Temporal resolution of photovoltaic electricity production and school energy consumption: a London primary school case study

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Abstract
In line with the UK goal to reach carbon neutrality by 2050, the combination of photovoltaic electricity and the electrification of heating systems is considered an effective way to reduce greenhouse gas emissions, while 88% of schools in the UK are gas-heated. This paper analyses the electricity consumption at a 15 and 30min resolution of different scenarios for the retrofitting of a primary school in London, UK, with an electrified heating system and the electricity production of different PV installations. High temporal resolution allows consideration of economic balances, in light of rising costs of energy in the UK in 2022, and the possibilities PV can have on decarbonizing heating systems in UK primary schools.

Practical application - The high temporal resolution allows to provide a project economic balance with close to reality figures. It also allows schools to rely on energy produced on site with less price fluctuation and to have the educational benefit of the PV installation. The high temporal resolution also provides data on what types of activities are the most energy consuming and can inform behaviour/time schedules changes.

Keywords primary school, photovoltaics, temporal resolution, electrification of heating systems

1.0 Introduction
In the UK, schools make up around 15% of public sector CO_2 emissions (1) which accounts for less than 2% of the overall national emissions (2). Today, 88% of primary schools in the UK are gas-heated, with a similar proportion for London primary schools (3) and have thus high CO_2 emissions levels. In a paper by Godoy-Shimizu et al (1), it has been found that PV panels could meet the annual demand of electricity for 59% of the schools assessed in London. In addition to having a potential high environmental impact in providing low-carbon electricity, even more when coupled with a highly efficient heating system, such as a heat pump, PV installations have many social and educational benefits in educational buildings in raising environmental awareness (4). Furthermore, the Global London Authority has launched the Solar Action Plan for London, to make London reach net zero by 2050 by using solar technologies with the aim of installing 2 gigawatts of installed solar capacity by 2050.

In the context of global warming, reaching net zero in the UK by 2050 and the potential of the electrification of the primary schools heating systems supported by photovoltaic electricity, this research paper analyses the high-resolution assessment at a 15 and 30min timestep of onsite photovoltaic electricity production and the consumption of an electrified London primary school. The paper also analyses the possible economic balance of a PV installation on a school considering 2022 UK energy prices.

2.0 Critical review

2.1 PV installation and actual energy consumption

As the first knowledge gap, no study, similar to *Ibrik et al., 2019.(5)*, and *Çiftçi et al., 2020.(6)*, have investigated the potential of a photovoltaic installation with the actual energy consumption of a school in the UK. The studies presented presented only case studies in Turkey and Palestine which have very different climate, energy consumptions patterns and different energy systems.

2.2 PV installation and school retrofit

B*ilir et al., 2017* (7) is the only paper that combines the installation of photovoltaic panels as well as a school retrofit, which consists mainly of the electrification of the building heating/cooling system. In the UK, 88% of the primary schools are gas-heated (8). As a result, electrifying the heating or cooling systems with air-source or ground-source heat pumps would not only reduce the total building energy consumption but would also shift the demand from fossil fuels to electricity.

2.3 Temporal resolution

For *Bilir et al., 2017*.(7), *Ibrik et al., 2019*.(5), *Çiftçi et al., 2020*.(6), the PV production and building energy consumptions were computed monthly and results compared with annual values. As developed in *Ibrik et al., 2019*.(5), the annual values underlie a difference in production as well as in consumptions over the year, with summer months providing a surplus of electricity and winter months creating a reliance on grid electricity.

This paper will examine what could be learnt from the comparison of photovoltaic production and primary school energy consumption at a high temporal resolution, in the context of electrified heating.

3.0 Methodology

The main aim of the study is the comparison of the temporal resolution of electricity production and consumption of an electrified London primary school. The following sections detail the used methodology, from the selection of the case study and the PV installation scenarios to their modelling.

