OUTPUT 5.3
Living Lab Pilot (UoP)

Document prepared by University of Portsmouth

Executive summary

Living labs are defined as user-centered, open innovation ecosystems based on a systematic user co-creation approach integrating research and innovation processes in real-life settings. The key stakeholders of a university-based living lab are academic staff, researchers, students, and external partners.

A living lab provides the opportunity for staff and students to build solutions that directly address immediate real-world problems and to analyse the behaviour of real systems as they operate. Moreover, university-based living labs provide access to live testbeds for innovative scientific research and training. They can serve as flexible tools that allow users to focus on issues and themes of importance at a real scale. External stakeholders benefit from living labs by gaining access to expertise and facilities that support them in addressing important issues that affect them.

As part of the SOLARISE project funded by Interreg 2 Seas and the European Regional Development Fund, a living laboratory has been created consisting of installations at two buildings at the University of Portsmouth.

This report describes the facilities and purpose of the Solar Living Laboratory at the University of Portsmouth, it provides an overview of the monitoring set up at each site, and it offers examples of the kind of data that is being collected through the living lab facilities

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1. Introduction

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A living lab provides the opportunity for staff and students to build solutions that directly address immediate real-world problems and to analyse the behaviour of real systems as they operate. Moreover, university-based living labs provide access to live testbeds for innovative scientific research and training. They can serve as flexible tools that allow users to focus on issues and themes of importance at a real scale. External stakeholders benefit from living labs by gaining access to expertise and facilities that support them in addressing important issues that affect them.

As part of the SOLARISE project funded by Interreg 2 Seas and the European Regional Development Fund, a living laboratory has been created consisting of installations at two buildings at the University of Portsmouth. The two buildings involved in the installation are the Port-Eco House and the Future Technology Centre building.

The Port-Eco House, shown in Figure 1, is a research facility consisting of an instrumented 3 bedroom household for research in energy efficiency and building performance. SOLARISE will allow the eco-house to be provided with solar panels, energy storage, energy monitoring and other technologies for demonstration purposes.

The Future Technology Centre, shown in Figure 2, is a £12m facility opened in 2018 for project based learning and innovation in engineering and product design. The building is equipped with solar photovoltaics and has been provided with an energy storage system and monitoring through SOLARISE.

This report describes the facilities of the Solar Living Laboratory at the University of Portsmouth, it provides an overview of the monitoring set up at each site, and it offers examples of the kind of data that is being collected through the living lab facilities.

The University of Portsmouth Solar Living Lab is an open platform for demonstration, training, research and development on solar energy technologies, covering various aspects of solar PV technology, but making emphasis on the following aspects:

- Studying interplay between PV solar installations and energy storage.
- Demonstrating the benefits of solar energy.
- Demonstrating the benefits of energy storage when associated with solar energy.
- Monitoring of environmental variables, systems variables and performance
- Energy management systems
- Modelling and control of solar inverters
- Management of the energy storage system
- Operation of virtual power plants
- Smart metering and its interaction with solar PV installations.
- Showcasing novel solar energy technologies

Figure 1: Aerial view of the Port-Eco House.

Figure 2: The Future Technology Centre.

2. Description of the Solar Living Lab facilities

2.1 INSTALLATION AT THE PORT-ECO HOUSE

The installation at the Port-Eco House was completed on 7th May 2021. The solar panels were ground mounted on a small lawn area adjacent to the Port-Eco House, as shown in Figure 3. The total photovoltaic capacity is 5 kW peak. The installation of the solar panels required planning permission, which was approved by the local planning authority in October 2020. The connection of the solar panels and battery storage to the University electrical network required permission from SSEN, the distribution network operator, which was also granted late in 2020. Table 1 describes the various items of equipment that were installed, along with their location.. Figure 4 shows the Tesla Powerwall 2 battery installed in a storage room at the back of the Port-Eco house. Figure 5 shows a diagram with the main the system at the Port-Eco House.

Table 1: Equipment installed at the Port-Eco House

Item description	Quantity	Location
JA Solar HAN60S10 335 W monocrystalline solar module	15	Lawn area adjacent to the Eco-House.
Renusol ConSole CS+ standalone ballasted PV-mounting system	15	Under the solar modules
SolarEdge P370 Power Optimizer	15	Under the solar modules
SolarEdge SE5000H single phase inverter	1	In the control room inside the Port-Eco-House
Tesla Powerwall 2 battery, single phase 230V AC connection, 13.5 kWh usable energy capacity.	1	In a storage room behind the Eco-Hose.
Tesla Powerwall 2 Backup Gateway.	1	In the control room inside the Port-Eco-House

Figure 3: This image shows the installed 5kW photovoltaic solar array on the adjacent lawn by the Port-Eco House, which is shown to the right of the panels.

Figure 4: The image shows the Tesla Powerwall 2 battery that was installed in a storage room at the back of the Port-Eco-House.

