ACCESSIBLE SOLAR ENERGY TECHNOLOGY FOR DOMESTIC APPLICATIONS IN THE UK: EDGE SOLAR

Heaton, Alex (1);
Sung, Kyungeun (2);
Isherwood, Patrick (3)

1: HiB Ltd, UK;
2: De Montfort University, UK;
3: Loughborough University, UK

ABSTRACT

Renewable energy is increasingly used and promoted. In the UK, for example, large scale renewable energy farms have been used to supply electricity with great effect. Given the large number of homes, there is considerable impact to be made by small scale residential renewable energy systems. Despite solar panels being the most common form of residential renewable energy technology, only 4% of buildings in the UK support solar technology of any kind. For direct electricity generation, silicon-based photovoltaic (PV) arrays are the most utilised, and when used in a residential setting, they are typically mounted on the sloped roofs. This is where the problem lies. The technology comes with a high cost, and there is further financial burden of installation and maintenance, making solar energy inaccessible for many UK homeowners. This paper presents a research and design innovation project to make PV technology more accessible in the UK. Edge Solar, the innovative, affordable, new PV system concept for UK homes may become a promising solution to significantly improve the accessibility to the PV technology and renewable energy at the household level in the UK and beyond with further development and commercialisation.

Keywords: Conceptual design, Design engineering, Innovation, Photovoltaic technology, Renewable energy

Contact:
Sung, Kyungeun
De Montfort University
United Kingdom
kyungeun.sung@dmu.ac.uk

Cite this article: Heaton, A., Sung, K., Isherwood, P. (2023) ‘Accessible Solar Energy Technology for Domestic Applications in the UK: Edge Solar’, in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.45

1 INTRODUCTION

Renewable energy is increasingly used and promoted in many parts of the world. In the UK, for example, large scale renewable energy farms have been used to supply electricity to UK homes with great effect. For example, located in the North Sea, the Hornsea Project remains the world's largest offshore wind farm, supplying sufficient energy to power over a million homes (Ørsted, 2022). Similarly, the UK is home to 469 solar farms, the largest of which spans 250 acres (DeegeSolar, 2022). Given the large number of homes, however, there is considerable impact to be potentially made by small scale residential renewable energy systems being installed across the UK. Whilst wind power may be reliable in an offshore setting, due to the nature of urban environments, solar power provides a more consistent source of energy, reflected in its dominance over the residential renewable energy market. Despite solar panels being the most common form of residential renewable energy technology, about 4% of buildings in the UK supports solar technology of any kind (SolarEnergyUK, 2022). In terms of direct electricity generation, silicon-based photovoltaic (PV) arrays are the most utilised, and when used in a residential setting, they are typically mounted on the sloped roofs of houses. This is where the problem lies from the perspective of consumers. The technology comes with a high cost, and there is further financial burden of installation and maintenance, which makes solar energy inaccessible for many UK homeowners. Combined with long payback periods, for those who can afford such a system, the investment may not appear financially viable.

There is a space for innovation in the adaptation of existing PV technology to make it accessible to a wider demographic of citizens. By identifying key limitations and barriers preventing homeowners from installing solar arrays, changes can be made. As the apparent issue lies in the initial access to solar technology, some of the possible changes (such as reducing the cost and scale) may result in reduced performance compared to current roof-mounted arrays. If implemented on a larger scale through an extended consumer base, however, the overall impact on UK residents' dependency on renewable energy would be increased. This is both beneficial to the environment through the reduction of fossil fuel dependency, and to the consumes/citizens by providing clean, free energy. Acknowledging this innovation opportunity, this paper presents a research and design innovation project to make PV technology accessible to a wider demographic of citizens in the UK. This was MSc Product Design project completed at De Montfort University between October 2021 and September 2022. The MSc student, Alex Heaton (first author), was supervised by Kyungeun Sung (second author) and advised by Patrick Isherwood (third author). The majority of work including research, generation of design brief, and actual design was conducted by the first author.

