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Performance study and LCA of a ZigZag PV noise barrier: Towards mass-customization of IIPV applications

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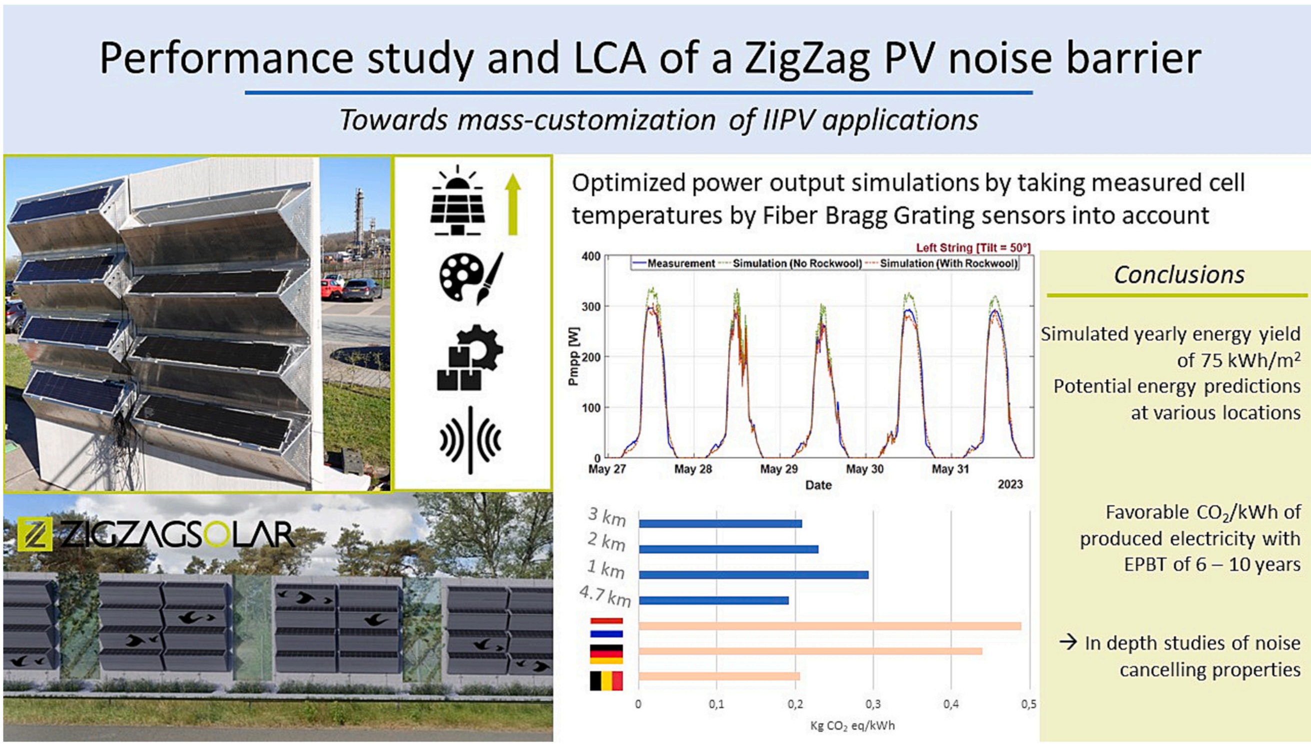
GRAPHICAL ABSTRACT



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ABSTRACT

Photovoltaic noise barriers (PVNB) offer dual functionality in reducing traffic noise and generating renewable electricity. In this research, the potential of ZigZag PVNBs has been investigated. The ZigZag Solar product, developed by Wallvision, has proven to offer multiple advantages in energy yield and aesthetics for building façade applications. For noise barrier applications, the ZigZag structure could offer interesting features in safety and noise cancellation (obtained by filling the ZigZag construction with Rockwool material) on top of the advantages in aesthetics and energy yield. A ZigZag PVNB has been designed and constructed at the Brightlands Chemelot Campus in Geleen, after which the electrical performance has been automatically monitored under Dutch climate conditions. The measurements have been compared to simulated data, which allowed optimization of the model. As Rockwool material is used in the ZigZag construction, the thermal model had to be optimized to reduce significant differences in measured and simulated V_{MPP} data. Temperature measurements by a novel Fiber Bragg technology revealed that temperature differences between measured cell temperature and input temperature for the simulations are between 10 and 20 °C. After optimizing the thermal model, the power output of the ZigZag PVNB could be predicted more accurately, resulting in a yearly potential energy yield up to 1066 kWh/kWp. Measured data over the period June 2023 till April 2024 showed an energy yield up to 873 kWh/kWp. A deviation of 18 % between measured yearly energy yield can be related to system losses such as cabling and inverters. Life Cycle Assessment (LCA) of several configurations of a global system, including concrete infrastructure, solar panels, ZigZag cassettes, cabling and converters shows a Global Warming Potential (GWP) score varying from 190 to 290 CO_2 eq/kWh, according to the models developed in this study, indicating its interest compared to the Dutch and German electricity mixes. In addition, the energy required to produce and install the ZigZag PVNB system at various lengths has a predicted payback time of 6–10 years (maximum 30 % of the total expected lifetime). The balance of system, in specific the DC/DC converters followed and battery system) followed by the concrete element on which the ZigZag PVNB was mounted are the largest contributors to the carbon footprint of the ZigZag PVNB demonstrator. The carbon footprint could potentially be reduced by using cleaner battery technologies or energy storage systems.

1. Introduction

Increasing the market share of solar and wind energy is a crucial goal in providing energy security, reducing effects of energy poverty, and reduce global warming [1,2]. The REPowerEU plan, induced to rapidly reduce the dependency of the European Union on Russian energy import, states a target of 320 GW installed photovoltaic (PV) capacity by 2025 and almost 600 GW by 2030 [3]. In 2022 the PV capacity installed in the EU was 208.9 GW which is expected to rise towards 262 GW by 2023 and 484 GW by 2026 [4]. The International Energy Agency (IEA) expects that the electricity generation from wind and solar more than doubles within the next five years, providing almost 20 % of the global energy generation in 2027. It is expected that the cumulative installed PV capacity worldwide triples to over 2350 GW in 2027 and become the largest installed electricity capacity worldwide [5].

To reach the sustainable energy goals, aspects like the amount of skilled workforce, ensuring a stable PV supply chain, improving PV integration to the grid and spatial planning are crucial to the successes [6]. With respect to spatial planning, availability of area is a trivial aspect in increasing the amount of installed PV capacity. Especially in densely populated countries like the Netherlands, availability of land along with social-acceptance issues may hamper the growth of installed PV capacity. Building Integrated PV (BIPV) products have already demonstrated that high solar energy yield can be obtained along with multifunctional use of area combined with optional aesthetical parameters, tackling issues around social-acceptance and space [7–10]. Well-known examples are solar roof tiles, solar roofs, solar facades and transparent solar roof tops developed by companies like Solinso [11], Solarix [12], BEAUsolar [13], Wallvision [14] and Loci [15]. Besides the built environment, space is available in the infrastructure to generate renewable energy. In total, the Netherlands counts 4.190 km^2 surface in the infrastructure which includes highways, roads for heavy and light traffic, noise barriers and verges [16]. This potential area for the installation of solar panels is 3,5 times more than the potential area on buildings and green houses. Increasing renewable energy generation in infrastructure is in line with electrification goals of traffic, potentially resulting in a close alignment in energy generation and consumption [17].

Various products have been developed to convert solar irradiation to renewable electricity such as PV installation on verges, solar roads and PV integration and application to noise barriers [18,19]. In the specific case of the Netherlands, the increasing population is giving pressure on the housing market with urgent need for increased housings [20,21]. This growth is related to increased attention to spatial planning of districts to create comfortable, healthy and accessible living environments with respect to traffic noise and air pollution [22–24]. Photovoltaic noise barriers (PVNB) offer dual functionality in reducing traffic noise and generate renewable electricity. After the first PVNB was realized in 1989 in Switzerland, various pilot projects of PVNBs have been realized showing various possible configurations such as top-mounted PV, zigzag design and bifacial [19,25,26]. As the safety of drivers is of key importance, integration of PVNB technologies in the infrastructure brings challenges with respect to preventing undesired sun and traffic light reflection on glass surfaces and monotone views [27,28]. In this research, the ZigZag PV structure, developed by Wallvision for aesthetical and high performance energy facades for building, has been investigated as potential PVNB product [14]. The solar panel, mounted in the “zig” plane, is oriented towards the sun, while the “zag” plane increases the light coupling to the underlying solar panel [7]. As the solar panel is oriented towards the sun and not directed towards the driver, this design may limit undesired sun and traffic light reflection on the glass surface of the solar panel, contributing to the safety of the driver. In addition, the safety of the driver can be increased by the aesthetical “zag” of the construction by avoiding monotone views. The third potential advantage is the ability to reduce noise reflections of traffic by incorporating noise cancelling materials in the hollow ZigZag structure.