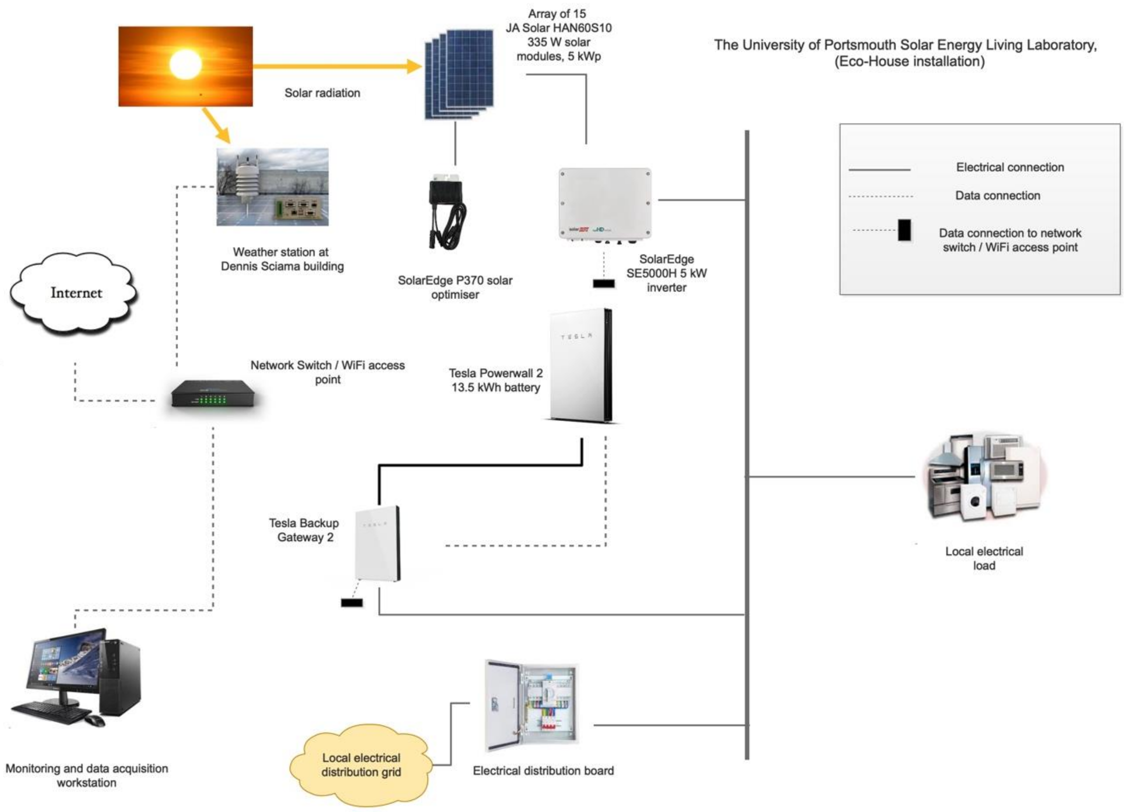


Figure 5: Diagram showing the main elements of the Solar Living Lab installation at the Port-Eco House and their interconnectivity.

2.2 Installation at the Future Technology Centre

The Future Technology Centre already had solar photovoltaic panels installed on the rooftop of the building as well as windows equipped with photovoltaic cells. The building is shown in Figure 2. The total installed photovoltaic capacity on the building is 25 kW peak. Two three-phase inverters rated 20 kW and 5 kW, respectively, connect the photovoltaic generation with the building's electrical network.

As part of the SOLARISE investments, a smart battery storage bank with a total capacity of 40.5 kWh was installed in this building. The work was completed on 7th May 2021. The battery storage system consists of three Tesla Powerwall 2 batteries, which are shown in Figure 6. Each battery was connected to a different phase of the building's three-phase electrical network. The installation of the Powerwall 2 batteries required the use of a Tesla Powerwall Gateway 2, which acts as an electrical and communications interface for the batteries. Table 2 lists the installed equipment at the Future Technology Centre building. Figure 7 shows a diagram that illustrates the different elements of the system and how they interrelate.

Table 2: Equipment installed at the Future Technology Centre

Item description	Quantity	Location
Tesla Powerwall 2 battery, single phase 230V AC connection, 13.5 kWh usable energy capacity.	3	In electrical room on the 3rd floor of the building
Tesla Powerwall Gateway 2	1	In electrical room on the 3rd floor of the building

Figure 6: The image shows a bank of three Tesla Powerwall 2 batteries installed at the Future Technology Centre with a total energy storage capacity of 40.5 kWh.

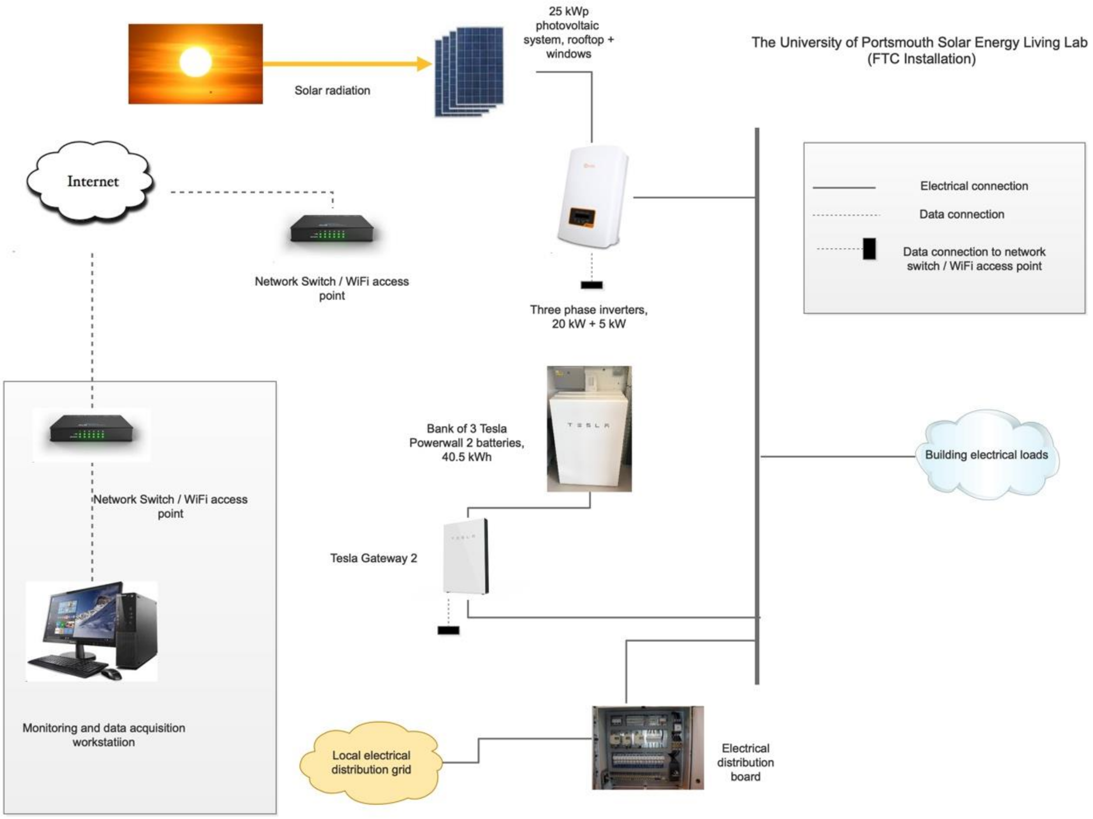


Figure 7. Diagram illustrating the main components of the system at the future technology centre and how they interrelate.

2.3 Additional Equipment

Apart from the installations described in Sections 2.1 and 2.2, additional equipment and consumables have been purchased to complement and support the operation of the University of Portsmouth Solar Living Lab. The main additional items that have been purchased, which are stand alone in nature and are not subject to building installation, are listed in Table 3. Minor items (such as cables) and consumables (such as electronic components) are not listed.

These items will also support PhD, MSc and undergraduate student projects. Some of these items can also be used to demonstrate aspects of solar and energy storage technology to other stakeholders, such as visitors or prospective students.