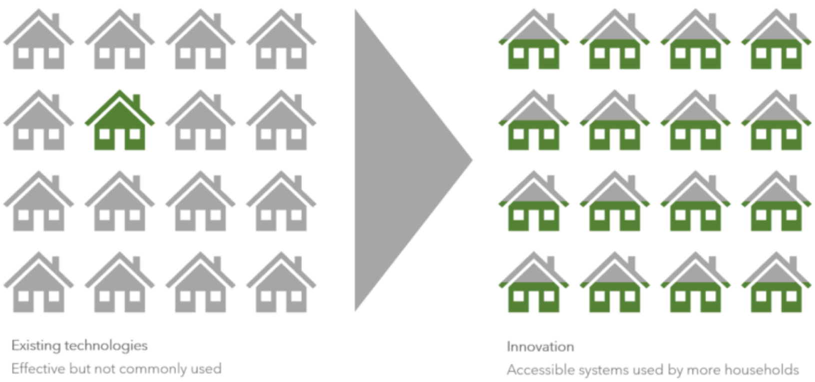

Figure 1. Innovation opportunity in more accessible PV systems

2 LITERATURE REVIEW ON RENEWABLE ENERGY TECHNOLOGIES

The use of fossil fuels such as coals, oils and natural gases is not sustainable for two reasons: they are finite resources which cannot be regenerated; and the burning process releases large quantities of carbon emissions and other greenhouse gases, contributing to the effects of global warming. In 2020, over 41% of the energy generated in the UK came from the use of fossil fuels (BEIS, 2021). Measures have been taken to address the issue of unsustainable energy generation and consumption. In terms of

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electricity generation, the UK is a large advocate of wind power, with the Hornsea Project One off the coast of Yorkshire being the world's largest offshore wind farm upon its completion in 2020 (Ørsted, 2022). In the review of the UK's renewable energy generation, the Office for National Statistics states that wind energy generation accounts for 24% of total electricity generation (ONS, 2021). However, the UK imported 36% of its energy needs, with 90% of those being sourced from gas and oil (Bolton, 2018). With the recent conflict between Russia and Ukraine, the UK has been severely affected in terms of energy bills, showing the heavy dependency on imported energy. This highlights the urgent need to have higher capability of UK energy generation based on renewable sources. The following sub-sections review existing solutions that could be applicable to the UK and elsewhere.

2.1 Large scale solutions

Many countries have invested in large scale renewable electricity generation depending on the conditions and resources that are available. For instance, UK's Hornsea Project, an offshore wind farm, has a total capacity of 1.2GW to power over one million UK homes (Ørsted, 2022). Located in the North Sea, the 174 turbines are situated in an area of consistent high wind speeds to ensure a reliable output of electricity. Similarly, hydroelectric power stations can be relied upon for consistent energy outputs as they are situated on sites with a constant high-volume flow of water. The Three Gorges Dam in China consists of 32 main turbines generating a total of 22,500MW. The problem of this, however, is its ecological impact described as a severe threat to wildlife (Liu et al., 2020). Solar farms can generate meaningful quantities of electricity based on vast areas of land. For example, the Copper Mountain Solar Facility in Nevada, USA occupies an area of 6km^2 and has a capacity of 552MW (Thymianos et al., 2021). The current largest PV farms are in India (Bhadla Solar Park) with a capacity of 2.25GW and in China (Huanghe Hydropower Hainan Solar Park) with a capacity of 2.2GW (Ornate Solar, 2022). Wind and solar are the two cheapest large-scale energy generation technologies that are also fastest to roll out in the UK when it comes to large scale solutions.

2.2 Small scale solutions

Small scale off-grid or decentralised energy technologies can offer renewable energy to areas not directly linked to a main power grid or provide an additional source of energy to those who are. Decentralised energy technologies are particularly effective in rural areas or in countries with a low population density. They are also strategically valuable from the security perspective since taking out highly dispersed generators is much harder than a single strike against one large power station. For these reasons, they are being increasingly utilised in developing countries in areas with poor connections to the main power grid (Kemausuor et al., 2018; Moner-Girona et al., 2021). They are also used in more developed but less densely populated countries such as Finland and Norway, where the cost of installing power lines and the environmental effects of transporting the energy are far greater than having individual systems for each home (Inderberg et al., 2018; Kainiemi et al., 2019).

2.2.1 Micro wind generators

Micro wind generators or domestic wind turbines are available in two forms, free standing pole mounted turbines, and more commonly in the UK, building mounted systems. According to the research into the use of micro wind turbines in the UK domestic sector, the latter are typically available in models in the 0.4-2.5kW size range (Peacock et al., 2008), and 1.5kW turbine in the UK typically shows the annual yield of 277kWh which equates to 6.7% of the 4,124kWh of average annual electricity demand of a UK home (Richardson et al., 2010). Currently, very few UK homes accommodate a wind turbine. There are several potential reasons for this: not all buildings are suitably designed to support domestic wind turbines; the initial installation costs of a roof mounted turbine can be up to £3,000 (OVOenergy, 2021); and some users may find the sight and potential vibrations of the system a disturbance.

