ARV

CLIMATE POSITIVE CIRCULAR COMMUNITIES

D.6.1 GUIDELINES FOR INTEGRATED DESIGN AND IMPLEMENTATION OF RENEWABLE ENERGY SYSTEMS AND ENERGY STORAGE SYSTEMS FOR BUILDINGS AND NEIGHBORHOOD ENERGY NEEDS IN OSLO

WP6 INTEGRATED RENEWABLES AND STORAGE SYSTEMS

Aileen Yang (SINTEF), Hicham Johra (SINTEF) Benjamin M. Delgado (SINTEF), Ge Song (NTNU), Italo A. Campodonico-Avendano (NTNU), Åse L. Sørensen (SINTEF), Natasa Nord (NTNU), Amin Moazami (SINTEF)

25.06.2025

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036723

PROJECT INFORMATION

Project acronym	**ARV**[1]
Project title	Climate Positive Circular Communities
Project number	101036723
Coordinator	Norwegian University of Science and Technology / Inger Andresen
Website	www.GreenDeal-ARV.eu

DOCUMENT INFORMATION

Deliverable Number and Title	**D.6.1 Guidelines for integrated design and implementation of Renewable Energy Systems and Energy Storage Systems for buildings and neighborhood energy needs in Oslo**			
Due Month	Month 42 (June 2025)			
Work Package Number and Title	WP 6. Integrated renewables and storage systems			
Task number and Title	Task 6.2 Integrated innovative RESs & ESSs solution in demo Oslo			
Dissemination Level	PU = Public, fully open			
Date of Delivery	**25.06.2025**			
Lead Author	Aileen Yang (SINTEF), Hicham Johra (SINTEF), Benjamin Manrique Delgado (SINTEF), Ge Song (NTNU), Italo Aldo Campodonico-Avendano (NTNU)			
Contributors	Natasa Nord (NTNU), Åse L. Sørensen (SINTEF), Amin Moazami (SINTEF)			
Reviewers	Ingeborg Eiriksdatter Høiaas (Oslobygg KF)			
Status	Completed			
Revision Log	Version	Author	Main changes	Date
	V.01	Delgado et al.	First draft	10.09.23
	V.02	Yang et al.	Final version for review	10.06.2025
	V.03	Yang et al.	Final version	25.06.2025

[1] *ARV is a Norwegian word meaning "heritage" or "legacy". It reflects the emphasis on circularity, a key aspect in reaching the project's main goal of boosting the building renovation rate in Europe.*

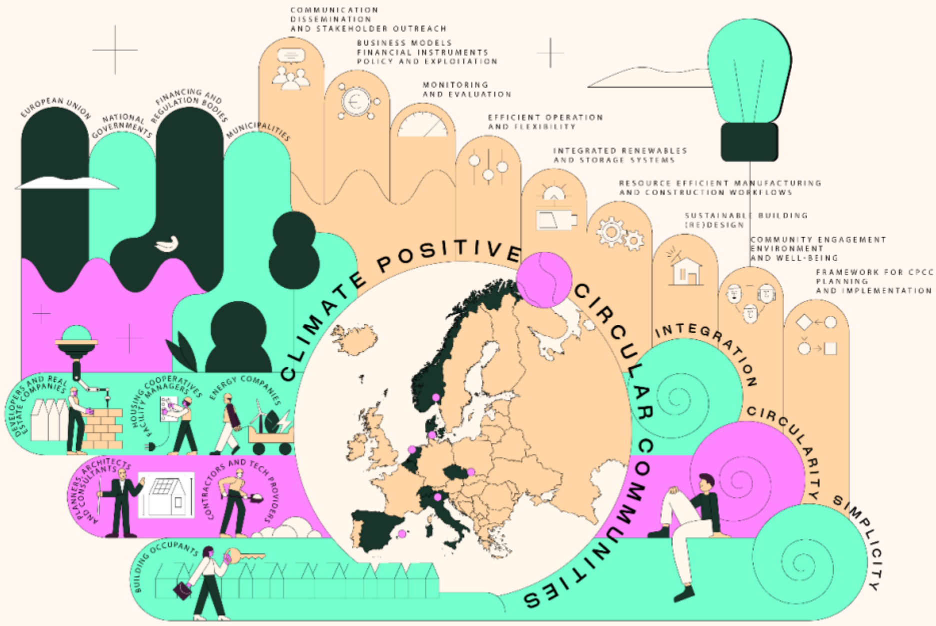
ABOUT THE ARV PROJECT

The vision of the ARV project is to contribute to speedy and wide scale implementation of Climate Positive Circular Communities (CPCC) where people can thrive and prosper for generations to come. The overall aim is to demonstrate and validate attractive, resilient, and affordable solutions for CPCC that will significantly speed up the deep energy renovations and the deployment of energy and climate measures in the construction and energy industries. To achieve this, the ARV project will employ a novel concept relying on a combination of 3 conceptual pillars, 6 demonstration projects, and 9 thematic focus areas.

The 3 conceptual pillars are integration, circularity, and simplicity. **Integration** in ARV means the coupling of people, buildings, and energy systems, through multi-stakeholder co-creation and use of innovative digital tools. **Circularity** in ARV means a systematic way of addressing circular economy through integrated use of Life Cycle Assessment, digital logbooks, and material banks. **Simplicity** in ARV means to make the solutions easy to understand and use for all stakeholders, from manufacturers to end-users.

The 6 demonstration projects are urban regeneration projects in 6 locations around Europe. They have been carefully selected to represent the different European climates and contexts, and due to their high ambitions in environmental, social, and economic sustainability. Renovation of social housing and public buildings are specifically focused. Together, they will demonstrate more than 50 innovations in more than 150,000 m^2 of buildings.

The 9 thematic focus areas are 1) Effective planning and implementation of CPCCs, 2) Enhancing citizen engagement, environment, and well-being, 3) Sustainable building re(design) 4) Resource efficient manufacturing and construction workflows, 5) Smart integration of renewables and storage systems, 6) Effective management of energy and flexibility, 7) Continuous monitoring and evaluation, 8) New business models and financial mechanisms, policy instruments and exploitation, and 9) Effective communication, dissemination, and stakeholder outreach.



The ARV project is an Innovation Action that has received funding under the Green Deal Call LC-GD-4-1-2020 - Building and renovating in an energy and resource efficient way. The project started in January 2022 and has a project period of 4 years, until December 2025. The project is coordinated by the Norwegian University of Science and Technology and involves 35 partners from 8 different European Countries.

EXECUTIVE SUMMARY

The Norwegian demo case "Voldsløkka School and Cultural area" comprises the construction of a new building and the renovation of an existing listed building, with a total of roughly 14 000 m^2 floor area. The demo site has high environmental ambitions and will be built as Oslo's first plus energy school: the annual onsite generation must be greater than the energy needs of the building. For this purpose, the demo site incorporates a system for onsite electricity generation, and highly efficient heat supply technologies.

This deliverable describes the onsite solar Photovoltaic (PV) systems, and the Low-temperature thermal heating and high temperature thermal cooling (LowEx) HVAC system installed in the Norwegian demo site in the ARV project. The PV installation consists of two systems in the school building: BAPV (Building Applied Photovoltaics) on the roof, and BIPV (Building Integrated Photovoltaics) on the façade. Particularly, the design of the BIPV system on the school façade required a balance between energy production and aesthetic expression and appearance. The LowEx system consists of a combination of CO_2 ground source heat pump (GSHP) and district heating. It utilizes the same infrastructure to deliver the low temperature heating and the high temperature cooling. This system is utilized for ventilation heating and cooling and floor heating and cooling. Originally, the project planned to include a second-life battery energy storage system (ESS) to enhance energy flexibility and self-consumption. However, due to budget constraints, the physical battery installation was canceled. To fulfill ARV's commitment to evaluating storage solutions, this deliverable incorporates simulated battery performance based on modeling from a separate study, adapting findings to Voldsløkka's context.

The aim of the report is to present the design phase and performance of these two systems, thermal and electricity with PV, with the aim of motivating other planners and stakeholders to pursue sustainable building re(design), incorporating onsite storage and generation capacity as well as highly efficient thermal solutions.

TABLE OF CONTENTS

1. Introduction **7**

2. DESCRIPTION OF THE DEMO PROJECT **7**

2.1. Status of the demo before the ARV project 7

3. RENEWABLES AND STORAGE SYSTEMS ROLE IN CPCC **8**

4. INTEGRATED DESIGN OF RESS SYSTEMS **9**

4.1. Energy demand 10

4.2. Environmental aspects 12

4.3. Architectural aspects 13

4.4. Social aspects 14

4.5. Economical aspects 15

5. IMPLEMENTATION OF RESs & STORAGE SYSTEMS **16**

5.1. New construction projects 16

5.2. Renovation projects 19

5.3. Tendering process 21

6. IMPLEMENTED INNOVATIVE ENERGY SOLUTION IN THE DEMO **22**

6.1. BAPV and BIPV systems 22

6.2. Battery energy Storage system (BESS) 25

6.3. Thermal system 26

7. OPERATION AND EVALUATION **28**

7.1. General energy demand 28

7.2. Solar photovoltaic installation operation 31

7.3. Performance of the solar photovoltaic production forecasting solution 35

7.4. Simulations and performance of the battery system 36

Return of investment (ROI) 36

Self-consumption (SC) 39

Self-sufficiency (SS) 40

Local flexibility markets (LFM) 41

7.5. Performance of the thermal system 42

8. SCALABILITY AND REPLICATION OF THE INNOVATIVE SOLUTION **44**

8.1. Scalability processes 44

8.2. Replication potential 45

8.3. Readiness for Future and New Technologies 46

9. LESSONS LEARNED **48**

References **50**

Acknowledgements and Disclaimer **51**

Appendix A – Glossary of Terms **52**

Partner Logos **53**

1. INTRODUCTION

Work package WP6 deals with the system design, deployment, and evaluation of the overall ARV innovative solutions in the different demonstration sites with respect to renewable energy sources (RESs) and energy storage systems (ESSs) implemented in buildings and neighborhoods. This is essential to achieve the ambitions of the ARV project in creating net positive energy and zero emission communities.

Task 6.2 in WP6 deals with the electricity generation system and the LowEx heating and cooling system in the Norwegian demo site in the ARV project: Voldsløkka school. The electricity generation system comprises building integrated photovoltaics (BIPV) and building applied photovoltaics (BAPV) installations in the demo site. Particularly, the design of the BIPV system on the school façade required a balance between energy production and aesthetic expression and appearance. The LowEx heating and cooling system is one of the innovations within this demo. The LowEx system is utilizing the same infrastructure to deliver the low temperature heating and the high temperature cooling. This system is utilized for ventilation heating and cooling and floor heating and cooling. While the initial plan included a second-life battery to store surplus PV energy and mitigate grid peak loads, budget limitations prevented its installation. To address this gap, simulated battery performance data have been integrated into this deliverable.

This deliverable aims to provide an overview of the design, implementation and evaluation of the implemented RESs (BIPV/BAPV) and the LowEx thermal system at Voldsløkka School. A simulation of the second-life battery system was also conducted to explore its potential to enhance energy flexibility, self-consumption, and cost savings. Lastly, the deliverable provides lessons learnt and guidelines for public building owners and planners to integrate RESs and ESSs, balancing energy performance, aesthetics, and economic feasibility in a Norwegian context

2. DESCRIPTION OF THE DEMO PROJECT

2.1. STATUS OF THE DEMO BEFORE THE ARV PROJECT

The Norwegian demo case, Voldsløkka School and Cultural area, is located in the mid/northern part of Oslo. The demo includes the construction of a new secondary school building (S-building) and retrofitting of an existing cement factory (the Heidenreich buildings) to host 810 students. In addition to the school, the demo case also includes a cultural centre, a cultural hall, and a sports hall. The cultural hall is used as a sport facility until the completion of the multi-purpose sport hall in the nearby plot of land. The school and cultural activities will cover an area of 11 100 m^2 in the new construction and 2 900 m^2 in the Heidenreich building (H-building). The two buildings will be connected via a bridge on the second floor.

The new school facility will be integrated as part of the surrounding local area, which complements the area with new functions and activities and strengthens the area's green structure. The school started operating in August 2023. Oslobygg KF (OBF) is the enterprise responsible for the demo, and is also in charge of owning, managing, maintaining and developing the real estate assets of the City of Oslo.

Figure 1. *The figure shows an aerial view of the Voldsløkka school project. Image courtesy: Veidekke.*

Summary of activities to achieve ARV ambitions is as follows:

- Positive energy building, 50% reduction of GHG and emission-free construction site.
- Installing a very high energy-efficient building envelope.
- Installing large PV surfaces and a very efficient low-exergy thermal system.

3. RENEWABLES AND STORAGE SYSTEMS ROLE IN CPCC

The city of Oslo has a climate strategy towards 2030 where Oslo will transform into a zero-emission city. There are 16 selected priority areas to ease this transition, and areas 9 and 10, as described in the climate strategy, point to three measures in energy: more local, onsite, renewable energy production, increased energy flexibility, and increased energy efficiency. The goal is to reduce the overall energy use in Oslo by 10 % by 2030. The three potential measures to facilitate more local renewable energy production are the following: 1) installation of solar PV panels and solar thermal collectors on the municipality's own buildings and facilities, 2) to offer subsidy scheme for installation of PV panels in housing associations and commercial buildings and 3) pilot buildings with energy target set according to the FutureBuilt program with high ambitions for low energy use and a high proportion of self-produced energy.

