A high temporal resolution assessment of photovoltaic electricity production and energy consumption of an electrified London primary school

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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. Without a battery storage, thanks to high temporal resolution assessment, only 35 to 47% of the school energy consumption can be met. High temporal resolution allows consideration of to economic balances and the possibilities PV can have on decarbonizing heating systems in UK primary schools.

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

1.0 Introduction

Following the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, it has been made clear that “achieving global net zero CO_2 emissions is a requirement for stabilizing CO_2-induced global surface temperature increase” (27). In relation to this science-based assessment, the UK has set GHG domestic target to achieve carbon neutrality by 2050 under the Climate Change Act of 2008 (11).

Also in the UK, buildings are responsible for 40% of the national CO_2 emissions and thus a considerable improvement to the building stock will be required to meet this target (4). Interestingly, the electrification of buildings can play a massive role to reach net zero. Low carbon electricity can now be produced more cheaply than high-carbon electricity in the UK (11) and 34% of the carbon abatement to 2030 could come from energy efficiency measures which include a switch to high efficiency electric heating (11).

The targets are to have an electricity carbon intensity of 100-200gCO_2eq/kWh by 2025 and of 50-100gCO_2eq/kWh by 2030 (10). Fossil-fuels have a high carbon intensity, ranging from 350 to 1100gCO_2eq/kWh for coal and gas in the UK and from 180 to

300gCO_2e/kWh for coal and gas with carbon storage and capture (42). Low-carbon electricity sources include nuclear, with 5 to 25gCO_2eq/kWh, as well as renewable sources, such as wind, hydro and geothermal, with 5 to 50gCO_2eq/kWh and photovoltaic (PV) electricity with a commonly used value of 80gCO_2eq/kWh in the UK, considering all the stages of the PV panels life-cycle-analysis (28).

In the UK, schools make up around 15% of public sector emissions (21) which accounts for less than 2% of the overall national emissions (4). Today, 88% of primary schools in the UK are gas-heated, with a similar proportion for London primary schools (24) and have thus high CO_2 emissions levels. In a paper by Godoy-Shimizu et al (21), 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 (13). 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 meantime, research has gone further with the report on the London Solar Opportunity Map (18) which made a high-resolution solar irradiation mesh available. Modeling tools are also advanced enough to model buildings energy demand and photovoltaic electricity production at a short timestep, up to every 10minutes in EnergyPlus. As a result, from 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 analyzes the high-resolution assessment at a 15 and 30min timestep of onsite photovoltaic electricity production and the consumption of an electrified London primary school.

2.0 Critical review

2.1 Literature review

Research purpose	**Reference**	**Key findings**
Potential of photovoltaics	Bódis et al., 2019	A high geospatial resolution assessment of the photovoltaic potential on rooftops has been led in the European Union. EU rooftops could potentially produce 680TWh of electricity (24,4% of the EU electricity consumption). The UK has the 5th biggest potential of solar electricity production, with potentially 25 000 GWh/year, with a price of 12-15EURcent/kWh and 20 000 GWh/year with a price of 15-18EURcent/kWh, thus with competitive rates.

	Palmer et al., 2018	A GIS tool has been created to quickly evaluate the potential of rooftops for PV installation thanks to LiDAR data.
	UCL Energy Institute, 2020	Higher resolution of irradiation values was computed in tiles of 0,5x0,5m in the London Solar Opportunity map (previously 1x1km tiles) thanks to the data of the Light Detection and Ranging Environmental Agency (LiDAR). As a result, it is possible to use these values to better estimate a PV installation energy output.
	UK Department of Energy & Climate Change, 2018	Many benefits such as reduced electricity bills, revenue generation, CO_2 emissions reduction, education and engagement improvement for the installation of PV in schools in the UK.
PV production over school electricity consumption	Bilir et al., 2017	An assessment of the economic value and energy production was led after the design of two case scenarios in a school building in Izmir, Turkey that would use a heat pump (COP of 2,5). PV production and consumption were calculated monthly and cases scenarios offered 110% and 75% coverage ratio.
	Çiftçi et al., 2020	A PV generation simulation has been done with monthly and annual results in a typical Turkish school with irradiation and consumption values of a school in Midyat, Turkey. The purpose of this study is that it can be easily replicated for other typical Turkish school buildings. Results are annualized and between 1/4 and 1/3 of the school electricity consumption is being met by the PV installation production.
	Godoy-Shimizu et al., 2021	« This paper examines the potential for PV to improve the building performance of primary schools in London. Disaggregate data including energy use is compared with modelled PV generation, showing that electricity demand could theoretically be met in 59% of the schools investigated. The impact of several key factors is then considered, including architectural heritage, building age and form. The results show that the greatest PV potential exists in newer schools, as well as those that are shorter and with less dense forms. »
	Ibrik et al., 2019	An energy and economical assessment were led for potential PV installations in 3 case-studies schools in Palestine. Each installation offered a theoretical payback time of less than 5 years. PV installation produced less than the actual school consumption on a yearly basis. On a monthly basis, there was an over production of electricity compared to the consumption in summer and not enough production in winter.