Table 3: Main additional items not subject to building installation that have been purchased to support the University of Portsmouth Solar Living Lab

Item description	Quantity
100 W monocrystalline solar panel with 5m cable	3
Victron smart solar mppt 75/15 15a solar charge controller	1
Victron Lithium SuperPack - 12.8V 20AH battery	1
Victron BMV712 Smart Battery Monitor Kit	1
1000W 12V pure sinewave power inverter with on/off remote control battery	1
Polinovel's HD series LiFePO4, 12V , 50Ah battery	1
GW Instek PEL-3041 - 350W Programmable DC Electronic Load	1
PEL-3111 1050W Programmable D.C. Electronic Load	1
110PV Surface mount thermistor 5M CAB	1
Jackery Explorer 500 Portable Power Station	1
Jackery SolarSaga 100W Monocrystalline Foldable Solar Panel	1
Stone Desktop PC, Intel Core i7-9700K, 32 GB RAM	1

2 Monitoring setup at the Solar Living Lab

3.1 Monitoring setup at the Port-Eco House

There are two sub-systems of interrelated equipment at the Eco-House that are part of the Solar Living Lab. The first sub-system consists of the solar array, module optimisers and inverter. The second sub-system consists of the Tesla Powerwall 2 battery and the Tesla Backup Gateway 2. Table 1 describes the monitoring variables for each sub-system.

All variables are sampled every 5 minutes. The data for the solar array sub-system is logged by the SolarEdge monitoring servers and can be accessed via a Web browser or the SolarEdge mobile app, while the data from the battery sub-system is logged by the Tesla monitoring servers and can be accessed via the Tesla mobile app.

Table 4: Monitoring at the Port-Eco House

Sub-system description	Monitored variables
Solar array sub-system: - 15x JA Solar HAN60S10 335 W monocrystalline solar modules, - 15x SolarEdge P370 Power Optimizer, - SolarEdge SE5000H single phase inverter, 5 kW.	Solar Module level: - DC current, - DC voltage, - power, Solar array level - DC voltage, - DC current, - DC power, inverter - AC current, - AC voltage, inverter - AC power
Battery sub-system: - Tesla Powerwall 2 battery, single phase 230V AC connection, 13.5 kWh usable energy capacity, - Tesla Powerwall 2 Backup Gateway.	- Battery AC power, - inverter AC power, - Building power demand, - Imported power from (or exported power to) the external grid

3.2 Monitoring setup at the Future Technology Centre

Table 5 lists the measured variables that are available through the installation of the Tesla battery bank at the Future Technology Centre building. All variables are sampled every 5 minutes. The data from the battery bank is logged by the Tesla monitoring servers and can be accessed via the Tesla mobile app.

Table 5: Variables monitored at the Future Technology Centre

System description	Monitored variables

- 3x Tesla Powerwall 2 battery, single phase 230V AC connection, 13.5 kWh usable energy capacity (40.5 kWh in total), - Tesla Powerwall Gateway 2	- Battery AC power, - inverter AC power, - Building power demand, - Imported power from (or exported power to) the external grid

3.3 Weather monitoring setup at the Dennis Sciama Building

An existing weather station is available at the Dennis Sciama building, University of Portsmouth, which allows logging meteorological data, which can be useful to support the research and training at the Solar Living Lab. Some of the measured meteorological variables can be very useful for modelling purposes and for correlating with various photovoltaic system variables. The weather station is located within 20m from the Eco-House and within 200m from the Future Technology Centre building. The variables monitored by the weather station are described in Table 3.

Table 6: Data provided by the weather station at the Dennis Sciama building

Variable	Units
Month	-
Date	-
Time: 24 hour clock	-
Relative Humidity	%
Air Temperature	Degrees C
Net Radiation Mean	W/m^2
CNR Mean	W/m^2
Solar Radiation Mean	W/m^2
Solar Radiation Total	kJ/m^2
Wind Speed	m/s
Wind Direction	Degrees clockwise from north
Standard Deviation of Wind Speed	m/s
Rainfall	mm

3 Examples of monitoring data from the Solar Living Lab

4.1 Monitoring data from the Port-Eco House system

This section presents examples of the data that can be obtained from the system at the Port-Eco-House. Figure 8 shows the total energy production per solar module at the Port-Eco House from 7 May 2021 to 28 October 2021. Notice that the differences between modules are due to varying shading from nearby structures. Figure 9 shows the AC power production from the inverter at the Port-Eco House during the month of June 2021. Notice the variability that occurs day-by-day, which is due to the varying weather conditions. Figure 10 shows the solar energy production at the Port-Eco House for each month since the installation took place on 7 May 2021 until 22 January 2022. Notice that the May 2021 and January 2022 data do not include the whole month. The seasonal variations in energy production are apparent in this figure.

Figure 11 shows the power flows at the Eco-House on 17 July 2021, while Figure 12 shows the state-of-charge of the Powerwall 2 battery during the same day. Notice how the excess solar power is stored in the battery between approximately 08:00 and 13:00. At around 13:00 the battery becomes fully charged and the excess solar power is exported into the local grid until about 15:20. Also notice that during this day the house was electrically self-sufficient, with no electrical energy being imported from the grid. During this day, the total electricity demand of the house was 8.1 kWh, while the generated solar energy was 18.9 kWh.

Since its installation on 7 May 2021 until 22 January 2022 the photovoltaic solar array at the Port-Eco House has generated a total of 2.46 MWh of energy, which represents 627.53 kg of CO2 emissions that have been saved.