Solar PV panels can be installed both on roofs and façades and as free-standing ground-mounted installations in the terrain. Solar PV panels are currently the most natural choice for installation in buildings due to the high versatility of electricity, but for buildings with hydronic heating systems, solar thermal collectors can be an alternative. Building façades are great alternatives for PV panels in Norway due to the low altitude of the sun, resulting in a higher incidence of diffuse light compared to the roof. Solar PV panels on façades facing the south, east, and west usually produce less than south-facing roof systems; however, façade panels can also produce electricity when the sun is low, and they are not hindered by snow cover – a problem that is accentuated in Norway due to its geographic location. On the contrary, snow on the ground can reflect up to 80% of the sunlight and contribute to increased production, thus electricity can be produced all year round. The cold climate in Norway is also advantageous as the efficiency of PV systems increases at lower temperatures. Solar PV systems can make a significant contribution to reducing emissions and improving the overall economy of the energy system. This is because, during operation, the electricity generation from solar PV systems does not require the combustion or transformation of any fuel, so no fuel needs to be purchased and no emissions take place. Moreover, the prices of solar PV systems have drastically dropped in the last two decades – from 5 USD per Watt installed in 2000 to 0.2 USD in 2020, and very little expenditure goes into operation and maintenance. However, there are some considerations regarding solar PV systems. Electricity production from PV systems is non-dispatchable, so, other than by turning them off, the user has no control over when generation occurs. and can primarily be used to reduce the delivered energy to the building. Therefore, on days when the sky is clear and electricity demand is low, the generation from the PV system may be higher than the electricity use in the building.

Since 2020, there has been a drastic increase in PV installations in Norway, from 108 MW to 769 MW in 2025 [1]. This has, in turn, resulted in a marked demand for local storage of produced electricity. Use of new or second-life Li-ion batteries as energy storage in buildings has been recognized as a solution to drive a wider adoption of renewable energy sources. Over the past decade, battery storage costs have seen a dramatic decline [2]. According to the International Renewable Energy Agency (IRENA), the cost of battery storage projects fell by 89% between 2010 and 2023 from USD 2,511 per kWh to USD 273 per kWh. With the availability of a battery energy storage system (BESS), the surplus energy can be exported to the electricity grid or stored for later use, depending on the optimization algorithm. Local guidelines and regulations on energy sharing and export to the grid must be considered.

Providing thermal energy via GSHP and district heating gives another possibility to increase circularity and sustainability for the heating of existing areas (residential and commercial buildings). The LowEx system utilizes the same infrastructure (heating and cooling equipment) to deliver low-temperature heating and high-temperature cooling. This system is utilized for ventilation, heating, and cooling, and floor heating and cooling. In this way, suitable temperature levels for the utilization of the GSHP and free cooling are provided. Consequently, this gives a stable operation of the GSHP that can be supplied with electricity from the PV system. Moreover, the use of a GSHP reduces the total energy use of the building, as less electricity is required to cover the heating demand of the school. Therefore, the LowEx system allows for the electricity produced from the PV system to be used for other services in the buildings, also, thus resulting in less dependency on seasonality, or mismatch between energy delivered and energy use.

4. INTEGRATED DESIGN OF RESS SYSTEMS

The Voldsløkka project is situated within the concession area of the city district heating system, which necessitates the establishment of necessary infrastructure to connect new buildings with the district heating network. Furthermore, the Regulatory Plan has established requirements regarding the architectural appearance of the new school building, while the building that will be retrofitted is culturally protected. The combination of these factors, along with the ambition of creating a plus-energy building, led to the optimization of the positive energy concept solely for the new school building.

The thermal needs of the school building are primarily met using a CO_2 based GSHP. The design intention was that 80-90% of the heating load would be covered by the GSHP, while, during the coldest days of the year, district heating would account for the remaining 10-20%. The new S-building will receive heat from both the GSHP and district heating, while the existing and retrofitted cement factory (the H-building) will solely rely on district heating. Heat pumps are typically designed to meet only a fraction of the total heating demand of a building, while a secondary or top heating component addresses the remainder. This approach helps to lower investment costs and enhances the heat pump's coefficient of performance (COP) by enabling it to operate at nominal capacity as much as possible. Such dual solutions, in which an additional heating supply component (like district heating or an electric heater) functions during peak demand periods, are common in buildings with GSHP.

The installed GSHP will provide heat and cooling to the buildings. Boreholes or energy wells serve as the heat source for the GSHP and for free cooling. Additionally, the GSHP evaporator can also provide free cooling for the ventilation system. This approach optimizes the heating and cooling loads of the building, ensuring that the GSHP operates effectively and minimizes electricity requirements for the compressor. Consequently, integration with PV and utilization of the electricity generated onsite will be improved.

The energy demand of the building can be offset with on-site generation using a combination of BIPV and BAPV. Due to the aesthetic requirements, innovative solutions with regard to the building facade could make it more attractive to incorporate renewables in new construction projects or renovation projects. This can be particularly effective for BIPV systems on the façade, since they can be seen from the street level and thus, they have a much larger impact on the appearance of the building than BAPV systems, which are typically on the roof and out of sight.

4.1. ENERGY DEMAND

The H-building has a conservation status, meaning its façade and outside appearance must be preserved as much as possible. Therefore, solar PV panels cannot be installed on it, and it was not possible to achieve a plus-energy level. Only the S-building is relevant for the plus-energy concept. Therefore, only the energy simulations for the S-building performed in the software SIMIEN (v 6.017) by the consulting company Norconsult are presented here. SIMIEN calculates the energy framework according to NS3031:2014 – Calculations of energy performance of buildings – Method and data [3]. These calculations provide the basis for an optimized design of the energy system, its energy supply, and the energy required from PV production for the S-building to reach the requirements of a Plus-Energy building. Input data for energy use related to technical equipment and heating of domestic hot water (DHW) was based on data from another school in Oslo that was built according to the passive house standard. The input data for operating time and occupancy were based on statistics from similar projects. Table 1 shows the simulated annual energy demand based on Futurebuilt's Plus-Energy definition.

According to the Plus-Energy definition established by Futurebuilt in 2014, the energy demand for appliances should be subtracted from the calculations if the building has more than four floors. Voldsløkka consists of six floors, including the basement. Therefore, the net energy demand is calculated as 448 386 kWh/year minus 122 876 kWh/year, resulting in 325 510 kWh/year.

Moreover, the share of renewable energy in the district heating system can be credited using a weighting factor, which is set to 0.43. Delivered energy from the district heating is thus 2 404 · 0.43 = 1 034 kWh. Therefore, the building needs to be able to cover the total net delivered energy, which amounts to 164 810 kWh after taking into consideration the direct electricity demand, the COP of the GSHP, and the reductions. Finally, the building must deliver 2.0 kWh/m2 per year to be defined as Plus-Energy. Consequently, the energy from PV generation needs to be at least 164 810 kWh + (9 267 m^2 · 2 kWh/m^2) = 183 344 kWh/year. As shown in **Table 2**, the PV system is designed to supply 234 000 kWh per year, which is approximately 30% larger than the calculated requirement.

Table 1. *Calculated annual net energy demand for the S-building based on Futurebuilt's Plus-Energy definition, by Norconsult.*

Parameter	**Energy demand (kWh year)**	**Specific energy demand (kWh/m²)**
1a Space heating	84 629	9.1
1b Ventilation heat	21 759	2.3
2 Domestic hot water	93 395	10.1
3a Fans	26 635	2.9
3b Pumps	3 500	0.4
4 Lights	72 902	7.9
5 Appliances	122 876	13.3
6a Room cooling	986	0.1
6b Ventilation cooling	21 704	2.3
Total net energy demand (sum 1 to 6)	**448 386**	**48.4**

Table 2. *Estimated PV generation to achieve plus-energy for the S-building.*

Parameter	**Energy delivered (kWh year)**	**Specific energy delivered (kWh/m²)**
Total delivered electricity	289 056	31.2
Appliances	- 122 876	13.3
District heating (weighted)*	- 1 370	0.1
Total net energy delivered	**164 810**	**17.8**
Required PV production	183 344	19.8
Estimated PV production	234 000	25.3
Surplus PV	**50 656**	**5.5**

*The share of renewable energy in the district heating system can be credited using a weighting factor, which is set to 0.43.

Regarding thermal energy, both buildings have demand for space heating, ventilation heating, and DHW. In addition, both buildings have cooling needs. As mentioned in the introduction of this section, only the S-building is capable of being a Plus-Energy building, and therefore, only the calculated heating and cooling needs for this building are given in **Table 3**.

Table 3. Estimated heating and cooling needs based on Futurebuilt's Plus-Energy definition, by Norconsult.

Parameter	Energy delivered (kWh year)	Specific energy delivered (kWh/m²)
1a Space heating	84 629	9.1
1b Ventilation heat	21 759	2.3
2 Domestic hot water	93 395	10.1
Total heating needs	**199 783**	**21.5**
Total cooling needs	**21 704**	**2.3**

Supply of the heating and cooling will happen via GSHP and district heating. Energy demand for the GSHP and district heating is given in **Table 4**. Please note that in **Table 4**, the total district heating demand without weighting is given.

Table 4. Estimated thermal energy supply based on Futurebuilt's Plus-Energy definition, by Norconsult.

Parameter	Energy delivered (kWh year)	Specific energy delivered (kWh/m²)
Electricity to GSHP	60 454	6.5
District heating	2 404	0.3

4.2. ENVIRONMENTAL ASPECTS

CO_2 emission factors for energy production in Norway are generally low because 95% of energy is produced from renewable sources, with the main source being hydropower (83%), followed by wind power (11%), and 1% from solar[4]. The calculated CO_2-factor for electricity use in Norway is 15 g CO_2e/kWh in 2023 [5].

The solar power installed capacity is still modest in Norway, but it is currently growing rapidly. Towards the end of 2022, approximately 300 MW of solar power was connected to the grid in Norway. Solar energy systems do not emit CO_2 during their operation years, yet indirect CO_2 emissions occur during other phases of the life cycle, such as the production phase. On average, solar energy systems will have a low emission of CO_2 per kWh in a life cycle perspective compared to fossil sources. Depending on the PV module technology, the carbon emissions associated with the generation of 1 kWh of solar electricity from PV systems ranges from 25.5 (Cadmium-Telluride) to 42.9 g (Mono Crystalline silicon) CO_2e [6]. Currently, environmental product declarations (EPD) are being developed for PV-panels [7].

The rise of electric vehicles has accelerated battery technology, but also created a growing market for used car batteries to store energy. It is cheaper than new batteries and can extend their lifetime by 7-15 years. Battery production also has a significant environmental impact due to energy use and mineral extraction. Thus, maximizing the lifespan of batteries is both smart and sustainable.

At the Voldsløkka school demo for the thermal system a combination of a CO_2 based GSHP and district heating is used for heating. District heating in Oslo is provided by municipal combustion and heat pumps, meaning that this part of the heat supply is environmentally friendly and satisfies economic circularity due to the use of garbage in a useful way. As the refrigerant, CO_2 is used in the GSHP. CO_2 as a refrigerant is an environmentally friendly fluid, because it does not contribute to ozone depletion.

4.3. ARCHITECTURAL ASPECTS

Three types of solar cell technologies are available today: Multi-crystalline solar cells, monocrystalline solar cells, and thin-film solar cells, all with silicon as the base material, with the two forms of crystalline solar cells dominating the market. Photovoltaic (PV) systems can be building-integrated (BIPV) or building-applied (BAPV). BAPV involves fitting modules to existing surfaces after the construction has been completed, which occurs during retrofitting. This approach allows traditional PV solutions to be easily mounted on most types of surfaces, such as roofs and the ground. Traditional PV solutions are also highly efficient, and their performance is well-documented. However, traditional PV solutions can be considered aesthetically unappealing and come in limited design options.

BIPV has the advantage that, in addition to producing energy, the PV modules themselves can be a construction element. BIPV can be included in new construction projects or afterwards, where certain sections of a building need renovation (roofs, windows, or cladding). This is the favoured approach when designing an "active" architectural product. **Figure 2** shows an energy retrofitted building in Oslo, a demo case in the 4RinEU-project, where prefabricated elements with integrated PV panels were used and the modules became part of the aesthetic design of the building [8].

Figure 2. *Rehab project at Haugerudsenteret. The PV panels are installed in pairs above the large windows (south façade) and integrated into the prefabricated elements. Image courtesy: Oslobygg.*

Preliminary calculations during the planning phase showed that the production of PV from the roof alone would not be sufficient to fulfil the Plus-Energy requirement set by FutureBuilt, thus additional PV energy production was needed. In addition, the Regulatory Plan had set requirements for the visual impact of the new building, and large monotonous surfaces of the most efficient, black-coloured PV panels were not accepted on the facades. Therefore, if the PV system were expanded to the building façade, typical panels would not be a suitable solution.

Various BIPV solar panels are currently available in the market, which allows customization to achieve the required visual and architectural expression [9]. For example, PV panels can be mixed up with a standard construction material, such as glass, and undergo special treatments by applying colours or patterns to mask the solar cells. It is also possible to mimic solar products with similar products commonly used in construction, with significant but tolerable loss of electrical performance. It was thus decided to follow this approach for the implementation of the BIPV system on the façade of the S-Building. The system would consist of a combination of typical black panels and custom-made panels with a glass cover of different colours (see **Figure 3** for a combination on the west-façade).