Previous studies on the potential of PVNBs address relevant topics as the effect of the produced energy on greenhouse gases savings [29], effect of PVNB designs on the simulated energy output [26,29,30], experimental validation of power output models [25], and large scale analysis of power potential [31,32] However, a comprehensive energy yield assessment by power output simulations, validation of the optimized simulation tool by experimental results, and Life Cycle Assessment (LCA) for noise barriers utilizing the ZigZag configuration has not yet been conducted. A ZigZag PV noise barrier demonstrator was built at the Brightlands Chemelot Campus in Geleen of which the electrical performance is measured. Measurements are compared with simulated data with which a model has been developed that has the potential to predict the energy yield of ZigZag PVNBs at various locations. Next to the technical properties and performances of the ZigZag solar noise barrier, it is important to quantify the environmental cost of every component during their production phase [26,33,34]. Therefore, this study includes LCA study of the ZigZag PVNB on element and system level for multiple variations. The amount of CO_2 per kWh produced per scenario is compared to the carbon intensity of the electricity mixes in Belgium, The Netherlands and Germany to define the environmental benefits of ZigZag solar noise barriers.

2. Materials and methods

2.1. ZigZag PVNB demonstrator

In close collaboration with Wallvision, a list of requirements was set describing design and functional parameters. Aspects that have been taken into account were for example mass-customization, circularity, performance and durability. Requirements were translated into potential designs, after which a final design was optimized and worked out in detail to produce the ZigZag PVNB demonstrator. The demonstrator consists of a concrete wall of 4 × 4 m (width x height), specifically the LX400 element from VB beton. Fig. 1 shows a schematic figure of the demonstrator illustrating details in dimensions. As shown, two ZigZag configurations were built next to each other with a total of four cassettes of each configuration. The two configurations demonstrate that the design can be altered to specific requirements of a location. As the two ZigZag configurations are likely to result in different power output, the demonstrator enabled validation of the energy yield simulations with measured data. All cassettes are completely filled with noise absorbing material to reduce undesired reflection of traffic noise by concrete walls. The infrastructure integrated PV (IIPV) demonstrator was built at the Brightlands Chemelot Campus in Geleen with a south-south-west orientation (see Fig. 2). Pictures and design details of the production process are illustrated in *Supporting Information SI 1*.

2.2. Performance measurements

Eight silicon solar panels, produced by Soltech, are mounted in a ZigZag frame on a concrete wall as described in the previous paragraph. Technical details of the solar panels can be found in the *Supporting Information SI 2*. Four solar panels with the same inclination angle are connected in series as shown in the electrical scheme in Fig. 3. Both strings are connected to an DC/AC converter with 4 MPP inputs (APS YC100–3) after which the AC electricity is fed into the grid. The DC generated power is monitored by QEED QI-power-485-LV measuring I_{MPP}, V_{MPP} and P_{MMP} every 2 min. The temperature of each solar panel is measured by DS18B20 temperature sensors on the back of the solar panels. In addition, Fiber Bragg Grating (FBG) sensors are installed in the lowest left and right solar panels with which the temperature of the silicon wafers could be monitored. The optical fiber only measures temperature changes as they are integrated in such a way that they are mechanically decoupled, as described by P. Nivelle et al. [35] A Lambrecht Meteo EOLOS-IND weather station containing a pyranometer, temperature and wind sensor was installed at the Brightlands Chemelot Campus in Geleen, allowing to translate performance measurements into power conversion efficiency of the solar panels. Data from all sensors is collected in a cloud which can be visualized by an InfluxDB account (see also Fig. 3).

2.3. Performance simulations

The electrical performance of the ZigZag PVNB demonstrator is simulated using imec’s energy yield (E-yield) simulation framework.

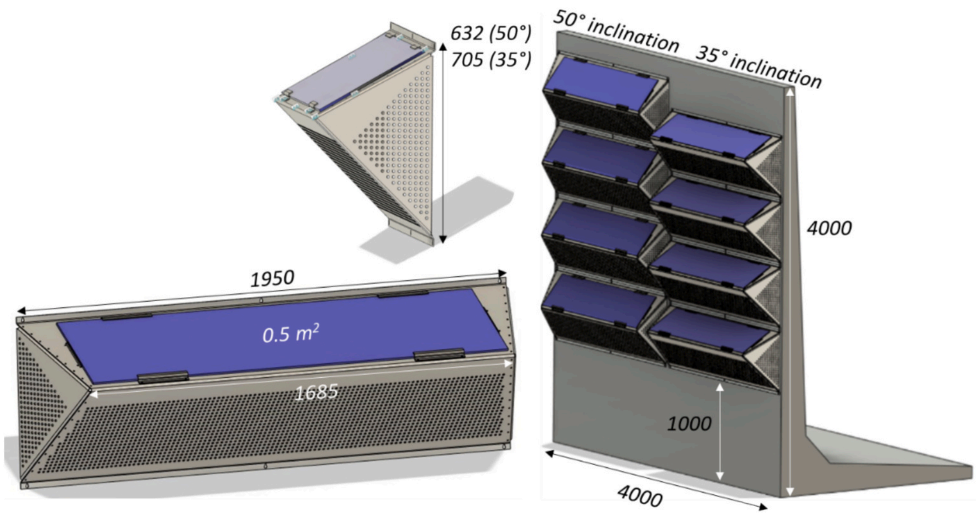

Fig. 1. Schematic illustration of the ZigZag IIPV demonstrator including dimensions in mm.

Fig. 2. Outdoor test facility for IIPV, BIPV and window innovations at the Brightlands Chemelot Campus in Geleen.

The E-yield framework is an advanced simulation tool developed by imec, which has been specifically designed to accurately calculate the energy yield of both mono-facial and bifacial PV systems [36]. The E-yield framework calculates the energy yield with exceptional precision as it considers the reflection of light from the ground, as well as the double-sided illumination (in the bifacial case) that is influenced by module frames, system components' geometry, and varying albedo (see also Fig. 4). The design of the PV plant is completed in the E-yield framework, considering all geometrical aspects such as the dimensions of the concrete wall, the cassettes, PV module dimensions, spacing, cover length, etc., as well as the tilt and orientation of the PV modules (the modules on the west side have a tilt of 50° while those on the east side have a tilt of 35°).

To account for the noise absorbing material (Rockwool) in the simulation, imec's simulation framework utilizes a thermal model, represented by an equivalent resistor-capacitor (RC) circuit [37]. Each component or layer of the PV module's thermal model is represented by an RC pair along with a current source to account for heat generation within the layer. The overall structure of the layered PV module is constructed using a 'Continued fraction circuit' scheme, also known as a ladder network [38]. To incorporate thermal radiation and convective cooling of the module surfaces, input-dependent thermal resistors are employed, which may exhibit time-varying and highly non-linear properties. The solution to this circuit allows for the computation of heat conduction within the layered structure, a critical factor in enhancing the accuracy of solar cell temperature assessment.

The electrical model employs the single diode equation with temperature-dependent diode, series, and shunt resistances, providing a balance between high accuracy and reasonable computational costs. The interaction between the thermal and electrical models is established by considering the net power absorbed by the solar cell, determined by the optical model (see also Fig. 4). A portion of this power is converted into electrical power, influenced by the single diode equation and the actual operating point, capturing the intricate dependencies on fluctuating weather conditions, non-uniformities (e.g., partial shading), and electrical operating points. The remaining part of the net power is transformed into heat and injected into the thermal network through a current source in the solar cell layer of the thermal RC network. Both this heat transfer process and the previously mentioned processes impact the solar cell temperature, subsequently affecting the temperature-dependent diode and modifying the extracted electrical power.