Table 1 – Literature review table

2.2 Knowledge gap

Thanks to the LiDAR data, it is now possible to have precise irradiation values for specific surfaces. While schools have a strong potential for PV installation as they are large buildings with possibly large roofs (13), renewable electricity can be produced at a competitive rate in the UK (7). Additionally, in London, electricity demand could be met via PVs in 59% of schools investigated (21). As a result, schools in the UK represent an interesting field of investigation for the installation of roof photovoltaics that can possibly produce electricity effectively at a competitive rate.

As the first knowledge gap, no study, similar to *Ibrik et al., 2019.(26)*, and *Çiftçi et al., 2020.(20)*, have investigated the potential of a photovoltaic installation with the actual energy consumption of a school in the UK. The studies found presented only case studies in Turkey and Palestine which have very different climate and thus different energy consumptions patterns and different energy systems requirements over the year, for instance the use of cooling system rather than a heating system. Furthermore, these two Turkish research use yearly and monthly data of electricity production and consumption. In both studies, the Swiss software PVSyst has been used to model photovoltaic electricity production with Polycrystalline modules with product specific values. PVSyst only allows for annual and monthly results and does not display which mathematical equation the model has been used.

Secondly, *Bilir et al., 2017* (6) is the only paper that combines the installation of a 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 (25). As a result, electrifying the heating or cooling systems with air-source or ground-source heat pumps would, for instance, not only reduce the total building energy consumption, thanks to an improved coefficient of performance, but would also shift the demand from fossil fuels to electricity. If the electricity is renewable, a low-carbon source of heating would have been provided, as per the guidelines of the *Committee on Climate Change, 2020* (11). Moreover, no paper provides an analysis of the implementation of a PV installation, with an electrification of the heating system and change of lighting devices, for *Bilir et al., 2017*.(17), coupled with the retrofit of the building envelope, which is one of the first effective measure to improve building performance (28).

Thirdly, for *Bilir et al., 2017*.(6), *Ibrik et al., 2019*.(26), *Çiftçi et al., 2020*.(9), the PV production and building energy consumptions were computed monthly and results compared with annual values. As developed in *Ibrik et al., 2019*.(26), the annual values underly 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. Again, no battery system has been studied in these 3 papers.

Interestingly, the question of the school occupancy over the course of a day, or over the course of a year, were not matters of discussion in the previously cited papers. Indeed, the reality of PV electricity production and consumption is not always direct as for many renewable energy sources (31).

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 case study. As a result, the conclusions and results of this study could be extrapolated and easily 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 (24).

- 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 (24).

- 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 which provides valuable geometric/architectural information.

Figure 1 - School Plan view from Google maps (48)

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.(8) 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. The combination of measures provides the following matrix of different scenarios:

	Base Case	**01a - Electrification of heating system**	**01b - Electrification, insulation, heating setpoint**	**01c - Electrification, insulation, heating setpoint and cooling**
2a - Sunmodule				
2b - Motech				
2c - Sunmodule 42° roof North/South				

Table 2 - Matrix of scenario combinations

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 (35).

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 (43). As a result, half of the roof is facing South, while the other half is facing North. The aim of this scenario is to explore if roof slope has a significant impact on electricity generation and to see the proportion of electricity produced on the North roof versus the South roof.

3.4 PV and school modelling

Different types of photovoltaic cells and panels are available on the market, of which two types are the most used, poly-crystalline and mono-crystalline due to their higher performance and competitive prices (9). 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 (45). 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 (45).

The photovoltaic panels have been modeled in EnergyPlus on all the roof surfaces to explore the school full potential for PV electricity generation. Less photovoltaic electricity generation would mean reducing the area of installed PV panels, while having a higher installed PV panels area would need additional building roof or ground-based PV installation which has not been considered in this study. 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. As all the needed input parameters are provided by PV panels manufacturers. 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 (14).