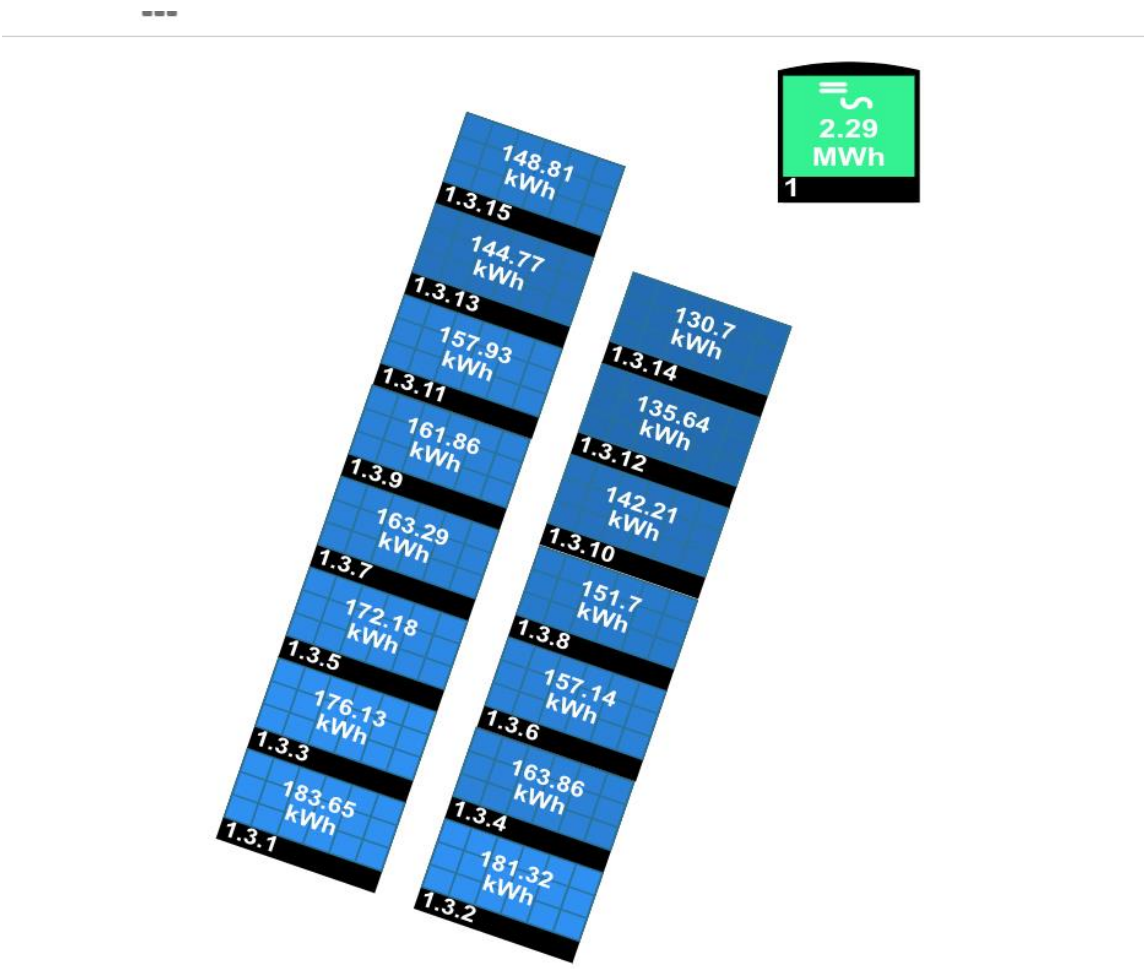


Figure 8. The image shows the total energy production per individual solar module at the Port-Eco House from 7 May 2021 to 28 October 2021. The differences between modules are due to varying shading from nearby structures.

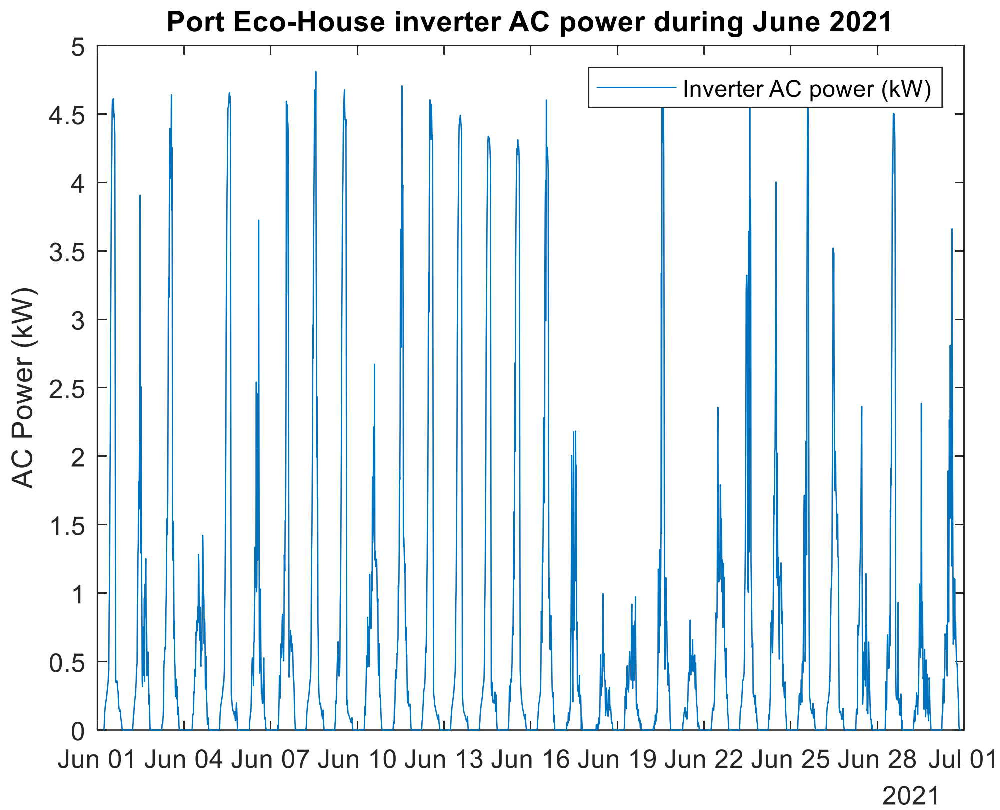


Figure 9. The image shows the AC power production from the inverter at the Port-Eco House during the month of June 2021.