2.4. LCA studies

A Prospective Life Cycle Assessment approach (pLCA) is considered to characterize the environmental impact of a potential commercial ZigZag PVNB system utilizing a similar demonstrator design as illustrated in Fig. 1 (see also *Supporting Information SI 3*). This type of LCA analysis allows to characterize the potential environmental impact of products or services of newly emerging technologies or at early stage of development [39–41]. Different scenarios are presented to show the relevancy of ZigZag PVNB systems in terms of their length and

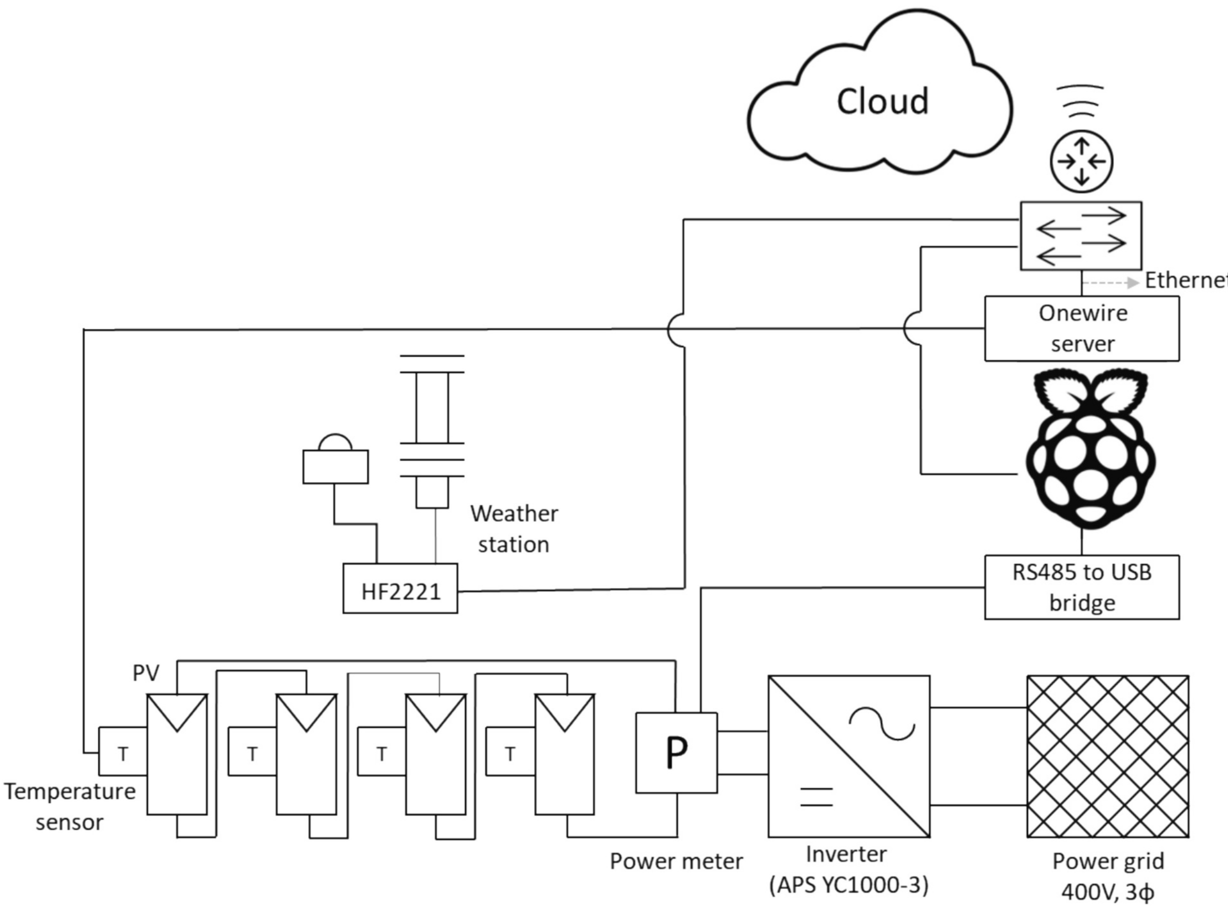

Fig. 3. Schematic illustrating the electrical measurement system of the PVNB demonstrator.

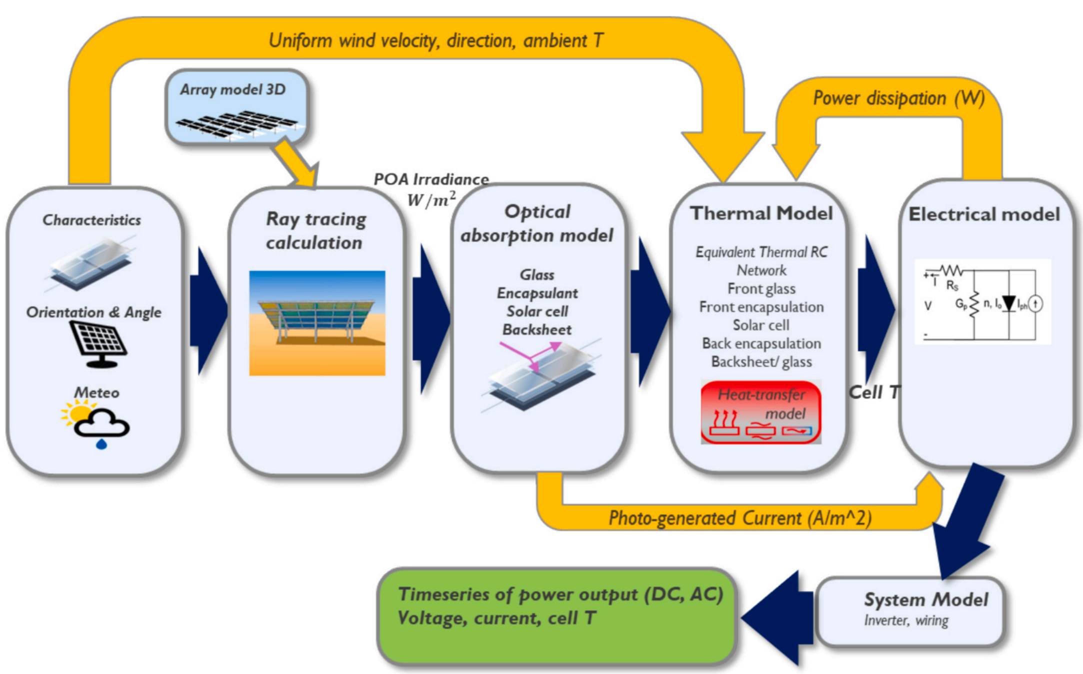

Fig. 4. Schematic overview of Imec's Energy Yield simulation framework.

theoretical amount of produced energy, in comparison to the national electricity mixes of the Euregio countries. Aside from the direct electricity generation, a Battery Energy Storage System (BESS) is considered, with 1 MWh capacity for all scenarios envisaged. This unique size of the energy capacity storage is determined for economical reasons, where smaller storage battery systems are considered to be too expensive or not sufficiently cost-effective.

The LCA study was performed under the standard ISO 14040 and 14044 using OpenLCA software 1.3.0 and Ecoinvent 3.8 for background dataset. Two indicators are selected from the E.F 3.0 (Environmental Footprint) methodology to assess the environmental impact: Global Warming Potential and Resource Use, fossils [42]. The latter indicator is employed to calculate the Energy Payback Time, a metric defining the period of time (in years) a photovoltaic system must operate to generate the same amount of energy needed to produce the system itself. Table 1 shows an overview of the main components considered in this LCA study and used data sources. A detailed list of input data and Life Cycle Inventory (LCI) for the LCA study can be found in *Supporting Information SI 4 and 5*.

The functional unit chosen is one kWh of AC electricity produced and considers the global impact of the ZigZag PVNB system, including the Balance of System (BOS) for a commercial installation. Hence, experimental and measurement devices implied for the demonstrator phase are not taken into account. The BOS assumptions are based on the use-case developed in the frame of the project available in supplementary material (see *Supporting Information SI 3*). The BOS is composed of DC/DC converters, DC/AC converters, cabling systems and battery energy storage system (BESS). For this latter, only the battery mass of a Li-Ion battery is considered (referred to NMC 811 battery production process in ecoinvent), excluding the impact of other components such as container mass, cooling system and other electrical devices needed for the operation. Concerning DC/DC converters, few extensive inventories of such devices exist in literature, hence the model used by Payet et al. [43] and scaled up by mass with datasheets from potential industrial devices [44] is used. DC/AC converter models and LCI are principally retrieved from Tschümperlin et al. [45] and also scaled according to power capacity.