2.2.2 Solar thermal collectors

Not all solar thermal collectors (STCs) generate electricity, depending on the system and what it is designed to do. Mostly they collect the energy of solar radiation and store it as thermal energy in a normal hot water cylinder (EIA, 2021). A typical flat plate collector generates hot water, whilst concentrator systems can be used for low-grade heating and hot water, heat for industrial processes, or electricity generation, depending on the resource, the degree of concentration, and the size (largest

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solar thermal power station generating 500MW) (Behar, et al. 2013). Some STCs are dependent on weather conditions: flat-plate (non-concentrator) systems work very well in the UK whereas concentrator systems (either solar thermal or PV) will not work so well due to the relative lack of beam light in the UK, making them less popular.

2.2.3 Photovoltaic panels

Photovoltaic (PV) panels contain cells consisting of layers of semi-conducting materials. Silicon is the most used semi-conductor in PV modules. An electric current and voltage are generated as photons interact with this material. PV panels do not require direct sunlight to operate, but the brighter the light source, the more energy will be generated (Ahmad et al., 2020). A study by Project Solar UK states that 1.5m^2 roof mounted panel running at 80% efficiency (nominal maximum) under typical UK conditions can produce 1.8kWh of electricity in a day with 6 hours of sunlight (ProjectSolarUK, 2020). In the UK, one in every 25 buildings supports solar technology without specifying the percentage of PV panel use (SolarEnergyUK, 2022).

2.3 Comparison between solutions

The weather conditions in the UK make it the ideal location for harnessing wind power (BEIS, 2011), hence the successful construction of the Hornsea Project One (Ørsted, 2022). However, micro wind turbines have not yet been widely adopted to make significant impact. This may be due to the high initial cost of installation and building restrictions. Another possible reason could be that consumers may find them unsightly since building mounted systems are allowed to extend up to three metres above the height of the chimney (HIES, 2022). Moreover, they are unlikely to have any notable impact anyway: wind turbine power output is partly a function of the swept area, therefore limited maximum power output by micro turbines. Photovoltaic (PV) solar panels on the other hand have become increasingly popular - close to a million domestic PV systems around the country (SolarEnergyUK, 2022). Although UK conditions are less conducive to optimising PV performance, their ability to function consistently even with lower levels of sunlight amounts to an increased yield. This consistency along with their more discrete design may make PV panels more popular than domestic wind turbines. Despite the popularity, about 4% (or lower) of buildings in the UK supports solar technology (SolarEnergyUK, 2022). Silicon-based PV arrays are most utilised in a residential setting for solar energy, typically mounted on the sloped roofs of houses which come with high cost of installation (with a significant part being the cost of scaffolding) and maintenance and therefore long payback periods (variable depending on the amount of energy generation, export and import of power, and use of electricity).

2.4 Research and innovation opportunity

The key hindrance in the application of domestic solar energy technology (or any other RETs - Renewable Energy Technologies) is the initial cost for consumers. Despite the government's solar panel grants, for many, the payback period is too long to make the installation worthwhile. For PV panels (and domestic wind turbines) a cheaper design may increase the number of applications. Although a lower budget may result in reduced efficiency of the systems, the increased usage could ultimately offset this. More can be done to seamlessly integrate solar energy technology (or RETs in general) into urban dwellings and normalise their use, as large numbers of users making small contributions would offset the need for a large fraction of fossil fuel-based energy.

There is an abundance of reliable scientific data available on the performance and efficiency of domestic RETs and the cost of installing various systems. However, there appears to be very little research into the social science behind consumers' decisions to purchase such systems. Some social and financial factors have been alluded to but further research into this area would indicate key changes that need to be made to domestic solar energy technology/system. Another important question would be how much money consumers are willing to pay for the system and the average payback time they would expect. This would indicate where improvements could be made and heavily influence design decisions. The assembly and installation processes of existing systems could be explored to aid in reducing initial installation difficulties and costs.

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3 RESEARCH FOR DESIGN

This section explains the research conducted to support the rationale for the design of the product.

3.1 Research methods

Mixed method (Robson, 2011) study combining online questionnaire and interview was conducted between February and March in 2022. An online questionnaire (Table 1) was sent to 100 potential end users (current and previous UK homeowners) in order to understand why there are so few homes with solar panels installed. Two experts in the field of PV technology and systems (one from academia and another from industry) were interviewed in order to understand the domestic solar energy technology/system and installation processes. The academic expert was asked about technical side of the solar energy systems. The industry expert was asked about the installation and market side of the PV systems.