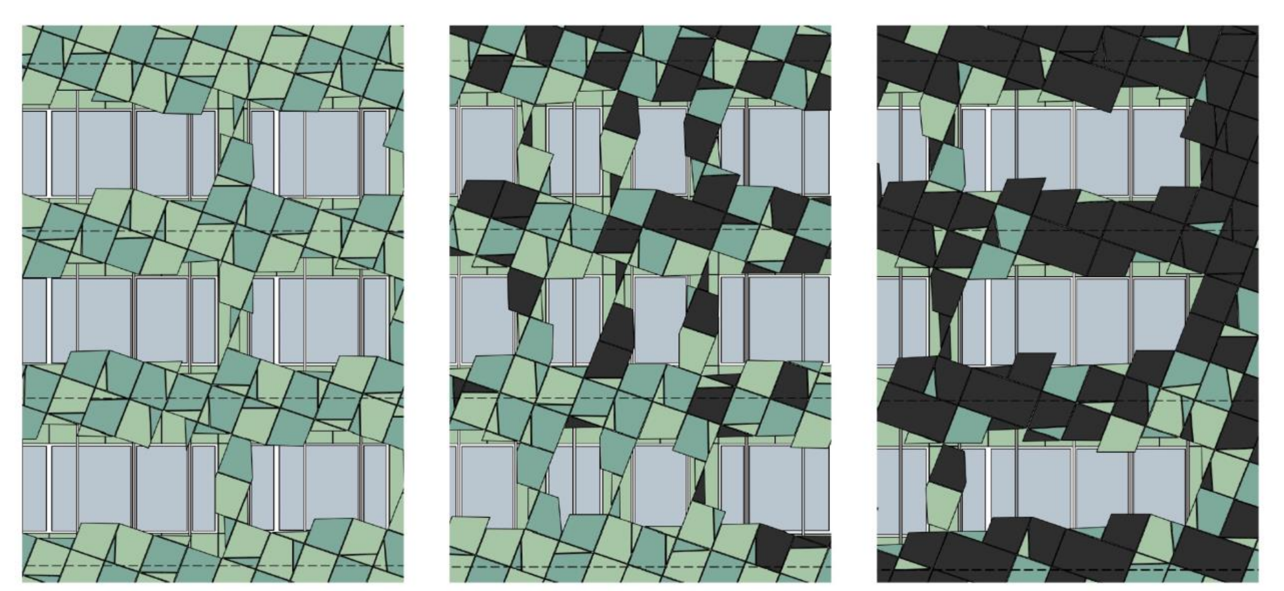


Figure 3. *The west facade of the S-building, showing the combination and transition of PV-modules with glass cover of different colors. Image courtesy: Spinn arkitekter KONTUR*

4.4. SOCIAL ASPECTS

Achieving a good indoor environment at a reasonable cost is crucial for schools, because pupils need good conditions to learn well and for their well-being in the school. However, for the school budget and performing other activities such as sports or music, it is important that the energy and overall maintenance costs for the school are low. The suggested solutions at the Voldsløkka school, including two innovations, the PV systems on façade and rooftop, and LowEx for heating and cooling, will enable a good indoor environment with low cost for the school.

The Voldsløkka school started operating recently, so it is difficult to identify all the relevant social benefits related to the energy system. Nevertheless, a few effects could be expected. Having a PV system that is visible from the street level can increase public awareness to a higher degree than one that is on a rooftop. Façade PV systems spark conversations, particularly a colourful and complex system like the one in Voldsløkka. Therefore, this demo site could help to raise awareness of the importance and impact that solar PV can have in reducing energy demand and lowering emissions. Also, pupils attending this school could become more used to PV systems on façades, which could improve their acceptance in further applications and implementations. The option to enable the pupils and teachers to follow the power production and consumption can also provide an educational and pedagogical dimension when RES are integrated into the building.

The aesthetic appearance of the solar PV system on the façade of the building can have a positive effect on the public acceptance of this type of system. Future projects could showcase the Voldsløkka school as an example that façade PV systems can have an interesting and colourful appearance, in which complexity can be added through custom-made panels. Thus, it may be easier to increase the will of the citizens and of the municipalities to accept and promote the use of façade PV systems.

As well, the combination of onsite generation from the PV system and the low energy demand thanks to the LowEx thermal system should lead to low operation costs in the school, and this will be accentuated by the low maintenance costs expected from both systems. This means that the allocation for energy expenses during the year should be significantly lower than those of a school with more typical, less efficient energy systems. These savings, in turn, can be used by the school for several other purposes.

4.5. ECONOMIC ASPECTS

The high and varying energy prices in the last few years have resulted in the payback time for investing in PV systems being reduced to approximately 10 years, whereas previous estimates yielded payback times of 15-25 years. For comparison, the expected lifetime of PV systems is more than 30 years. Another aspect to consider is that integrating BIPV on the façade or on the roof can result in saved material costs as the PV modules can have the added function as building envelope material. For example, in Brynseng school in Oslo, it is estimated that 3 000 NOK/m^2 would have been spent on façade materials, but those expenses were avoided through the installation of BIPV [10]. Compared to traditional PV modules, custom-made PV modules such as the ones installed in Voldsløkka school may cost up to twice the average price of glass-glass BIPV modules[11]. Furthermore, the choice of colour influences the panel temperature, thus influencing its efficiency[12]. However, the cost of the modules often represents only a small fraction of the total cost of the system, with other aspects such as balance-of-system, mounting, and planning usually having similar or greater costs. Therefore, the performance and payback period of custom-coloured BIPV systems are unique for each project. It is thus uncertain how much the use of coloured BIPV would affect the final price and the payback time.

Used car batteries repurposed as second-life battery energy storage system (BESS) can be a sustainable and economic solution. The combination of BESS with solar energy production will increase the share of self-consumed renewable energy, reduce electricity costs by peak shaving, load shifting, and offer flexibility services that help ease grid congestion and maintain energy balance. However, to justify the investment in battery systems, the savings from reducing or shifting peak loads should be high enough. Based on previous experience of Oslobygg KF, there is currently a lack of political incentives to invest in battery systems compared to PV systems. However, this might change in the future if there is an increased focus on energy flexibility and the flexibility market.

From the economic viewpoint, the use of the thermal energy system suggested in this study enables energy and economic flexibility, thereby enabling a stable economy for maintaining the building. Due to the good possibility of moving and storing the heat, the building can avoid high energy prices effectively. The heat storage in this building is enabled via water tanks in the short term, such as hours and days, and seasonally in the boreholes. Both storage methods give a possibility to avoid high electricity prices and operate the system in an efficient way. Due to the utilization of MPC, it may be possible to successfully avoid high electricity prices. Lessons learned showed that it is possible to save about NOK 40 000 per year for the electricity cost of running the GSHP due to implementation of the MPC compared to the traditional controllers.

5. IMPLEMENTATION OF RESS & STORAGE SYSTEMS

With regards to both new construction projects and renovation projects, the implementation of renewable energy sources will be highly prioritized. The City of Oslo prioritizes local onsite energy production and the exploitation of local energy resources.

Drivers such as sustainability, energy efficiency, and reduction of GHG emissions can influence which renewable and storage systems will be implemented in different types of projects. To implement innovation solutions can involve financing challenges. There are several financing instruments in Norway to support private and public stakeholders. ENOVA, a government-owned energy enterprise, offers guidance, support, and investment support for new energy-efficient buildings and for ambitious renovation projects. This support is offered both to large- and small-scale projects, for public and private buildings. The city of Oslo also has a support scheme for installing solar panels or solar collectors for housing cooperatives or condominiums. The scheme covers 20% of the costs, with a maximum support amount of NOK 3 million.

5.1. NEW CONSTRUCTION PROJECTS

Many of the measures to reduce energy use in buildings target new buildings. The requirements for energy efficiency have gradually become stricter through the national building regulations. For new construction projects, the ambitions have been raised from passive house standards to plus-energy buildings. The city of Oslo participates in the FutureBuilt programme, which has the goal to cut GHG emissions by at least 50% compared to current regulations and common practice. Several FutureBuilt pilot buildings have been built since the start of this programme, from which the Voldsløkka school draws experiences.

Lia Daycare, defined as a plus-energy building, was one of the first to implement a set of technological innovations back in 2017. The energy-related innovations include:

- Thermally Active Building Systems (TABS) in interaction with solar heating, thermal mass, heat pumps, and energy wells
- Battery pack (6 x AXIstorage Li 7S batteries with a total capacity of 40.8 kWh) for load balancing and increasing self-consumption of solar power. Batteries are placed in the technical room inside the daycare.
- PV system on the roof, covering an area of 150 m^2, is expected to generate 36 650 kWh of electricity per year.
- A heat pump system based on geothermal energy that covers the demand for heating and hot water. The building has three wells, each 280 m deep. The wells are spaced 15 m apart and the collector are single U-tube type. The system aims for a supply temperature to the heat pump of 5°C on average during the heating season. The well field is designed for a minimum temperature of -2°C from the well for space heating and a maximum temperature of 15°C from the well for free cooling.

Figure 4. *Lia daycare. Image courtesy: Oslo municipality.*

Lia daycare was a demo case in an innovation project for the industrial sector (2017-2019) where new integrated concepts for thermal energy supply in zero-energy buildings and plus-energy buildings were developed. Lia daycare also received funding of 1.45 mNOK from ENOVA to implement some of these technological innovation concepts.

One of the school buildings, Brynseng school, is the first near zero energy building (NZEB) in Oslo and was completed in 2017. It received 4.5 mNOK of financial support from ENOVA. To achieve the energy target, which represents a 70% reduction in energy consumption (based on new delivered energy to the site) compared to the building regulations, the following measures were implemented:

- BIPV was integrated into the south façade, covering an area of 1 046 m^2 which produces approximately 105 000 kWh/year. The PV-system consists of 656 modules in 26 different sizes with a nominal power of 166 kWp. As seen in **Figure 5**, traditional black PV-panels were mounted directly on the insulation and function as façade material as well. This results in an added profit gained from the PV-panels.
- The solar façade is designed to produce energy when there is a high demand for electrical energy.
- A ground source heat pump combined with 20 energy wells drilled 250 m deep into the ground was installed and covers approximately 90% of the demand for space heating and hot water.

Figure 5*. Brynseng school, a FutureBuilt pilot building and the first near zero energy building (NZEB) in Oslo.*

Another FutureBuilt pilot building, Ruseløkka school, was completed in 2021 and also aimed to be a NZEB school. The energy targets were achieved by mounting 205 m^2 custom-made BIPV modules on the south façade, adapted after the facade's dimensions and aesthetics. 196 traditional black PV panels were mounted on the green roof (with a 10° angle towards east and west). The combined PV system is estimated to have a total peak power of 105.76 kWp and produce 73 000 kWh/year. District heating is used as an energy source for space heating, hot water, and ventilation as the school is in the concession area of the local district heating system.

Figure 6. *Ruseløkka school, an NZEB school. Photo: Arkitektkontoret GASA AS.*

New construction projects within the concession area of the local district heating system are obligated to make use of district heating as part of the energy source. Exceptions can be made if alternative solutions can be more environmentally friendly, e.g., measures that will enable interaction between different alternative energy sources or solutions to reduce the grid peak load.

5.2. RENOVATION PROJECTS

The existing building stock accounts for a large share of the energy use, and its potential for reducing energy use is large. During rehabilitation projects, it is important to implement energy-saving measures as it is profitable, and results can be easily gained. For a renovation project to be successfully carried out, many key issues need to be considered. These include which technologies to be adapted, costs, and how high the ambitions are with regard to energy efficiency, sustainability, and GHG emissions. Moreover, there are also building-specific issues that need to be considered, e.g., tolerances, disturbance to the users, and architectural appearance (culturally protected building) could potentially limit the selection of RES solutions to be implemented. For rehabilitation projects, the ambitions are set to NZEB buildings.

RES such as PV systems can be easily implemented during renovation projects in different ways; by using prefabricated elements with integrated RES solutions, installation of solar PV systems, either integrated into the façade or systems on the rooftop.

To increase renewable energy production, most of the renovation projects typically select the implementation of BIPV and/or BAPV, some in combination with energy storage systems. Examples of a few selected renovation projects for school buildings in the city of Oslo are provided.

Nordseter school had set high environmental ambitions early in the project, such as being the pilot for an emission-free construction site. To cover the building's energy demand, PV panels were installed on the facades and on the roof, with a total of 177 kWp and an estimated production of 120 000 kWh/year. The building-integrated PV panels in the façade were designed to be an integral part of the building's expression.

Figure 7. *Nordseter school, where traditional PV-panels were integrated into the building façade and BAPV on the roof. Photo by Trygve Mongstad/Asplan Viak.*

Holmlia school, another rehabilitation project which was completed in 2020, chose a PV system that consisted of BIPV in combination with flat roof tiles to achieve the desired architectural expression. The PV system on the roof which covers an area of 1 349 m² has a peak power of 243 kWp and was estimated to produce 196 000 kWh/year. The installation of the solar system is somewhat special as it consists of two sub-systems located on two different buildings and the locally produced electricity is distributed between two schools to best utilize the locally produced electricity.

Figure 8. *The battery building at Holmlia school seen from the outside (left), and the installed battery modules (right). Photos by Aileen Yang/SINTEF.*

An energy storage system, which is in a separate building (9 m²), was implemented to increase the share of self-consumed renewable energy by storing the produced electricity from the PV system and to work as an intermediate storage. The storage system consists of ten used batteries from electric vehicles (Nissan Leaf), completed in autumn 2022, and has a capacity of 150 kWh. The combination of the PV system and the storage system provides the opportunity to reduce the peak load that typically occurs in the morning when all the technical equipment goes online in the building. The intermediate storage of electricity also makes it possible to save money and, at the same time, put less strain on the grid. The storage system is controlled by a fixed algorithm that assumes higher electricity prices at certain hours of the day and performs peak shaving at a fixed level. In other words, it is typically seasonally controlled and not connected to NordPool.