Concerning the solar modules, the upstream cell production is based on recent data published by Müller et al. [46] and completed for the mass-customization module process production with foreground data shared with project partner Soltech, specifically on key data such as electricity consumption. Due to confidentiality reasons, these numbers are not shown in this work. The Zigzag cassettes are modelled according to Bill Of Material (BOM) obtained from project partners and considers aluminium composite sheets folded, glasswool noise absorber and smaller substructure elements for fixation purpose such as bolts and screws. Finally, the goal of this LCA is threefold: highlighting the most contributing elements of the PVNB system to its Global Warming Potential (GWP) score in spite of its length, comparing it to national electricity mixes of the Euroregiomeuse countries according to the functional unit and finally calculating the Energy Payback Time (EPBT) in regards of the system lifetime, validating the relevancy of such systems.

Table 1
Components considered for the LCA main source of information.

Category	Component	LCI source
Infrastructure	Concrete element	Ecoinvent 3.8 (background) and partners data (foreground)
BOS	DC/AC converter	Tschümperlin et al.
	Cablings	Own calculation
	Battery cells	Ecoinvent 3.8
	DC/DC converter	Payet et al.
PV Panel	monoSi PERC cell	Friedrich et al. (background) and partners data (foreground)
	Top sheet - Solar glass	Ecoinvent 3.8 (background) and partners data (foreground)
	Back sheet - tempered glass	Ecoinvent 3.8 (background) and partners data (foreground)
	Encapsulant - EVA	Ecoinvent 3.8 (background) and partners data (foreground)
Cassette	Rubber, natural part	Ecoinvent 3.8 (background) and partners data (foreground)
	Rubber, synthetic part	Ecoinvent 3.8 (background) and partners data (foreground)
	Fixation (bolts, rivets, screws)	Ecoinvent 3.8 (background) and partners data (foreground)
	Cassette material	EPD (Environmental Product Declaration)
	Noise absorber material - glass wool	Ecoinvent 3.8 (background) and partners data (foreground)

3. Results and discussion

3.1. Demonstrator validation

After construction of the ZigZag PVNB demonstrator and installing all the required equipment and sensors, the demonstrator was validated to ensure that correct and accurate data is measured. Data validation has been performed by comparing the measured temperature coefficient and efficiency of the module with the data provided by Soltech (see also *Supporting Information SI 2*). A strong correlation between temperature and voltage at maximum power point (V_{MPP}) could be measured, as shown in Fig. 5. Measurements show a decreasing trend in V_{MPP} with temperature coefficients of -0.18 V/°C and $-$ 0.17 V/°C for respectively the 50° and 35° inclination angles of the solar panels (respectively, the left and right ZigZag constructions). These temperature coefficients in V/°C correlate, respectively, to -0.39 %/°C and $-$ 0.37 %/°C, which is in line with the measured temperature coefficient of -0.30 %/°C by Soltech. Small differences are likely related to the use of different equipment and sensors for lab scale compared to outdoor measurements. Along with the voltage decay, the efficiency of the solar panels after installation at the Brightlands Chemelot Campus was determined using maximum power point (MPP) and weather data. MPP data of seven sunny days was filtered to a time frame of 11 AM to 15 PM to reduce shadow effects. Data points were filtered to a sun light irradiance range of 600–900 W/m^2. Efficiency results of the 50° string are plotted in Fig. 6. Due to greater amount of shadow losses in the 35° string, this data was not taken into account for validating the setup. The boxplot shows that the vast majority of the data points are within an efficiency range of 16.2–17.1 % which is slightly lower than the efficiency of 17.2 % measured under standard test conditions (STC) by Soltech. This loss can be accounted to the cabling and inverter efficiency and different accuracy and methods of measuring. The analysis of the voltage decay with respect to temperature and efficiency of the solar modules show that the data of the PVNB noise barrier is in line with STC data provided by Soltech. It can be concluded that the data output of the PVNB demonstrator is reliable and accurate enough for the purpose of validating the technology.

3.2. Measured versus simulated power output

As described in chapter 2, meteorological data is measured onsite at the Brightlands Chemelot Campus in Geleen, The Netherlands, which is employed for simulations in the period of May-2023 toAugust-2023. The goals of simulating the electrical performance of the PVNB demonstrator was twofold: (*i*) to compare simulated and measured data with each other to develop and validate a model that can potentially predict energy generation profiles at various locations with similar climates, and (*ii*) to estimate yearly energy yield of the developed technology and translate this outcome to the potential of the technology in the energy transition. The simulation is conducted in the E-yield framework using two scenarios: (1) without Rockwool effect (no additional layer for the noise absorbing material in the thermal model) and (2) with Rockwool

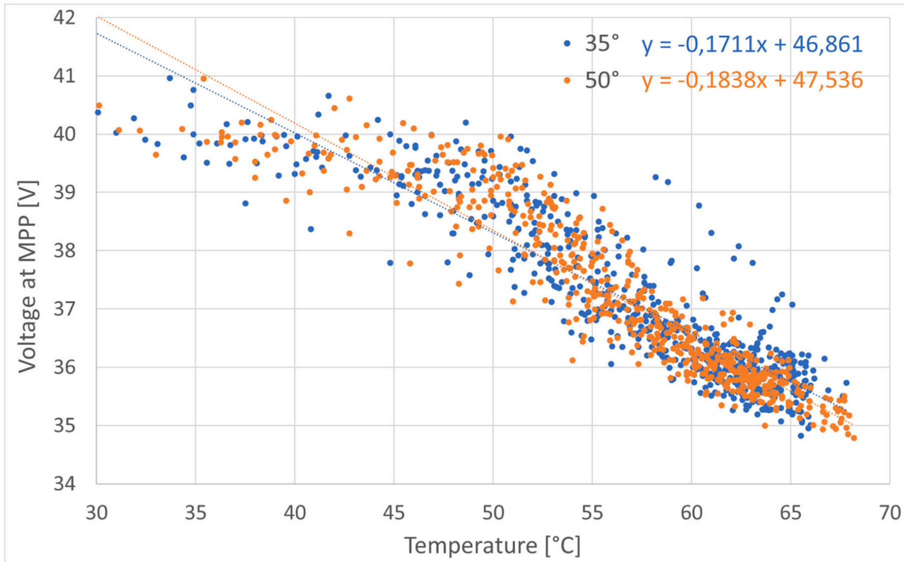

Fig. 5. MPP Voltage decay of the two PV noise barrier strings with respect to temperature.

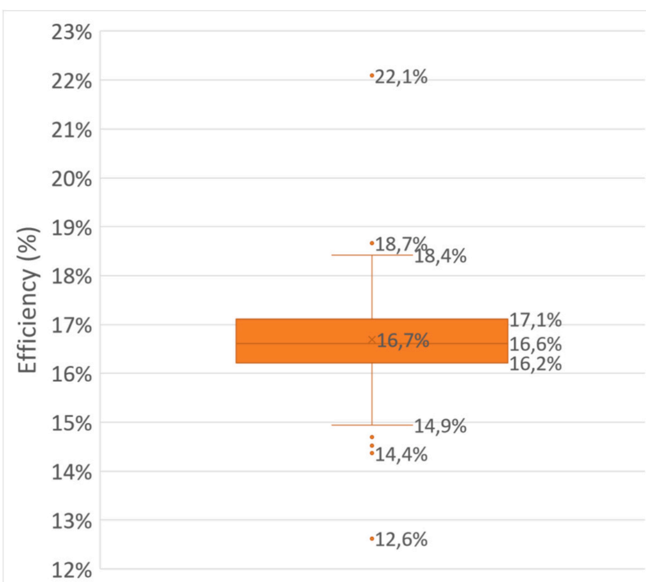

Fig. 6. Boxplot of the efficiency of the 50° string measured under an irradiance of 600–900 W/m^2.

effect (adding Rockwool material to the backsheet/glass layer in the thermal model). Fig. 7 shows the cauer network for the power output simualtions. The thermal resistance in K/W for each layer is according to the Eq. (1):

$$R_l = \frac{r_l \times t_l}{A_l} \tag{1}$$

Where, r_l (K·m/W) is the thermal resistivity of the material, t_l (m) is the thickness of the material, and A_l (m2) is the cross-sectional area through which heat is flowing. The thermal capacitance in J/K for each layer is given by the Eq. (2):

$$C_l = \rho_l \times c_l \times A_l \times t_l \tag{2}$$

where, ρ_l (Kg/m^3) is the material density, c_l (J/Kg·K) is the specific heat capacity of the material, and $A_l \times t_l$ (m3) is the volume of the layer.