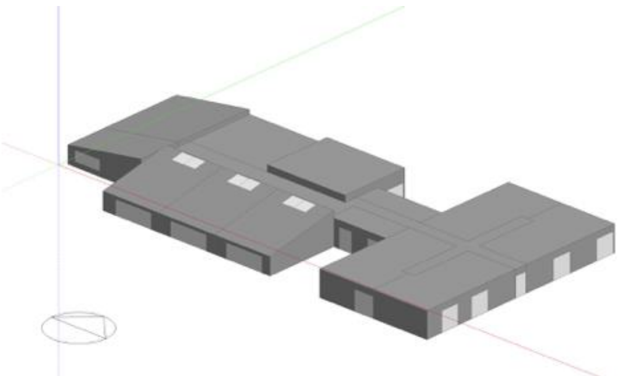


Figure 2 - School 3D model in DesignBuilder

The building envelope materials have been assumed from Schwartz, Y. *et al.,* 2021.(46) and occupancy schedules were taken from NCM schedules for primary schools, included in Design Builder (39). The schedules include the following: classroom, corridor, sport hall, changing room, computer room and office and were set in the model as stated on the documents of the London Borough of Barnet of 2001. The weather file dates from 2002 (19). 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 (25). 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 modeled 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 a 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.

4.0 Scenario Results

4.1 Annual Results

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

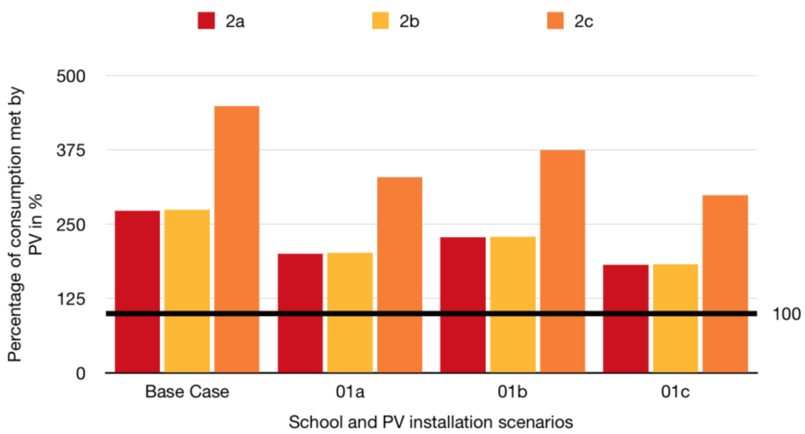


Figure 3 - Graph of the annual results of the percentage of consumption met by PV

	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 3 - Annual results of percentage of school electricity consumption met by PV

A few conclusions can be drawn from the annual results:

- all scenarios appear to be interesting as they all provide sufficient electricity production to meet electricity demand over the year.

- 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.

- the addition of cooling in scenario 01c increases the demand for electricity and electricity overproduction is the lowest compared to all retrofit school scenarios. Indeed, the cooling load is being added to the heating load, while cooling loads do not exist for other cases.

- 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, as detailed below. The aim is to understand what can be learned from this temporal resolution and compare the results with different temporal resolution 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 4 - Monthly results of percentage of school electricity consumption met by PV

A few conclusions can be drawn from the monthly results:

- none of the scenarios provides enough monthly PV electricity consumption to meet the monthly electricity demand for the months of December and only scenarios 2c provide enough electricity to meet the demand for January and November.

- values for August are much 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. As the sun position is lower in winter under UK latitude, a more vertical roof angle makes sun rays more perpendicular to the PV cell surface, which results in improved electricity generation.

4.3 Timestep Results

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

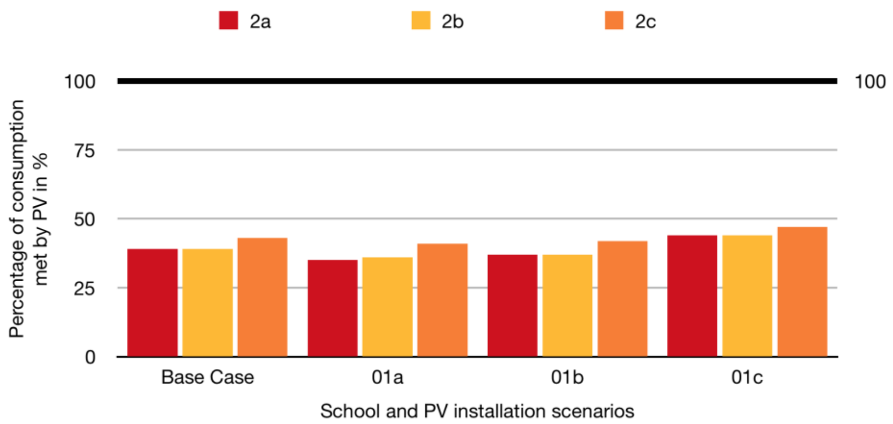


Figure 4 - Graph of the 15min timestep percentage of school electricity consumption met by PV

	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 5 – 15min Timestep results of percentage of school electricity consumption met by PV

A few conclusions can be drawn from the timestep results:

- for each school scenario, the PV technologies offer a difference of 1 point maximum.