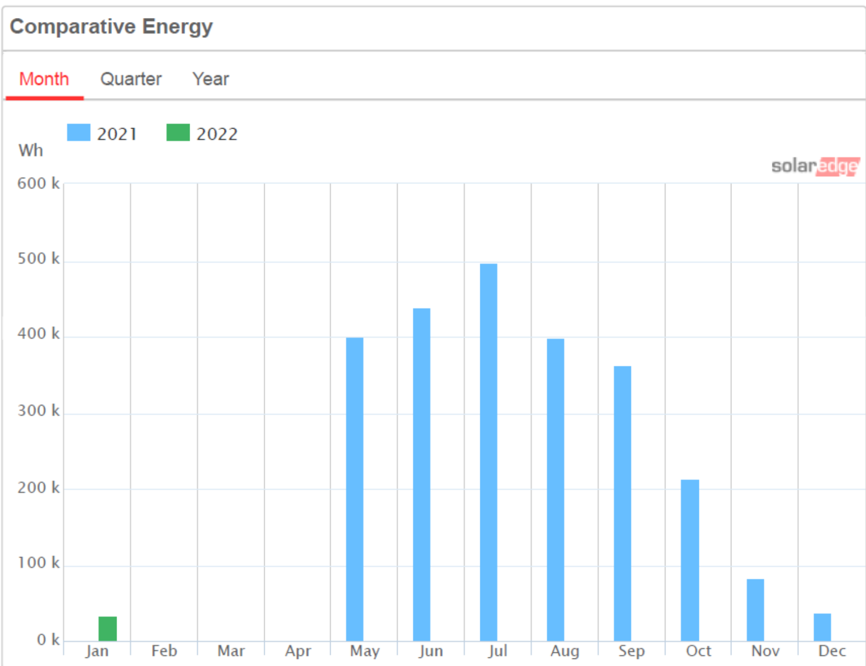


Figure 10. The image shows the solar energy production at the Port-Eco House for each month since the installation took place. On 7 May 2021. The May 2021 and January 2022 data do not include the whole month.

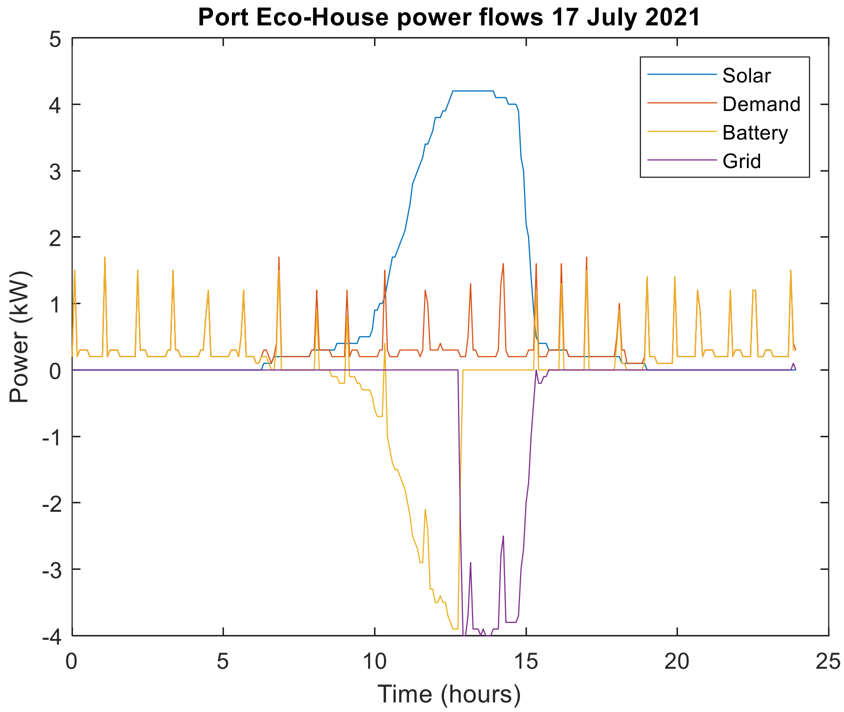


Figure 11: This plot shows the power flows at the Eco-House on 17 July 2021. The individual curves shown are the solar power production (blue), the power demand (red), the power flow from the battery (yellow, with a negative value indicating that the battery is charging), and import/export power from/to the grid (magenta, with a negative value indicating an export from the house to the local grid).

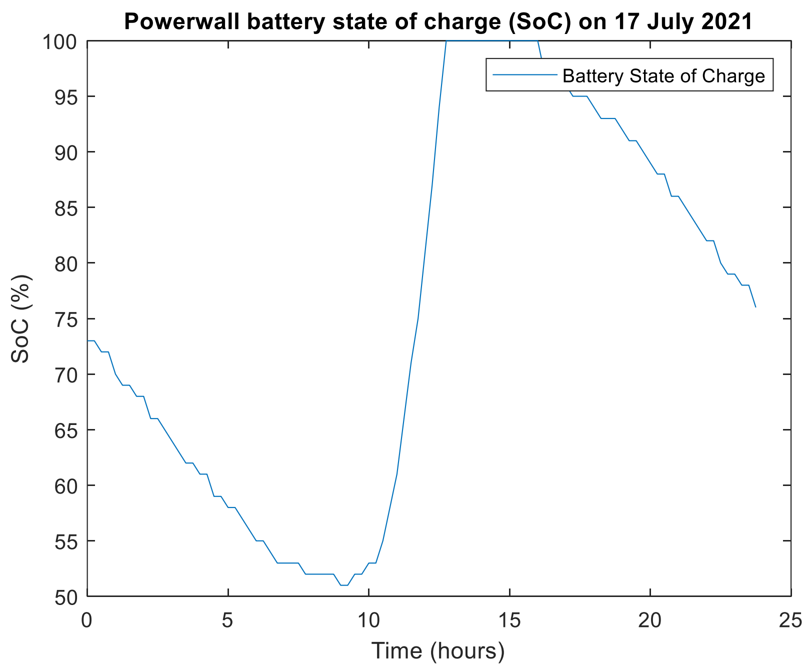


Figure 12: This plot shows the state of charge (SoC, percentage) of the Tesla Powerwall 2 battery at the Eco-House on 17 July 2021.

4.2 Monitoring data from the Future Technology Centre

This section presents examples of the data that can be obtained from the system at the Future Technology Centre. Figure 13 shows the power flows at the Future Technology Centre on 05 June 2021, while Figure 14 shows the state of charge of the Powerwall battery bank during the same day. Notice how the excess solar power is stored in the battery between approximately 10:00 and 17:20. At around 17:20, the battery bank reaches a maximum state of charge of 83% and it then starts to supply energy to the building until it fully discharges at about 22:00. During this day, the total electricity demand of the building was 236.5 kWh, while the generated solar energy was 139.1 kWh, and the total amount of energy supplied by the battery bank was 32.0 kWh. Note that between about 10:00 and 22:00 the power import from the grid was nil, so that the building was being served by a combination of energy from the solar panels and the battery. Also note that between 20:50 and 22:00, the battery bank alone was supplying 100% of the power demand of the whole building. The data is a good illustration of how battery storage working in conjunction with solar photovoltaics can help maximise the self-consumption of renewable energy.