In the first scenario (without rockwool effect), rear glass is considered in the backsheet/glass layer, in the second scenario (without rockwool effect), aluminium and rockwool materials are added to the backsheet/glass layer and the rear glass is ignored as follows (3 and 4):

$$R_{bk-gls} = R_{Aluminium} + R_{Rockwool} \tag{3}$$

$$C_{bk-gls} = \frac{1}{\frac{1}{C_{Aluminium}} + \frac{1}{C_{Rockwool}}} \tag{4}$$

In the second scenario, it is assumed that the rear glass with thickness of 3 mm has a minimal effect on cell temperature compared to the rockwool material with a thickness of 250 mm.

Fig. 8 shows the power output results for a 5 days period. It can be observed that disregarding Rockwool material in the thermal model results in an overestimation of the power output. This overestimation is confirmed by comparing the simulated data with measured data in August, as reported in *Supporting Information SI 6*. Interestingly, the overestimation in P_{MMP} is greater for the left string (50° inclination) compared to the right string (35° inclination). This may be related to lower shadow effects and therefore enhanced temperature effects for the left string. Current and voltage analysis at MPP show that the simulation of I_{MPP} perfectly matches the measured data, both in May and in August (Fig. S6). However, measured V_{MPP} data deviates significantly from the simulated data. Fig. 9 shows that the potential difference can be partly caused by a temperature difference of 10–20 °C between input temperature of the simulation and measured temperature of the module cells by the FBG system. According to the voltage decay trend described in Fig. 5, the temperature difference could account for up to 3.5 V of deviation between the measured and simulated results. In addition, Fig. 9 (a) and Fig. S7 show that the cell temperature deviates significantly from the standard method of temperature measurement on the back of the solar module. Fig. S8 compares the temperature profiles measured at the cell and on the backside of the PV module, showing significant differences of to 10 °C. As temperature measurements are traditionally performed by thermocouples on the backside of the PV module, a temperature difference with respect to the silicon cell must be taken into account when calculating or simulating cell performance.

The input cell temperature for the simulation has been optimized by increasing the resistance of the backsheet material. Fig. 8 shows that when Rockwool is taken into account in the thermal model, the P_{MMP} can be simulated more accurately. With the adjustment of the thermal model illustrated in Fig. 7, the simulated cell temperatures approach better the measured cell temperature by the FBG system, as shown in

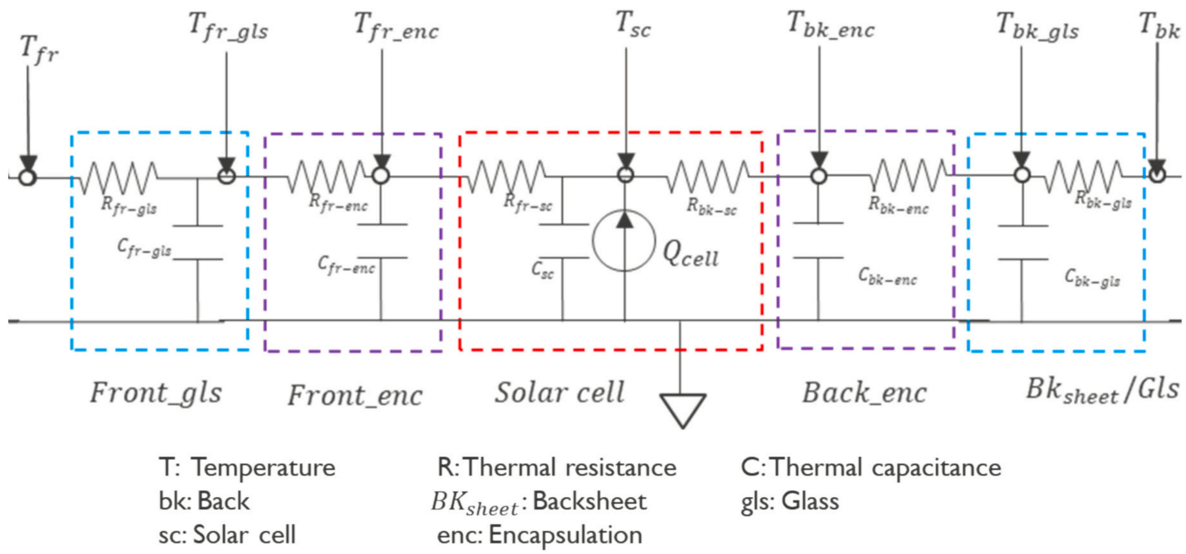

Fig. 7. Cauer thermal network used for the power output simulations, where properties of the insulating Rockwool material are added to the thermal capacitance of the backsheet (bk_sheet) layer.

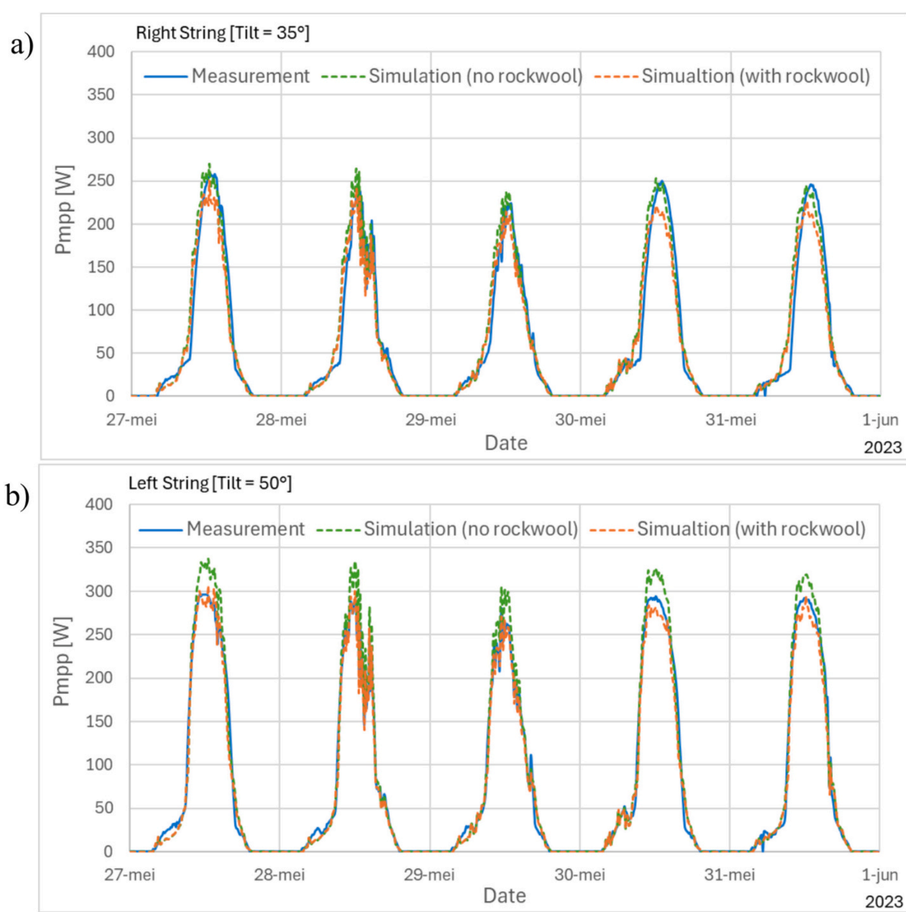

Fig. 8. Power at P_{MPP} with 10-Minute Resolution in Geleen, the Netherlands, (a) for the right string, and (b) for the left string in the noise barrier.