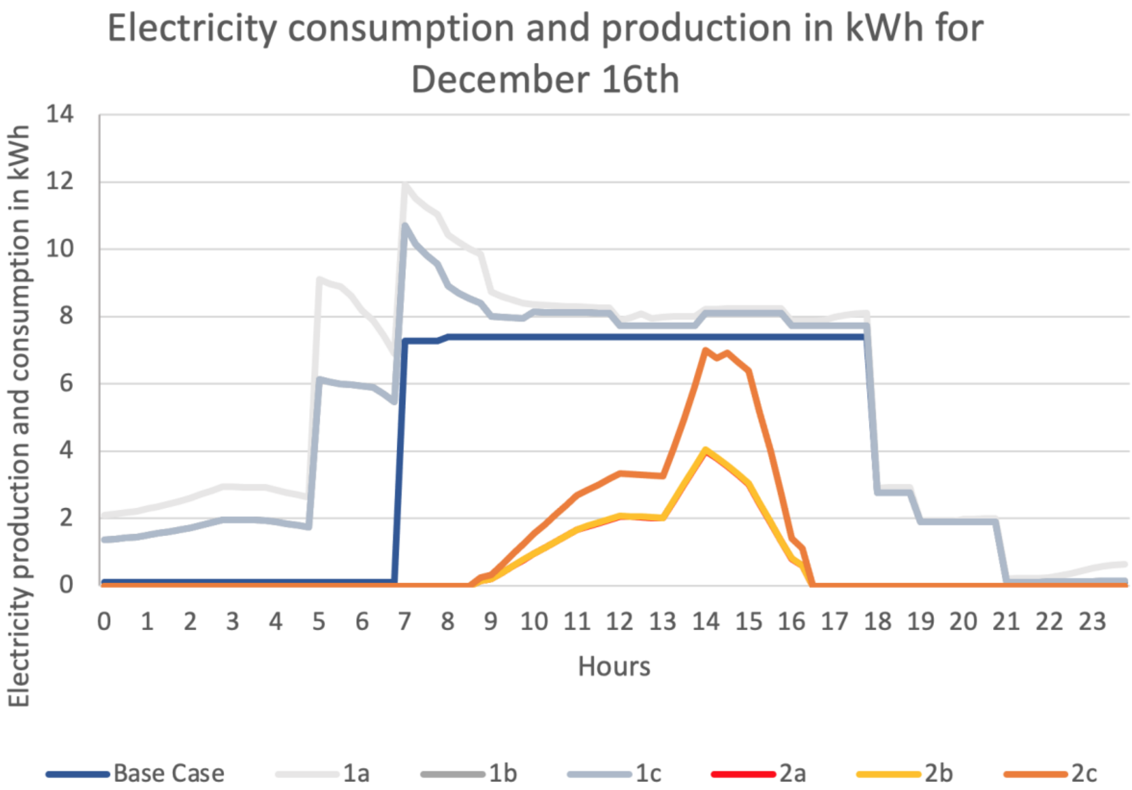
- for each school scenario, the PV scenario 2c with a 42° roof angle provides the best meeting of supply over demand, however this difference is of 4 to 6 points.

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

4.3 Discussion

From the annual, monthly and timestep simulations, each result provides a different type of information. A higher resolution of the school electricity consumption and the PV electricity generation reveals the advantages and the challenges of photovoltaic electricity production for primary schools.

First, the time resolution of the production over consumption provides 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. Both values are interesting indicators but reveal different information: the annual figure provides an averaged installation potential, while the high-resolution values indicate what reliance the school building can have on generated electricity.



