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RESEARCH AND ANALYSIS

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Life cycle assessment of an ecological living module equipped with conventional rooftop or integrated concentrating photovoltaics

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Abstract

Climate change is disrupting our environment and business-as-usual practices will fail to reverse its impact. This paper focuses on the impact of the building sector and, in particular, it questions the energy and environmental benefits of advanced integrated and more conventional building-applied photovoltaic (PV) systems, compared to a traditional municipality utility supply. A demonstration project named the ecological living module (ELM) is used to create a comparative life cycle assessment (LCA) of the adoption of these PV systems across three different climatic locations, namely New York City, London, and Nairobi. Findings show that, over the entire life cycle, the solar systems do better than the grid mix in reducing the building's dependence on nonrenewable resources. Unsurprisingly, in comparative terms, these systems do substantially better if the local grid mix is characterized by a predominantly nonrenewable energy profile. When comparing the two solar systems, the environmental impacts of the solar cells are negligible in the advanced system, whereas its structural components result in it being less environmentally friendly than the conventional solar PV. This highlights the possibility of future design iterations of these components to rethink their material ecology in terms of their life cycle—materiality, sourcing, and manufacturing, and so forth. The implications of this work suggest questioning, on a case-by-case basis, when and in what contexts integrated solar energy building systems are most plausible. This work also questions the scale at which grid scale distribution should occur.

KEYWORDS

buildings, concentrating solar, industrial ecology, life cycle assessment (LCA), photovoltaic, scenario analysis

1 | INTRODUCTION

1.1 | Background

Faced with impending energy and climate crises, fundamental changes to the building sector's consumption and production are indispensable for achieving global sustainable development. The built environment directly impacts nine of the seventeen UN Sustainable Development Goals (SDGs) (UN, 2015), and the sector is responsible for 40% of demand for the earth's natural resources (and specifically 40% of primary energy), contributing to a third of global greenhouse gas emissions (IRP et al., 2017). Population growth and increasing urbanization make the issue even more pressing. According to the UN (2018), world population is expected to grow by 32% by 2050, and while in 2015 about 54% of world population lived in an urban area, in 2050 this share will be almost 70%.

Therefore, the importance of construction methods and building technologies which can allow for zero and low-emission buildings is vital in combating environmental impacts.

This study considers using integrated or building-applied solar photovoltaics (PVs) to produce electricity on site. The energy and environmental performance of PVs has significantly improved in recent decades (Alsema, 2000; Alsema and De Wild-Scholten, 2004; De Wild-Scholten, 2013; Fthenakis et al., 2008; Leccisi et al., 2016; Raugei et al., 2007), and their application specifically on buildings has been the object of a number of studies (Menoufi et al., 2013; Perez et al., 2012).

Other studies focus on hybrid Photovoltaic/Thermal solar systems (PV/T) for buildings with LCA and / or energy metrics analysis (Kamthania & Tiwari, 2014; Lamnatou et al., 2019; Lamnatou et al., 2019; Souliotis et al., 2018). As discussed in a review by Lamnatou and Chemisana (2017), there is a gap in the literature regarding LCA for an environmental profile of integrated PV. Focusing on building-integrated PV/T, Lamnatou and Chemisana (2017) state that investigations which do exist present CO_2 emissions and energy pay-back time. In more recent work, Lamnatou et al. (2019) present an LCA of a façade-integrated PV/T prototype, highlighting that the largest fraction of a module's impact was from PV cells, especially regarding eco-toxicity and human toxicity-non-cancer (based on primary materials). Other studies of semi-transparent hybrid building integrated PV/T exist, such as Kamthania and Tiwari (2014) which focuses on energy metrics and carbon credits for options of a hybrid PV/T double pass façade across different weather conditions of Srinagar. These studies focus a particular technology or test a new prototype, however, the implications remain unaddressed of such technologies within broader temporal contexts of meeting operational energy demands over a building's lifespan, and how they compete with local grid mixes which are themselves evolving (and generally decarbonizing). Ritzen et al. (2019) acknowledges this, stating previous environmental impact studies of PV have been narrow in scope, focusing primarily on impacts of the specific technologies. To address this, Ritzen et al. compare three different BIPV systems, aiming to broaden the scope by calculating impacts related to carrying capacity.

To date, however, there is a sheer dearth of assessments of the dynamic, year-by-year accruement of energy demand and environmental impacts of a building equipped with on-site PVs versus those of the same building, but fully dependent on the local grid. This work is aimed precisely at this knowledge gap, and also at the additional complexity introduced by a range of geographical locations, with their own evolving electricity generation mixes.

The analysis is carried out with the Ecological Living Module (ELM) as a case study. The ELM is a demonstration house exhibited on the United Nations (UN) Plaza, New York in Summer 2018 at the UN High Level Political Forum. ELM is a built-environment framework that addresses the provision of clean, on-site energy in many different climatic contexts, especially where existing energy infrastructure does not exist. The ELM is designed to integrate either into a local (smart) mini-grid or into the (smart) national/regional grid, allowing services such as bi-directional power management, demand side management, remote metering, remote operations (e.g., available power variation, connection and disconnection), etc.

1.2 | Systems under study

The ELM is a collaboration between UN Environment, UN Habitat, Yale University School of Architecture, Yale Center for Ecosystems in Architecture (CEA) and Gray Organschi Architecture. The project aims to heighten awareness of urban housing crises, and provoke redesign and rethinking of building systems and urban infrastructure. As illustrated in the Supporting Information S1 (Figure S1.1), the ELM manages onsite clean energy, safe sustainable water, fresh indoor air quality, urban micro-farming, bio-based renewable materials, and waste management within a self-sufficient home. The concept addresses nine SDGs relating to built environment. The built environment ecosystem framework of ELM has been published elsewhere (UN Environment, 2018; Keegan, 2018), hence this paper's primary focus is on Life Cycle Impacts of the solar systems within ELM, namely a conventional, building-applied PV system (BAPV) and an integrated concentrating solar façade (ICSF[1]).

For BAPV, the choice was made to consider crystalline silicon (c-Si) technologies, which represent over 95% of global PV production in terms of installed power, and specifically on the more common (60% of global production) multi-crystalline variant (mc-Si), as it is only marginally less efficient than single-crystalline (16.7% vs. 18% module efficiency) (Fraunhofer ISE, 2019) at significantly less cost.

To represent building-integrated photovoltaics (BIPV), the ICSF was considered (cf. Figure S1.2 of Supporting Information S1). ICSF is conceived to address a building's simultaneous requirements for daylighting quantity and quality, electricity, and thermal control. The system comprises an array of largely see-through modules layered between the external and internal glazing lites of a deep-mullion curtain wall, or the layers of a canopy system (such as within ETFE pillows). The modules are concentrators which house multi-junction photovoltaics and focusing optics. The concentrators are dynamically actuated to track the sun, via the frames in which they hang. ICSF allows the direct component of insolation to be treated distinctly from the diffuse: Direct normal insolation is intercepted to generate power and reduce (or re-direct) solar gain, while diffuse daylight

[1] The Integrated Concentrating Solar Façade (ICSF) system is applicable on facades or vertical surfaces of buildings, hence its name. However, it can also be deployed in horizontal and inclined systems such as skylights and canopies. In this paper we discuss the system as an integrated concentrating solar 'roof'; however, we will continue to refer to the system as ICSF.

from the sky dome filters through and into the occupied space, with minimal attenuation or spectral change. In conception and in tested prototypes, excess thermal energy is harvested from concentrators via hydronics, generating energy storage at temperatures sufficient to drive thermodynamic processes such as sorption cooling (Novelli et al., 2015). In this study, however, details of ICSF are drawn from a commercialized instantiation wherein the concentrators are air-cooled.