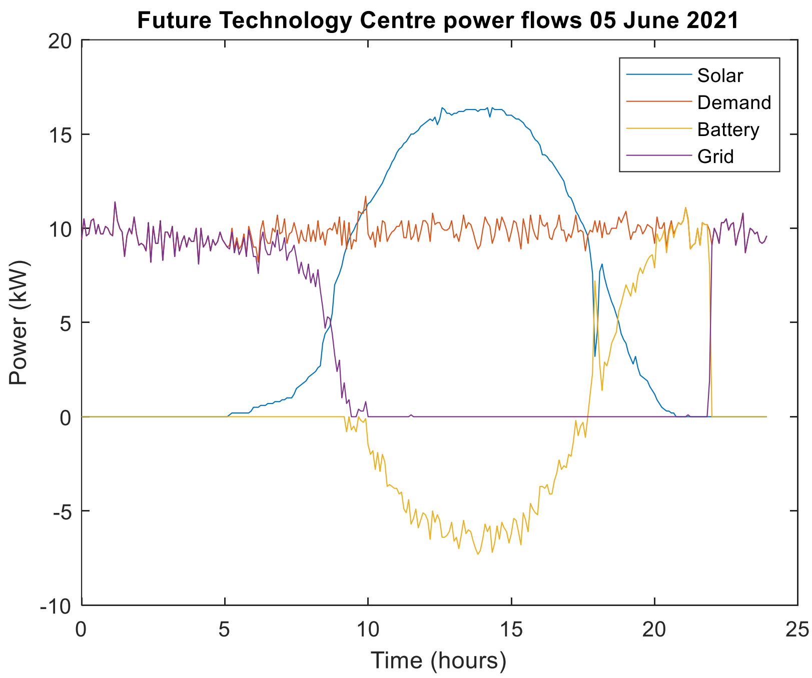


Figure 13: This plot shows the power flows at the Future Technology Centre on 05 June 2021. The individual curves shown are the solar power production (blue), the power demand (red) of the building, the power flow from the battery (yellow, with a negative value indicating that the battery bank is charging), and import/export power from/to the grid (magenta, with a negative value indicating an export from the building to the local grid).

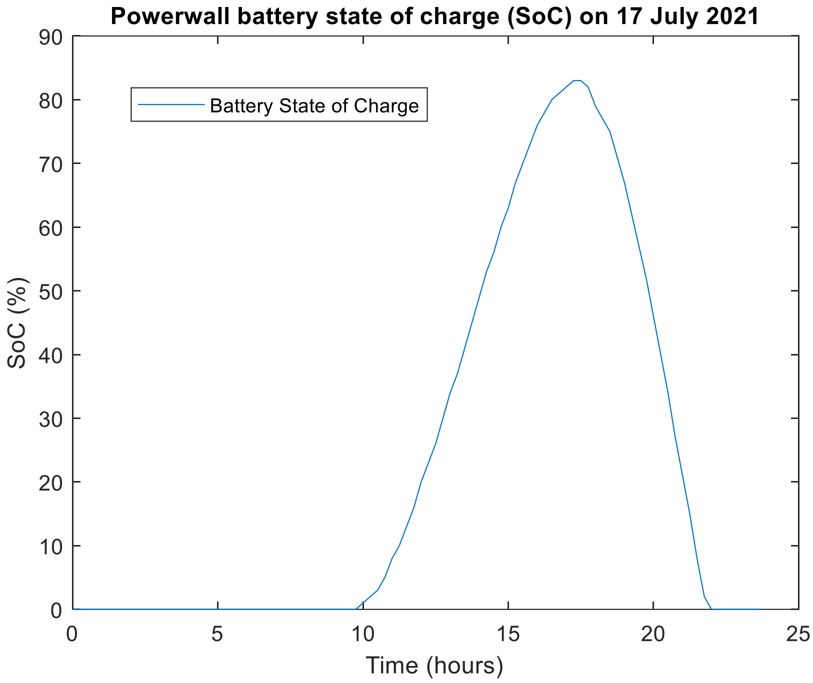


Figure 14: This plot shows the state of charge (SoC, percentage) of the bank of three Tesla Powerwall 2 batteries at the Future Technology Centre on 05 June 2021.

4.3 WEATHER MONITORING DATA

This section presents examples of the data that can be obtained from the weather station at the Dennis Sciama building. Figure 15 shows the mean solar radiation measured by the weather during the whole month of June 2021. Figure 16 shows the air temperature during the same period. A correlation can easily be observed between the solar inverter AC power of June 2021 at the Eco House, which is shown in Figure 9, and the measured solar irradiance during the same month that is shown in Figure 15.

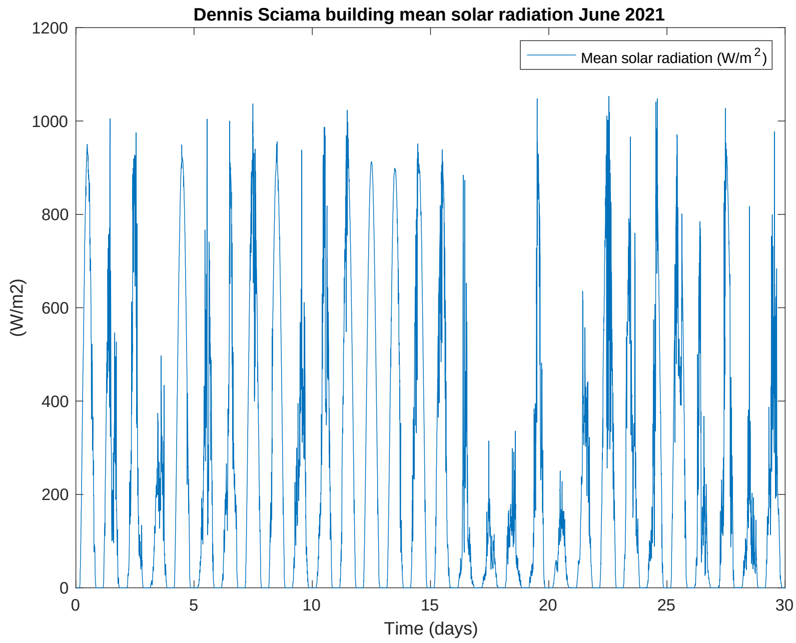


Figure 15: This plot shows the mean solar radiation (W/m^2) measured by the weather station at the Dennis Sciama building, University of Portsmouth, during the month of June 2021.