Figure 9. *The BIPV system on the roof of Holmlia school. Photo by Klima og Bygg AS.*

The rehabilitation project received 3.9 mill NOK funding from Oslo Municipality climate budget, which also included the installation of the PV system at the school. The battery system, including design and execution, cost NOK 2.15 million excluding VAT. In addition, the battery building cost NOK 1.2 million excluding VAT. The school could save more than NOK 100,000 annually by load shifting and reducing electricity costs through the combined use of the solar PV system and the battery. The return of investment for this project was estimated to be at least 18 years.

5.3. TENDERING PROCESS

The procurement process for Oslo Municipality is shown in **Figure 10**. As a public building owner, Oslobygg KF adheres to the Norwegian Public Procurement Act and the accompanying Public Procurement Regulations. These regulations implement the European Union's public procurement directives as part of Norway's obligations under the EEA Agreement, detailing the procedures for all stages of the procurement process.

The framework establishes critical budget thresholds that dictate the required procedures and outlines the rules for public announcements of tenders. For the procurement of its turnkey contracts, Oslobygg generally applies the open (single-step) procedure, allowing any interested supplier to submit a tender. Oslobygg has framework agreements with different teams of professionals (architects, consultants) to handle the pre-project phase, where decisions are made on the design concept, energy target, and so on. During the pre-project, the tender documents will be made before a competition is held, and the offers are evaluated based on time, price, environmental criteria, and quality.

The entrepreneur at Voldsløkka, which won the tender, will make the final decisions on which suppliers to choose for the technical and renewable energy systems.

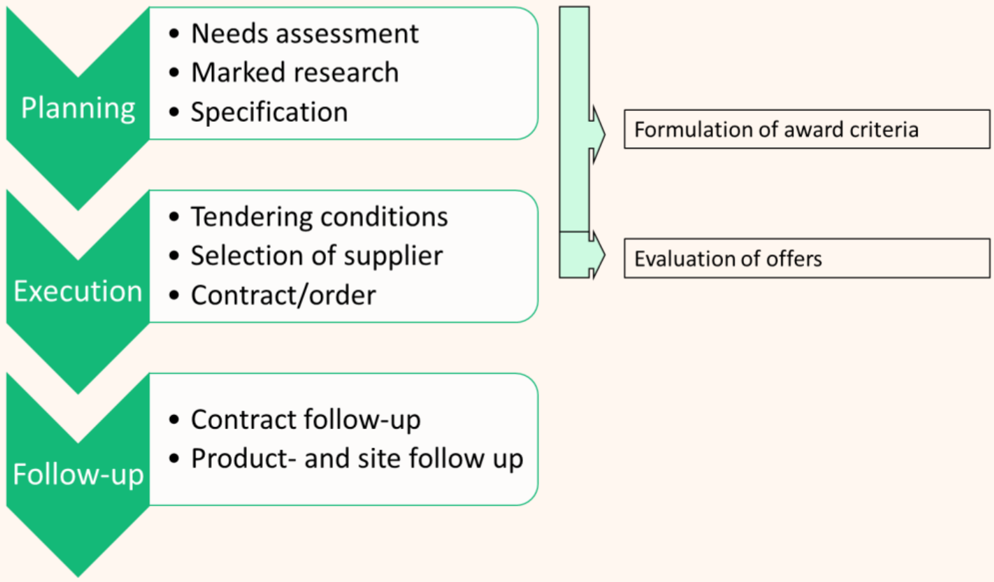


***Figure 10**. Tendering process in the city of Oslo.*

The majority of the new construction school projects in Oslo use a design and built contract where the environmental strategies and qualities are described in the tender documents. New projects draw from experience and lessons learned from the previous projects, particularly regarding energy production, implementation of solar panels in combination with energy storage solutions, purchasing and regulations. The involvement of the contractor, architect, and other relevant consultants from design development and further into the design phase ensures a continuous process. Award criteria are also used to award those with best solutions regarding climate emissions from materials and emission-free construction sites,

6. IMPLEMENTED INNOVATIVE ENERGY SOLUTIONS IN THE DEMO

The school building in the Voldsløkka demo project was designed to be the first *Plus-Energy* school building in Oslo (designed according to the *FutureBuilt* definition of 2014 [15]). According to this concept, the PV installations on the school building are sized and designed to generate 2 kWh/m^2 per year of electricity more than the total yearly energy use of the building. The design energy demand of the school building is 19 kWh/m^2 per year. The PV installation should thus generate 224 000 kWh/year. In addition, the Plus-Energy concept requires that the building systems reflect a certain architectural expression and aesthetics. In that context, an innovative solution combining BIPV, BAPV, and a low-exergy heat supply system was implemented to ensure that the energy and architectural goals were met. The implemented BIPV system received the national award "Solar system of the Year 2022" (årets anlegg 2022) for combining energy production and aesthetics in an impressive and exemplary way [13].

6.1. BAPV AND BIPV SYSTEMS

The onsite renewable energy generation system of the demo school building is a PV system consisting of five PV systems for a total installed capacity of 337 kW$_p$ and covers a total area of 1 853.45 m^2: two east/west-oriented building-attached photovoltaic (BAPV) systems on the roofs ($BAPV.1_R^{E/W}$ and $BAPV.2_R^{E/W}$), one south- and west-oriented BAPV system on the façade ($BAPV_F^S$), and two south- and west-oriented building-integrated photovoltaic (BIPV) systems on the façades ($BIPV_F^S$ and $BIPV_F^W$) (see **Figure 11**). The PV system is designed to generate 230 MWh of electricity per year.

Figure 11. *Overview of the ARV demo Voldsløkka school with PV systems on the roof and facades of S-building (on the left): Image courtesy of Veidekke [16].*

One can find the technical characteristics of the different PV systems of the S-building in **Table 5.**

Table 5. *Overview of the different PV systems installed on the S-building facades and rooftop.*

System	Description	Tilt, Azimuth (N=0°)	Capacity [kW$_p$]	Area [m²]	Modules
$BAPV.1_R^{E/W}$	BAPV Flat roof	Tilt 10 °, Azimuth 71°/251°	124.8	615.2	320 x Trina TSM-390 DE09.08 (20.3% efficiency)
$BAPV.2_R^{E/W}$	BAPV Above technical room	Tilt 10 °, Azimuth 71°/251°	102.4	492.1	256 x Trina Vertex S TSM-400 DE09.08 (20.8% efficiency)
$BAPV_F^S$	BAPV Technical room façade	Tilt 90 °, Azimuth 161°	45.6	219.2	114 x Trina Vertex S TSM-400 DE09.08 (20.8% efficiency)
$BIPV_F^S$	BIPV South façade	Tilt 90 °, Azimuth 161°	26.4	216	216 x custom 40% black, 60% green
$BIPV_F^W$	BIPV West façade	Tilt 90 °, Azimuth 251°	37.9	311	311 x custom 25% black, 75% green

The BIPV modules are both green and black with an innovative pattern, orientation, and design to balance energy performance and aesthetic aspects (see **Figure 12**). The design of the PV module layouts has been generated by a parametric design optimization considering the PV's orientation to the sky, the orientation of the school building's longest façades, and the regulatory requirements regarding the aesthetics of the façade.

The mounting system of the angled modules was designed and tested to ensure the easy installation and replacement of PV components.

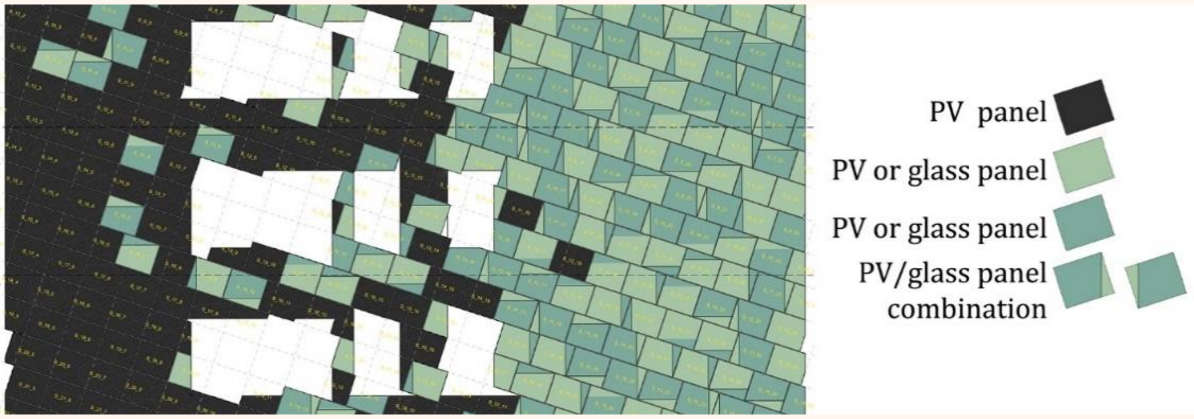


Figure 12. *Positioning of the BIPV panels on the south façade of the school S-building ($BIPV_F^S$). Original image by KONTUR and SPINN Arkitekter, edited by Nicola Lolli (SINTEF).*

The rotation of the PV panel's vertical axis determines the number of panels that can be installed on the façade due to several conditions. First, it is necessary to keep the windows reasonably unobstructed. Therefore, gaps must be left in the PV cover where windows are located. Due to the rotation of the panels and the variety of window sizes, several panels need to be individually cut into specific shapes. Second, since PV panels cannot be cut, glass panels are installed in locations where a full panel cannot fit. Consequently, the rotation of the panels affects the overall energy production of the façade.

The parametric design tool from Format Engineers Ltd was used by the designers to test the panel orientation and calculate the panel cuts [14]. Additionally, the placement of allowable modules and the energy production were assessed. The custom-made BIPV modules, available in various shades of green as shown in **Table 6**, were evaluated to achieve the highest electricity output.

Table 6. *Overview of the different types of PV modules and their related power output and efficiency.*

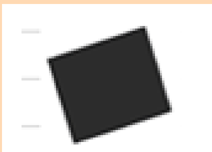
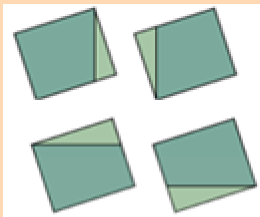
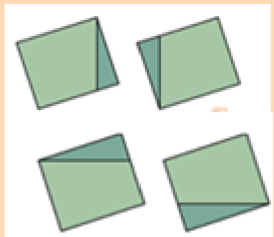
			
	Trina TSM-400 DE09.08 **Trina TSM-390 DE09.08**	**ML Custom**	**ML Custom**
P_{max}	140 W	110 W	120 W
V_{oc}	20.5 V	20.5 V	20.5 V
I_{sc}	8.64 A	6.74 A	7.3 A
V_{MPP}	17 V	17.3 V	17.2 V
I_{MPP}	8.2 A	6.39 A	6.96 A

Figure 13 shows how the bi-colored BIPV modules are mounted on the façades and combined with the typical black PV panels. The ratio of green-colored modules to black modules is as follows: approximately 25% of the modules on the west façade and approximately 40% on the south façade are black. All other modules feature two different shades of green, such that each PV panel consists of two distinct green-colored parts. **Table 6** shows that four different combinations of the bi-colored panels were used to create the appearance of eight distinct panel types installed on the façade (see **Figure 13**). These panels were installed either in an upright position or rotated by 180 degrees.

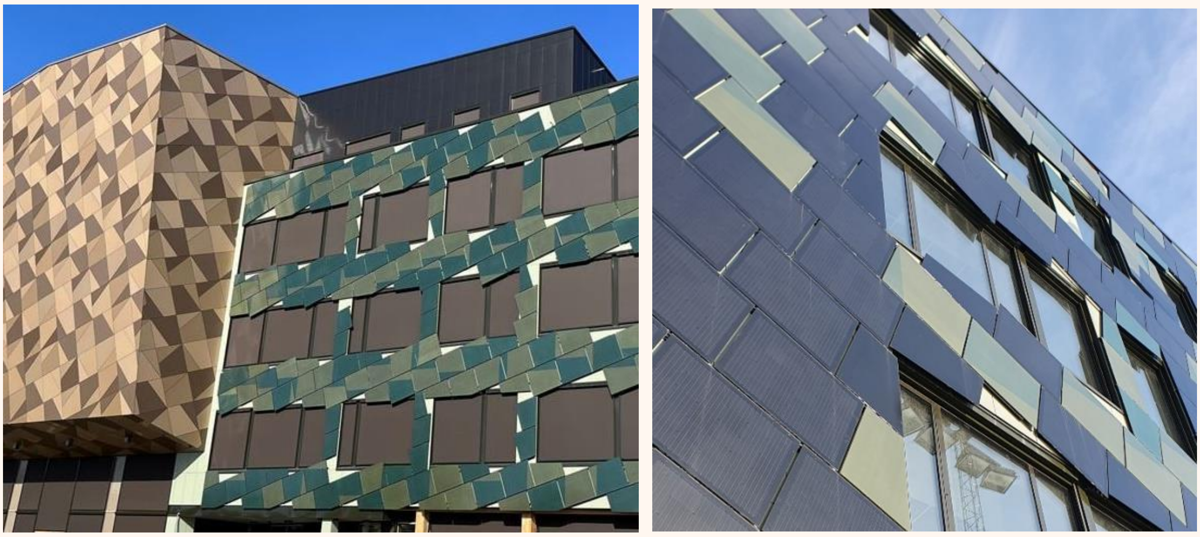


Figure 13. *Images of the mounted BIPV modules on the facades of the school building. Photos by Nicola Lolli/SINTEF.*

6.2. BATTERY ENERGY STORAGE SYSTEM (BESS)

Due to budget constraints, OBF was not able to install batteries in the battery storage room during the project period. However, second-life batteries have been installed in other projects, as shown in section 5. The projects are located in areas and contexts that are comparable to the ARV demo project at Voldsløkka. While both ESS solutions are integrated with RES, different technical, safety, and energy management choices have been made. The design and operation of these systems will be evaluated in ARV, and simulations will be done for the demo project [17] .