Three alternative configurations are compared, namely:

(i) ELM without any PV, where all operational electricity demand is grid-supplied;
(ii) ELM with conventional building-applied photovoltaics (ELM+BAPV), where on-site generation displaces part of the grid demand;
(iii) ELM with integrated concentrating solar façade (ELM+ICSF), where—similarly—on-site generation displaces part of the grid demand.

To investigate dependence on available solar resources, as well as on grid mix composition during the use phase, the analysis was repeated in three locations: (a) London, UK; (b) New York City, NY, USA; and (c) Nairobi, Kenya. The active area of BAPV was adjusted so that on-site generation matched that provided by the fixed-size ICSF system in each location.

It is useful to note that ICSF is designed to provide sum benefits (reduction in lighting and cooling loads, power generation) for large building typologies in direct solar climates. Buildings such as offices, airports, and stadiums have larger wall and canopy areas into which active systems such as ICSF can be integrated. This potentially results in district-scale net power generation, and reduction of heat island effects, as less solar energy is absorbed by thermally massive environmental components, and less grid power is imported (and down-graded into heat through on-site use). Because of the smaller (single-unit residential) scale of the ELM studied here, and the relatively mixed solar contexts analyzed, the indirect impacts on building energy usage (lighting and cooling power reduction) were assumed to be negligible, and only direct PV generation was evaluated.

2 | METHODS

2.1 | Functional unit and system boundary

The analysis was done according to ISO standards 14040 (ISO, 2016a) and 14044 (ISO, 2016b) for life cycle assessment (LCA). The analysis unit comprises the manufacturing and use of one ELM over the first 50 years of its life, assuming demand for electricity during use phases is constant across all three configurations (i.e., irrespective of the presence or specifics of the installed solar system). The analysis unit includes all supply chain processes required for the extraction, processing, and delivery of the required materials and energy carriers over the system manufacturing and use phases, and the analysis was carried out dynamically, tracking the energy and environmental impacts as they accumulate over time, from the installation of the systems in the year 2018 through decommissioning in 2067. Regarding inputs during the operational phase, this paper focuses on electricity demand and supply, excluding other building-related consumables. This exclusion is deemed scope-appropriate, in line with the goal to use on-site solar as a sustainable source for operational energy. However, while the impacts associated with the other use-phase inputs to the ELM may be reasonably expected to be significantly smaller, they should be included, in principle, for complete quantification if whole life-cycle impacts are sought. End-of-life (EoL) treatment of the photovoltaic systems is also included, albeit limited to the replacement of modules and inverters. The EoL phase of the structural components of the solar technologies, as well as of the remainder of the ELM itself, then falls outside the analysis' system boundary, assuming that those elements will outlast the considered 50-year time frame.

2.2 | Life-cycle inventories and related assumptions

Foreground inventory data for the ELM structure were experimentally determined, as reported in the Supporting Information S1. It is noteworthy that the skylight's aluminium and glass structure is revised in configuration (iii) (ELM+ICSF), because ICSF requires a deeper curb depth than does the simple skylight in the other configurations. As such, its installation requires an additional 560 kWh of electricity (cf. Table S1.1 of Supporting Information S1), which is assumed provided by the location's grid mix, that is, respectively, that of the UK, New York State and Kenya (for London, New York City and Nairobi). The expected service lifetime of the ELM is in excess of 50 years.

As amply documented (Fraunhofer ISE, 2019), the PV industry has experienced marked improvements in recent decades, making it important to use the latest industry-vetted inventory information when assessing PV's life-cycle performance. Specifically, the foreground manufacturing inventory data of conventional mc-Si PV modules used in this study was sourced from an IEA Photovoltaic Power Systems (PVPS) Task 12 Report (Frischknecht et al., 2015a), which refers to work published in 2014 but reporting data from 2011 (De Wild-Scholten, 2014). Therefore the utilized inventory database is ultimately not very recent, but was still the most recent, reliable information available at the time of writing. To partially compensate for the vintage of the data, mc-Si PV module efficiency was adjusted based on the latest reported figures (Fraunhofer ISE, 2019). Also,

TABLE 1 Main performance parameters and assumptions for BAPV system

Parameter	Value	Ref.
Global tilt irradiation (GTI) [kWh·m^{-2}·yr^{-1}]	1200 (London) 1700 (New York) 1900 (Nairobi)	Global Solar Atlas (2016)
DC system efficiency	16.7%	Fraunhofer ISE (2019)
Performance ratio (PR)	0.80	Frischknecht et al. (2016)
AC system efficiency	13%	= (DC system eff.) x (PR)
BAPV system area [m^2]	4.8 (London) 5.7 (New York) 4.7 (Nairobi)	Calculated so as to deliver the same electricity per year as the fixed-size ICSF system
Yearly degradation rate	0.5%	Jordan and Kurtz (2013)
System lifetime [yr]	25	Conservative assumption, after: Frischknecht et al. (2016)
Electricity production [kWh/yr] Year 2019	611 (London) 1018 (New York) 950 (Nairobi)	First year of operation
Electricity production [kWh/yr] Year 2043	542 (London) 903 (New York) 842 (Nairobi)	+25 years = at end of first PV system's lifetime
Electricity production [kWh/yr] Year 2044	841 (London) 1402 (New York) 1.308 (Nairobi)	Right after replacement of PV system
Electricity production [kWh/yr] Year 2068	746 (London) 1243 (New York) 1160 (Nairobi)	+50 years

Chinese module production was assumed, as this represents over 70% of global production (Fraunhofer ISE, 2019), and the model for the electricity used in PV manufacturing was duly adapted based on the current Chinese grid mix. Further details on the LCA model used for mc-Si PV modules is available in previous publication by some of the same authors (Leccisi et al., 2016).

LCI data for the balance of systems (BOS) of the BAPV (including structure and electrical components) for a typical rooftop-mounted installation were sourced from the widely accepted Ecoinvent v3.5 LCI database (Wernet et al., 2016). Also, for all processes, the Ecoinvent default "allocation at the point of substitution" model was adopted.

Table 1 summarizes performance parameters and assumptions for the BAPV system, with associated references. Global Tilt Irradiation (GTI) values are used, as the ELM's roof pitch is designed at a similar angle to the location's latitude. The BAPV's lifetime was conservatively assumed to be 25 years, meaning that it was assumed to be replaced mid-way through the expected lifetime of the ELM. As mentioned in Section 2.1, however, such replacement was limited to the solar panels and the inverter, while the structural BOS was re-used. Based on reported roadmaps for c-Si PV efficiency improvements (Frischknecht et al., 2015b), the replacement PV modules installed in year 2044 (i.e., 2018 + 25) were assumed to be 23% efficient.