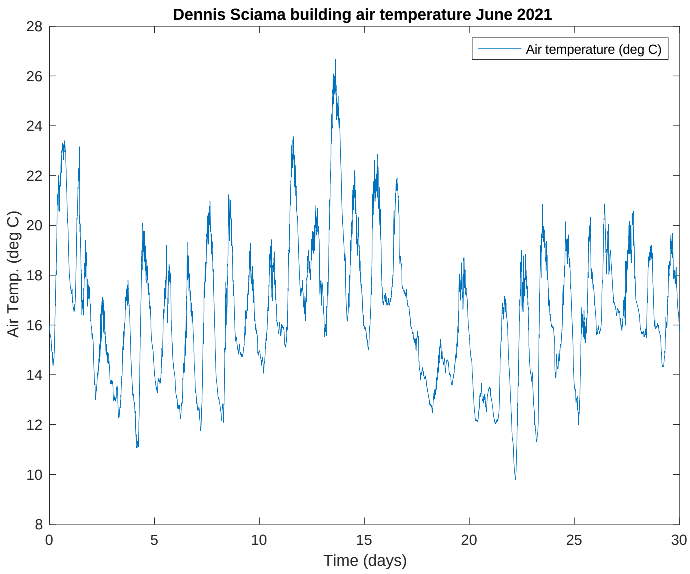


Figure 16: This plot shows the air temperature (degrees C) measured by the weather station at the Dennis Sciama building, University of Portsmouth, during the month of June 2021.

4. Modelling of the Port-Eco House system

A computer-based model of the system at the Port-Eco-House has been implemented using the software package PVSYST[1], including representations the specific JA Solar solar modules, SolarEdge power optimisers, SolarEdge inverter, Tesla Powerwall 2 battery, and the structures around the solar array that cause shading. The demand of the house has represented with constant power and a daily energy demand of 10 kWh. A perspective of the solar array and its surroundings is shown in Figure 16.

Figure 17 shows various energy quantities predicted by the model over the one generic year, divided into individual months. The meaning of the top labels is as follows. 'Earray' is the total energy produced at the output of the array. 'E_user' represents the total energy demand of the household. 'E_solar' is the energy supplied to the user from the solar energy, 'E_grid' is the total energy exported to the grid, 'EFrGrid' is the total energy imported from the grid. The green table to the right shows the measured production values between the months of June through October. Notice the similarities between the values predicted by the model values and the measured values. The differences are mainly explained by the random variability in the cloud cover. The table shows in the bottom right that the house is predicted to be essentially electrically self-sufficient over the year, in the sense that the exported energy to the grid (932.9 kWh) is very similar to the imported energy from the grid over the year (896.5 kWh).

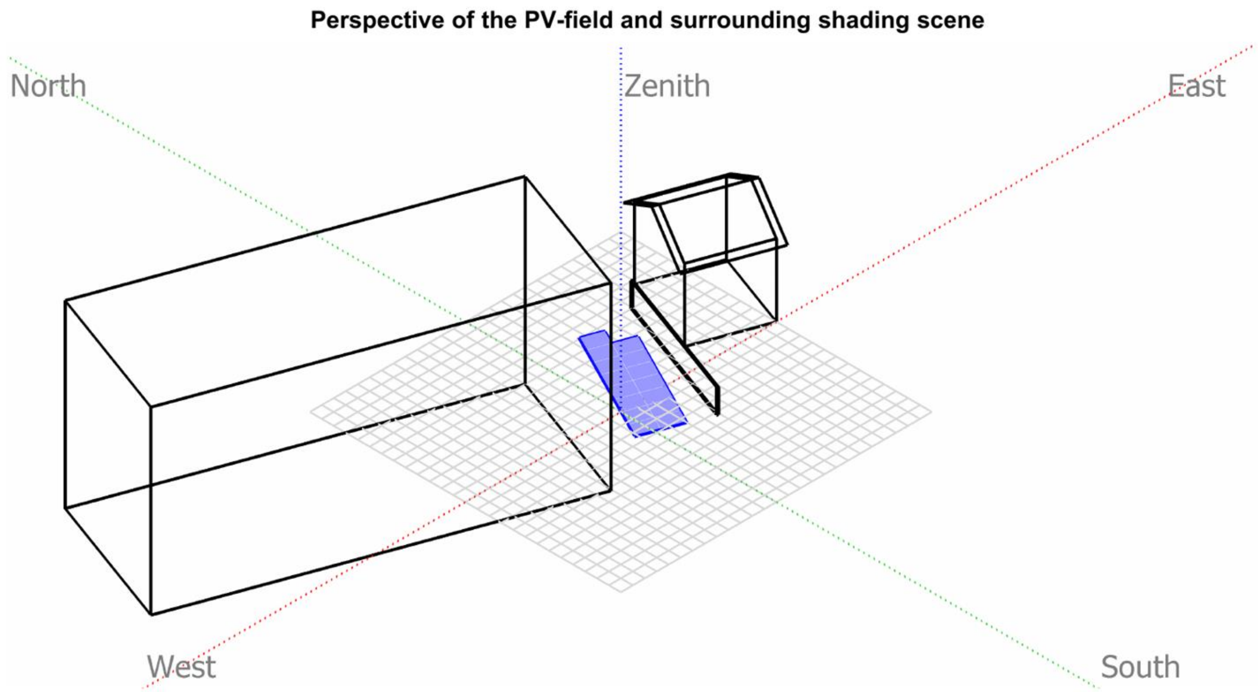


Figure 17: Perspective of the photovoltaic array at the Port-Eco House and surrounding structures, including the Eco-House itself, the wall to the right of the array and the Dennis Sciama building to the left of the array.

[1] https://www.pvsyst.com/

	EArray kWh	E_User kWh	E_Solar kWh	E_Grid kWh	EFrGrid kWh
January	130.0	309.5	122.9	0.0	186.6
February	170.4	279.6	152.7	0.0	126.9
March	349.2	309.5	269.7	44.0	39.8
April	470.2	299.5	285.5	160.4	14.0
May	506.6	309.5	306.1	163.6	3.4
June	517.2	299.5	299.5	186.9	0.0
July	505.0	309.5	308.3	166.2	1.2
August	449.9	309.5	296.9	131.6	12.6
September	366.3	299.5	267.3	64.5	32.2
October	241.4	309.5	211.1	15.7	98.4
November	149.8	299.5	135.2	0.0	164.4
December	103.1	309.5	92.5	0.0	217.0
Year	3959.2	3644.2	2747.6	932.9	896.5

Measured energy on the inverter side (kWh)
June 440
July 500
Aug 495
Sep 370
Oct. 213

Figure 18: This figure shows various energy quantities predicted by the model over one generic year, divided into individual months. The meaning of the top labels is as follows. 'Earray' is the total energy produced at the output of the array. 'E_user' represents the total energy demand of the household. 'E_solar' is the energy supplied to the user from the solar energy, 'E_grid' is the total energy exported to the grid, 'EFrGrid' is the total energy imported from the grid. The green table to the right shows the measured production values between the months of June through October.