Fig. 9 (a). This results in a correction of the V_{MPP} simulation which better approaches the measured data as can be seen in Fig. 8 (b). Deviation between measured and simulated V_{MPP} has been minimalized significantly, however not reduced to zero. The remaining difference could be attributed to approximately 15 m of cabling between the PVNB demonstrator and measuring devices, resulting in potential losses. In addition, mismatch between simulated and measured V_{MPP} can arise from impedances losses of the inverter during affecting the measurements.

With the implementation of Rockwool into the thermal model, the simulated output voltage (V_{MPP}) and hence the power output at MPP has been optimized significantly. In the current simulation, the model shows

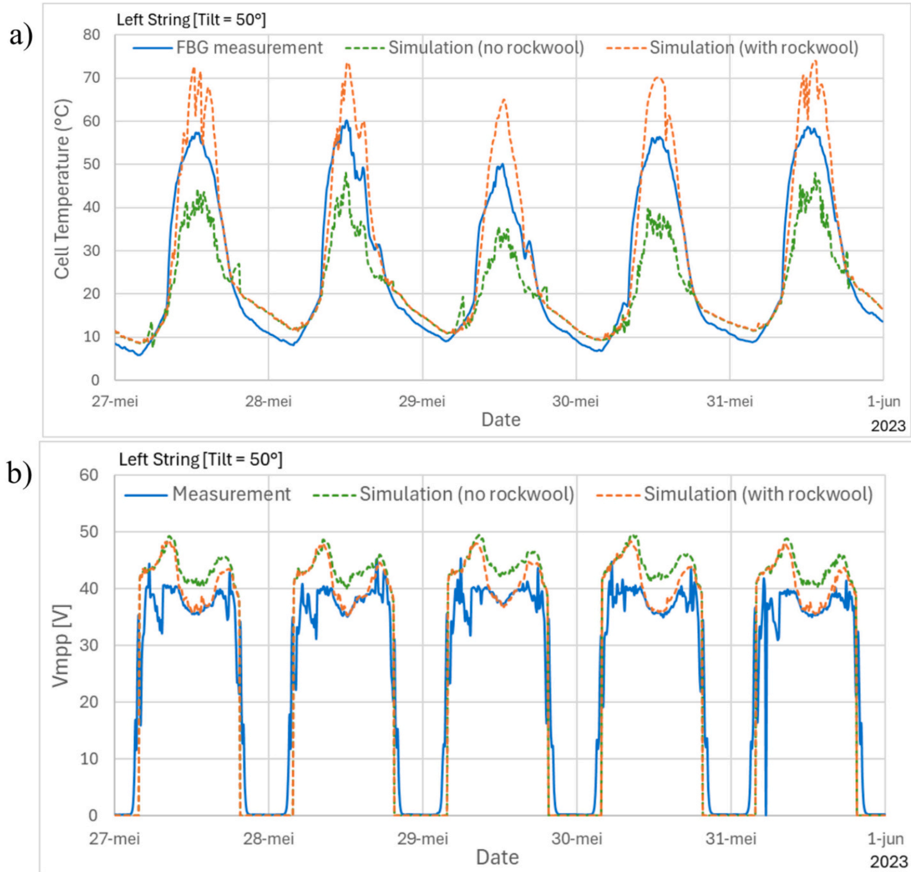

Fig. 9. (a) Temperature data used for the simulation (dashed lines) versus the measured temperature of the cell by the FBG system (blue line), along with (b) the measured and simulated V_{MPP} data in May for the left string. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

good accuracy with an normalized root mean square error (NRMSE) of 5 % for the right string (tilt 35°) and 3 % for the left string (tilt 50°), indicating reliable prediction of power output. The optimized simulation may provide insights of the power output of ZigZag PVNBs at various locations. With the optimized simulation model, monthly yields can be obtained based on hourly TMY (Typical Meteorological Year) data for the Chemelot location from the PVGIS database. The results show that a 50° tilt angle generally yields higher energy production across different seasons compared to 35° tilt, especially in summer months (see Fig. 10). The reason for this is the reduced shading from the upper ZigZag covers with a higher tilt angle. A yearly specific yield up to 941 kWh/kWp with a tilt angle of 35° and 1066 kWh/kWp with a tilt angle of 50° can be generated by the ZigZag PVNB demonstrator. Cumulative measured energy yield of the ZigZag PVNB demonstrator was

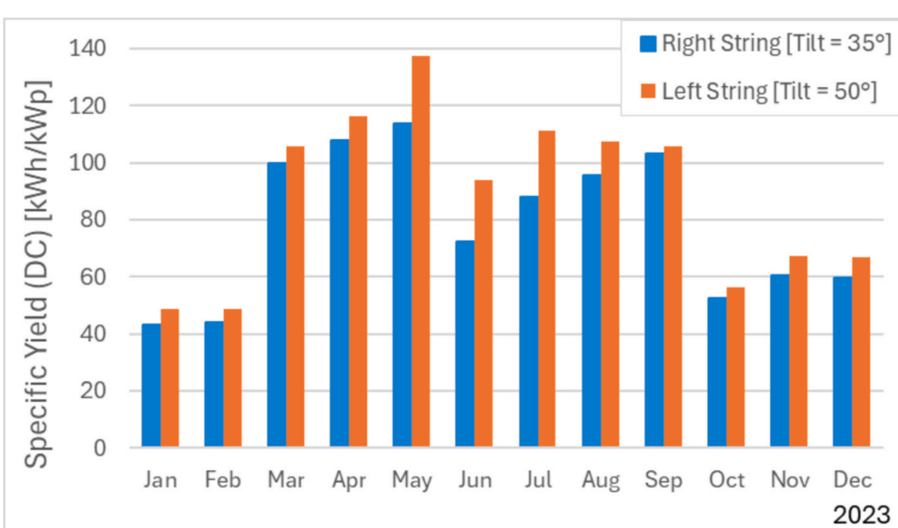

Fig. 10. Simulated monthly yield (kWh/kWp) for the right and left ZigZag strings, based on TMY data for the location of Chemelot.

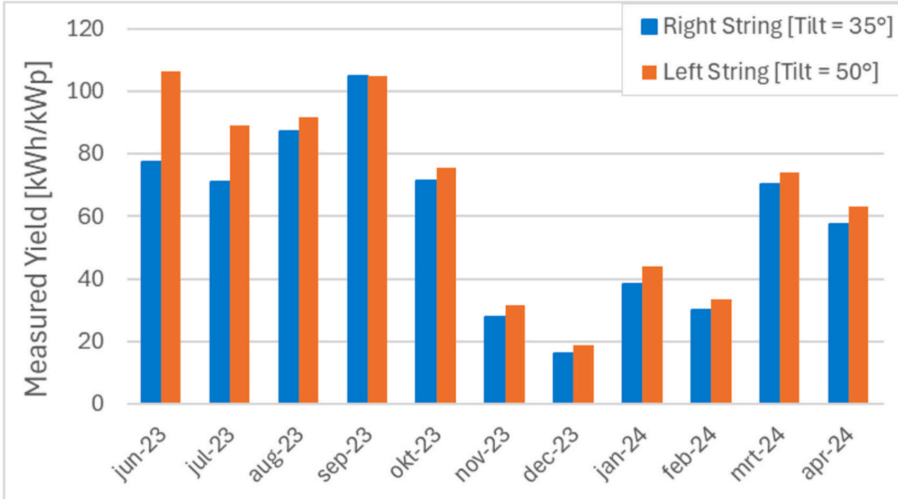

Fig. 11. Measured energy yield per month of the left (orange) and right (blue) string in the period of June 2023 till April 2024. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

calculated by adding all the measured energies in Wh. Missing data points were corrected by adding the monthly average energy yield. Fig. 11 shows the measured cumulative energy yield in the period June 2023 till April 2024. Data for this graph has been generated by calculating an hourly average energy yield of the energy yield per minute. Fig. 11 shows similar differences in the energy yield of the right versus the left string in respect to Fig. 10. In total, the right string generated 767 kWh/kWp and the left string generated 873 kWh/kWp when taking into account the simulated energy yields of May, which deviates 18 % from the simulated energy yield. This deviation between measured and simulated data can be partly attributed to system losses such as cabling and inverter losses.

3.3. LCA studies

LCA studies were performed to investigate the carbon footprint of the product and the energy it produces in four different case studies over the lifetime of the technology. Table 2 presents the main parameters considered in the four scenarios, varying in length, power output and number of BOS devices implied. Physical parameters such as irradiance, active surface, lifetime or type of material remain unchanged (see also Table 1). The type of battery was selected arbitrarily based on background database availability and current technology in commercial BESS systems.