Foreground inventory data for ICSF were determined from product data, excepting the manufacture of the InGaP/GaAs/Ge triple-junction solar cell, which was derived from a combination of the manufacturer datasheet (Spectrolab, 2011) and the few existing literature LCAs of this technology (Fthenakis & Kim, 2013; Hong et al., 2014). The inventory data for the electrical BOS were sourced from Ecoinvent. The LCA model used for the ICSF system is detailed in the Supporting Information S1 (Figure S1.3).

Table 2 summarizes the performance parameters and assumptions for ICSF, with associated references. Direct Normal Irradiation (DNI) values are referenced (rather than GTI) because ICSF is a tracking system that transmits the diffuse portion of incident solar energy as light, rather than collecting it for power conversion. But unlike free-standing tracking PV, because ICSF is integrated into the building's envelope, the DNI available for conversion is scaled down by the cosine of the angle of incidence (AOI) between the solar vector and the normal vector of the surface. Two additional factors attenuate the available insolation. One factor is the aperture ratio (AR), the fraction of total array area that is active collector surface (as opposed to tracking structure). The second factor is glazing losses: because ICSF is integrated into a deep-mullion window, there is glazing layer in front of the modules, which reflects and scatters some power.

TABLE 2 Main performance parameters and assumptions for ICSF system

Parameter	Value	Ref./Comment
Direct normal irradiation (DNI) [$kWh \cdot m^{-2} \cdot yr^{-1}$]	900 (London) 1500 (New York) 1400 (Nairobi)	Global Solar Atlas (2016)
Cosine law reduction	0.73	Due to constraint of dynamic tracking system integrated with static skylight
DNI*cos(AOI)	660 (London) 1072 (New York) 1012 (Nairobi)	Solar energy available to ICSF (on skylight surface) for conversion
Cell efficiency	38%	Spectrolab (2011)
(DC system eff.)/(cell eff.)	0.74	Kim et al. (2008)
DC system efficiency	28%	= (cell eff.) x (DC system eff.)/(cell eff.)
Aperture ratio (AR)	0.765	Per ICSF mechanical design
Glazing transmittance (GT)	0.88	Fresnel reflectance losses at varying AOI, glazing makeup
Effective DC system efficiency	18.8%	DC system eff. x AR x GT with respect to DNI*cos(AOI)
Performance ratio (PR)	0.80	Frischknecht et al. (2016)
AC system efficiency	15.1%	Effective DC system eff. x PR
ICSF system area [m^2]	4.5	Fixed ELM skylight size
Yearly degradation rate	0.5%	Assumed = mc-Si PV
System lifetime [yr]	25	Conservative assumption
Electricity production [kWh/yr] Year 2019	611 (London) 1018 (New York) 950 (Nairobi)	First year of operation
Electricity production [kWh/yr] Year 2043	542 (London) 903 (New York) 842 (Nairobi)	+25 years = at end of first PV system's lifetime
Electricity production [kWh/yr] Year 2044	812 (London) 1353 (New York) 1.263 (Nairobi)	Right after replacement of PV system
Electricity production [kWh/yr] Year 2068	720 (London) 1199 (New York) 1119(Nairobi)	+50 years

As with the BAPV, the core elements of ICSF were assumed to have a 25 years lifetime, and would be replaced mid-way through the expected lifetime of the ELM. The details of which ICSF components are assumed replaced are provided in the Supporting Information S1 (Table S1.2). Extrapolating the reported trends for triple-junction efficiency improvements of +5% every 10 years (NREL, 2019), the solar cells in the replacement ICSF to be installed in year 2044 (i.e., 2018 + 25) were assumed to be 51% efficient.

For both BAPV and ICSF systems, EoL management was modelled per current PV treatment facilities, as described in a second IEA Photovoltaic Power Systems (PVPS) Task 12 Report (Stolz et al., 2018). Accordingly, the model includes all the necessary inputs for the take-back of the modules and the recycling of the glass, aluminium and copper contents, plus the associated avoided burdens arising from the displacement of the respective shares of primary materials in the current market supply mixes. All masses were duly re-scaled to conform to the actual size and material composition of the BAPV and ICSF modules considered in this study. All other materials, including the Si and triple-junction photoactive layers, were instead assumed to be simply landfilled or, in the case of plastics, incinerated, since recycling these materials is still not economically viable, given the current PV waste stream volumes. While this situation may change in the future, when PVs are more widespread and a critical mass of modules starts reaching its EoL, and dedicated PV panel recycling plants may eventually become the norm (IRENA & IEA-PVPS, 2016; Komoto et al., 2018), a large degree of uncertainty remains, and the choice was made remain conservative and refer to current EoL practices.

Finally, all background processes (i.e., those for the supply chains of glass, steel, aluminium, and all the other material and energy inputs required by the analyzed systems at the foreground level) were modelled per the life-cycle inventory (LCI) information provided in Ecoinvent (Wernet et al., 2016).

2.3 Use-phase energy model

The gross yearly electricity demand of the ELM was quantified at 2200 kWh/yr for the London location, 2600 kWh/yr for New York, and 2100 kWh/yr for Nairobi. It is worth noting that typical residential buildings in these cities would have the following yearly electricity demand, 3080 kWh/yr for London (Ovo Energy, 2019), 6860 kWh/yr for New York (US EIA, 2019), and 2400 kWh/yr for Nairobi (Africa Check, 2017). The reduced area of the ELM footprint is one explanation for its reduced electricity demand. The New York example in particular has a smaller energy demand than a typical New York City residence by a factor of almost 2.5. Some of the reasons for this involve a number of features in the ELM's design (Dyson & Keena, et al, 2020). The ELM optimizes passive systems to reduce demand for energy, heating, and cooling. Designed for the Northeast United States, the roof slopes to face south for maximum solar exposure for the BAPV system, while the loft's operable clerestory window faces north to minimize unwanted heat gain and provide ample natural light during the day. At the other end of the ELM, the roof shades the sliding porch door during the summer months reducing the need for cooling via mechanical means. Another example of this is when the door is opened and cross-ventilation cooling occurs throughout the living area and provides fresh cool air up to the loft by harnessing the stack effect. These methods are effective in this climate type which is primarily a heating-dominated climate throughout the year with only three months of the year needing extensive cooling. The building's structural assemblies play an integral role in reducing the ELM's energy demands: exposed timber finishes act as a natural hygrothermal buffer to stabilize indoor air humidity and temperature, while the bio-insulated enclosure operates as a vapor open system to allow the building to mitigate its moisture content.

The gross yearly electricity demand of the ELM numbers were results of simulation using the building energy model engine EnergyPlus, described in Crawley et al. (2000), version 9.3. The ELM was modeled in the CAD software Rhinoceros. The Honeybee plugin for the graphical algorithm editor Grasshopper was used to generate the energy model definition for processing in EnergyPlus, including climate, geometry, and functions for photovoltaics and power handling, as well as assigning the building loads, occupancy schedules, and construction materials. ELM is constructed with Cross Laminated Timber (CLT), has a red cedar cladding and double-glazed fenestration. The annual results, for an ideal air loads system with 18°C and 25°C thermostat setpoints, are then broken down for cooling, heating, equipment, and lighting loads for all three climate types. As already mentioned in Section 1.2, in terms of operational energy we compared three scenarios:

(i) the first scenario assumed that the ELM sourced all its electricity demand from a local utility source;
(ii) the second scenario assumed the roof has a traditional BAPV calculated so as to deliver the same electricity per year as the fixed-size ICSF system;
(iii) the third scenario assumes the roof light has the ICSF system, that captures renewable solar energy and produces electrical energy to offset the electrical building loads. This system is acting as a shading device to the roof since it captures the direct solar rays and converts them into renewable energy, hence only allowing diffuse light into the building. For these reasons, total demand was assumed to be constant across scenarios, although it was specific to climate (cf. Supporting Information S1).