Table 1. Online questionnaire administered to potential end users

Question (answer options)
Which property type best describes your home? (Detached; Semi-detached; Terraced; Flat)
In your opinion, how important is it that we switch to renewable sources of energy? (1: not important at all; 5: very important)
Which renewable energy sources are you aware that you could install at your home? (Solar panels; Rooftop wind turbines; Solar thermal collectors; Biomass burners; Other)
If any, which renewable energy sources are present at your home? (Solar panels; Rooftop wine turbines; Solar thermal collectors; Biomass burners; Other)
If you have not had PV panels installed at your home, what are the reasons for this? (Have never considered it; Too high installation cost; Too high maintenance cost; Too long payback period; Property unsuitability; Other)
What changes to PV panels would make you consider installing PV panels at your home? (Reduced installation cost; Easier maintenance; Government scheme; Interactive feedback system; Appealing appearance; Other)
If an average household solar array saves £570 in electricity each year, how much would you be willing to pay for the system? (Less than £1,000; £1,000 to £3,000; £3,000 to £5,000; over £5,000)

3.2 Potential end user questionnaire results

The online questionnaire yielded 75 valid responses from the UK homeowners. The majority of the respondents (85.6%) answered that they live in a house rather than a flat: detached house (21.3%); semi-detached (40%); and terraced (24%). Most respondents (90.7%) stated that it is important to switch to renewable sources of energy: 'very important' (62.7%) and 'important' (28%). When it comes to the awareness level, the respondents were aware of the solar panels (97.3%) as their option but not so much of others: solar thermal collectors (29.3%), biomass burners (20%), and rooftop wind turbines (18.7%). The majority (89.3%) does not have any renewable energy sources at their home presently; five respondents (6.7%) said they have solar panels installed, two (2.7%) said solar thermal collectors installed, and one (1.3%) biomass burner. As the reasons for having not installed PV panels at home, the most frequent answer was 'too high installation cost' (64%), followed by 'too long payback period' (36%), 'property unsuitability' (30.7%), 'have never considered it' (20%), and 'too high maintenance cost' (17.3%). For the changes that will make them consider installing PV panels at home, the most frequent answer was 'government scheme' (73.3%), followed by 'reduced installation cost' (62.7%), 'easier maintenance' (29.3%), 'interactive feedback system' (17.3%), and 'appealing appearance' (12%). Taking into account the potential annual energy bill saving of £570, the cost for the system they are willing to pay was mostly £1,000 to £3,000 (60%) or less than £1,000 (25.3%). This cut off point (£3,000) suggests that this may be a suitable target recommended retail price.

3.3 Academic expert interview results

The expert suggested some important features to consider in the design process. For example, he thought that there may be interference from trees and buildings resulting in shade spots on the panel. If one cell on the panel is considerably more shaded than others, "you could end up with it having too high a current being pushed through by the other cells in the string because it's a diode" expert said.

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This would result in the panel being overloaded and possibly causing a failure. For this reason, "bypass diodes are added in parallel" between rows of cells in order to prevent this surge from overloading shaded cells (Vieira et al., 2020). With regards to the most efficient angle for solar panels to be mounted, the expert confirmed that 90 degrees to the incident ray of the sun is optimal. In fact, the average pitch angle of 32 degrees for UK house roofs combined with latitude of the UK results in an incident angle very close to this in the middle of the day in summer for south facing roof tops. The expert pointed out that this is less relevant in overcast conditions when the light is diffused. He said, "around 50% of the light we get is actually diffused", meaning that photons hit the cells from every angle relatively evenly. When asked about how and when solar panels fail, the expert answered that undue force such as "unexpected wind loading" is a known failure mechanism. The silicon wafers used in PV cells are "actually less flexible than glass". For this reason, panels are typically supported from many points to spread any undue loads evenly. For the same reason, solar panels typically feature a rigid aluminium frame on all four edges. Others include installer-caused damage, poor electrical connections leading to overheating, sealant failure and consequent water ingress leading to corrosion of the contacts, human errors, and various internal electrical failure mechanisms caused by a number of issues including cell manufacturing issues, shading effects, bypass diode failure, etc.