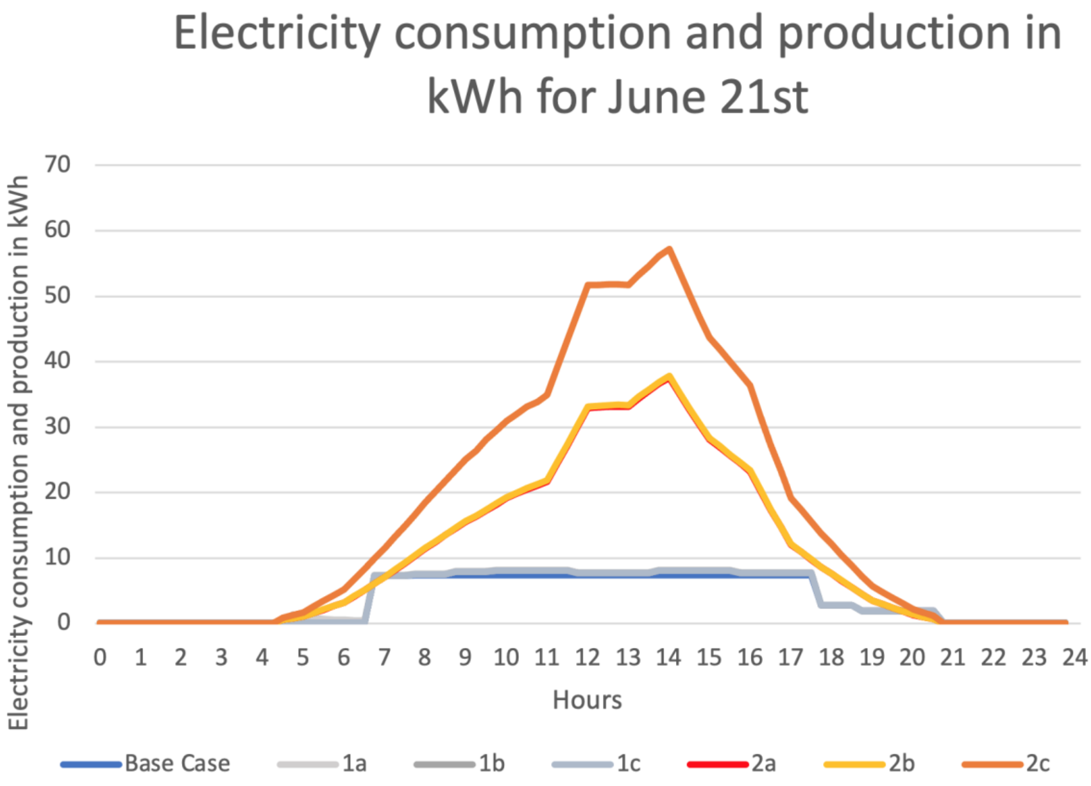


Figure 5 - Graphs of the electricity consumption and production in kWh for December 16th and June 21st 2002 for the different scenario combinations

Then, annual figures are averages and do not consider the PV production seasonal variability or electricity production and demand variability over the course of a day, as shown on figure 4. 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. Monthly values do consider this variability; however, they do not consider variation in electricity generation and supply over the course of a day. In addition to this seasonal variability, it is also essential to consider PV electricity production over the course of a day.

Indeed, PV electricity production is equal to zero at night, goes up during the morning to peak at midday and falls in the afternoon. However, in winter, especially November, December and January, the demand for heating has some variation depending on occupancy schedules and patterns, but the heating demand is contained between 0,5 to 3 kWh, while PV electricity production ranges from 0 to 7 kWh with a pike at midday for 16th of December. As a result, from the parameters of the heating system that should make the room temperature superior or equal to 21°C or 20°C depending on the school scenario and the nature of photovoltaic electricity generation, it is not possible for the PV electricity supply to meet the school demand 100% of the time without a battery system. As a result, because of this nature, even if PV has a high electricity generation potential, electricity demand can only be met 35 to 47% of the time according to this study and the scenarios established.

Following the same logic, possible school retrofits with electrification of the heating system decrease 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 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, monthly and high resolution of 15 and 30min timestep of electricity production and consumption provide significant differences in results. Yearly results average the higher summer electricity production and erases the lower electricity productions in winter months. It is especially significant for a primary school 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, it is important to highlight that during the night and the morning, electricity demand cannot be met by photovoltaics by the nature of this renewable energy. As a result, it is often in the morning and at the end of the day that the school would rely on national grid electricity.

However, when the school electricity demand relies on national grid electricity, the school demand follows a national peak in demand that has a high carbon intensity. Indeed, for the days for which electricity demand is almost met by photovoltaic electricity, electricity is still needed at night, in the morning and in the evening. At night, carbon intensity of electricity is generally low, inferior to 100gCO_2eq/kWh (8). However in the evening and especially in the morning, the combination of a growing national demand for electricity associated with a rise in carbon intensity, from 100gCO_2eq/kWh to 150-300gCO_2eq/kWh (8), As a result, a high demand for electricity before school starts makes for an carbon intensive heating.

The following table summarizes what can be learnt from each temporal resolution for electricity consumption and generation in the UK.

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

5.2 Economic balance

Many indicators can be taken into account when a PV project viability is explored. The PV electricity generation potential as well as the building electricity consumption can be taken into account, but the economic factor of a project should also be considered. The following graph and table present the quantities of electricity that should be purchased to meet the electricity demand to complete on site energy production and the quantity of electricity that can be sold, after meeting the primary school demand. The following graph presents the values of electricity that should be purchased or sold as well as the resulting economic balance.

