeling of the building lifecycle; (iii) calculation of cumulative energy demand (CED) for the different lifecycle phases, using the CED method and SimaPro 7.3 LCA support platform; (iv) modeling of PV systems comprising four different technologies, using Homer Energy software simulations.

The selected case study building is the (minLCee) Living Lab, designed for the University of Campinas – Brazil. The building's design incorporated low-energy strategies, integrated design process, resource use optimization, onsite renewable energy technologies and storm water management, low energy refrigerating system, online resource use and indoor monitoring, among other best practices. The overall system boundary established for lifecycle modeling in this study spans between Modules A1 and C2, shaded in Fig. 1.

Figure 1 - Building life cycle information stages and respective modules



Source: Adapted from BS EN 15978 (2011)

Operational energy consumption was simulated using Energy Plus. Ten neutralization scenarios (Table 1) using four different PV technologies were preset. NZ(CED)B Plus status (i.e.: compensation of total operational electricity - net zero (NZ) - *plus* non-renewable CED of building products) was originally targeted, and neutralization goals incrementally added compensation of the non-renewable primary energy embodied in raw material supply and manufacturing of building products. Finally, requirements to achieve two LC(CED) scenarios were also checked.

Table 1 - Compensation scenarios analyzed

Building lifecycle stage		**Renewable energy generation targets**
Operation (net zero, NZ) statuses		*The PV system must produce enough energy to compensate*
Operational Eletricity (NRen)	NZ(Emission) B (Torcellini et al, 2006)	The building annual non-renewable operational energy consumption
Operational Eletricity (Total)	NZ(E)B (Torcellini et al, 2006)	The total building annual operational energy consumption
CED of Operational Eletricity (NRen)	NZ(CED_{NRen}) Building	The non-renewable portion of the cumulative energy demand of Brazilian mix, grid-supplied operational electricity
CED of Operational Eletricity (Total)	NZ(CED) Building	The total cumulative energy demand of Brazilian mix, grid-supplied operational electricity
Beyond Operation *Plus* statuses (+ CED_{NRen}PROD)		*The PV system must produce enough energy to compensate…*
Operational Eletricity (NRen) + CED (NRen) of Building Products	NZ(Emission)EB Plus	The building annual non-renewable operational energy consumption *plus* the non-renewable portion of the cumulative energy demand of building products
Operational Eletricity (Total) + CED (NRen) of Building Products	NZ(E)B Plus	The total building annual operational energy consumption *plus* the non-renewable portion of the cumulative energy demand of building products
CED of Operational Eletricity (NRen) + CED (NRen) of Building Products	NZ(CED_{NRen})B Plus	The non-renewable portion of the cumulative energy demand of Brazilian mix, grid-supplied operational electricity *plus* the non-renewable portion of the cumulative energy demand of building products
CED of Operational Eletricity (Total) + CED (NRen) of Building Products	NZ(CED)B Plus	The total cumulative energy demand of Brazilian mix, grid-supplied operational electricity *plus* the non-renewable portion of the cumulative energy demand of building products
Lifecycle statuses		*The PV system must produce enough energy to compensate…*
Lifecycle CED (NRen)	LCNZ(CED_{NRen})	The non-renewable cumulative energy demand *over the whole building's lifecycle*
Lifecycle CED (Total)	LCNZ(CED)	The total cumulative energy demand *over the whole building's lifecycle*

Source: the authors

2.2 Building lifecycle modeling

The CED calculation is based on the method published by Ecoinvent version 1.01 (Frischknecht; Jungbluth, 2000). As implemented in SimaPro (PRé, 2008), characterisation factors are given for the energy resources in five impact categories, expressed by the renewable (biomass, wind/solar/geothermal and water) and non-renewable (fossil and nuclear) CED components. The CED, expressed in MJ, of each stage of the building's lifecycle was calculated by using Equations 2a to 6a and aggregated for whole lifecycle figures (Equation 1a).