The energy and environmental impacts arising during the use phase of the ELM were calculated twice, using two alternative methodological approaches and sets of assumptions.

In the first approach, which may be framed as a more conventional "attributional" life cycle assessment, the net demand for outsourced electricity in each year was first calculated as the difference between the gross demand by the ELM and the amount of electricity produced on site by the PV systems (such net demand remained positive in all scenarios and for all locations). The associated impacts were then simply computed on the basis of the impact indicators for the average grid mix that supplies electricity to the building (such information is provided in Tables 3, 4, and 5, respectively for London, New York, and Nairobi). This first approach is arguably more suitable to estimate the impacts accruing over the life time of an individual ELM when the electricity generated by the solar systems can be directly used on site in real time.

Instead, the second approach, which corresponds to the adoption of a "consequential" LCA viewpoint, starts by identifying specific "marginal" electricity generation technologies for each location, which are those that may be assumed to be readily displaced by a direct injection of electricity <u>from</u> the ELM <u>to</u> the grid, due to their output being more easily and economically modulated. The ELM use-phase impacts are then calculated as the difference between the impacts of its gross electricity demand as supplied by the grid (again using the grid mix-specific indicators provided in Tables 3–5), and the (avoided) impacts that would have been caused if using the marginal technologies to generate the same amount of electricity that is fed back to the grid by the on-building solar systems. This second approach is more applicable to the investigation of the energy and environmental consequences of a future scenario in which a (potentially large) number of ELMs would be installed, and the associated combined distributed solar electricity generation would effectively nudge the grid mix itself towards a reduced dispatching of the marginal technologies.

TABLE 3 Current (2018) and future (2050) composition for the grid mix in the UK (% electricity delivered by technology), and associated life-cycle impact indicators (CML, 2019) for the whole grid mix in terms of global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP), abiotic depletion potential (ADP, elements) and nonrenewable cumulative energy demand (nr-CED)

Technology	2018	2050
Coal steam turbines	5%	0%
Oil steam turbines	0.3%	0%
Natural gas combined cycles	39.5%	1.2%
Natural gas combined cycles with carbon capture and sequestration	0%	2.5%
Nuclear	19.5%	19.5%
Biomass steam turbines	7.3%	2.3%
Biogas steam turbines	3.6%	4.4%
Waste	1.8%	1%
Wind (offshore)	8.2%	44%
Wind (onshore)	9.3%	12%
Photovoltaic	4%	8%
Hydro	2%	2%
Tidal	0%	3%
GWP [kg CO_2-eq/kWh]	0.25	0.042
AP [kg SO_2-eq/kWh]	$1.7{\cdot}10^{-3}$	$1.5{\cdot}10^{-3}$
HTP [kg 1,4-DB-eq/kWh]	0.084	0.090
ADP [kg Sb-eq/kWh]	$2.9{\cdot}10^{-7}$	$1.5{\cdot}10^{-7}$
nr-CED [MJ/kWh]	7.10	3.8

TABLE 4 Current (2018) and future (2030) composition for the grid mix in New York State (% electricity generated by technology), and associated life-cycle impact indicators (CML, 2019) for the whole grid mix in terms of global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP), abiotic depletion potential (ADP, elements) and nonrenewable cumulative energy demand (nr-CED)

Technology	2018	2030
Oil steam turbines	2%	0%
Natural gas steam turbines	4%	0%
Natural gas combined cycles	33%	2%
Nuclear	34%	28%
Hydro	24%	48%
Wind (onshore)	3%	3%
Wind (offshore)	0%	14%
Photovoltaic	0%	5%
GWP [kg CO_2-eq/kWh]	0.21	0.023
AP [kg SO_2-eq/kWh]	$5.1{\cdot}10^{-4}$	$7.5{\cdot}10^{-5}$
HTP [kg 1,4-DB-eq/kWh]	0.074	0.045
ADP [kg Sb-eq/kWh]	$7.4{\cdot}10^{-8}$	$2.0{\cdot}10^{-7}$
nr-CED [MJ/kWh]	9.38	6.93

2.4 | Grid mix scenarios and marginal electricity generation technologies

In the UK, the whole electricity transmission network is owned and operated by a single company, National Grid, who also publish "Future Energy Scenarios" (FES) reports every year. These reports, among other things, contain a number of alternative roadmaps for the development of the UK electricity grid, in light of the technological and political developments in the country. In the latest edition of the FES report (National Grid, 2019), four such roadmaps are presented, with varying degrees of decentralization and increasing speeds of decarbonization. Among these, for the

TABLE 5 Current (2018) and future (2037) composition for the grid mix in Kenya (% electricity generated by technology), and associated life-cycle impact indicators (CML, 2019) for the whole grid mix in terms of global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP), abiotic depletion potential (ADP, elements) and nonrenewable cumulative energy demand (nr-CED)

Technology	2018	2037
Coal steam turbines	0%	10%
Oil steam turbines	34%	0%
Geothermal	28%	57%
Hydro	37%	25%
Wind (onshore)	1%	18%
GWP [kg CO_2-eq/kWh]	0.43	0.16
AP [kg SO_2-eq/kWh]	0.0035	0.016
HTP [kg 1,4-DB-eq/kWh]	0.16	0.13
ADP [kg Sb-eq/kWh]	$1.5 \cdot 10^{-7}$	$2.7 \cdot 10^{-7}$
nr-CED [MJ/kWh]	6.35	2.90

purposes of this work the choice was made to focus on the "Two degrees" scenario, which aims to meet the government's decarbonization target legally binding the UK to reduce the greenhouse gas emissions by at least 80% from 1990 levels by 2050 (Climate Change Act, 2008). Table 3 summarizes the 2018 UK grid mix composition (UK Gov., 2019) in terms of electricity generated, and the projected changes for the year 2050 according to the FES "Two degrees" scenario. Table 3 also reports the life-cycle impact metrics per kWh of grid-generated electricity (cf. Section 2.5), calculated using an LCA model described in detail elsewhere (Raugei et al., 2020). For the purposes of the present analysis, the focus was set on UK domestic generation (i.e., the <5% of electricity exchanged with the continent via the interconnectors was disregarded), and a linear transition in grid mix composition from 2018 to 2050 was assumed, and a constant grid composition thereafter until 2067.

When adopting the "consequential" approach, the first methodological step consists of the selection of the marginal electricity technologies that are assumed to be displaced by distributed renewable generation. Although in reality marginal electricity generation typically entails a mix of different generators (e.g., see Fell & Johnson, 2020), the specific technologies that stand out as the most favorable candidates for displacement are those that meet the following three criteria: (i) a comparatively high carbon intensity (so that displacing them results in a net carbon emission reduction), (ii) dispatchability[2] and (iii) a relatively fast response time (which allow them to be used to balance supply and demand in real time). Natural gas combined cycles (NGCC) meet all three such criteria, and in the UK they are expected to continue contributing to the mix all the way to 2050, albeit with progressively reduced penetration and, towards the very end of the considered time frame, with partial reliance on carbon capture and sequestration (CCS). Consequently, NGCC was selected here as the assumed marginal technology to calculate the avoided impacts associated to on-building solar generation in the UK.