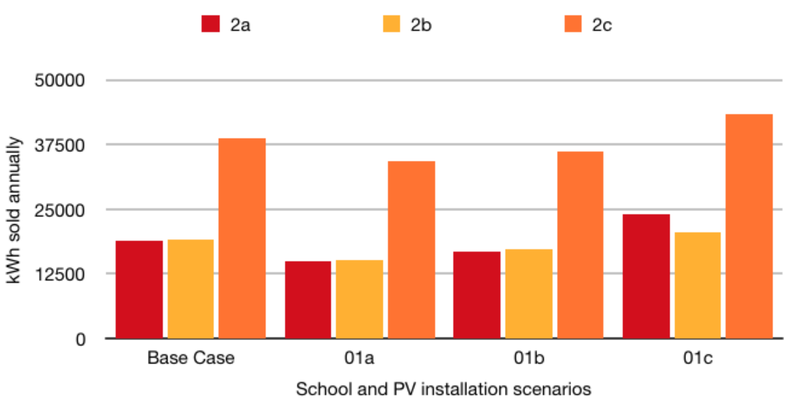


Figure 6 - Graph of the sold electricity for each scenario combination, with a timestep of 15min

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

From the 12 scenario combinations, when calculating the balance of sold electricity and purchased electricity, the balance is always interesting for the school as it provides a sell of 15,007kWh/year to 24,127kWh/year per year, so between £1,825/year to £2,934/year for the actual building school and from 38,677kWh/year to 43,513kWh/year if the school had a 42° roof, so between £4,460/year to £5,291/year, considering a price of 0,1216£/kWh (49). The current school has an estimated expenditure of £9,136/year for electricity and of £3,483/year for gas.

From these estimations, consultancies could help schools as well as the Department for Education, to design project differently in taking in consideration the generated income from sold electricity. The design of schools could be changed to a close to 42° angle pitched roof to integrate PV on the roof, or similar taking into account other local shades and factors. The generated income could be used by the school to provide better facilities or could be reinvested in low-carbon systems and technologies or their maintenance.

5.3 Carbon emissions and reliance on offsite energy

As this study is set in the context of reducing greenhouse gas emissions, the high resolution of electricity production and consumption allows to explore the potential benefits of photovoltaic electricity carbon intensity versus the national grid carbon intensity, expressed in gCO_2eq/kWh. The national grid carbon intensity with a timestep of 30min is publicly available (8) and photovoltaic electricity has a carbon footprint of 80gCO_2eq/kWh, considering the photovoltaic panel life-cycle-analysis (28). Following the same approach with yearly, monthly and timestep results, the following tables show the national grid carbon intensity with the electricity production and consumption for the different scenarios.

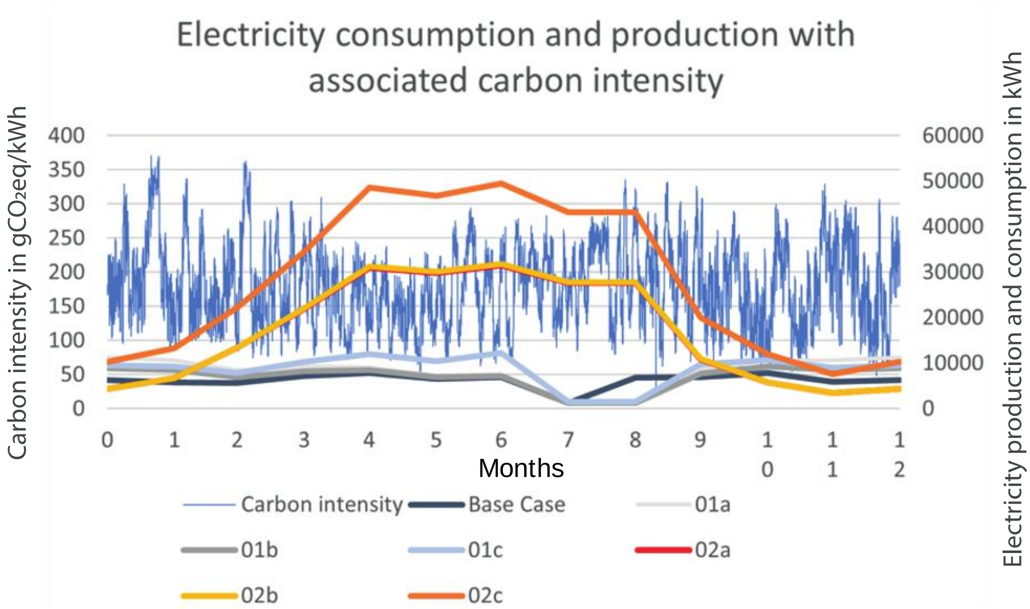


Figure 7 - Graph of the electricity consumption and production with associated carbon intensity with annual results with a 30 min timestep

For the yearly results, the national grid carbon intensity appears to be lower in summer than in winter, as energy demand decreases with increasing temperatures. Photovoltaic electricity production is at its peak during summer months and provides approximately 5 times more electricity than the school consumption. The photovoltaic electricity production is at its lowest in November, December and January, due to sun position and cloud coverage.

When considering an 80gCO_2eq/kWh for photovoltaic electricity, the different PV scenarios present an interesting advantage to decarbonize the electricity from national grid from February to September. However, national grid electricity would be needed in November, December and January to meet the demand, when carbon intensity of electricity is at its highest.