Based on received information from ECO STOR, a battery energy storage system (BESS) is developed to support the PV production and enhance self-consumption in Voldsløkka school . The size of the existing battery room (13.5 m^2) allows for up to six battery modules. Each module consists of second-life battery packs from Renault Zoe (22 kWh first life) or Nissan Leaf 3rd generation (28 kWh in first life) in ready-to-install cabinet modules with a measured second-life capacity of 40 kWh (2 battery packs) and inverters for delivering 20 kW.

Simulations assumed a 20% to 90% state-of-charge limit and are optimized for cost minimization using 2024 electricity prices [18] and PV data. Peak shaving and load shifting management of the solar gains, as well as the capacity of importing and exporting energy directly to the grid, are also considered.

The physical limitations restrict the BESS design to a sensitivity analysis involving the installation of 1 to 6 modules in the available space. Additional specifications are shown in **Table 7**.

Table 7. *Battery modules and system characteristics.*

Value	Unit	Description
W:800x D:1200x H:1800	mm	Dimensions.
160 000	NOK/module	Cost per module.
4 000	NOK/kWh	Cost per effective capacity.
40	kWh	Second life capacity.
20	kW	Charge/discharge power.
90.0	%	Maximum state of charge SOC_{max}. [19]
20.0	%	Minimum state of charge SOC_{min}. [19]
82.6	%	Round-trip AC2AC efficiency η_{RTE}. [20]
90.9	%	Charging efficiency η_c.
90.9	%	Discharging efficiency η_d.
60.0 (first-life) – 75.0 (second-life)	%	End-of-Life (EoL) – SOC minimum limit. [21]

6.3. THERMAL SYSTEM

The thermal energy system is based on a CO_2 GSHP to cover both heating and cooling needs. Energy wells are used as an energy source, for free cooling, and for storing excess heat. District heating is used to cover peak loads. A diagram of the system is shown in **Figure 14**. The thermal energy supply has two main modes, heat pump mode with free cooling, and cooling mode. The outdoor temperature and a calendar function determine the operation mode of the thermal energy system. The innovative LowEx system that is used for ventilation and floor heating can be operated in either heating or cooling mode.

Figure 14 shows energy flows coming from different systems. The H-building is provided by heat from the district heating only, while the S-building is supplied with heat from the CO_2 GSHP and the district heating. The CO_2 GSHP uses boreholes as the heat source. The capacities of the plant shown in **Figure 14** are obtained from the design phase.

The innovative heating and cooling system called the LowEx system, using low-temperature heating and high-temperature thermal cooling, uses the same infrastructure for heating and for cooling. The LowEx system is supplied with heat from the CO_2 GSHP and district heating as peak load plant. The installed CO_2 heat pump installations and the water tanks are shown in **Figure 15** and **Figure 16**, respectively. For the S-building to make better coupling between the CO_2 GSHP and the LowEx system, the supply temperature of the district heating system is set to 55 °C. In **Figure 14**, the LowEx system can be observed at the right-hand side of the figure and marked with two temperature levels.

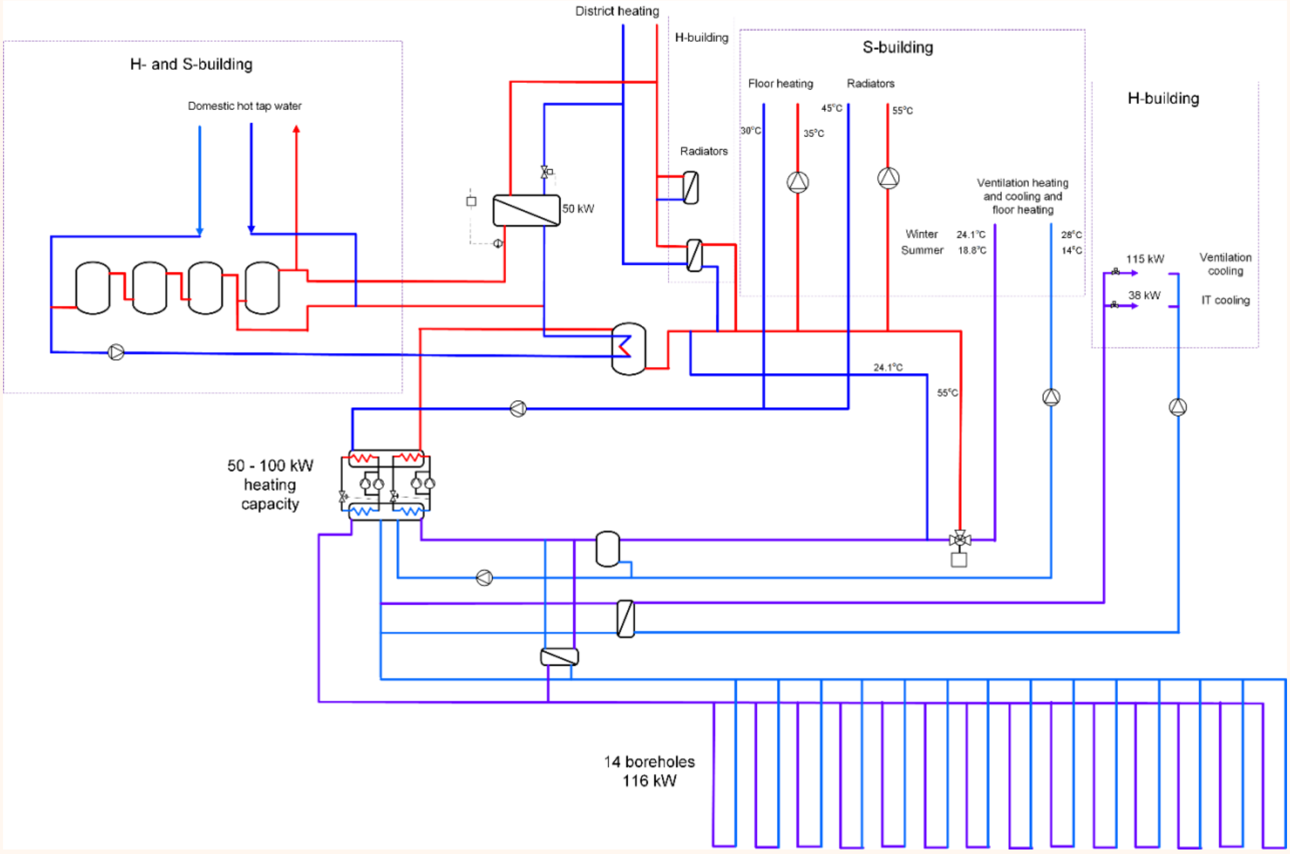


__Figure 14.__ Thermal supply system for both H- and S-building including the LowEx system.

__Figure 15.__ Installed CO_2 heat pump at the Voldsløkka school.

Figure 16. *Installed water tanks for short-term thermal storing.*

7. OPERATION AND EVALUATION

7.1. GENERAL ENERGY DEMAND

The S-building school is newly built in 2021. The primary energy demand for this new Oslo demo school is 19 kWh/year per m^2 of the usable floor area. The monitored primary energy demand for the S-building in 2024 was 49 kWh/year per m^2. The electricity consumption of the CO_2-based heat pump is 6.83 kWh/m^2 per year, which closely aligns with the design target of 6.5 kWh/m^2, as presented in **Table 4**. Although the real yearly PV production was as high as designed, it only covered half of the real energy demand of the S-building. The performance gap can be explained by different operational conditions and some inefficiencies in the control and operation of the building. Feedback from the operation technician indicated that it took longer to operate the building as planned due to issues with the control of the building. This might have resulted in higher energy use, particularly related to the thermal part.

Nevertheless, the primary energy demand of school buildings in Oslo built after 2010 was between 50 and 100 kWh/year per m^2. The regulatory maximum limit for the total energy demand in schools in Norway is 110 kWh/year per m^2 (Building regulation TEK17). The Voldsløkka school is thus energy efficient when compared to other similar buildings (see **Figure 17**).

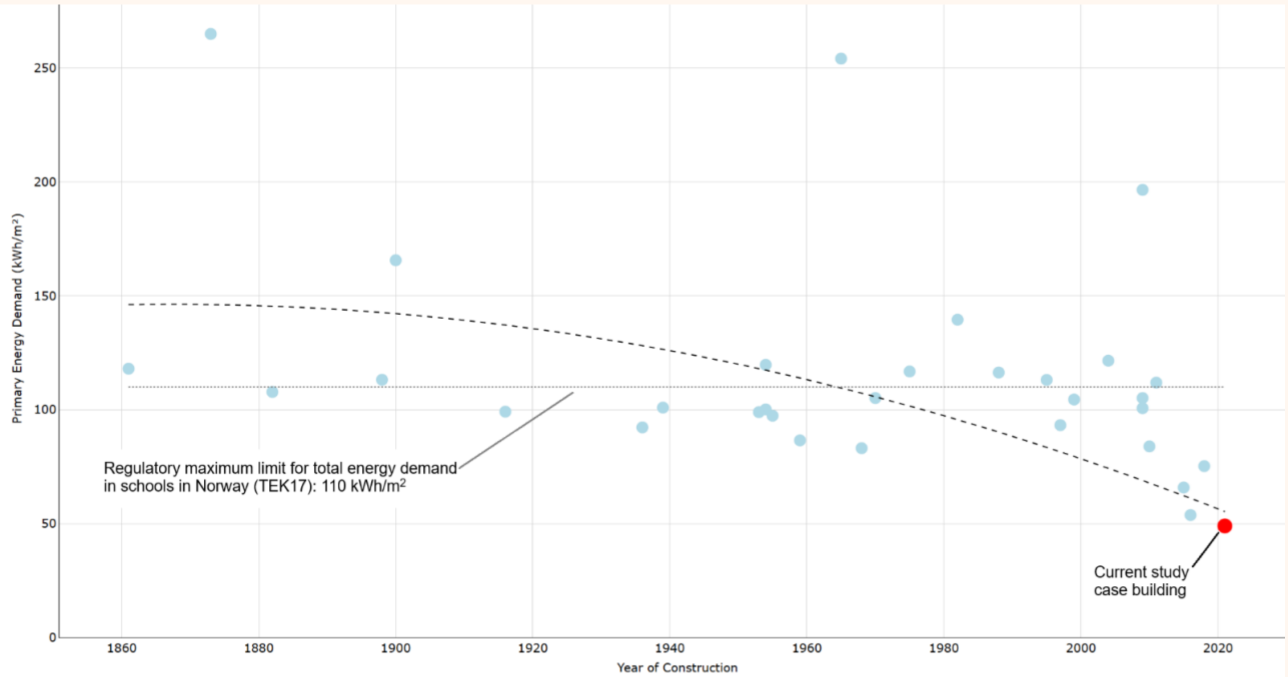


Figure 17. *Primary energy demand of school buildings in Oslo as a function of their year of construction. The red data point is the current study case S-building school.*

When looking more in detail at the energy use of the school, one can observe that the daily energy use of the school follows the occupancy patterns of the building, which is driven by the normal weekly calendar rhythm: standard and regular occupancy during week days/working days, and no occupancy during weekends and holidays (e.g., 1st of January or1st of May) (see **Figure 18** and **Figure 19**).

In the winter, the energy use is dominated by the heating needs for space heating and sanitary hot water production (see **Figure 18**). Most of the heating supply is provided by the ground-source heat pump, and the remaining part is supplied by the district heating network. The PV production is very limited during the winter.

In the warm season, the space heating is negligible, and only heat is needed to produce the sanitary hot water. Most of the heat is provided by the district heating network (see **Figure** 19). The PV production is very large, often larger than the energy needs of the building, and production and demand peaks match very well.

The energy use for artificial lighting is slightly larger during the winter period, while the energy use for the other systems (fans, pumps, and other technical systems) remains stable throughout the whole year. During the winter, a temperature heating setpoint setback is active, which results in decreasing the space heating energy need during periods with no occupancy (see **Figure 18**). One can also notice that fans and pump systems are turned off or reduced outside of occupancy periods. However, one can notice that there is residual artificial lighting energy use during non-occupancy hours. The energy efficiency of the building could thus be increased by improving the smart management of the building systems, turning off artificial lights outside of occupancy hours, detecting lights that stay on all the time, running a model predictive control on the heating system to turn off the heating system before the end of the occupancy periods, and turning it back on right on time to ensure a good indoor thermal comfort only during occupancy hours, while leveraging the forecast of free solar gain into the indoor environment and the thermal inertia of thermally-activated building systems (for heating storage).