The electricity grid of New York is managed by the New York Independent System Operator (NYISO), who runs the wholesale market for the state and acts as the balancing authority. The New York state senate recently adopted Bill S6599 (The New York Senate, 2019), which amended the previous Clean Energy Standard (New York State Public Service Commission, 2016) and requires 70% renewable electricity generation by 2030, and also specifically mandates the installation of 6 GW of PV by 2025, 9 GW of offshore wind by 2035, and 3 GW of energy storage by 2030. Table 4 summarizes the projected change in the NY grid mix composition from 2018 to 2030 according to such model, and the calculated life-cycle impact metrics per kWh of grid-generated electricity (cf. Section 2.5), using an LCA model developed and described elsewhere (Murphy & Raugei, 2020). For the purposes of the present analysis, a linear transition in grid mix composition from 2018 to 2030 was assumed, with a constant grid composition from then on until 2067.

In the case of New York, the selection of the marginal electricity generation to estimate the avoided impacts in the "consequential" approach was complicated by the fact that NGCCs are expected to be drastically phased out earlier, with their share in the mix already dropping to below 2% by 2030. As a consequence, the assumption was made that after 2030, hydroelectricity (a large share of which is imported from out of state) would replace NGCCs as the most readily displaced "marginal" technology. However, while from a technical standpoint reservoir hydro plants are often characterized by even faster response times and hence lend themselves even better to grid balancing, from an environmental perspective the emission and energy benefits of displacing them with distributed solar generation are clearly reduced versus NGCCs.

In Kenya, the Ministry of Energy, in direct collaboration with the Energy Regulatory Commission, produced an Energy Sector Report intended to guide the sector on sector status, generation expansion opportunities, transmission infrastructure target network expansion as well as resource requirements for the expansion programme until the year 2037 (Energy Regulatory Commission, 2018). Table 5 summarizes the projected change in the Kenyan grid mix composition from 2018 to 2037 according to such report, and the resulting life-cycle impact metrics per kWh of grid-generated

[2] Dispatchable generation refers to sources of electricity that can be turned on or off, or can adjust their power output, at the request of power grid operators.

electricity (cf. Section 2.5), using an LCA model developed specifically for this study. For the purposes of the present analysis, a linear transition in grid mix composition from 2018 to 2037 was assumed, with a constant grid composition from then on until 2067.

At present, the choice of marginal technology for the Kenyan grid is straightforward: the "oil steam turbines" in widespread use in the country are typically small Diesel or light fuel oil (LFO) generators, which are not only readily dispatchable, but high-carbon and polluting units, too, with obvious benefits in terms of avoided impacts. However, Kenya is planning their complete phase-out by 2037. The few large coal power plants that are going to partially replace them are bound to have much slower response times and will therefore not lend themselves to being exploited for anything else than stable "baseload" generation. Instead, the country's planned future reliance on geothermal energy for more than half of the electricity grid mix, coupled with recent technological development trends for such technologies (Michaelides, 2016), may be taken as indications that geothermal will likely become the go-to "marginal" technology for Kenya in the future, and this is the assumption that was made in this study for 2037 onwards.

2.5 | Life-cycle impact and energy assessment

In terms environmental impacts, the focus was set on four prominent impact categories, namely global warming potential (GWP, excluding biogenic carbon), acidification potential (AP) human toxicity potential (HTP) and abiotic depletion potential (ADP, elements[3]), all assessed at mid-point level using the widely-adopted CML life cycle impact assessment (LCIA) method (CML, 2019). Normalization and weighting were not conducted because, while potentially facilitating the interpretation of the results by a less technical audience, they inevitably remain the most arbitrary steps in any LCA, and the choice of the weighting factors is to a large extent political, with little scientific relevance. In fact, because of this, according to ISO, normalization and weighting are always optional steps and are discouraged for any "comparative assertion intended to be disclosed to the public" (ISO, 2016b).

It is noteworthy that the HTP and ADP results are inevitably affected by larger margins of uncertainty. These are respectively due to: for HTP, the intrinsic methodological difficulty of comparing and combining into a single indicator the individual toxicity potentials of a wide and diverse range of organic and inorganic emissions; and for ADP, its dependence on current extraction rates and estimated ultimate reserves, which makes it susceptible to obsolescence, especially when it is used to assess a depletion-related impact taking place several decades into the future (van Oers et al., 2019). In light of this, the choice was made here to report the HTP and ADP results along a logarithmic (as opposed to linear) axis, to provide a better visual suggestion of the fact that their interpretation should focus only on the relative orders of magnitude, instead of any small differences, which are rendered statistically insignificant by the inherent methodological uncertainty.

The life cycle impact assessment was then complemented by an assessment of total nonrenewable primary energy harvested[4] from the environment over the full life cycle of the analyzed system, resulting in the nonrenewable cumulative energy demand (nr-CED) indicator (Frischknecht et al, 2015c; Hischier et al., 2010). Besides being an indicator of renewability and hence sustainability, nr-CED is also a valuable proxy indicator of energy sovereignty and independence for those systems located in geographical regions that are lacking in local nonrenewable resource deposits, like New York State and, to a lesser extent, also the UK and Kenya.

3 | RESULTS

3.1 | Life-cycle scenario results for London

Figure 1 presents the LCIA and nr-CED results for the three analyzed system alternatives installed in London; the blue and red continuous lines indicate "attributional" LCA results (in which on-site solar electricity is assumed to displace the average grid mix), whereas the dashed lines indicate "consequential" LCA results (in which solar electricity displaces the assumed marginal technologies).

When assuming the displacement of electricity coming from the average grid mix, due to a combination of comparatively low global and direct solar irradiation and an aggressively improving grid mix in terms of global warming potential, the two (ELM+BAPV and ELM+ICSF) systems have a hard time significantly offsetting the additional initial carbon emissions due to their own production. This is particularly true in the case of the (ELM+ICSF) scenario, where the GWP impact actually remains marginally higher than that of the ELM without any on-site generation capacity throughout the lifespan of the building. The (ELM+BAPV) system initially fares comparatively better, thanks to the lower up-front impacts of the BAPV system versus the ICSF one, but it still only manages to net a comparatively minor carbon benefit over the ELM system on its own, towards the end of its lifetime.

[3] This impact category excludes the input resources directly used for energy generation purposes, such as fossil fuels and uranium.

[4] Quoting from Frischknecht et al (2015c): a "unifying option is the 'energy harvested' approach which quantifies the amount of energy resources made available for human use"; this same methodological approach applies to "all energy resources, that is, renewable, fossil and nuclear". When considering all three energy resource types, the resulting indicator is called "Cumulative Energy Demand" (CED); conversely, when excluding the renewable energy inputs, the resulting indicator is suitably referred to as "nonrenewable Cumulative Energy Demand" (nr-CED).