$$\mathrm{CED_{LC}} = \mathrm{CED_{PROD}} + \mathrm{CED_{TR}} + \mathrm{CED_{CON}} + \mathrm{CED_{OP}} + \mathrm{CED_{EOL}} \quad (1)$$

Where CED_{LC} stands for lifecycle CED, in MJ; CED_{PROD} is the CED of extraction/manufacturing of the building products, in MJ (Equation 2); CED_{TR} is the CED of transport activities, in MJ (Equation 3); CED_{CON} is the CED of construction activities, in MJ (Equation 4); CED_{OP} is the CED of operation activities, in MJ (Equation 5); CED_{EOL} is the CED of end of life (EOL) treatment activities, in MJ (Equation 6).

- **Product stage (Modules A1 and A3)**

CED_{PROD} (Modules A1 and A3) was calculated using Equation 2.

$$\mathrm{CED_{PROD}} = \sum_{i=1}^{n} \mathrm{Q\ x\ CED_i} \quad (2)$$

Where CED_{PROD} stands for CED of extraction/manufacturing of the building products, in MJ; Q is the consumed quantity of a given building product (in mass, volume or area); n is the number of building products; CED_i is the specific CED, in MJ, per building product functional unit (kg, m^3 or m^2).

Based on the construction drawings and bases of design (BODs) documented for the Living Lab, the materials and components included in the design were quantified and inventory data sourced for the best possible match. With the exception of concrete (authors' data) and the green roofing system (manufacturer's brochure), materials and components production processes were adapted from Ecoinvent v.2.2, ELCD v.2.0, Industry Data v.2.0 and US LCI v.1.6 databases (PRé, 2008). Ecoinvent database v.2.2 (Ecoinvent, 2007) offered information for most items and was preferred for consistency sake, but merging different inventory databases and secondary sources was unavoidable.

- **Construction process stage - Freight and CDW transport**

CED_{TR} of freight transport registered within the supply chain (Module A2) and later on in the construction process stage (Module A4) was calculated using Equation 3.

$$\mathrm{CED_{TR}} = \sum_{i=1}^{n} \mathrm{M\ x\ D\ \ x\ CED_i} \quad (3)$$

Where CED_{TR} stands for CED of transport activities, in MJ; M is the transported mass, in tones; D is the travel distance, in km; n is the number of freight modals used per transport functional unit; CED_i is the specific CED, in MJ, per transport functional unit (tkm) of the used type of fuel and modal autonomy.

CED_{CON} of construction activities (Module A5) was calculated using Equation 4.

$$\mathrm{CED_{CON}} = \sum_{i=1}^{n} \mathrm{C\ \ x\ CED_i} \quad (4)$$

Where CED_{CON} stands for CED of construction activities, in MJ; C is the construction item/activity considered, in respective functional unit; n is the number of construction items/activities; CED_i is the specific CED, in MJ, per construction item/activity functional unit.

Transported mass and transportation distances were included either accurately based on actual travel distances or on best of knowledge estimations in case of missing information. Data from Ecoinvent v.2.2 and ELCD v.2.0 databases were used for modals and fuel types. The original material mass and corresponding transportation and material usage impacts were corrected using wastage factors derived by Agopyan et al (n.d.) or observed in actual construction practice. Since the case study is not built yet, construction equipment fuel use was estimated using data for consumption per m^2 of gross floor area (Yan et al, 2010) for a high-rise building in Hong Kong. Even though construction practices may differ significantly from the original context, as well as the fuel intensity for high and low-rise building construction, Brazilian data for construction activities separated from materials usage are not readily available, and a potentially more suitable figure was not found in the literature reviewed.