3.1 Case study: Queenswell Junior Primary School

A case study has been chosen among all gas-heated London primary schools. Its characteristics, detailed below, make it a representative school. As a result, the conclusions and results of this study could be extrapolated and be applicable to other London primary schools with similar characteristics. Note that even if some characteristics do vary, it is the combination of all the school parameters that make it a representative case study of all the population of London gas-heated primary schools. The school case study is the Queenswell Junior Primary School, Sweets Way, London N20 0NQ, UK and has the following characteristics:

- 360 pupils and 1716 m^2 close to the values of all London gas-heated primary schools, with 332 pupils and 1742 m^2 on average.
- a gas consumption of 86 kWh/m^2/year and an electricity consumption of 35 kWh/m^2/year, with consumptions of respectively 140 kWh/m^2/year and 43 kWh/m^2/year on average for London gas-heated primary schools.
- was built post-war, as most schools built in cities deeply impacted by World War II, such as London, Birmingham, Manchester or Liverpool (3).
- has architectural characteristics widely spread among the population of primary schools built post-war, such as the use of prefabricated construction elements, being a single-storey building and having low windows so that children can see outside (3).
- has available data and can be observed through Plans and Google Earth in 3D. The available data consists of the Display Energy Certificate (DEC), the database from the Department for Education as well as the 2001 documents for the building extension from the London borough of Barnet.

Figure 1 - School Plan view from Google maps (9)

3.2 Temporal Resolution Analysis

In this study, the school electricity consumption and PV electricity production will be compared and discussed at annual, monthly and sub-hourly timesteps (30min and 15min) under different combinations of scenarios (Section 3.3). A 15min interval allows for a deep understanding of energy patterns while a 30min interval allows the results to be linked to the UK carbon intensity available at carbon-intensity.github.io. (10) The selected indicator is the percentage of electricity production over school electricity consumption, studied at different time intervals :

*PV electricity production for time interval / school electricity consumption for time interval * 100*

3.3 Scenarios

The proposed scenarios aim to explore different packages of retrofit measures for the case study school. The considered measures were selected to be realistic retrofit and PV installation packages. Each scenario (Base Case, 01a, 01b and 01c) is being studied with different PV technologies (2a is Sunmodule, 2b is Motech, 2c is Sunmodule with a 42° roof North South angle), see next section.

00_Base Case - this scenario is the school model as it is today, with a gas boiler (assumed 65% efficiency), a heating setpoint of 21°C and a natural ventilation of 1 ac/h, which were found to be parameters that provided annual energy consumptions in line with the 2019 DEC.

01a_Electrification of heating system - this scenario is the same as the base case except that the gas boiler has been changed to a heat pump system with a coefficient of performance (CoP) equal to 3, all year long, for heating only, the lowest found value in *Naicker, 2011*.(11).

01b_Electrification, insulation, heating setpoint - this scenario is the same as 01a, except that the school has been insulated to match Part L Standards (0,28 W/m2.K for walls, 0,18 W/m2.K for roofs) which consists in the change from 0,05m to 0,115m of Stone Wool on walls, from 0,07m to 0,155m of extruded polystyrene for roofs. In addition, the heating setpoint has been changed from 21°C to 20°C, still in comfort criteria of CIBSE Guide A, in line with indoor comfort criteria for young children.

01c_Electrification, insulation, heating setpoint, cooling - this scenario is the same as 01b, except that cooling has been added in addition to heating. Cooling is provided by the heat pump with an assumed CoP of 3. with a setpoint of 26°C, in relation to comfort criteria of CIBSE Guide A. This scenario explores the impact of cooling on the electricity demand, as average temperatures will rise in relation to climate change as well as the frequency of heatwaves and cooling demand can generate a consumption up to 28,5% in buildings (12).

02a_PV electricity generation with Sunmodule - this scenario consists of covering the school roof, flat and with 15° slope with Sunmodule mono-crystalline PV panels. Electricity is generated by the PV installation.

02b_PV electricity generation with Motech -this scenario consists of covering the school roof, flat and with 15° slope with Motech mono-crystalline PV panels.

02c_PV electricity generation with Sunmodule on 42° angle South/North roof - this scenario is a theoretical scenario: the school is assumed to be oversimplified, measuring 70m on West-East axis and 25m on North-South axis, thus occupying 1750m2 (Queenswell Junior school measures 1716m2). Instead of having different volumes with different heights, the school has one single pitched roof with a 42° angle, which has been found to be the optimized angle for PV performance for London, UK (13). As a result, half of the roof is facing South, while the other half is facing North.