Figure 18. *Energy demand and onsite PV generation time series for the S-building school from 1-14. January 2024.*

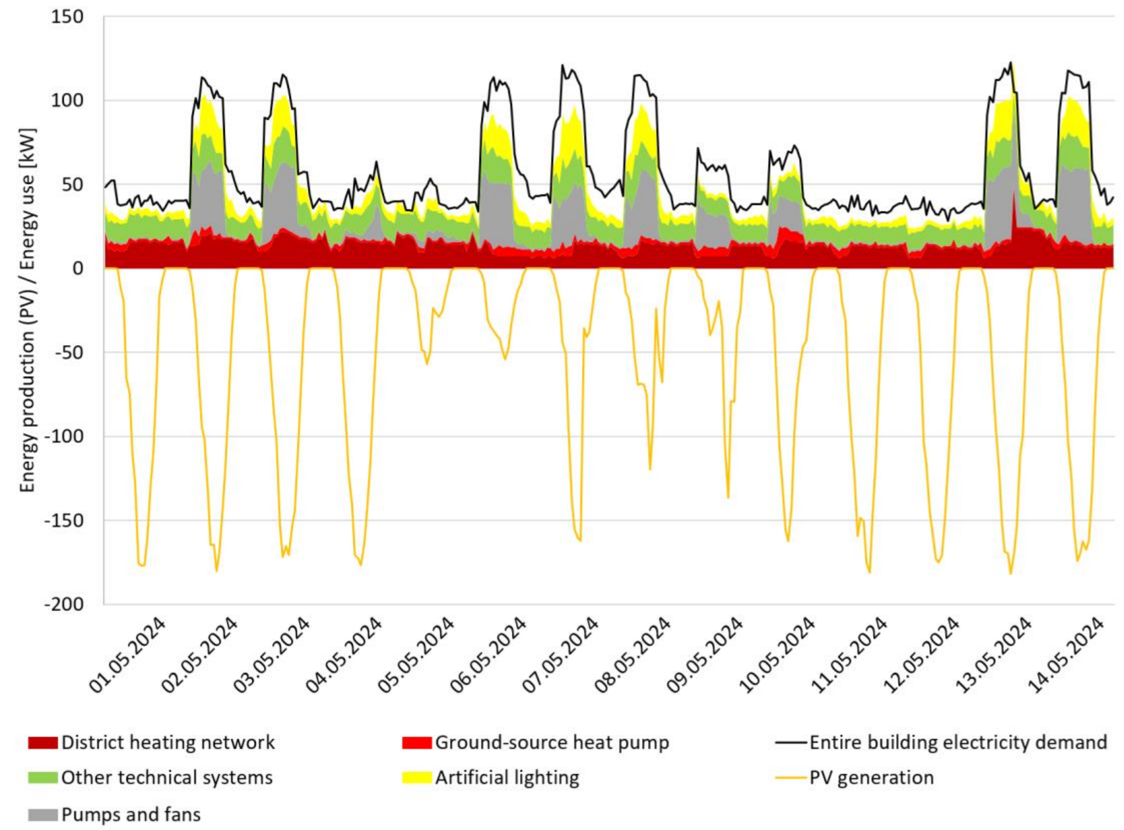


Figure 19. *Energy demand and onsite PV generation time series for the S-building school from 1.-14. May 2024.*

7.2. SOLAR PHOTOVOLTAIC INSTALLATION OPERATION

The monitoring system of the solar PV installation at Voldsløkka School has been functional since the end of May 2023. The preliminary analysis of the performance of the BAPV and BIPV systems during summer shows that the former is responsible for 80% of the energy production. This is in line with the distribution of the installed capacity of BAPV, with 81%, and BIPV, with 19%. Therefore, these results indicate that BIPV shows similar performance to that of the more typical BAPV. A longer period of measurements is nevertheless needed to make a more conclusive assessment of the performance of the solar PV installation.

Figure 20 presents the energy generation profiles of five PV subsystems, each corresponding to a specific inverter and its associated panels. They are located on the south façade, west façade, technical room façade, rooftop area around the technical room, and the main roof. The sixth curve represents the total output from all five inverters combined. **Figure 21** displays the average daily generation over week 23 in 2023, with key numerical results summarized in **Table 8**.

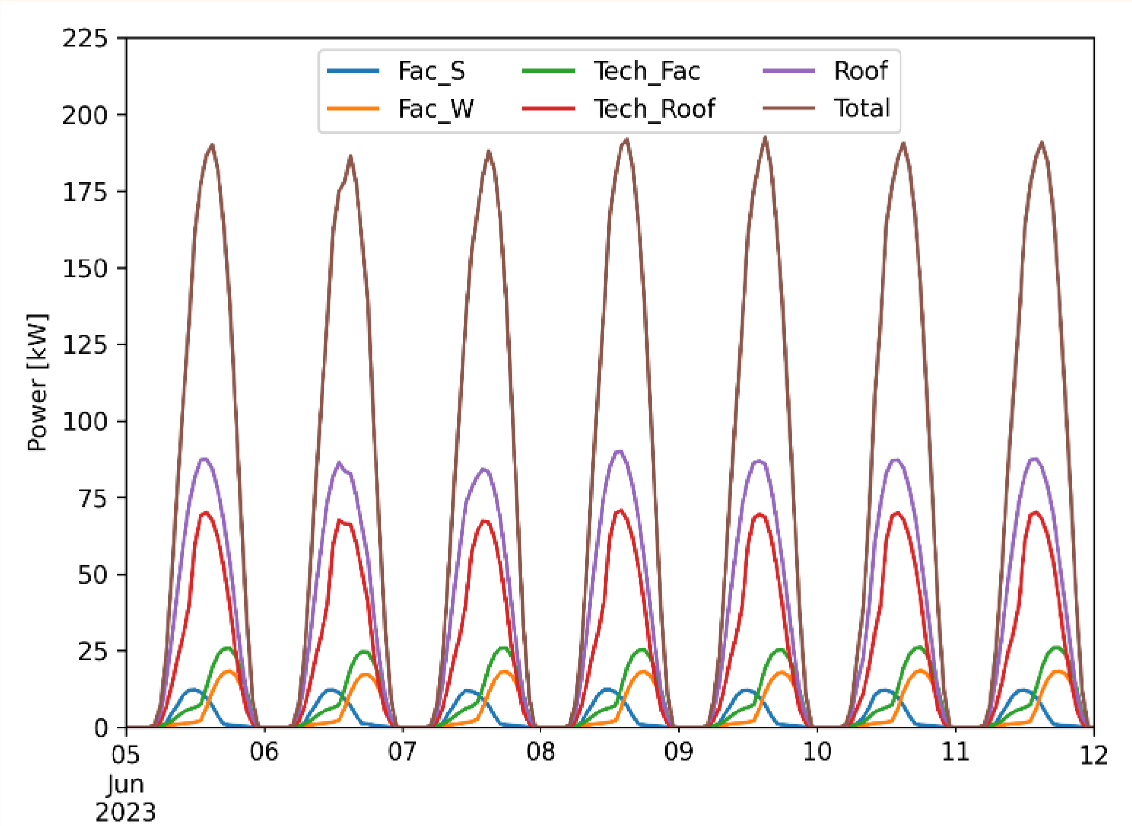


Figure 20. *Generation by the solar PV system, shown for each inverter and for the total, for week 23 of 2023.*

Because of the system's layout and the orientation of the PV panels, the modules on the south façade and rooftop begin generating electricity early in the morning. In contrast, the systems installed on the west façade and the façade of the technical room only start producing significant power around 13:00. By 15:00–16:00, generation from the south façade has already declined to near zero, while the west-facing systems continue generating into the evening. This sharp afternoon decline from the south façade systems may be attributed to its actual orientation, which is slightly southeast rather than due south, which results in reduced solar exposure in the afternoon. Meanwhile, the west façade and the façade of the technical room (both west-facing) show a pronounced rise in generation starting at 13:00. A further notable feature is the system located on and around the technical room rooftop, which shows a sharp increase in output around 11:00. This is likely due to the shading effect cast by the technical room itself on modules positioned to its west.

Interestingly, the system's total peak generation typically occurs between 15:00 and 16:00 rather than at solar noon, with a maximum output of 193 kW observed during the week. This total peak is lower than the sum of the individual inverter peaks, reflecting the varied orientations and associated mismatch in peak generation times among the subsystems. As one can observe in **Table 8** the rooftop systems dominate energy production, contributing approximately 80% of the total weekly generation.

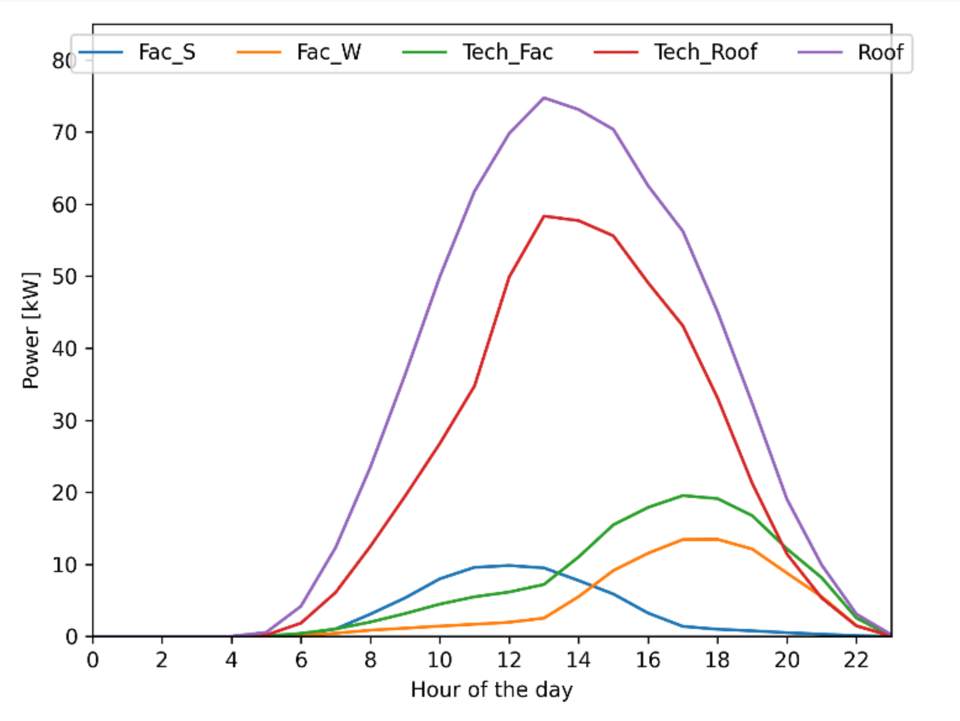


Figure 21. *Average day of the generation by the solar PV system during week 23 of 2023.*

Table 8. *Summary of the generation by the solar PV system during week 23 of 2023.*

	Generation [kWh]	**Percentage of the total**	**Peak generation [kW]**
Fac_S	582	5	12
Fac_W	831	7	19
Tech_Fac	1 371	11	26
Tech_Roof	4 072	32	71
Roof	5 909	46	90
Total	**12 766**	**100**	**193**

A more comprehensive analysis of the hourly PV production monitoring data was conducted for the period from June 2023 to May 2024. Operational data from the school (energy use), local weather (e.g., Global Horizontal Irradiance: GHI), and electricity spot prices from the NordPool zone NO1 (including VAT) for 2023-2024 were also included in the analysis [15]. Key performance indicators (KPIs) such as energy generation, self-consumption, and cost savings (PV production multiplied by spot price) are calculated for the five PV installations presented above. The annual energy generation from the PV systems in 2024 was 215 MWh. The GHI for 2024 is 923.5 MWh, which is about 3% lower than the average GHI for the 2019-2024 period.

Table 9 presents the system-specific KPIs calculated from June 2023 to May 2024 for the five different PV systems. The total GHI during this period is only 2% higher than that of 2024. The specific energy production varied from 371 to 772 kWh/kWp, with roof-mounted systems $BAPV.1_R^{E/W}$ and $BAPV.2_R^{E/W}$ achieving the highest annual electricity generation. The roof-mounted, east/west-oriented system $BAPV.2_R^{E/W}$ produced 15% more per installed kW_p than the south-oriented façade system $BAPV_F^S$, despite having similar PV technology [15].

Table 9. *Performance of the different PV systems (average from June 2023 to May 2024) [15].*

System		Specific energy production [kWh/kW_p]	Specific energy production density [kWh/m^2]	Specific cost savings [NOK/kW_p]	Cost savings [NOK/kWh]
$BAPV.1_R^{E/W}$	Roof	772	156.6	409	0.53
$BAPV.2_R^{E/W}$	Tech_Roof	650	135.4	333	0.51
$BAPV_F^S$	Tech_Fac	567	118.0	321	0.57
$BIPV_F^S$	Fac_S	498	60.7	293	0.59
$BIPV_F^W$	Fac_W	371	45.2	205	0.55

Figure 22 displays the average daily electricity production and electricity spot price profiles for the five PV systems, shown month by month throughout the year. The roof-mounted systems present a significantly higher production performance in the summer months compared to other seasons. In contrast, the façade-integrated systems exhibit a more stable profile across the year. They outperform roof-mounted systems during spring, autumn, and winter (when the sun is lower in the sky), but produce less during summer. Due to Norway's geographical location, the sun sets late in the evening during summer, which explains the extended electricity generation observed from solar PV systems into the late hours. Orientation also plays a key role in shaping daily production: east-facing systems generate more in the morning, south-facing systems peak around midday, and west-facing systems produce more electricity in the afternoon. Notably, the PV system on of the technical room's façade generates electricity later in the day because of the large proportion of west-oriented modules in this system [15].