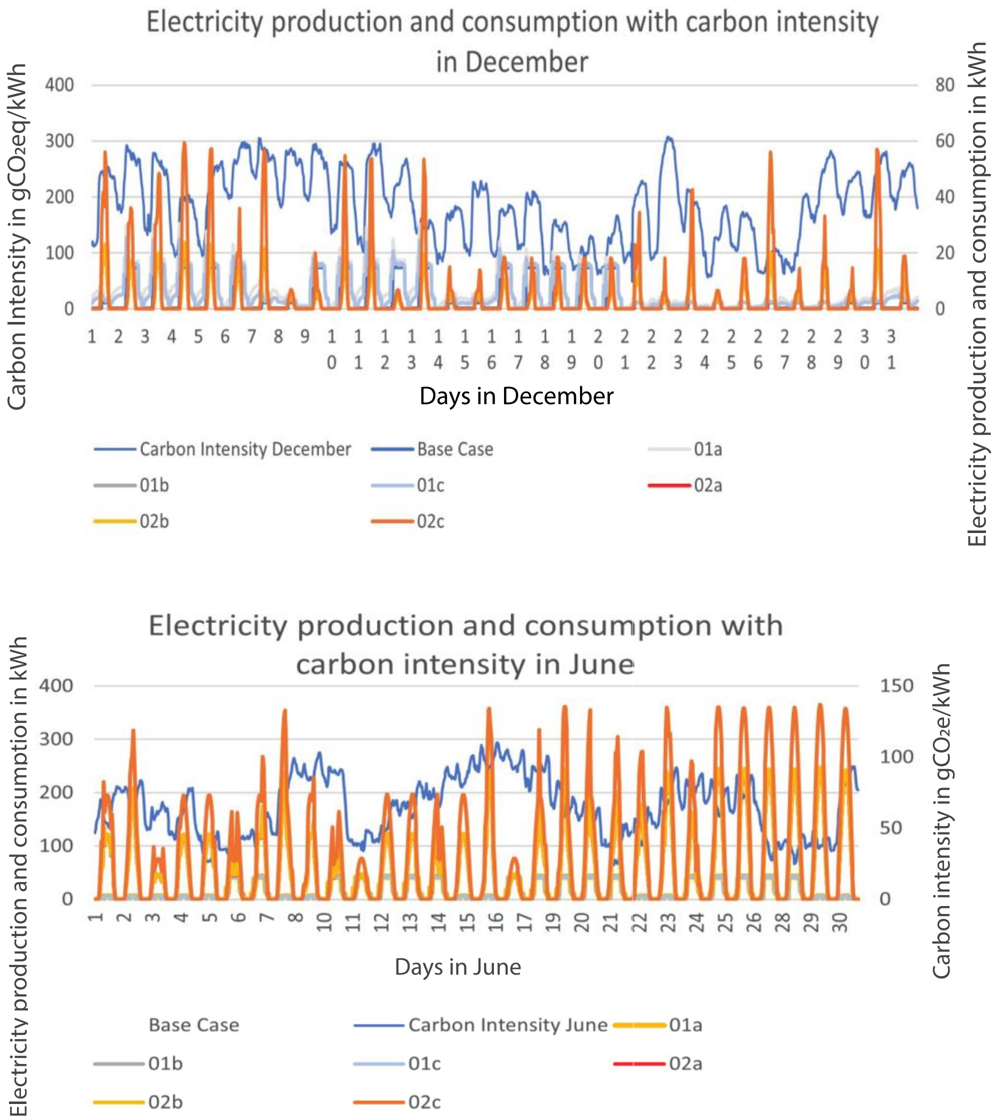


Figure 8 - Graphs of the electricity consumption and production in kWh for December and June 2002 for the different scenario combinations with carbon intensity for a 30min timestep

For the monthly results, it is to note that photovoltaic electricity production ranges from 0 to 60 kWh for production peaks in December, while production peak reaches 130 kWh in June. December and June show not only variability in peak electricity production, but also daily variation. As a result, in December, the electricity consumption is met on the 7th or the 13th, but not the 16th. In June, even with daily variability, the school electricity demand appears to be met every day of the month.