3.4 PV modelling

Different types of photovoltaic cells and panels are available on the market. Poly-crystalline and mono-crystalline are highly used due to their higher performance and competitive prices (16). Mono-crystalline panels *Sunmodule SW 325XL Mono* were used as they provide best energy performance as mono-crystalline panels and best economic value in their category in the UK in 2020 (14). For a second scenario, mono-crystalline panels *Motech-XS72D3-320* are used as they provide the best performance for PVs in the UK in 2020 (14).

The photovoltaic panels have been modelled in EnergyPlus on all the roof surfaces to explore the school's full potential for PV electricity generation. The roof is flat or with a 15° angle to the South or the West. As the Simple Model mathematical equation is being used to predict PV electricity generation, it is the efficiency coefficient that is used as the main parameter to simulate PV electricity production. The weather file used for modelling solar irradiation is GBR_London.Gatwick.037760_IWEC.epw, available on EnergyPlus weather files database. All the dimensions and roof angles were taken from the planning permission documents and a model has been built in Design Builder v7 trial version (18).

EnergyPlus has been selected for the purpose of this study for the number of input parameters that is offered and its clarity in the mathematical calculations. Indeed, EnergyPlus provides three different models with different mathematical calculation methods to determine the PV electricity generation : the simple model, the equivalent one-diode model and the Sandia photovoltaic performance model. The simple model has first been sidelined as the model relies only on a few set of parameters and could thus have neglected certain systemic impacts, such as the cell temperature over the system efficiency (19). The equivalent one-diode model has been found to provide sufficient accuracy with a reasonable complexity which is the main reason why it is the most widely used model in PV studies (20) over the Sandia photovoltaic performance model. However, the Equivalent-One-Diode model could not run in EnergyPlus due to the high efficiency of the selected PV panels available in the 2020 UK PV market, which is a common issue in EnergyPlus for high power PV panels. As a result, the simple model has been used, which should provide adequate results (20) but with limitations.

3.5 School modelling

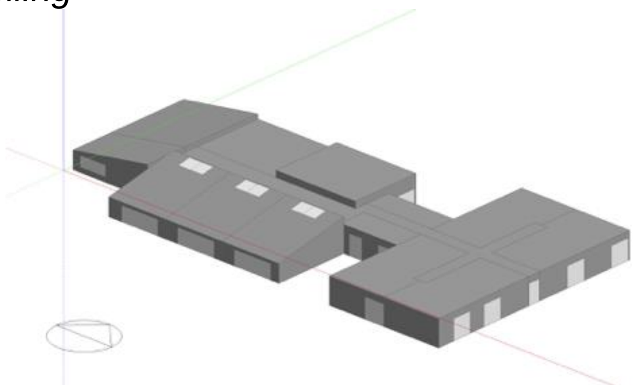

Figure 2 - School 3D model in DesignBuilder

The building envelope materials have been assumed from Schwartz, Y. *et al.,* 2021.(15) and occupancy schedules were taken from NCM schedules for primary schools, included in Design Builder (18). The weather file dates from 2002 (16). As the school DEC dates from 2019, it is possible that simulation results may not be fully aligned with the metered data.
While the school dimensions, construction materials and occupancy schedules should be quite close to reality, a few building parameters have been assumed and modified. These assumptions include the absence of a mechanical ventilation system and 1ac/h met by natural ventilation, as only 9,4% of primary schools have mechanical ventilation, and 87,2% use natural ventilation (9). Assumptions also include:

- computers and appliances are turned off when not used
- gas boiler has an efficiency of 65%, which is the lowest SEDBUK grade, assuming the boiler is old
- heating setpoint of 21°C. CIBSE Guide A advises an operative temperature of 19-21°C for winter conditions. The building has been initially modelled with a 19°C heating setpoint but too low heating loads were found. CIBSE Guide A also mentions that « 20 °C is the minimum recommended temperature for the very old and the very young » to avoid health risks. » Iterations were done using 20°C and 21°C heating setpoints. The model with the 21°C heating setpoint provided heating loads more in line with building DEC and has been kept.

3.

4.0 Scenario Results

4.1 Annual Results

This section presents the results from the simulations of different scenarios with annualised values. The aim is to understand what can be learned from this temporal resolution and compare the results with different temporal resolutions in Section 4.3.