In terms of economics, the annual specific cost savings from dynamic spot pricing, normalized by installed PV capacity, are highest for the roof-mounted systems owing to their greater specific energy output. Savings range from 409 NOK/kWp for $BAPV.1_R^{E/W}$ to 205 NOK/kWp for $BIPV_F^W$. In addition, daily spot price variations impact both the cost savings from self-consumption and the income from feed-in (electricity export) to the grid. As shown in **Figure 22**, spot prices tend to peak in the morning and late afternoon and are generally higher during the colder months. Interestingly, the cost savings per kilowatt-hour of PV production are higher for façade systems (ranging from 0.55 to 0.59 NOK/kWh) compared to roof-mounted systems (0.51 to 0.53 NOK/kWh) [15].

Finally, self-consumption of the onsite PV production can be improved by storing energy in the thermal storage of the building, performing heat temperature setpoint modulation for the indoor space conditioning, and installing electrical battery storage systems. The latter solution is explored further in the present report.

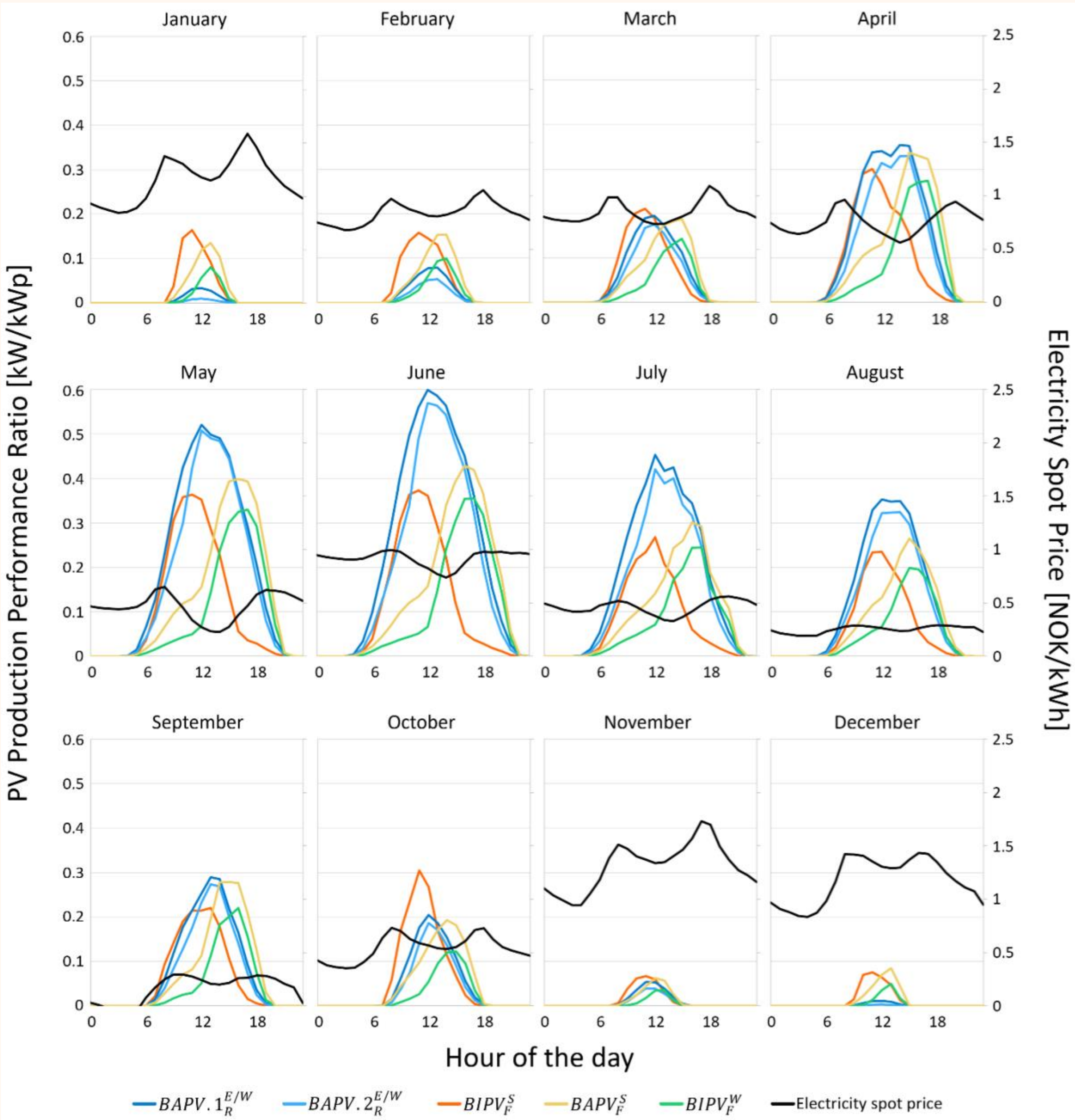


Figure 22. *Average daily PV generation profiles for each month across the five different installations and the associated average electricity spot prices (June 2023 – May 2024) [16].*

7.3. PERFORMANCE OF THE SOLAR PHOTOVOLTAIC PRODUCTION FORECASTING SOLUTION

The PV production forecasting solution implemented in this demo case is a commercial solution based on a physics-informed machine learning-driven algorithm that provides PV production forecasting each hour with a forecasting horizon of 48 hours. This forecasting model is optimized for trading electricity, meaning that it is best suited to predict the spot PV production at a given time step in the future. The model is recalibrated/adjusted around 4 times a day with the actual monitored PV onsite production. The forecasting model accounts for the predicted solar irradiance and outdoor temperature at the location of the PV installation. The uncertainty about the irradiance forecasting will thus impact the PV production forecasting as well.

One can see in **Figure 23** and **Figure 24** that the performance of the forecasting PV production model is satisfactory. However, the relative forecasting error is large during winter when the PV production is very small. One can note that, overall, the forecasting model slightly underestimates the PV production. Moreover, there are a few instances of missing data from the forecasting model (0 kW of forecasted PV production). During the first five months of 2025, there were two forecasting service outages. Because there was no automated detection of service interruption, the service provider had to be contacted manually to re-establish the forecasting service data stream via the dedicated API and retrieve missing historical forecasting data.

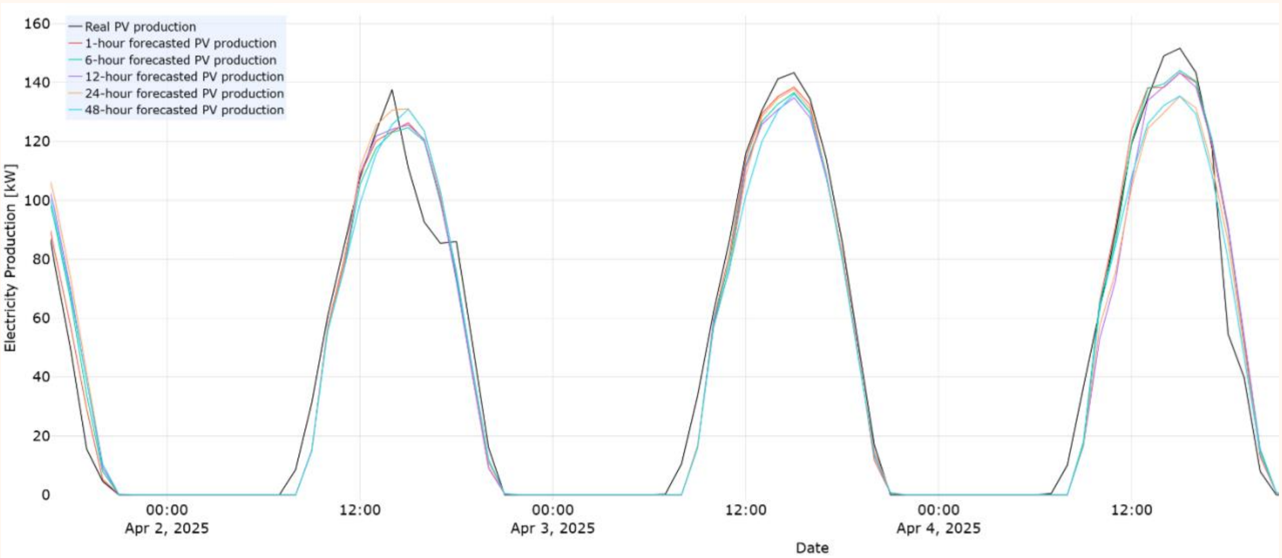


Figure 23. *Time series of the real PV production and PV production forecast for different prediction horizons during typical sunny day of April 2025.*

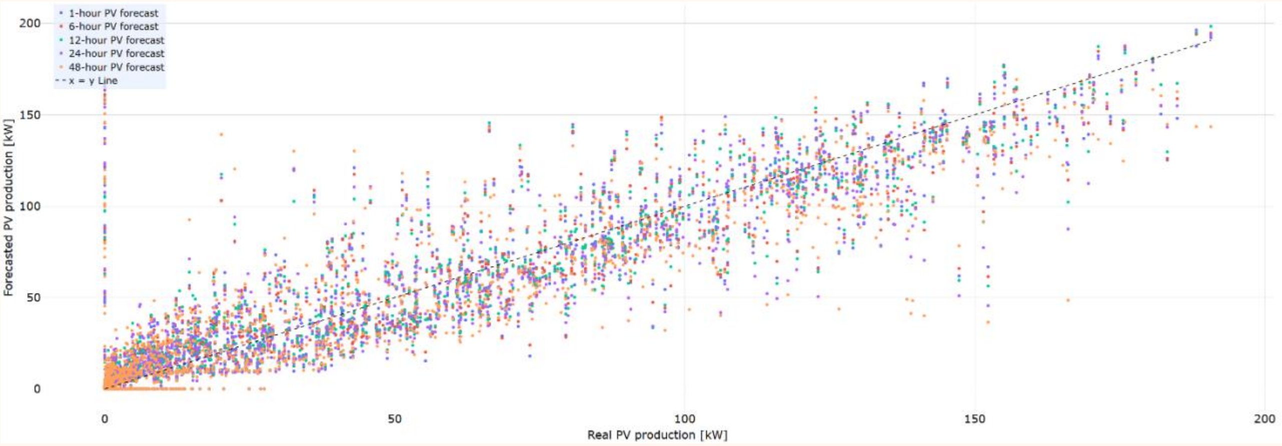


Figure 24 . *Comparison of the forecasted PV production (forecasting model) with the real PV production (monitored data from the building case from 1st of January to 15th of May 2025).*

When formally assessing the accuracy of the PV production forecasting service at different time horizons with a common performance metric (here, the Normalized Mean Absolute Difference between the prediction and the forecast, with the installed peak power production of 337 kWp as the normalization factor), one can see that it performs well, with a normalized error ranging from 1.7% to 3.8% (see **Table 10**). Logically, the accuracy of the forecast is better if accounting for nighttime PV production, which is 0, and matches perfectly the real recorded production. Finally, one can observe that the forecasting error is slightly increasing with the prediction time horizon.

Table 10 *Accuracy (Normalized Mean Absolute Difference: NMAD) of the PV production forecasting model for different prediction time horizons: 1, 6, 12, 24, and 48 hours. Based on forecast and monitoring data from 1st of January to 15th of May 2025.*

Forecasting horizon [hour]	**Normalized Mean Absolute Difference (all the time) [%]**	**Normalized Mean Absolute Difference (daytime only) [%]**
1	1.7 %	2.8 %
6	1.7 %	3.0 %
12	1.7 %	3.1 %
24	1.9 %	3.3 %
48	2.1 %	3.8 %

7.4. SIMULATIONS AND PERFORMANCE OF THE BATTERY SYSTEM

The optimization of the stored load in the battery system is developed as a mixed-integer linear programming (MILP) model using Scipy [17]. To minimize computational costs, the optimization is performed monthly, even though yearly hourly data is utilized. Three key performance indicators (KPIs) are used to evaluate the economic and operational performance of the battery system, these include the return of Investment (ROI), self-consumption (SC) and self-sufficiency (SS).

RETURN OF INVESTMENT (ROI)

The ROI indicates the number of years required for the initial investment (CAPEX) to be paid back through the savings generated by the investment and the reduced operational costs (OPEX) compared to the baseline (only demand and solar generation). In this case, each installed battery module has a price of ~160 000 [NOK/module] or 4000 NOK per usable kWh. The estimated costs are referenced from ECO-STOR and specified for the module, including the inverter. Next, the payback period is estimated as follows (without including the interest rate):

$$PB = \frac{CAPEX_{tot}}{OPEX_{baseline} - OPEX_{bess}}$$

The willingness-to-pay (WTP) reflects how quickly building owners expect to recover their investment. For solar PV systems, potential buyers who are not already adopters typically require a payback period of five years or less before considering the installation of panels [22]. Battery systems exhibit similar trends in project adoption. Therefore, it is reasonable to expect that potential BESS buyers in the commercial sector will also seek a payback timeframe of around five years or less.

Based on this discussion, the subsidy needed to reach the desired willingness-to-pay period for the project can be calculated as follows:

$$S = CAPEX_{tot} - \sum_{t=0}^{t_{WTP}} (OPEX_{baseline,t} - OPEX_{BESS,t})$$

where t_{WTP} represents the willingness-to-pay period, established as 5 years for this study.
For comparison, the subsidy S is presented in the results normalized per effective capacity [NOK/kWh].