3.4 Industry expert interview results

The industry expert stated that the most commonly installed systems on UK homes are 4kW arrays and these require 29m^2 of roof space. An average retail price to install such a system is apparently around £6,000 to £8,000. The expert explained that the installation typically requires two workers at a maximum rate of £500 per person per day. The 4kW systems generally take two days to install, meaning the average installation cost up to £2,000 leaving £4,000-£6,000 being spent on the panels alone. Depending on the scale of the system, annual savings of £160-£430 can be achieved, resulting in an "average payback period of 15-25 years". This might have changed recently with the rising energy cost (with the current residential electricity rates of ~32p+ /kWh): with 100% producer usage, we might be able to expect about £1,000 or more per year in savings, therefore 5-7 years payback time. The expert highlighted two types of solar panel installation. The less common arrangement is "more expensive solar batteries for storing the charge gained from the PV system". He implied that the more common method used is a "net metering system" whereby electricity generated is supplied back to the national grid and the net usage is monitored through a smart meter (Bruce, 2022).

3.5 Implications for design

The online questionnaire results showed that UK homeowners value renewable sources of energy (90.7% of respondents) with the high awareness of the solar panels as their option (97.3%). But the majority (89.3%) did not have solar panels or any other types of renewable energy technology/system at home mostly due to the high installation cost (64%) and long payback period (36%). They would be encouraged to install solar panels with government scheme (73.3%) and reduced installation cost (62.7%). The design considerations also included easier maintenance, interactive feedback system, and appealing appearance. The target retail price including installation should be up to £3,000. Regarding the design development, one key detail to consider was the mechanical strength of the panels and the necessary support structure to keep the brittle silicon layers from cracking. In order to reduce the risk of overloading shaded cells, the number of bypass diodes should be increased. The current market information provided by the industry expert were used as an important reference throughout the design process. In order to meet the target retail price, one of design aims was set to remove/reduce the need for paid labour (and the scaffolding costs) to install the system. This would involve relocating the PV system to a more accessible location.

4 DESIGN DEVELOPMENT

The following design brief was created on the basis of the research (Section 3): "To create a PV array to be used at ground level in the gardens and back yards of typical UK homes. The system should be more accessible to the average consumer financially, and more personal in terms of performance feedback and interaction. This will be done by removing the need for high installation costs and scaling down the system compared to existing products. This new solution should be a more accessible product for users with the aim of making PV panels common place in homes across the UK". Six

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initial ideas were generated (Figure 2). Each variation could theoretically meet the project aim, with the difference in installation and user interaction. Amongst these, two concepts (green box in Figure 2 (a)) were selected on the basis of the potential user survey (n=97): two thirds preferred the selected concepts over others.

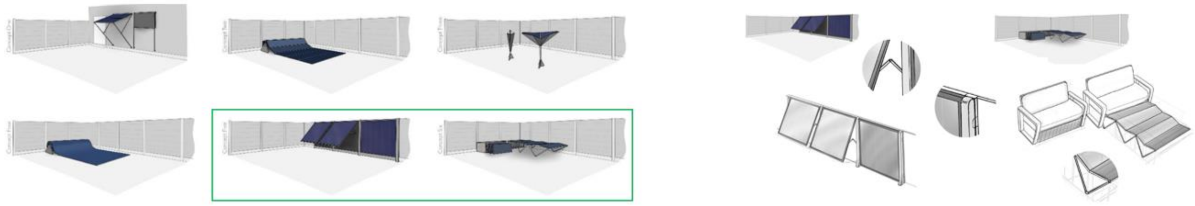

Figure 2. (a) Six initial ideas (on the left); (b) two promising concepts (on the right)

The two selected concepts were further explored (Figure 2(b)), and their potential benefits and limitations were identified as follows. The first concept, PV panels sitting in front of garden fence panels (left images of Figure 2(b)), may have benefits of large usable surface area, easy deployment, easy cleaning and maintenance, and development with standardised fence panel dimensions, whereas the limitation might be potentially difficult installation for large scale installation. The second concept, garden furniture with foldable PV panels (right images of Figure 2(b)), provide multi-functions and compact storage out of sight with no installation, whereas the limitations are cost brought up by including secondary function (furniture) and its use as a garden furniture in sunny weather when panels are most productive. Based on this rationalisation, the first concept (PV panels attached to the garden fence panels) was selected for further development due mainly to the cost-effectiveness for energy generation.

The selected concept was developed, refined and confirmed through a number of testing in terms of technical feasibility and potential user needs/wishes. The testing included: (a) user testing with Augmented Reality (AR) with three potential users in different garden environment; (b) PV panel cell efficiency testing (tested at the specified angle of 50 degrees) under two different lighting conditions (broad daylight and overcast) using four different positions around a typical UK house garden (east, west, south and north facing) at midday; and (c) post spike testing with test rigs (constructed to carry the load of 27.5kg of PV panels) to test the ease of installation, performance and stability (Figure 3).