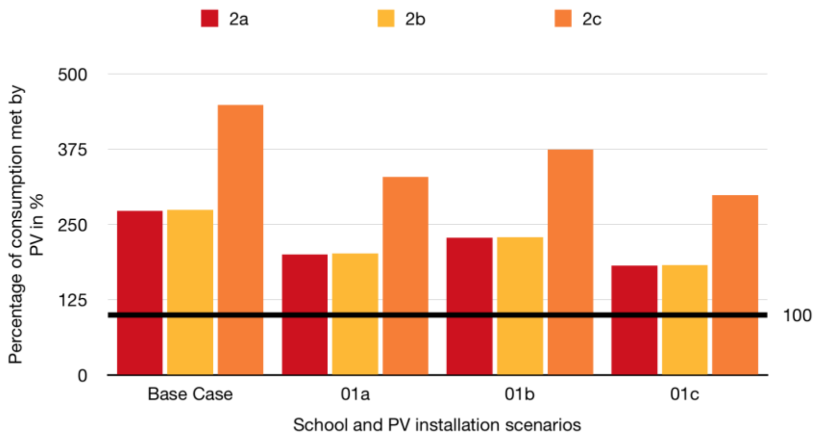

Figure 3 - Graph of the annual results of the percentage of consumption met by PV

	Base Case	01a - Electrification of heating system	01b - Electrification, insulation, heating setpoint	01c - Electrification, insulation, heating setpoint and cooling

Electricity Consumption (kWh/m^2)	43,8	59,7	52,5	65,8
2a - Sunmodule Percentage of consumption met (%)	272,6	200,0	227,6	181,3
2b - Motech Percentage of consumption met (%)	274,4	201,4	229,1	182,6
2c - Sunmodule 42° roof Percentage of consumption met (%)	448,6	329,2	374,5	298,4

Table 1 - Annual results of percentage of school electricity consumption met by PV

A few conclusions can be drawn from the annual results:

- the school electrification, insulation and change of heating setpoint from 21 to 20°C has a significant impact, with 27,6% to 29,1% of additional electricity production compared to electrification only.

- PV panel reference, either Sunmodule or Motech provides a difference in electricity production over consumption comprised between 1,3 and 1,8 % across all scenarios

- roof angle has a large impact on electricity production over consumption with differences between 117,1 and 129,2 %

4.2 Monthly Results

This section presents the results from the simulations of different scenarios with monthly values. The aim is to understand what can be learned from this temporal resolution and compare the results with different temporal resolutions in Section 4.3.

Supply over demand percentages for each scenario	**Base Case**			**01a - Electrification of heating system**			**01b - Electrification, insulation, heating setpoint**			**01c - Electrification, insulation, heating setpoint and cooling**		
	2a	**2b**	**2c**	**2a**	**2b**	**2c**	**2a**	**2b**	**2c**	**2a**	**2b**	**2c**
January	70	70	165	39	39	92	49	49	116	46	46	109
February	114	115	227	63	63	124	79	79	156	71	72	142
March	237	238	393	159	160	263	191	193	317	169	171	281
April	306	308	480	236	237	370	268	270	420	214	216	336
May	395	397	618	341	344	535	367	370	576	260	262	407
June	456	459	714	414	416	648	432	435	677	285	287	447
July	456	459	716	425	427	667	436	439	684	258	260	405

August	2219	2234	3472	2213	2228	3464	2240	2255	3505	1763	1775	2760
September	266	267	422	235	237	374	250	252	397	179	181	285
October	157	158	289	126	127	231	140	141	258	112	112	205
November	74	74	154	54	54	113	63	63	130	54	54	112
December	57	58	126	32	32	71	40	41	89	38	38	83

Table 2 - Monthly results of percentage of school electricity consumption met by PV

A few conclusions can be drawn from the monthly results:

- no scenario provides enough monthly PV electricity consumption to meet the monthly electricity demand for the months of December. Only scenario 2c provides enough electricity to meet the demand for January and November.

- values for August are higher because the school electricity demand is reduced. Indeed, in August the school facility is unoccupied in relation to the UK school calendar (39).

- without noting August values, it is to note that for a same scenario, electricity production over electricity consumption values can vary by up to a factor of 13,3 between December and July for combination 01a/2a, in relation to sun position, cloud coverage and irradiation values.

- as for annual results, scenario 2c, with 42° roof angle, has a large impact on energy production providing more than two times more electricity production over consumption for the months of November, December and January.