- **Use stage (Modules B1-B6)**

CED_{OP} of the use stage was calculated using Equation 5, by adding contributions from maintenance/repair/replacement (Modules B1-B5, i.e. material intake and transportation to the building, as well as corresponding CDW transport to EOL treatment) and operational use of energy (Module B6, 100% electricity).

$$\mathrm{CED_{OP}} = \sum_{i=1}^{n} \mathrm{Op\ x\ CED_i} \quad (5)$$

Where CED_{OP} stands for CED of use and operation activities, in MJ; Op is the operation item/activity considered, in respective functional unit; n is the number of operation items/activities; CED_i is the specific CED, in MJ, per operation item/activity functional unit.

Operational energy consumption was simulated using Energy Plus. Data from Ecoinvent v.2.2 (Ecoinvent, 2010) for low voltage electricity in the Brazilian mix were used for operational electricity impact calculation. Substitution of building products during the building's service life (Use stage, in Figure 1), was planed in accordance with the Brazilian performance standard (ABNT NBR 15575, 2013), which establishes minimum design service lives (DSL) for major building subsystems.

- **End of life stage (Modules C1-C2)**

CED_{EOL} of the end of life stage was calculated using Equation 6, by adding contributions from demolition/dismantling equipment energy use (Module C1) and from CDW transport to end of life treatment facilities (Module C2).

$$\mathrm{CED_{EOL}} = \sum_{i=1}^{n} \mathrm{EOL\ x\ CED_i} \quad (6)$$

Where CED_{EOL} stands for CED of end of life (EOL) treatment activities, in MJ; EOL is the end of life item/activity considered, in respective functional unit; n is the number of end of life items/activities; CED_i is the specific CED, in MJ, per end of life item/activity functional unit.

Two EOL scenarios were considered): (1) demolition as usual (BAU, 0% reuse | 76% recycling | 23%landfill), with 90% of material recovery rate, followed by crushing of concrete, recycling of metals as scrap and incineration of wooden material without energy recovery and landfilling of the remaining CDW; and (2) 90%-recovery efficient selective dismantling (19% reuse | 60% recycling | 20%landfill), followed by partial (40%) reuse of steel frame, crushing of concrete, recycling of steel rebar and 60% of the structural frame and incineration of wooden material without energy recovery and crushing of uncoated glass, and landfilling of the remaining CDW.

2.3 Energy demand scenarios and photovoltaic (PV) system modelling

Four crystalline silicon (single-Si, multi-Si) and thin film (amorphous-Si and CIGS) PV technology generations were simulated. a-Si is the most efficient technology in terms of system power demanded and could be a good alternative for projects with more surface available, whereas single-Si PV technology is the most efficient alternative in terms of area needed to deliver each kWp.

PV system sizing procedure using Homer Energy software discounted generation losses (1) as the orientation and exposure angle of the envelope surfaces varied for facade- and rooftop-mounted applications; (2) when the panel is subjected to outdoor temperatures above the standard test conditions[2] (Table 2); and (3) over time. To account for the latter, a degradation factor of 0.5% per year was applied, assuming a 25-year panel service life (Lima et al, 2012) to ensure that the desired performance is maintained over the whole period of study.

Table 2 - Characteristics of the different PV modules simulated here

PV technology	Module Efficiency	γP_{MPP}
single-Si	**12% to 19%**	**-0.42%/K to -0.56%/K**
multi-Si	**11% to 15%**	**-0.40%/K to -0.49%/K**
a-Si	**4% to 8%**	**-0.19%/K to -0.20%/K**
CIGS	**7%** to **12%**	**-0.36%/K to -0.42%/K**

Source: the authors (adapted from Fthenakis; Kim, 2011; EPIA, 2011; Makrides et al, 2009: Ito et al, 2008; Bravi et al, 2011)