Fig. 12 presents the contribution analysis for the Global Warming Potential indicator in all scenarios. In the baseline scenario, the main contributor to GWP remains the Balance Of System (32 %), due to the DC/DC converter impact as well as the battery system, followed by the concrete block (31 %), the modules (21 %) and finally the cassette representing the last 15 %, giving a global impact of 190 g CO_2 eq per kWh. The DC/DC converters impact can be explained by the high number of devices employed in regards of their capacity per unit (5 kW) and the important mass of device (4.1 kg), leading to a total of 579 devices (193 units replaced 3 times for a 30 years lifetime system). The total contribution from silicon cell (included in module contribution) is also important with 18 %, which is not surprising given the high energy intensive processes requiring electricity and hence relying on national electricity mixes. Aluminium composite for the cassette structure

Table 2
Assumptions and parameters calculated for the global lifetime of the noise barrier infrastructure. Solar module with PERC monoSi technology of 0,596 [m^2] with active area of 0,50,064 [m^2], lifetime of 30 years, mean efficiency of 15,9 % (initial efficiency of 17,2 %) and Power capacity of 0,103 kWp per panel. Irradiation settled to 1017 kWh/m^2.year. Lifetime for electronic devices (DC/DC, DC/AC converters and battery) of 10 years and 30 years for cablings. Global PR of 0,75.

Global parameters	Baseline scenario	Scenario 2 (1000 m)	Scenario 3 (2000 m)	Scenario 4 (3000 m)
Length of noise barrier [m]	4700	1000	2000	3000
Total number of cassette [unit]	9400	2000	4000	6000
Total active surface [m^2]	4706	1001	2003	3004
Theoretical energy production per year [kWh/y]	571,092	121,509	243,018	364,527
Total energy production [kWh]	17,132,749	3,645,266	7,290,531	10,935,797
Total power capacity [kWp]	964	205	410	615
Number of concrete elements	1175	250	500	750
Electrical and lifetime assumptions on BOS				
System lifetime	30	30	30	30
Capacity of DC/DC converter [kWp/unit]	5	5	5	5
Type of DC/AC converter [kWp/unit]	20	20	20	20
Capacity for cabling [kWp/km]	209	209	209	209
Energy density for battery system [kWh/kg]	0,108	0,108	0,108	0,108
Total capacity of battery needed [kWh]	1000	1000	1000	1000
Type of battery system	NMC 811	NMC 811	NMC 811	NMC 811
Physical assumptions on BOS				
Number of DC/DC converters considering lifetime	579	126	249	372
Number of DC/AC converters considering lifetime	30	6	13	19
Cabling length needed considering lifetime [km]	4611	0,981	1962	2943
kg of batteries needed considering lifetime	27,778	27,778	27,778	27,778

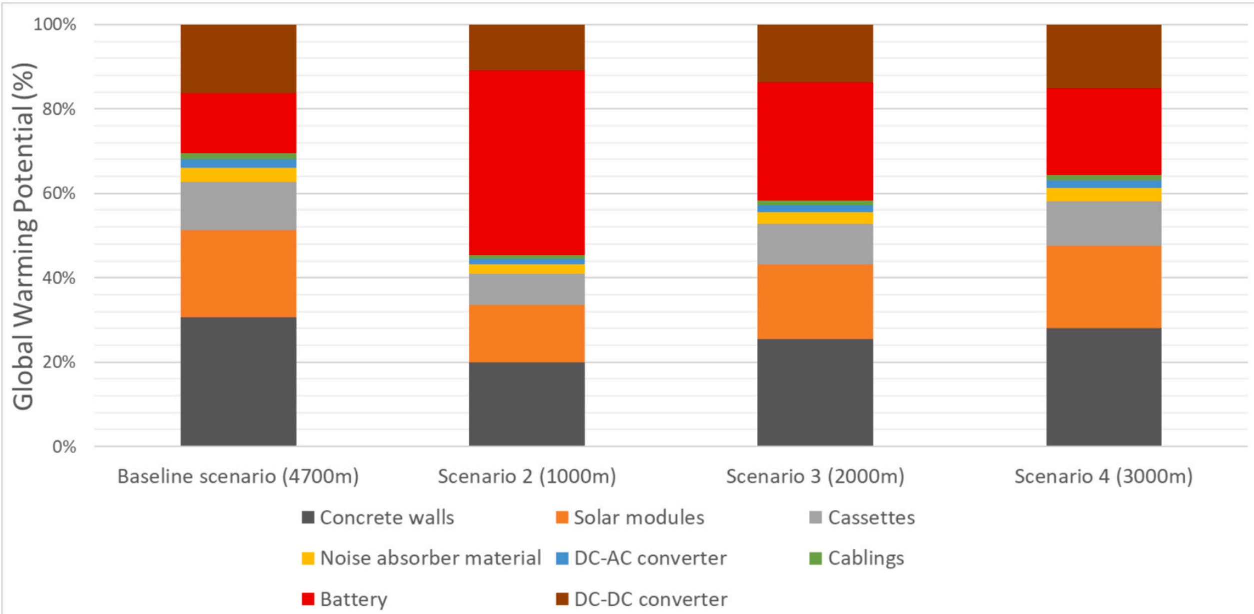

Fig. 12. Contribution analysis of the Global Warming Potential of all components of the ZigZag PV noise barrier for each scenario. Solar modules include front and backsheet in solar glass, monoSi PERC cells and EVA encapsulant. Cassettes include the aluminium structure and steel substructures such as bolt and screws.

represents 11 % of the total contribution, but no further details on the upstream process can be distinguished to explain this high share. The noise absorber material (glasswool), glass sheets for modules, substructure components (screws, bolts, etc.) have lower contribution (5 %, 2 % and 1 % respectively).

Fig. 13 presents a comparison of the GWP scores per kWh of three national energy mixes (based on ecoinvent 3.8 processes) with the scores obtained with all scenarios envisaged. The baseline scenario has the lowest score, shortly followed by the Belgian electricity mix, mainly composed of nuclear electricity and known as one of the lowest CO_2 emitting source for energy production, explained by the high energy output generated throughout the lifetime of this technology. With lower energy production due to shorter lengths, the other scenarios have a higher impact compared to Belgian mix and baseline scenario, but always lower compared to German and Dutch electricity mixes, mostly based on fossil fuel (natural gas or coal). Also, it has to be noted that all national electricity mix scores do not consider any energy storage system, in contrast with the PVNB system scenarios, which significantly burden their GWP score per kWh. These scenarios scores can be improved by sizing properly the energy storage system (BESS), which was to the real energy production, in parallel to develop cassette implemented on already-existing noise barrier system.

Next to the contributions of all components to the global warming potential and the carbon footprint of the produced electricity by ZigZag PVNBs, the energy payback time (EPBT) has been calculated for the four scenario's. The EPBT is calculated according to the Eq. (5):

$$EPBT = \frac{E_{input}}{E_{output}} = \frac{E_{input}}{I \times A \times \eta \times \frac{PR}{\varepsilon}} \tag{5}$$

where, E_{input} is the Cumulative Energy Demand obtained through Resource Use, Fossil score from E.F v3.0 (superseded) methodology concerning material, transport and manufacture of all system devices and structure. Operation and maintenance phase are not considered and End of Life (EoL) phase is included when processes were available in background database.

E_{output} is the energy generated by the system throughout its lifetime (30 years).

I is the irradiance at location place (Geleen), settled to 1017 kWh/m^2·year. This value is lowered compared to PVGIS simulation tool showing a yearly irradiation of 1227 kWh/m^2·year for a tilt angle of 50°.