4.3 Timestep Results

This section presents the results from the simulations of different scenarios with timestep values. The aim is to understand what can be learned from this temporal resolution and compare the results with different temporal resolutions in Section 4.3.

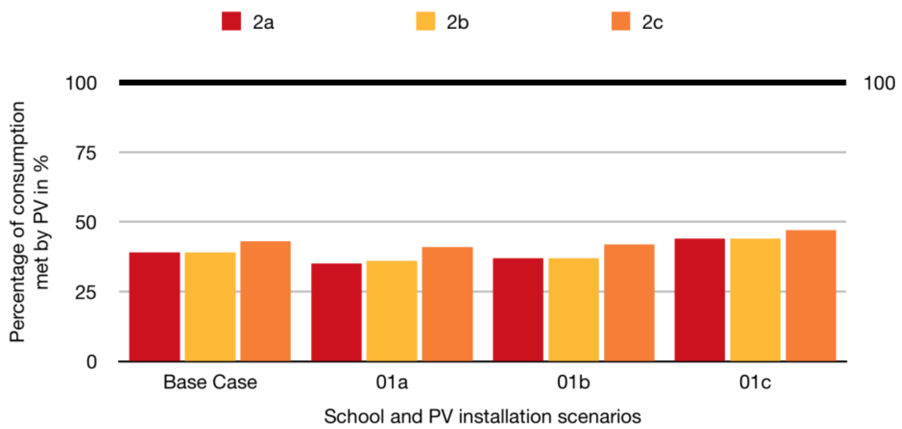

Figure 4 - Graph of the 15min timestep percentage of school electricity consumption met by PV

	Base Case			01a - Electrification of heating system			01b - Electrification, insulation, heating setpoint			01c - Electrification, insulation, heating setpoint and cooling		
	2a	**2b**	**2c**	**2a**	**2b**	**2c**	**2a**	**2b**	**2c**	**2a**	**2b**	**2c**
Supply over demand met every 15min (%)	39	39	43	35	36	41	37	37	42	44	44	47

Table 3 – 15min Timestep results of percentage of school electricity consumption met by PV

A few conclusions can be drawn from the timestep results:

- the PV technologies offer a difference of 1 point maximum.

- the PV scenario 2c with a 42° roof angle provides the best meeting of supply over demand, however this difference is of 4 to 6 points.

- overall, school energy demand is met only between 35% to 47% of the time

4.3 Discussion

4.3.1 Temporal resolution assessment

Annual, monthly and timestep simulations provide different types of information. Indeed, many studies, developed in section 2, as well as project developments rely on annual or monthly figures (6, 9, 26) to determine what percentage of the building or the school electricity demand can be met with the installation of PVs. With annual values only, for this case study, it appears that the PV installation is interesting in order to provide the school with renewable and low carbon energy. However, at a higher resolution with a timestep of 15min, the electricity demand can only be met between 35 to 47% of the time. The annual figures provide an averaged installation potential, while the high-resolution values indicate what reliance the school building can have on generated electricity.

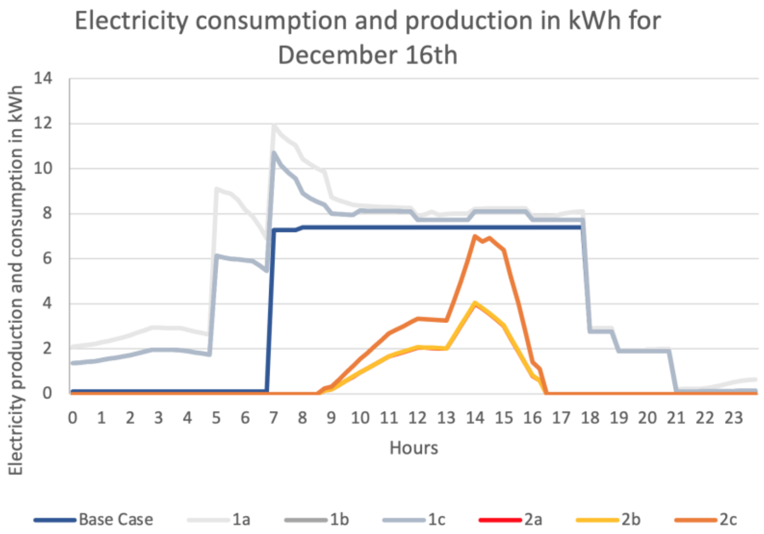

Figure 5 - Graphs of the electricity consumption and production in kWh for December 16th for the different scenario combinations