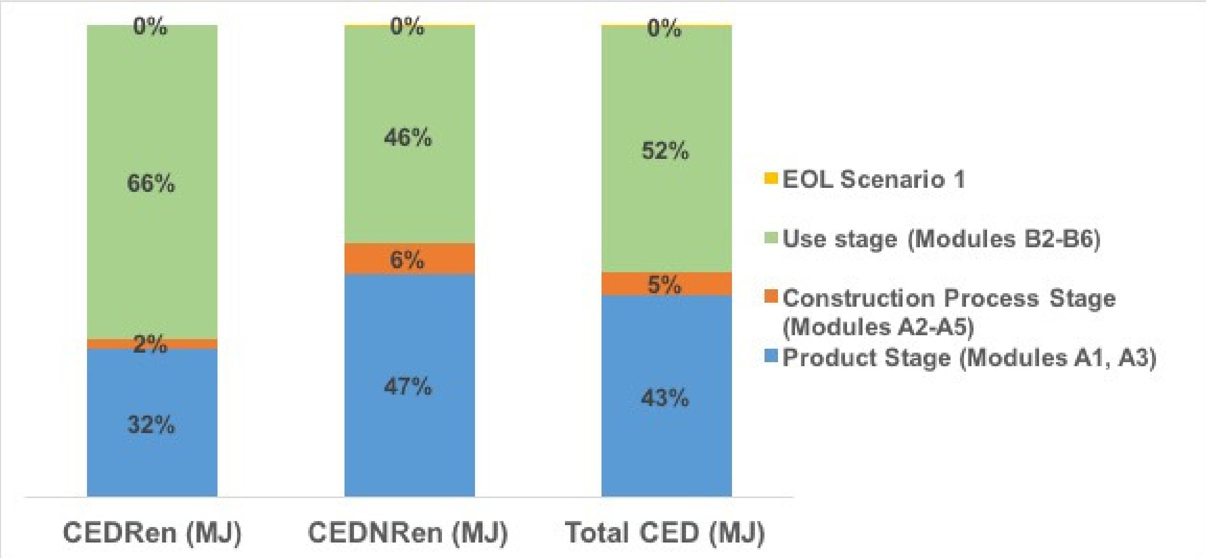
3 RESULTS PRESENTATION AND DISCUSSION

Raw material supply and manufacturing (43%) and the use stage (52%) are almost even regarding lifecycle CED (Figure 2), proving the importance of pre-use stages in energy assessment of high efficient energy buildings.

[2] Solar cell temperature of 25 ± 2°C; radiation level of 1,000 W/m^2 normal to the surface and solar spectrum of 1.5 AM (Ruther, 2004)

The structural system (41%), partitions (34%, particularly from galvanized steel frame), the PV system plus BOS (16%) and façade panels (7%) were the major contributors to CED embodied in building products. Material replacement and transportation of the corresponding CDW mass increase the CED during use stage by a factor of over four. EOL treatment scenario simulations, though highly speculative, had negligible effect on overall CED (<1% CED_{LC}).

Figure 2 – Contribution of the different stages to the life cycle CED of case studied



Source: the authors

Table 4 shows the results for the ten energy balance scenarios simulated, which ranged from net zero to complete building life cycle. Offsetting Scenarios 1, 2, 3 and 4 (ranging from the non-renewable portion [Scenario 1] to total operational electricity CED [Scenario 4] are potentially achievable using all technologies but a-Si, in the last case. This brings important flexibility to decision-making, particularly in terms of costs and smooth integration to architecture.

In fact, addition of the non-renewable CED embodied in building products to the neutralization targets ('Plus' statuses) basically rule out surface-intensive PV technologies. NZ(Emission)EB Plus status [Scenario 1a] is still achievable by using single-Si or multi-Si, but all remaining scenarios would only be accomplished if single-Si PV is used.