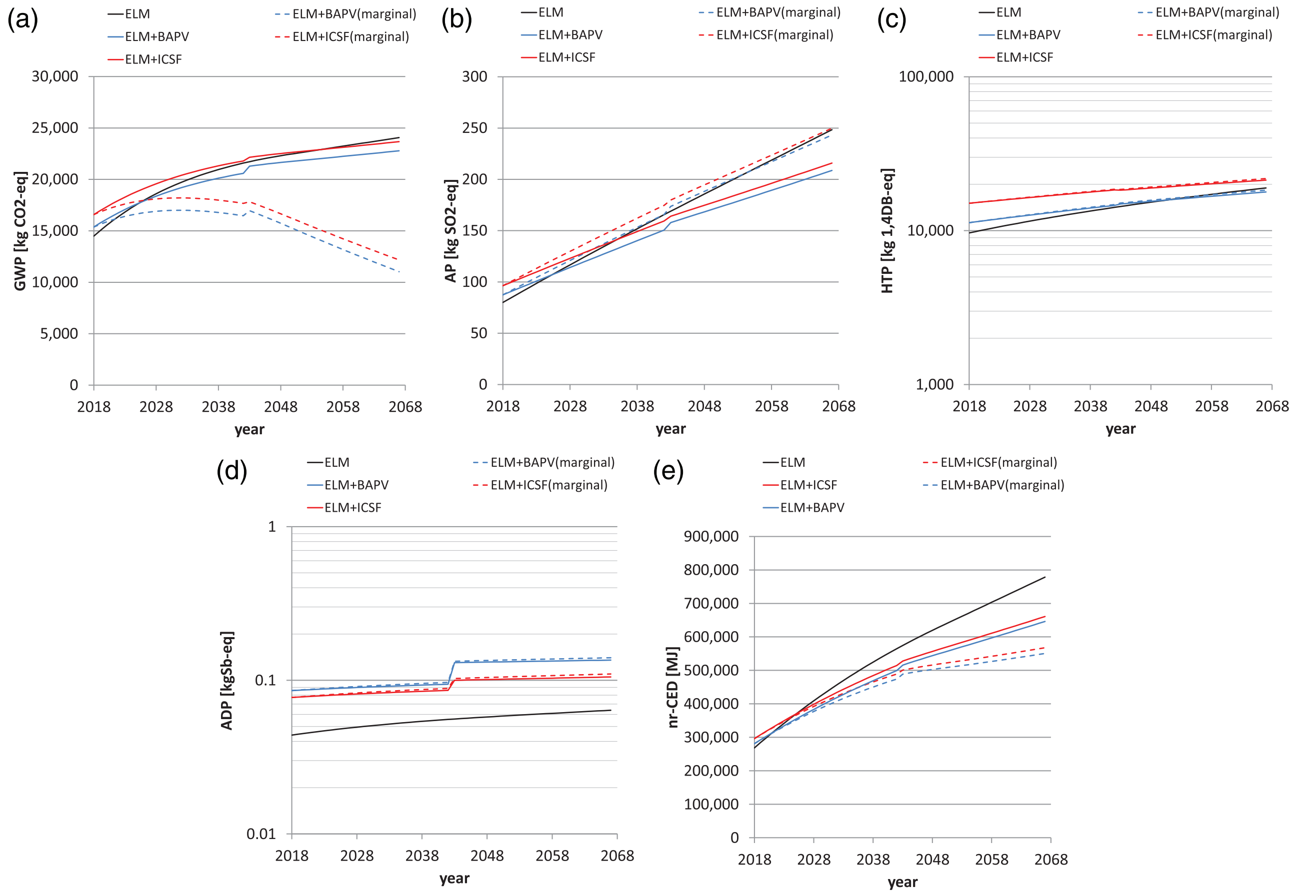

FIGURE 1 Dynamic trends for the life-cycle environmental and energy impacts of the three alternative systems (ELM, ELM+BAPV, ELM+ICSF) installed in London (UK). (a) Global warming potential (GWP); (b) acidification potential (AP); (c) human toxicity potential (HTP); (d) abiotic resource depletion potential (ADP); (e) nonrenewable cumulative energy demand (nr-CED). Continuous lines indicate attributional LCA results (PV electricity replaces grid mix); dashed lines indicate consequential LCA results (PV electricity replaces assumed marginal technologies). Underlying data used to create this figure can be found in the Supporting Information S2

The results in terms of acidification potential are slightly more promising for the two ELM systems with on-site PVs, mostly due to the fact that the projected UK grid mix evolution is less likely to be effective at curbing its own acidic emissions. However, this result is affected by some uncertainty, since it is in large part caused by biogas-fired electricity emissions, which could potentially be reduced if the biogas were upgraded to biomethane (Raugei et al., 2020).

As discussed in Section 2.5, the human toxicity potential results are to be interpreted with an even larger grain of salt; given the associated inevitable methodological uncertainty, the fundamental take-home message seems to be that none of the alternatives is markedly better than the others.

When considering the abiotic depletion impact category, both PV systems' relatively intensive demand for metals (primarily copper and aluminium), when compared with the grid mix on the common basis of units of electricity delivered, causes a significant net increase in impact over the baseline ELM without on-site electricity generation capacity. This finding is in line with previous assessments (Hertwich et al., 2015; Raugei et al., 2020), and can be considered a weak spot of renewable electricity generation in general. Also interestingly, in the particular case of ADP, the BAPV system fares comparatively worse than the ICSF, partly due to the silver conductive paste used in the c-Si modules.

Finally, when looking at the life-cycle demand for nonrenewable energy (nr-CED), both (ELM + on-site solar PV) systems start looking like more clearly recommendable options. This is due to the fact that, while in the "Two degrees" development scenario the UK grid mix is set for rapid decarbonization thanks to the phasing out of coal- and gas-fired steam turbines, its continued reliance on nuclear energy for a sizeable share of the total electricity produced still entails a large demand for nonrenewable primary resources; and compared to that, the electricity produced on-site by the BAPV and ICSF systems presents a clear advantage.

When instead assuming the displacement of just "marginal" electricity generated by gas turbines, the reduced carbon emission benefits of on-site solar generation become much more significant, with both ELM+solar systems even achieving a remarkable inversion of the cumulative emission trends after 2030. These results are paralleled by further improvements in terms of reduced nr-CED, too.