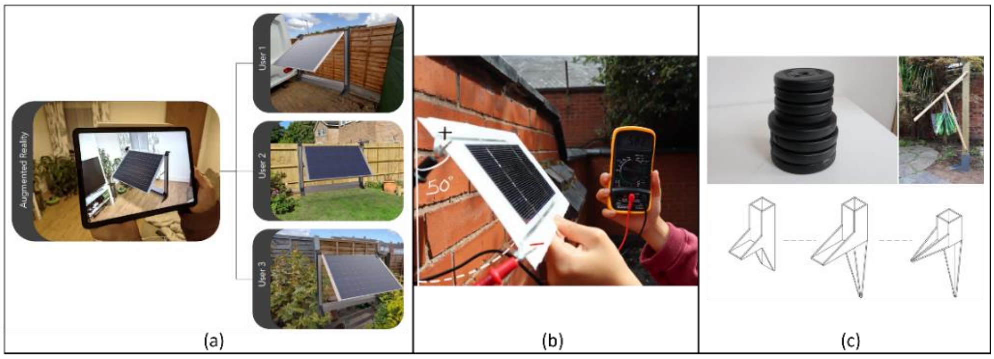

Figure 3. (a) user testing with Augmented Reality (AR); (b) PV panel cell efficiency testing; and (c) post spike testing

The proposed final solution, Edge Solar (Figure 4), could be a more accessible solar energy technology product for domestic application in the UK (and beyond) by removing the need for high installation cost (on the roof) and scaling down PV arrays. Edge Solar has modular design with easy self-assembly, installation and disassembly on the ground level. The construction (assembly and installation) has been brough down to a level that would be comfortable for most homeowners with DIY knowledge, with light weight components and plug and play technology surrounding the microinverter system (Figure 6), meaning panels can be linked onto one another without the need for complex rewiring. Although it is supposed to be self-installed, it can be an option to have it installed by professionals too. The easy assembly and disassembly also enable the relocation of the system

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when moving to another property. This is a huge benefit over conventional systems, as many (potential) users see the repayment periods as being too long and too much of a commitment to fit permanent panels to their home.

Figure 4. Edge Solar final design solution proposal

Gas struts assist in extending and retracting panels - adjustable angle up to 50 degrees (Figure 4 and 6) and panels can be stored vertically when the outdoor space is needed (Figure 4). When installed multiple sides of the garden fences, Solar Edge system could continue generating electricity throughout daylight hours, regardless of the direction of the garden. The performance feedback app allows users to monitor their panels' efficiency and performance, calculate savings on their energy bills, and share their results with friends and family, working towards awareness raising (Figure 5). Compared to the current roof-top system which costs around £5,000 excluding installation on the surface area of 29m^2 for 3000kWh of annual yield - 4kW system, Edge Solar could be an affordable, scaled-down solution based on the surface area of 13.9m^2 (equivalent to 5 standard UK fence panels) for the expected annual yield of 1,438kWh (1.9kW system estimated). The estimated total cost of Edge Solar could be around £2,890 (£2,090 for PV Panels + £400 for microinverters + £200 for manufacturing with other materials - mostly aluminium and stainless steel for frames and structure + £200 for reduced installation for connecting the system to the national grid by a specialist) which meets the potential users' expectation (£3,000 or less).

Figure 5. Edge Solar performance feedback app

5 DISCUSSION AND CONCLUSION

The proposed solution, Edge Solar, in theory, meets the aim of the project: making solar energy technology accessible for domestic applications in the UK (and beyond) by scaling down and brining the solar arrays to ground level in a more manageable way. The design's structural and technical feasibility has been proven through rigorous testing. The concept as a whole, however, remains unproven with a lack of real-world testing. Further development would involve building a full-scale prototype of the mechanism for testing. There is a space for further development and optimisation of the assembly and installation of the system. A more in-depth cost analysis is necessary to ensure that this product is in fact a viable option for most consumers. With more development and commercialisation effort, this concept could become a promising solution to make domestically sourced renewable energy common place in the UK households. In terms of limitations, we regretfully acknowledge that this paper lacks the literature references in the state of the art which account for the need of a new study in this field and that there are some contents omissions (e.g. detailed information on each initial idea, process of developing AR and prototypes) due mainly to the page limit. Another limitation is rather narrow scope of this project - it addresses the UK market only. Despite the limitations, this paper contributes to the design community with the novel design outcome as a

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promising solution that is potentially worth patenting once the rigorous prototyping and testing is done. We are also sharing this as an exemplary MSc Product Design project that could inspire other educators (and practitioners). We are also planning to use this paper as one of the important learning materials for our MA and MSc Product Design programme.