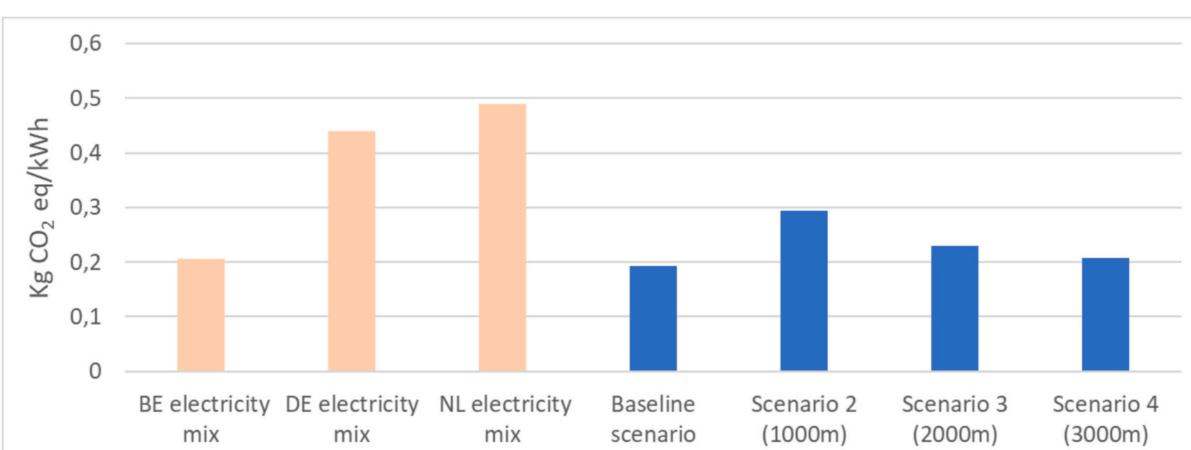

Fig. 13. Results of the carbon intensity per kWh of each scenarios in comparison with national electricity mixes of the EuroRegioMeuse countries.

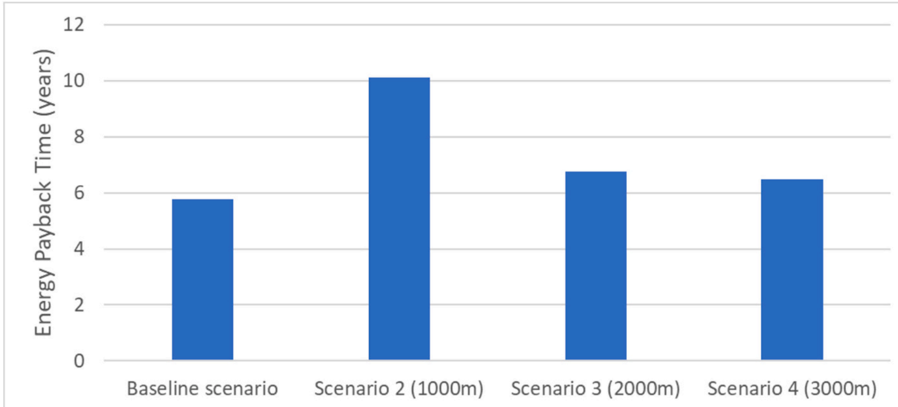

Fig. 14. EPBT values obtained with Eq. (1). These numbers are based on ideal conditions and performance, following methodological guidelines from IEA PVPS and assumptions described in Table 2.

Table 3
Values calculated for Energy Input (Cumulative Energy Demand/Resource Use, Fossils) and Energy Output calculated through Eq. (1) and assumptions fixed for key parameters.

	Baseline scenario	Scenario 2 (1000 m)	Scenario 3 (2000 m)	Scenario 4 (3000 m)
E_{output} in kWh total	17,132,749	3,645,266	7,290,531	10,935,797
E_{output} in kWh per year	571,092	121,509	243,018	364,527
E_{input} in MJ	33,675,082	12,548,536	16,756,973	24,071,876
kWh conversion factor	0,28	0,28	0,28	0,28
E_{input} in kWh	9,429,023	3,513,590	4,691,952	6,740,125
Primary energy conversion factor	0,35	0,35	0,35	0,35

η is the mean cell efficiency in percentage during a 30 years lifetime and including cell degradation rate of 0.5 % per year.

A Total active surface with modules incorporated in cassettes (number depending on length and scenarios).

PR is the Performance Ratio settled to 0,75 according to common practice and IEA PVP Task 12 guidelines on photovoltaic system [47].

ε is the electrical to primary energy conversion factor, settled to 0,35 according to literature review [48,49].

Fig. 14 shows the EPBT values calculated for the different scenarios envisaged. Regardless of shorter lengths and considering a lifetime of 30 years, the input energy is lower in all scenarios, indicating that the system is able to offset the energy implied for its construction in a relatively fast period, in all cases, before its dismantling and hence proving its energetical relevancy. It must be noticed that these numbers must be taken in regards of the assumptions made for this model, such as the simplification of the most impacting elements (BESS and DC/DC converters), where further developed and relevant life cycle inventories should be employed. Thus, the EPBT value for the ZigZag PVNB system can increase in respect of a more detailed model for these elements and more inclusive system boundary including the entire phases of its life cycle such as installation, operation and dismantling. Finally, the calculated energy output is based on theoretical assumptions and hence ideal conditions and performance throughout the year, as presented in Table 3.

4. Conclusions

A ZigZag PVNB demonstrator was designed and constructed at the Brightlands Chemelot Campus in Geleen taking circularity and mass-customization into account. The two inclination angles of the solar panels in the ZigZag constructions show the possibility to alter the design to the requirements related to a specific location. Based on the power output measurements of the two ZigZag PVNB constructions, a thermal model has been developed and optimized with which the energy yield can be simulated. Significant differences in backside module temperature and cell temperature up to 10 °C have been measured by thermocouples and FBG sensors, respectively, allowing to optimize the thermal model for accurate power output simulations. Based on this simulation, a yearly energy yield up to 1066 kWh/kWp can be expected for an inclination angle of 50°. Measured data confirmed a maximum annual energy yield of 873 kWh/kWp for the same inclination angle. Deviation between measured and simulated annual energy yield can be partly caused by system losses. Further research with respect to the noise cancelling properties of the ZigZag construction is ongoing. Preliminary sound pressure simulations in COMSOL for a ZigZag PVNB indicated that smaller tilt angles are more effective in noise reduction due to enhanced sound diffusion. The energy yield outputs for various tilt angles showed that the annual yield is not highly sensitive to the tilt angle, with only a 10 % variation for angles ranging between 20° and 80°. Therefore, a tilt angle between 20° and 40° can be considered optimal for balancing both yield and noise reduction. These results have been submitted for publication elsewhere. The LCA indicates a potential interest of producing electricity through ZigZag PVNB in comparison with national electricity mixes, according to the assumptions and LCI availability, with a reduction of 56 % and 61 % compared to the German and Dutch electricity mixes respectively and a carbon intensity of 190 g/kWh produced for the baseline scenario of a noise barrier of 4.7 km long. This LCA study is performed on a system level and includes the ZigZag PV structure, concrete walls, DC/DC and DC/AC converters, battery cells and cablings. Further investigations should be implemented for the LCI of electronic devices, which represents the first contributor of the GWP score, where simplified models were implemented. The second contributor highlighted remains the concrete structure, indicating the interest to develop a clip-on system of the ZigZag cassette on already-existing noise barrier walls, and hence withdrawing the contribution of the concrete infrastructure. Further development and modelling concerning the dismantling, end of life and recycling system of these components should also be considered to obtain a more complete analyse. Finally, the Energy Payback Time in all scenarios and including the concrete infrastructures varies between 6 and 10 years, which offsets the energy needed for device and infrastructure production after a third of the total lifetime of the system.

CRediT authorship contribution statement

Fallon Colberts: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Investigation, Data curation. **Sara Bouguerra:** Writing – review & editing, Writing – original draft, Software, Investigation, Data curation. **Arnaud Wieclawski:** Writing – review & editing, Writing – original draft, Software, Investigation, Data curation. **Marta Casasola Paesa:** Writing – review & editing, Writing – original draft, Data curation. **Wim Brand:** Writing – review & editing, Investigation, Data curation. **Sven Mullenders:** Writing – review & editing, Investigation, Data curation. **Hareim Ahmed:** Data curation. **Richard de Jong:** Writing – review & editing, Software. **Tatjana Vavilkin:** Writing – review & editing, Resources. **Wim van de Wall:** Writing – review & editing, Resources. **Christian Mass-Protzen:** Writing – review & editing, Software, Data curation. **Jeroen Bergman:** Investigation. **Jörgen Boumans:** Investigation. **Michaël Daenen:** Writing – review & editing, Supervision, Project administration. **Zeger Vroon:** Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fallon Colberts reports financial support was provided by Interreg Maas-Rijn. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.124724.

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