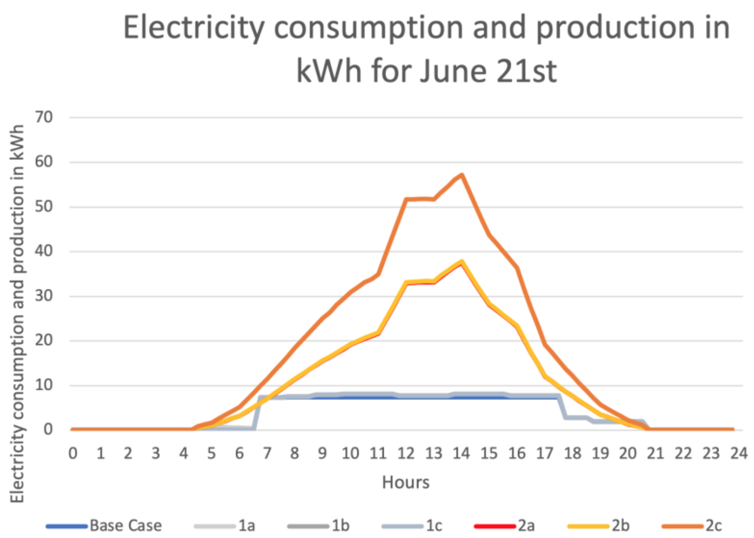

Figure 6 - Graphs of the electricity consumption and production in kWh for June 21st 2002 for the different scenario combinations

4.3.2 PV intermittency

Annual figures are averages and do not consider the PV production intermittency. Indeed, production over consumption value can differ by a factor of 13,3 over the year for the same installation, depending on sun position and irradiation levels.

In winter, the heating demand is between 0,5 to 3 kWh, while PV electricity production ranges from 0 to 7 kWh. By its nature, and without any changes, PV electricity cannot supply the entire school electricity demand without a battery. Electricity demand can only be met 35 to 47% of the time according to this study and the scenarios established.

4.3.3 School energy consumption, retrofit and PV intermittency

Possible school retrofits with the electrification of the heating system decreases the overall energy demand. However, the percentage of time spent where PV electricity supply meets the demand does not significantly increase. Indeed, the measures of scenario 01b, insulation to Part L standards and change of heating setpoint from 21°C to 20°C, generated a decrease of 12% of annual electricity consumption. However, for both scenarios, the time spent for which electricity demand is met by PV varies only by 1 (02b) to 2 (02a) points. As a result, school building retrofits are efficient ways to reduce a primary school's energy consumption but have only a limited impact on the increase on time spent where PV electricity production meets school electricity demand.

5.0 Implications for the industry

5.1 High temporal resolution of PV electricity production and school electricity consumption

Yearly results average the higher summer electricity production and erases the lower electricity productions of winter months. This is significant for primary schools as they are unoccupied in the UK in August due to summer holidays. Monthly results offer a more detailed understanding of the variability across the year, with electricity underproduction in winter and overproduction in summer. At a daily timestep, there is some variability in electricity production related to cloud cover and sun position up to a factor of 5. Finally, when looking at a 15min timestep, PV production and school electricity demand can be analysed and production gaps can be found in the morning and evening.

The trend of having a higher temporal resolution, also allows to link electricity production with national grid carbon intensity. This is true for the 30min timestep, as well as for the monthly timestep: in the National Calculation Methodology (NCM) 2022, PV electricity and national grid have different carbon emission intensities.

	For each temporal resolution, there is the possibility of :
Annual	• understanding the potential of a photovoltaic installation
Monthly	• understanding of the trends in energy consumption and photovoltaic electricity production over the course of the year, with seasonal variability • identify the months that would require additional electricity supply
Daily	- assessing the daily variability in energy consumption and photovoltaic electricity production
30 min	• assessing the variability in energy consumption and photovoltaic electricity production • identifying the time frames for which PV electricity production is insufficient • identifying the time frames with high electricity demand and high electricity overproduction • linking electricity production and electricity consumption with national carbon intensity to place the project in the wider scope of energy production and the paths to reaching net zero

15 min	• identifying the time frames for which PV electricity production is insufficient • identifying the time frames with high electricity demand and high electricity overproduction • high precision in determining the time spent for which PV electricity production meets the school electricity demand, compared to any other temporal resolution

Table 4 - Comparison of annual, monthly, daily, 30min and 15 min resolutions of electricity production and electricity consumption assessments

5.2 Economic balance

When a PV project viability is explored, different factors can be considered: the PV electricity generation potential, the building electricity consumption and the economic balance of the operation. The following graph and table present the quantities of electricity that should be purchased or sold to meet the primary school demand.