Table 4 - Energy balance scenarios simulated and respective system power and effective area requirements for the four PV technologies tested

PV Technology/ scenarios	System power (kWp)	Effective generation area (m²)	PV Technology/ scenarios	System power (kWp)	Effective generation area (m²)
1. Operational electricity (NRen) [NZ(Emission)EB]			**1a. Operational electricity (NRen) + CED (NRen) PROD [NZ(Emission)EB Plus]**		
single-Si	3.5	**20.59**	**single-Si**	64.47	**379.10**
multi-Si	3.49	24.94	multi-Si	64.29	459.06
a-Si	3.41	48.73	a-Si	62.77	897.03
CIGS	3.47	28.87	CIGS	63.81	531.52
2. CED Operational Eletricity (NRen) [NZ(CED_{NRen})B]			**2a. CED Operational Eletricity (NRen) + CED (NRen) PROD [NZ(CED_{NRen})B Plus]**		
single-Si	12.61	**74.14**	**single-Si**	**73.58**	**432.65**
multi-Si	12.57	89.78	multi-Si	73.38	523.9
a-Si	12.28	175.44	a-Si	71.64	1023.75
CIGS	12.48	103.95	CIGS	72.82	606.6
3. Operational electricity (total) [NZ(E)B]			**3a. Operational electricity total + CED (NRen) PROD [NZ(E)B Plus]**		
single-Si	22.74	**133.72**	**single-Si**	**83.71**	**492.22**
multi-Si	22.68	161.92	multi-Si	83.48	596.04
a-Si	22.14	316.41	a-Si	81.51	1164.71
CIGS	22.51	187.48	CIGS	82.85	690.13
4. CED Operational Eletricity (total) [NZ(CED)B]			**4a. CED Eletricity Operational total + CED (NRen) PROD [NZ(CED)B Plus]**		
single-Si	40.24	**236.62**	single-Si	101.21	**595.13**
multi-Si	40.13	286.53	multi-Si	100.93	720.65
a-Si	39.18	559.9	a-Si	98.54	1408.21
CIGS	39.83	331.76	CIGS	100.17	834.41
5. LC CED (NRen) [LCNZ(CED_{NRen})]			**5a. LC CED (total) [LCNZ(CED)]**		
single-Si	129.28	**760.17**	single-Si	180.56	**1061.69**
multi-Si	128.92	920.51	multi-Si	180.06	1285.63
a-Si	125.87	1798.73	a-Si	175.8	2512.21
CIGS	127.95	1065.81	CIGS	178.7	1488.57

Source: the authors

All net zero (NZ) energy and CED statuses would be easily reached through PV onsite generation, so that no electricity would have to be drawn from the grid during operational phase on an annual basis, as established for net zero definitions. Sizing of the PV array sufficient to cover the NZE Emission building [Scenario 1] makes it very evident that such concept does not stimulate much progress in contexts with high renewable content electricity mixes, like in Brazil.

The desired NZ(CED)B Plus goal (Scenario 4a) was missed by little, and could possibly be achieved upon slight design or modeling improvement. Optimized usage of the current envelope area met the requirements for offsetting the total operational electricity plus the non-renewable CED embodied in Product stage [NZ(E)B Plus status, Scenario 3a]. This is understood as the practical feasibility limit for the present design, given by the envelope surface available for PV mounting while keeping its architectural coherence. The corresponding 674.30 m^2 of installed single-Si PV was inserted in the building's CED lifecycle calculations (Table 3). Beyond this threshold, all scenarios simulated would require extra land use, which depend on effective generation areas larger than the building's footprint and envelope area added together.

4 CONCLUSIONS AND FINAL REMARKS

For being a demo building, the maximum generation capacity was basically limited by the available surface for applying traditional rooftop - and façade-mounted PV. The use of BIPV was not explored and could bring further material intake benefits. Ubiquitous use of visible PV panels sends a powerful message for passersby and is tuned with this particular building's mission, but would not necessarily suit other construction types. Furthermore, in real-life implementation studies, cost would still probably be a more important aspect restricting aggressive energy and GWP reducing goals.

All that said, this experience indeed helps to ground concepts and shows that they are achievable in our context, as well as the major gaps and challenges to turn NZ e CED budgeting goals into mainstream practice.

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