Figure 19 shows the breakdown of the energy losses in the Port-Eco-House system predicted by the model. Figure 20 shows the CO_2 emissions balance of the photovoltaic system at the Port-Eco-House, as predicted by the model. Notice that the system is predicted to become carbon neutral after approximately 5 years.

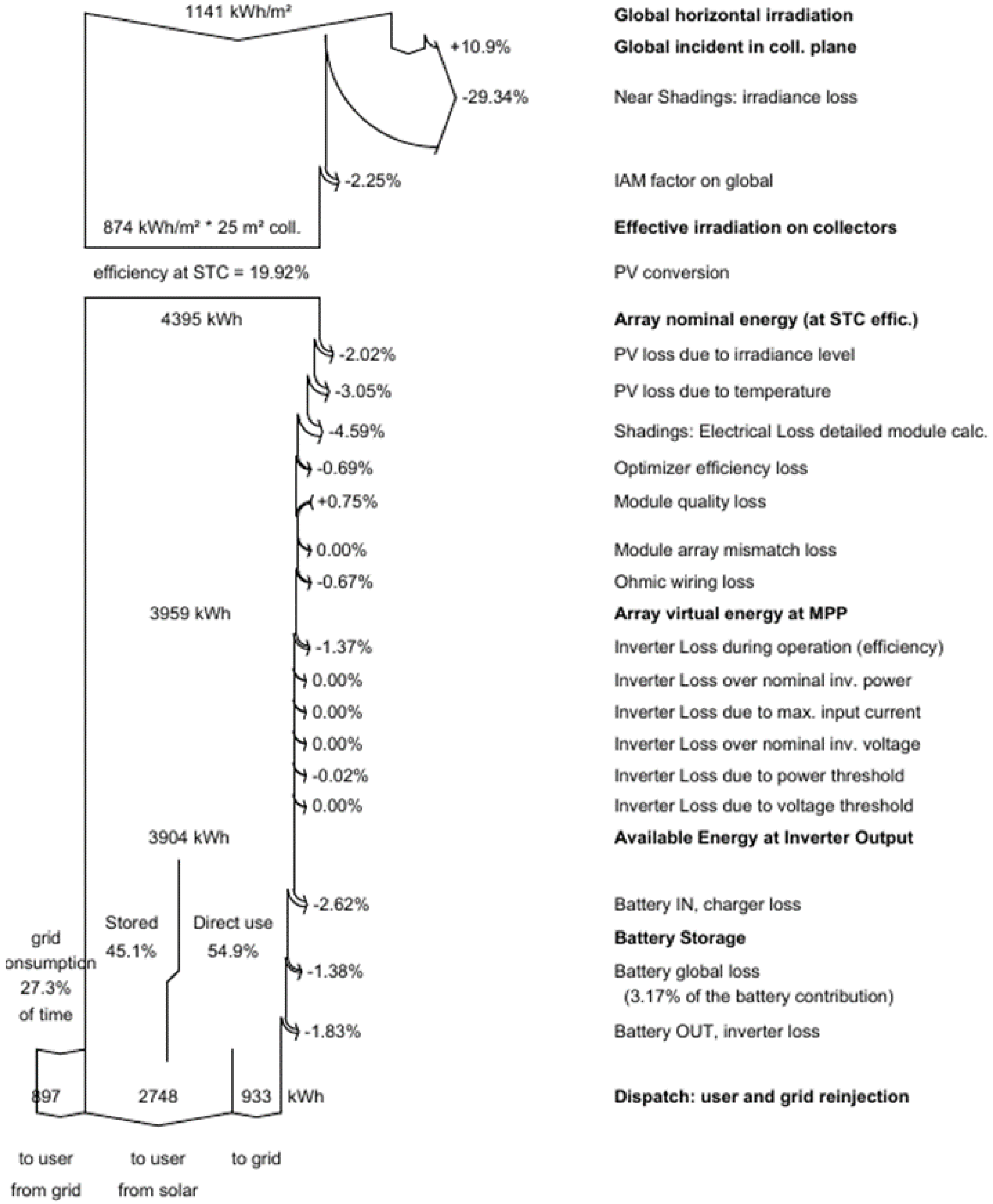


Figure 19: This figure the breakdown of the energy losses in the Port-Eco-House system predicted by the model.

CO_2 Emission Balance

Total: 38.4 tCO_2

Generated emissions

Total: 9.39 tCO_2

Source: Detailed calculation from table below:

Replaced Emissions

Total: 55.0 tCO_2

System production: 3903.92 kWh/yr

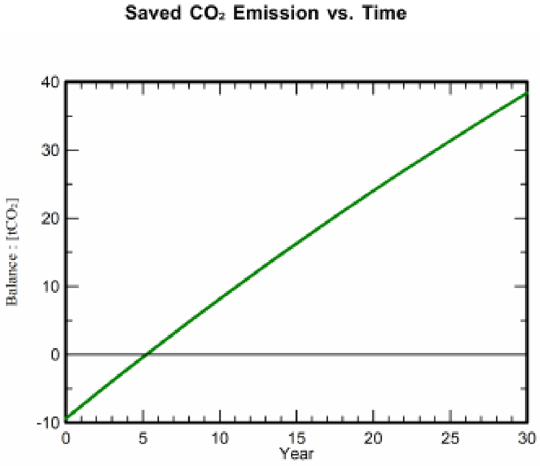
Grid Lifecycle Emissions: 470 gCO_2/kWh

Source: IEA List

Country: United Kingdom

Lifetime: 30 years

Annual degradation: 1.0 %



System Lifecycle Emissions Details

Item	LCE	Quantity	Subtotal
			[$kgCO_2$]
Modules	1713 kgCO2/kWp	5.03 kWp	8606
Supports	3.13 kgCO2/kg	150 kg	470
Inverters	311 kgCO2/units	1.00 units	311

Figure 20: This figure shows the CO2 emission balance of the photovoltaic system at the Port-Eco-House. Notice that the system is predicted to become carbon neutral after approximately 5 years.