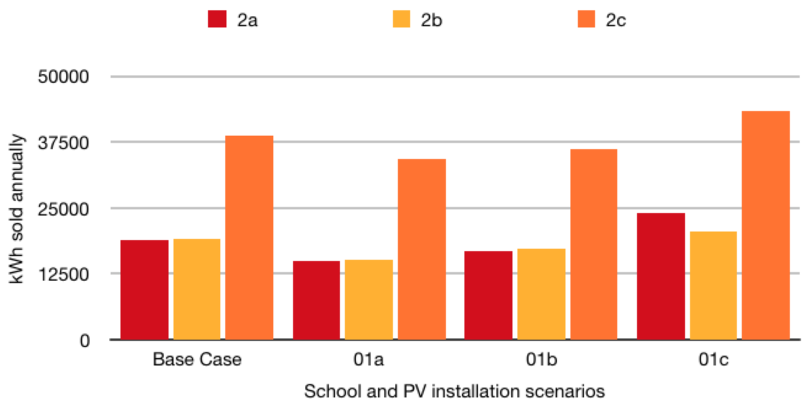

Figure 7 - Graph of the sold electricity for each scenario combination, with a timestep of 15min

		Base Case (kWh)	**01a - Electrification** (kWh)	**01b - Electrification, insulation, heating setpoint** (kWh)	**01c - Electrification, insulation, heating setpoint and cooling** (kWh)
2a - Sunmodule	Purchased	3378	6643	4973	2197
	Sold	22379	21650	21907	26324
	Total	**19001**	**15007**	**16934**	**24127**
2b - Motech	Purchased	3366	6628	4959	5873
	Sold	22570	21838	22096	26524
	Total	**19204**	**15210**	**17137**	**20651**
2c - Sunmodule 42° roof	Purchased	2259	5596	4028	2006
	Sold	40936	39980	40338	45519

	Total	**38677**	**34384**	**36310**	**43513**

Table 5 - Purchased, sold and total sold energy for each combination of scenarios

As seen from table 5, the balance between purchased and sold electricity is always negative, meaning that in all the above scenarios, the schools are electricity exporters. As electricity exporters, the sale of energy can provide an income, non-negligible compared to the school fixed costs.

For the actual building, the installation provides a balance of sold electricity between 19,001kWh/year to 19,204kWh/year per year, so between £6,460/year to £6,529/year.

If the retrofitted school had a 42° angle, it would be able to sell between 34,384kWh/year to 43,513kWh/year.This results in a £11,690/year and £15,474/year considering a price of 34p/kWh (18) as of 2022. The current school has an estimated expenditure of £9,136/year for electricity and of £3,483/year for gas. As energy prices become higher (12p/kWh in 2021 and 34p/kWh in 2022 in the UK), the return on investment of each installation and the possible income becomes more and more interesting (18).

6.0 Conclusion

High resolution at a 15-30min timestep is a valuable indicator compared to monthly or annual values. Annual or monthly assessments are averages and thus smooth the results. Thanks to the high resolution, the assessment makes understandable the impacts of the electrification of the heating system on electricity demand patterns. It also allows to assess the rate for which the actual photovoltaic electricity meets the school demand, which can vary by more than 6 times compared to annual results. High resolution PV electricity production should be modelled at a 30min interval or lower as PV technologies and batteries resource intensive and lithium reserves worldwide are limited and are not sufficient for a large shift towards renewables and their intermittency (21). The economic balance of such systems could be studied by consultancies and sold electricity could allow for school development, retrofit or maintenance. Many related research questions can be explored, either on technological systems comparisons in terms of cost and environmental impacts, but also on occupancy schedules and the change of lifestyles.

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8.0 List of figures