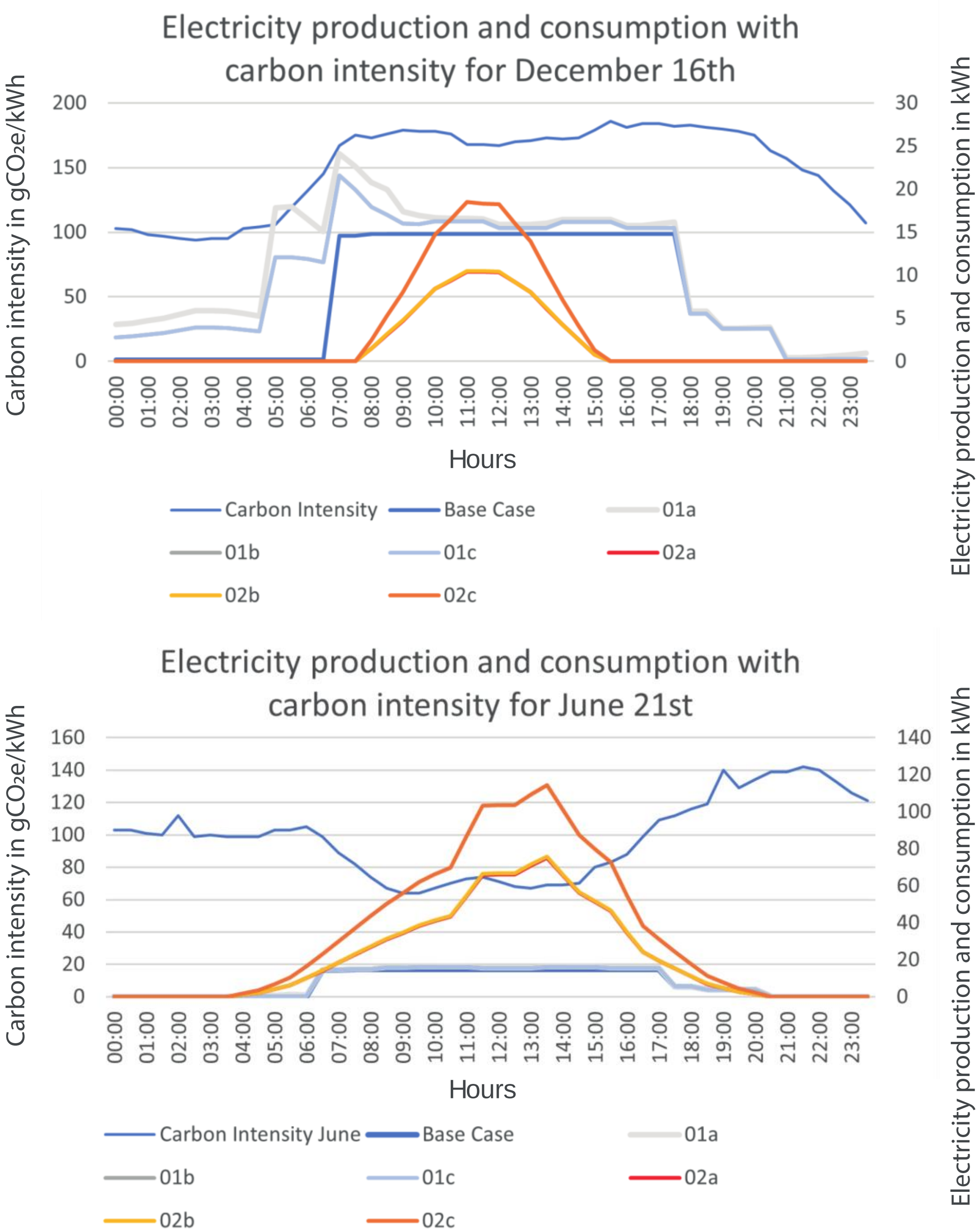


Figure 9 - Graphs of the electricity consumption and production in kWh for December 16th and June 21st 2002 for the different scenario combinations with carbon intensity for a 30min timestep

For the daily results, for December 16th (low production for December) and 21st of June (high production for June) show two extremums in the energy production and consumption on two school days.

While the school electricity demand is hardly met by photovoltaics installation, due to sun position and cloud cover, it is to note that the national grid carbon intensity follows the rise and fall of electricity demand, with a rise from 4 to 7am and a fall from 6 to 11pm. For June 21st, where the school electricity demand is almost met entirely by photovoltaics, the electricity production peak corresponds to the lowest associated carbon intensity, around 60gCO_2eq/kWh.

From the analysis of the carbon intensity related to the photovoltaic electricity production and the school electricity consumption, a few conclusions can be drawn. Firstly, no matter how much electricity is produced by PVs, this electricity has almost always lower associated carbon emissions than the carbon intensity of the national grid. The installation of photovoltaic technologies as a mean to decarbonize the electricity is thus relevant at any time of the year. However, while school electricity demand is met all the days in June, the school should still rely on the national grid electricity during low electricity production days in December, which is an electricity with a carbon intensity over 150gCO_2eq/kWh.

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 smooth the results. Thanks to the high resolution, the assessment allows to understand 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. It is to note that PV technologies as well as battery systems, are resource intensive and that lithium reserves worldwide are limited and are not sufficient for a large shift towards renewables and their intermittency (34). 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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