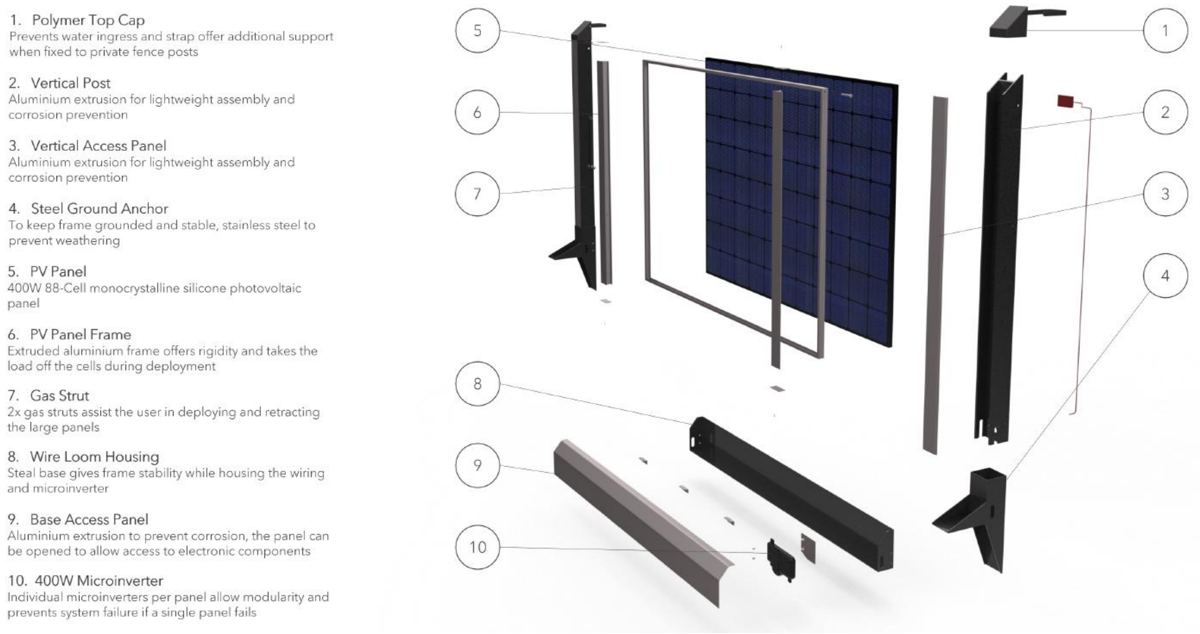

Figure 6. Edge Solar technical solution per panel

ACKNOWLEDGMENTS

This work (including conference attendance) was supported by the AHRC Research Networking grant for International Upcycling Research Network [grant number AH/W007134/1] and with the generous staff innovation allowance from De Montfort University (DMU). DMU Faculty (Arts, Design and Humanities) Enhancing Research Culture Funding also partially supported the conference attendance. We thank Guy Bingham, Stuart Lawson, Kelley Wilder, Kate Cheyne, Siobhan Keenan, Deborah Cartmell and Heather McLaughlin for supporting this research at DMU.

REFERENCES

Ahmad, L., Khordehgah, N., Malinauskaite, J. and Jouhara, H. (2020). "Recent advances and applications of solar photovoltaics and thermal technologies". *Energy*, *207*, 118254.

Behar, O., Khellaf, A. and Mohammedi, K., (2013). "A review of studies on central receiver solar thermal power plants", *Renewable and Sustainable Energy Reviews*, 23, 12-39.

BEIS. (2011). *UK Renewable Energy Roadmap*. [online] Department for Business, Energy and Industrial Strategy. Available at: (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48128/2167-uk-renewable-energy-roadmap.pdf) (17/11/2022).

BEIS. (2021). *UK ENERGY IN BRIEF* 2021. https://www.gov.uk/government/statistics/uk-energy-in-brief-2021

Bolton, P. (2018). *Energy imports and exports.* [online] House of Commons Library. Available at: (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://researchbriefings.files.parliament.uk/documents/SN04046/SN04046.pdf) (17/11/2022).

Bruce, J. (2022). *Are Solar Panels Worth It In The UK? Solar PV In UK.* [online] Solar Empower. Available at: (https://www.solarempower.com/blog/are-solar-panels-worth-it-in-the-uk-solar-pv-in-uk/) (17/11/2022).

DeegeSolar. (2022). *The UK's 5 biggest solar farms.* [online] Deege Solar. Available at: (https://www.deegesolar.co.uk/uks_biggest_solar_farms/) (17/11/2022).