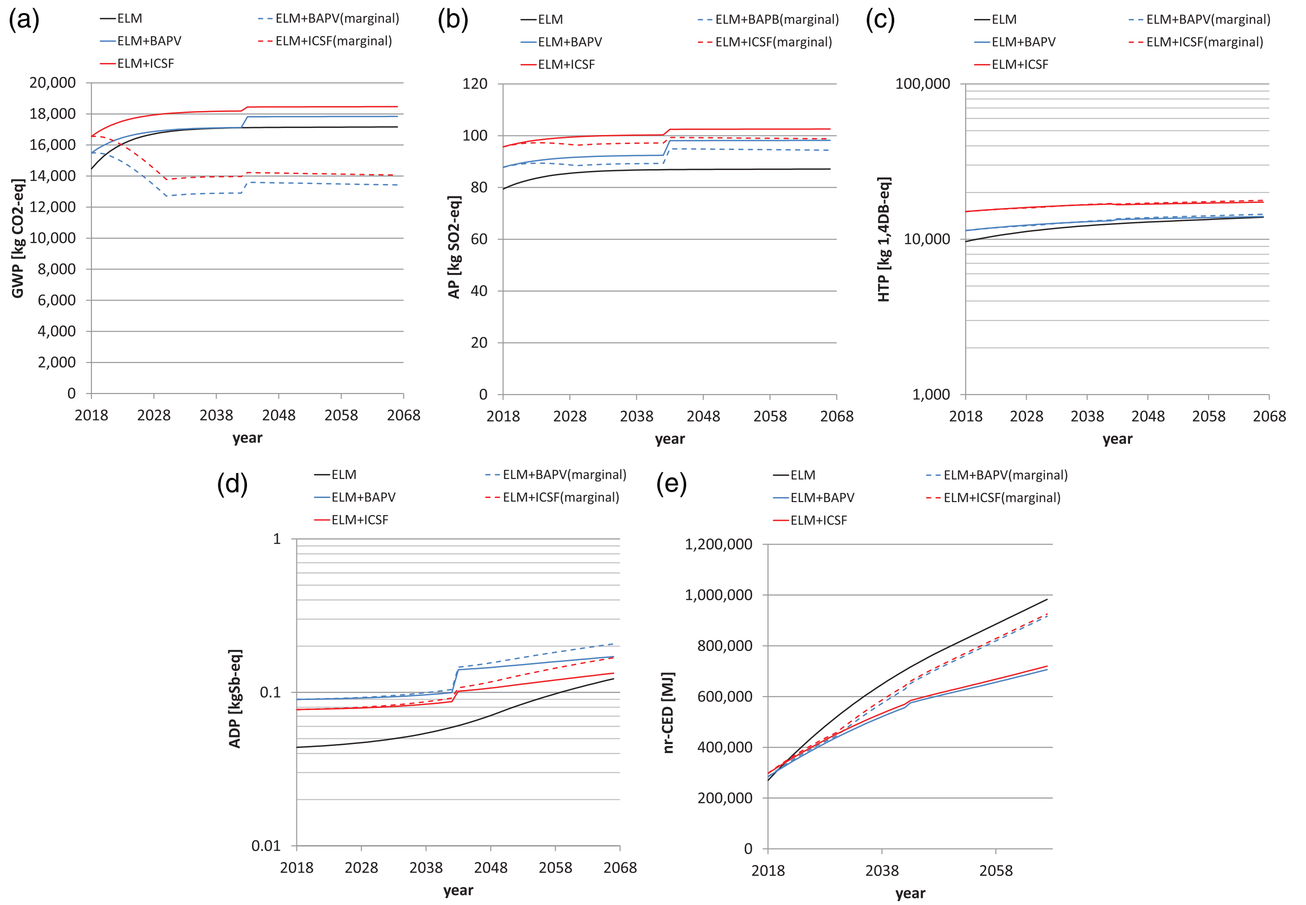

FIGURE 2 Dynamic trends for the life-cycle environmental and energy impacts of the three alternative systems (ELM, ELM+BAPV, ELM+ICSF) installed in New York City. (a) Global warming potential (GWP); (b) acidification potential (AP); (c) human toxicity potential (HTP); (d) abiotic resource depletion potential (ADP); (e) nonrenewable cumulative energy demand (nr-CED). Continuous lines indicate attributional LCA results (PV electricity replaces grid mix); dashed lines indicate consequential LCA results (PV electricity replaces assumed marginal technologies). Underlying data used to create this figure can be found in the Supporting Information S2

Acidic emissions, instead, no longer benefit from the displacement of biogas-fired electricity, and as a result remain broadly aligned with those for the "baseline" ELM without on-site solar generation capacity.

Finally, the systems' performance in terms of HTP and ADP is essentially unaffected by the switch from displacing the grid mix to displacing NGCCs.

3.2 | Life-cycle scenario results for New York

The "attributional" results for the case of New York in Figure 2 (continuous lines) are broadly similar to those for London. Here too, and in spite of a higher solar irradiation level, the results point to a similar ranking of the three alternative options, with the sole exception of the acidification potential impact category, where the two ELM systems with on-site PVs fare worse. Essentially, both on-site PV systems struggle to "pay back" the up-front environmental impacts associated to their production, when confronted with the alternative of a grid mix that is expected to stick to a rapidly improving trend in terms of reduced carbon intensity (and associated reduced acidic and toxic emissions). At the same time, however, once again the sustained reliance of the NY grid on nuclear as a key player in the mix leads to a clear benefit for the (ELM+BAPV) and (ELM+ICSF) systems when it comes to their comparative demand for nonrenewable energy (nr-CED), compared to the ELM system on its own, with all its operational electricity being sourced from the grid.

Moving on to the "consequential" analysis, the main difference with respect to the "attributional" results lies in the markedly reduced carbon emissions from the (ELM+BAPV) and (ELM+ICSF) systems over the first ten years, when the assumed displaced marginal technology is NGCCs. After that, the switch to hydropower prevents further benefits from accruing; even so, the initial reduction in GHG emissions is enough to stabilize the GWP trends at values well below those for the "baseline" ELM system without on-site solar generation capacity.