EIA. (2021). *Solar explained Solar thermal collectors.* [online] USA Energy Information Administration. Available at: (https://www.eia.gov/energyexplained/solar/solar-thermal-collectors.php) (17/11/2022).

HIES. (2022). *Home Wind Turbines.* [online] HIES. Available at: (https://www.hiesscheme.org.uk/renewable-energy/home-wind-turbines/) (17/11/2022).

Inderberg, T.H.J., Tews, K. and Turner, B. (2018). "Is there a prosumer pathway? Exploring household solar energy development in Germany, Norway, and the United Kingdom", *Energy Research & Social Science*, *42*, 258-269.

https://doi.org/10.1017/pds.2023.45 Published online by Cambridge University Press

Kainiemi, L., Eloneva, S. and Levänen, J. (2019). "Transition towards a decentralised energy system: analysing prospects for innovation facilitation and regime destabilisation in Finland", *Technology Analysis & Strategic Management*, *31*(9), 1003-1015.

Kemausuor, F., Sedzro, M.D. and Osei, I. (2018). "Decentralised energy systems in Africa: coordination and integration of off-grid and grid power systems—review of planning tools to identify renewable energy deployment options for rural electrification in Africa", *Current Sustainable/Renewable Energy Reports*, *5*(4), 214-223.

Liu, M., He, Y., Baumann, Z., Zhang, Q., Jing, X., Mason, R.P., Xie, H., Shen, H., Chen, L. and Zhang, W. (2020). "The impact of the Three Gorges Dam on the fate of metal contaminants across the river–ocean continuum", *Water Research*, *185*, 116295.

Moner-Girona, M., Bender, A., Becker, W., Bódis, K., Szabó, S., Kararach, A.G. and Anadon, L.D. (2021). "A multidimensional high-resolution assessment approach to boost decentralised energy investments in Sub-Saharan Africa", *Renewable and Sustainable Energy Reviews*, *148*, 111282.

ONS. (2021). *Wind energy in the UK: June 2021.* [online] Office for National Statistics. Available at: (https://www.ons.gov.uk/economy/environmentalaccounts/articles/windenergyintheuk/june2021) (17/11/2022).

Ornate Solar. (2022). *The 5 Largest Solar Power Plants in the World (2022). [online] Ornate Solar. Available at:* https://ornatesolar.com/blog/the-5-largest-solar-power-plants-in-the-world#:~:text=Location%3A%20Rajasthan%2C%20India&text=Bhadla%20Solar%20Park%20is%20the,of%20over%201.3%20billion%20dollars. *(29/11/2022)*.

Ørsted. (2022). *Hornsea Project One: About the project.* [online] Ørsted. Available at: (https://hornseaprojectone.co.uk/about-the-project#project-timeline-2020) (17/11/2022).

OVOenergy. (2021). *A guide to domestic wind turbines and how they can power your home.* [online] OVO energy. Available at: (https://www.ovoenergy.com/guides/energy-guides/home-wind-turbines-pros-cons-and-how-much-they-cost) (17/11/2022).

Peacock, A.D., Jenkins, D., Ahadzi, M., Berry, A. and Turan, S. (2008). "Micro wind turbines in the UK domestic sector", *Energy and Buildings*, *40*(7), 1324-1333.

ProjectSolarUK. (2020). *How much electricity does a solar panel produce?* [online] Project Solar UK. Available at: (https://www.projectsolaruk.com/blog/how-much-electricity-does-a-solar-panel-produce/) (17/11/2022).

Richardson, I., Thomson, M., Infield, D. and Clifford, C. (2010). "Domestic electricity use: A high-resolution energy demand model", *Energy and Buildings*, *42*(10), 1878-1887.

Robson, C. (2011). *Real world research: A resource for social scientists and practitioner-researchers* (3rd ed.). John Wiley & Sons, Chichester.

SolarEnergyUK. (2022). *Empowering the UK solar transformation.* [online] Solar Energy UK. Available at: (https://solarenergyuk.org/) (17/11/2022).

Thymianos, K., Salahi, S. and Brown Jr., W.E. (2021). *Operating Solar Projects in Nevada, 2021.* [online] The Data Hub at The Lincy Institute & Brookings Mountain West. Available at: (https://digitalscholarship.unlv.edu/bmw_lincy_env/5/) (17/11/2022).

Vieira, R.G., de Araújo, F.M., Dhimish, M. and Guerra, M.I. (2020). "A comprehensive review on bypass diode application on photovoltaic modules", *Energies*, *13*(10), 2472.