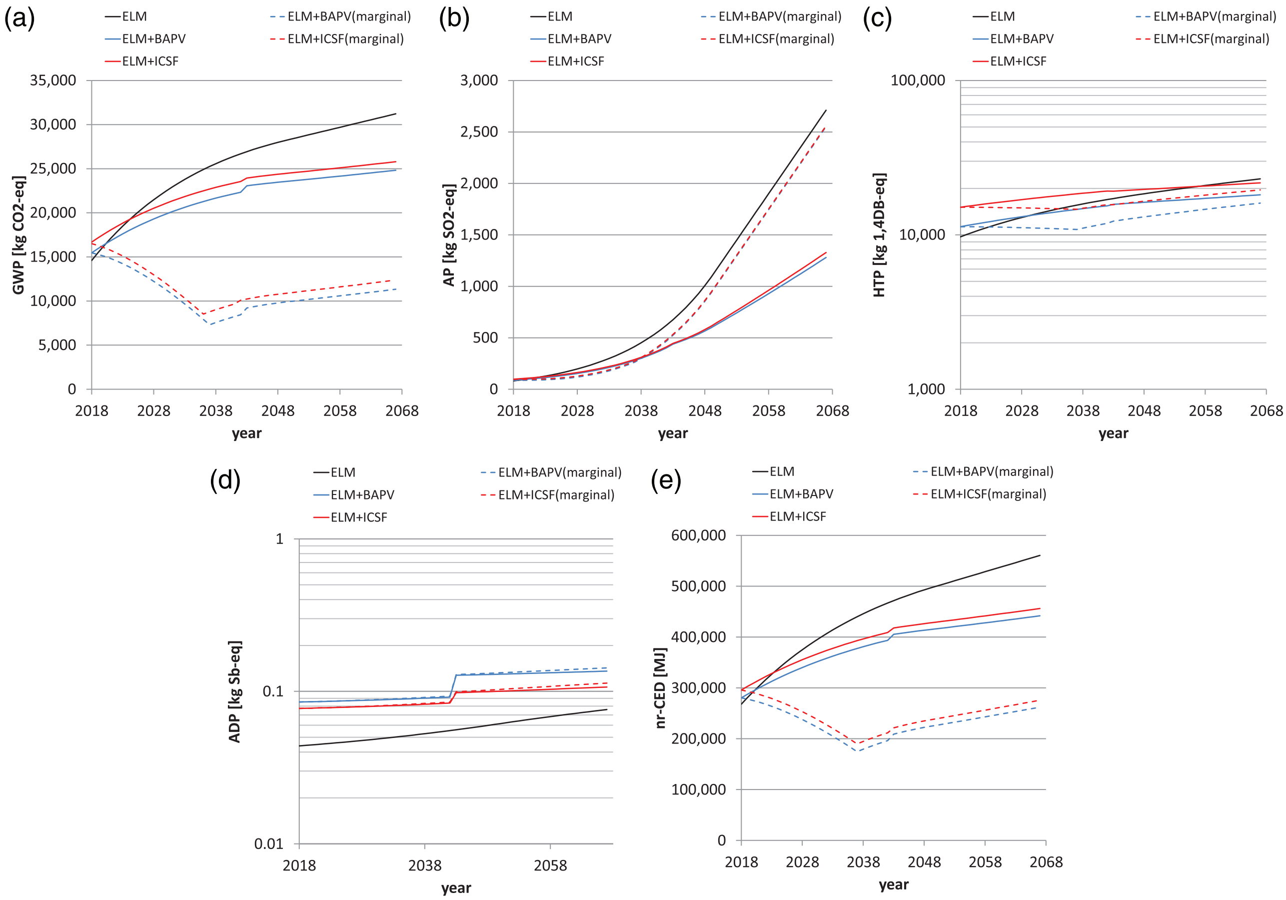

FIGURE 3 Dynamic trends for the life-cycle environmental and energy impacts of the three alternative systems (ELM, ELM+BAPV, ELM+ICSF) installed in Nairobi (Kenya). (a) Global warming potential (GWP); (b) acidification potential (AP); (c) human toxicity potential (HTP); (d) abiotic resource depletion potential (ADP); (e) nonrenewable cumulative energy demand (nr-CED). Continuous lines indicate attributional LCA results (PV electricity replaces grid mix); dashed lines indicate consequential LCA results (PV electricity replaces assumed marginal technologies). Underlying data used to create this figure can be found in the Supporting Information S2

Conversely, the use of hydropower as the assumed displaced marginal technology after 2030 leads to steeper trend lines for nr-CED when compared to the displacement of the grid mix, since in those circumstances the solar electricity generated on-site is no longer be assumed to displace a share of nuclear energy generation (a nonrenewable primary source).

Finally, like in the case of London, the HTP and ADP results remain essentially unaffected.

3.3 | Life-cycle scenario results for Nairobi

Finally, Figure 3 presents the same set of results for the case of Nairobi. In this case, the ranking of the three alternatives in the "attributional" model is radically affected by the fact that the Kenyan government is planning to replace its ageing and inefficient oil-fired power plants with a combination of not only two renewable and low-carbon technologies (geothermal and wind), but also a new range of coal-fired power plants. This strategy is set to limit the margin of improvement for the grid in terms of its overall greenhouse gas emissions per kWh delivered, and to actually increase its acidic emissions over time (which is also partly caused by the AP of geothermal energy). In comparison, the electricity produced on-site by the PV systems is clearly more environmentally friendly, and enables the (ELM+BAPV) and (ELM+ICSF) to rapidly offset the additional GWP and AP impacts due to the production of the solar systems, and proceed to deliver significantly better environmental associated profiles throughout most of their service lifetimes.

When considering the nr-CED indicator, the competitive advantage of the two (ELM + on-site solar PV) systems is also confirmed.

Instead, the impact in terms of HTP is still broadly the same across all three scenarios, and the ADP is once again significantly worse for the two (ELM + on-site solar PV) systems, for the same reasons discussed above.

When adopting the "consequential" approach, the benefits of on-building solar electricity generation are put in even starker relief, with the displacement of Diesel/LFO generators bringing about a sheer drop in both GHG emissions, nr-CED, and also HTP until 2037. Those same indicators then resume similar upwards trends as in the "attributional" approach, when geothermal replaces oil as the assumed marginal electricity generation technology, but even so the resulting trends remain well below their "attributional" counterparts all the way to 2050.

The acidification potential (AP) results instead tell a different story, since displacing geothermal instead of the grid mix after 2037 prevents solar electricity from being credited for the avoidance of the significant acidic emissions caused by coal-fired electricity.

Finally, like in both previous locations, the ADP results remain essentially unaffected by the different modelling approach.

4 | DISCUSSION

The multi-faceted analysis presented here (three alternative systems, assessed from the point of view of four independent energy and environmental impact categories, in three different locations with associated future grid mix developments) has produced results that do not lead to simple, clear-cut answers as to which option is always "best." Instead, what it has highlighted is that there are often trade-offs between the different alternatives, depending on the impact category considered and on where the system is installed and used. Also, the twin sets of results ("attributional" vs. "consequential") have highlighted the sometimes conspicuous differences that may derive from the selection of the assumed displaced technologies (i.e., average grid mix vs. marginal technologies). Rather than the result of an arbitrary choice, however, such selection should be made so as to accurately reflect the definition of a very specific goal and scope for the analysis, as discussed in Section 2.3.

In general, as expected, both on-site PV systems can more easily offset their associated up-front environmental impacts whenever the electricity generators that they displace are characterized by comparatively worse environmental profiles. When displacing the grid mix, in the UK and in New York, it has been found that installing solar PV systems on the Ecological Living Module is more effective at reducing the building's dependence on nonrenewable energy resources throughout its life cycle, than it is at curbing its use-phase carbon emissions. However, this is entirely due to both those grid systems being bound to aggressive decarbonization targets, while at the same time still relying on nuclear power for a sizeable share of the mix. Selectively displacing gas-fired electricity, instead, brings about clearer benefits in terms of reduced carbon emissions in both locations. In the case of Nairobi, Kenya, having either on-site PV system has resulted in clear advantages from the point of view of most of the considered environmental and energy indicators, whether displacing electricity generated by the grid or by the assumed marginal technologies (the only exception being acidification, which would keep rising if solar electricity only displaced geothermal after 2037, instead of the whole mix that is also expected to include coal).

A noteworthy weak spot of PV-generated electricity was found to be the comparatively higher demand for metals, such as Cu and Al, per unit of delivered electricity, which confirms similar previous findings.

Finally, in relative terms, and irrespective of location, the life-cycle environmental and energy performance of the (ELM+BAPV) system has been confirmed to be at least marginally (and in some cases, significantly) better than that of the (ELM+ICSF) system. However, given that the energy and environmental performance of the (ELM+ICSF) system does not appear to be held back by the employed photovoltaic technology per se, but rather by its structural elements, and the construction of the glazed enclosure system into which it is integrated (cf. Supporting Information S1), both of which may benefit from significant improvements over time thanks to possible future design optimizations. It should also be noted that the typology of ELM and the chosen climates represent nearly optimal use cases for BAPV, while the use cases are suboptimal for ICSF, which is expected to benefit larger architecture projects in more direct solar-dominated climates, with their more complex lighting and cooling requirements. Since single-family detached dwellings such as ELM represent only a fraction of building stock (and its impact generally), it could prove fruitful to expand this analysis to additional building typologies and climates.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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