With the current configuration and considering only the variable costs of the final bill, the baseline variable costs to cover the building demand, including the solar generation, are NOK 551,585. In **Figure 25** the cumulative cash flows for the different BESS sizes are depicted considering an average CAPEX cost (160000 NOK/module). Starting with one module, the payback period starts at 9 years, while with six modules, the period increases to 16.2 years with the current conditions. Even with larger return periods, over one module shows a steeper forecast, meaning that higher operational savings are expected under the current conditions once the capital costs are covered.

The End-of-Life (EoL) for a second-life battery pack is estimated at 60% of the maximum SoC (assuming an initial SoC of 80% for the second-life battery). Thus, the degradation of all the models leads to an EoL of approximately 19 years, 3 more years than the PB period of the 6 modules case.

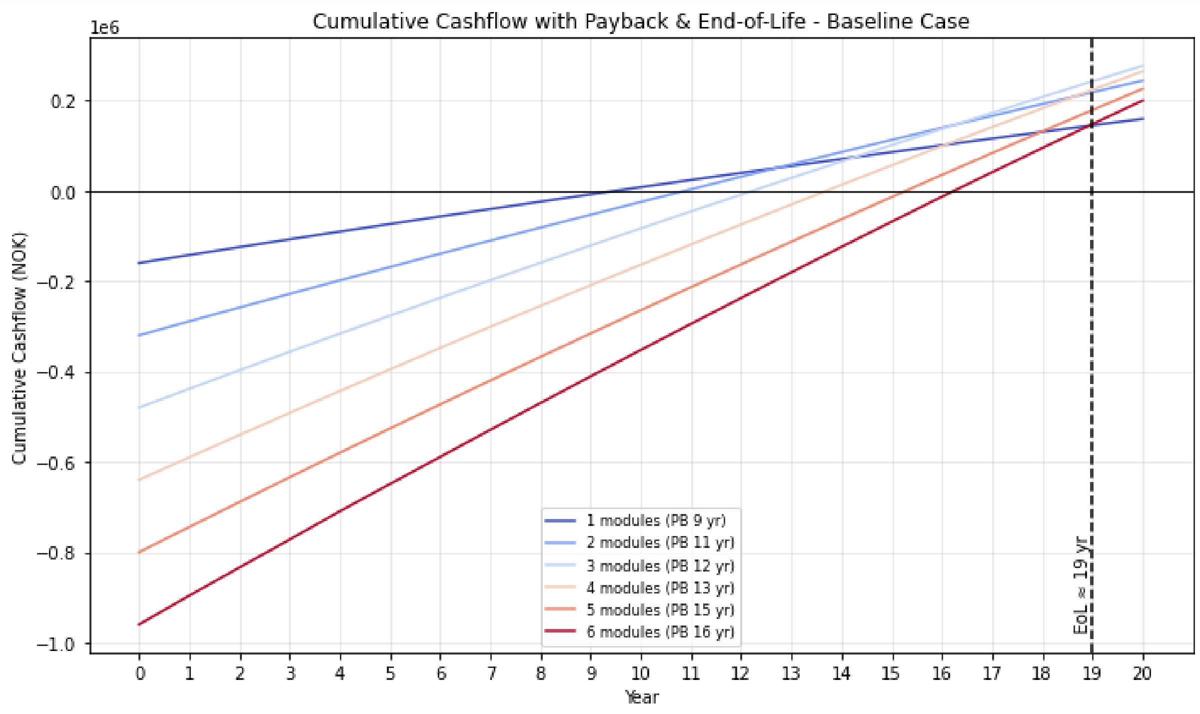


***Figure 25**. Cumulative cash flow for the different BESS sizes.*

In relation to the subsidy required for installation with a payback period of five years, the results are illustrated in **Table 11**. For a single module, the installation may require a subsidy of 1,843.2 NOK/kWh. However, for six modules, this value rises to approximately 2,704.9 NOK/kWh. This represents an increase of 21.5% from one to six battery modules, indicating that as the system size increases, the necessary subsidy in comparison to its CAPEX costs also increases.

***Table 11** Subsidy amount for reaching a 5-year payback in the baseline case. The results are shown normalized per NOK/kWh and in a fraction of the initial CAPEX.*

Modules	**1**	**2**	**3**	**4**	**5**	**6**
[NOK/kWh]	1843.2	2111.9	2305.6	2472.3	2631.7	2704.9
[%]	46.1	52.8	57.6	61.8	65.8	67.6

Figure 26 illustrates the demo building's current baseline demand and PV generation. The total annual demand is 655.5 MWh/year, averaging 54.6 ± 7.6 MWh/month. The highest monthly consumption occurs in March, reaching 68.4 MWh/month, while the lowest demand is at 44.8 MWh/month in October. The total peak power output of the system is 337 kWp. The PV system produces an annual energy generation of 215.0 MWh, with the highest monthly production reaching 40.1 MWh in May and the lowest monthly production at 1.5 MWh in December.

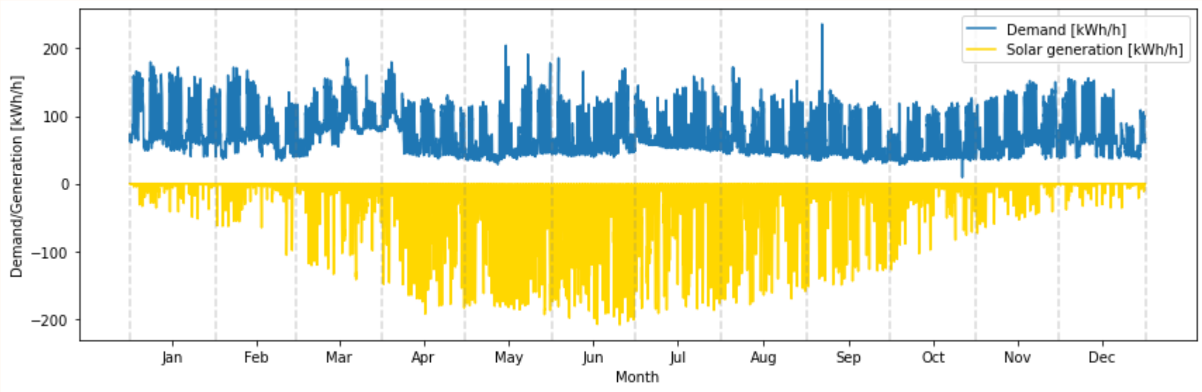


Figure 26. *Demand and PV generation for the year 2024.*

Figure 27 depicts the monthly energy imported and exported from the grid. During the winter months, no significant variations are observed. However, in the summer months, the imports and exports increase with the addition of one battery module. From there, the increase in size of the BESS system is inversely proportional to a reduction in the importation and exportation of electricity to the grid and proportional to self-consumption, which is described next.

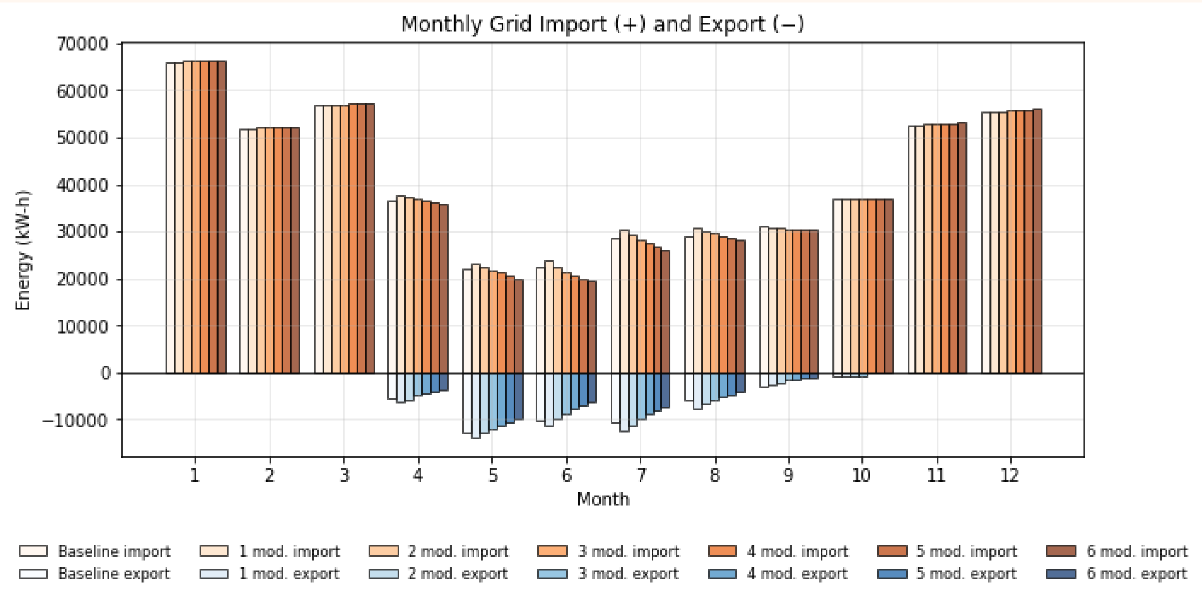


Figure 27. *Monthly energy imports and exports in [kWh/month] for the initial year calendar. The simulation includes 1 to 6 battery modules.*

SELF-CONSUMPTION (SC)

Ratio between 0 and 1. Represents how much of the solar generation was consumed on-site.

$$SC = \frac{\sum_t \mathrm{solar}_t - \sum_t G_{\mathrm{exp}}(t)}{\sum_t \mathrm{solar}_t}$$

The self-consumption KPI can indicate how well solar generation and the dynamic tariffs are utilized within the building premises. **Figure 28** shows that the larger the BESS size, the larger the self-consumption is in the summer months, confirming the hypothesis for the decreases in energy imports and exports shown in **Figure 28**. Moreover, no significant changes are shown in the winter months due to the low solar generation. Overall, the baseline can reach an SC of 77.4%. With one module, the SC is reduced to 75.3%. As expected, a maximum of 85.2% is reached with 6 modules installed.

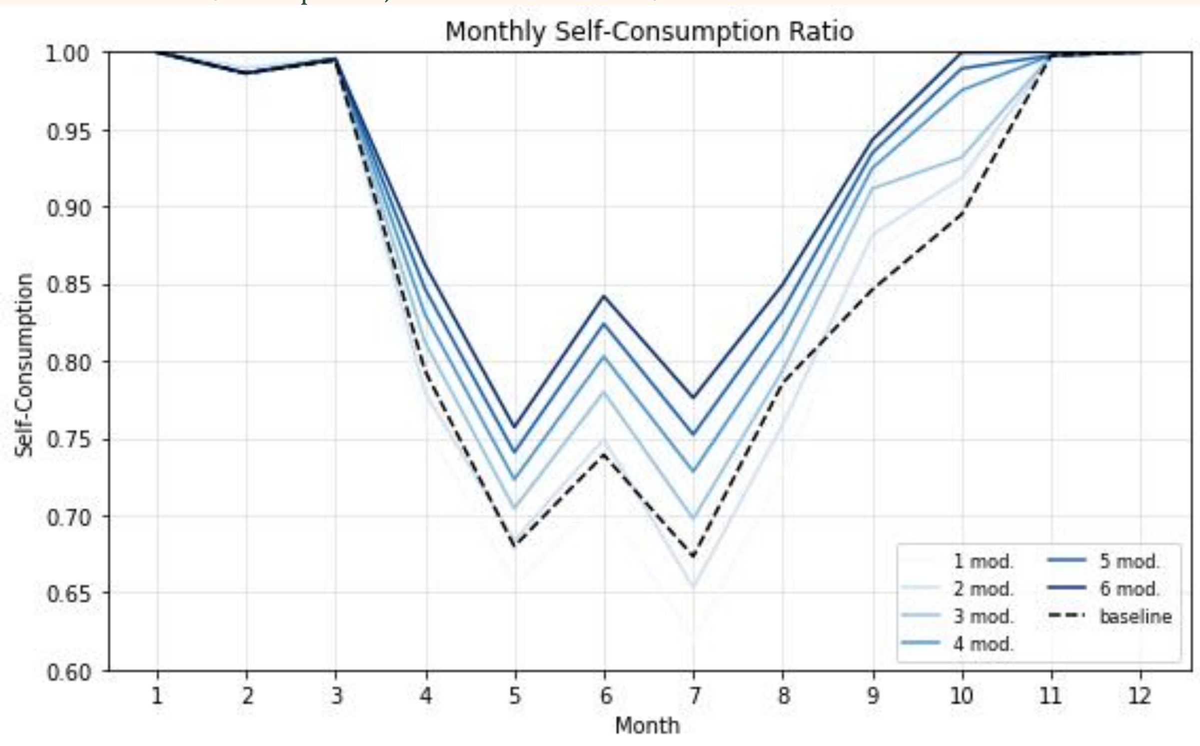


Figure 28. *Self-consumption ratio for the different BESS modules.*

SELF-SUFFICIENCY (SS)

Ratio between 0 and 1. Represents how much of the load was met without grid imports.

$$SS = \frac{\sum_t \text{load}_t - \sum_t G_{imp}(t)}{\sum_t \text{load}_t}$$

Finally, self-sufficiency indicates the ratio of demand that is covered without importing from the grid. The baseline SS is estimated at 25.4%, with high peaks in summer (around 55.0%). Implementing BESS helps improve the summer months' SS, as shown in **Figure 29**. However, this has the opposite impact in the winter months. This behavior is understood because of the available generation, which, when combined with larger energy storage and optimal control, can lead to greater independence from the grid. In the summer period, a maximum percentual difference of 6% is achieved in June compared to the baseline case.

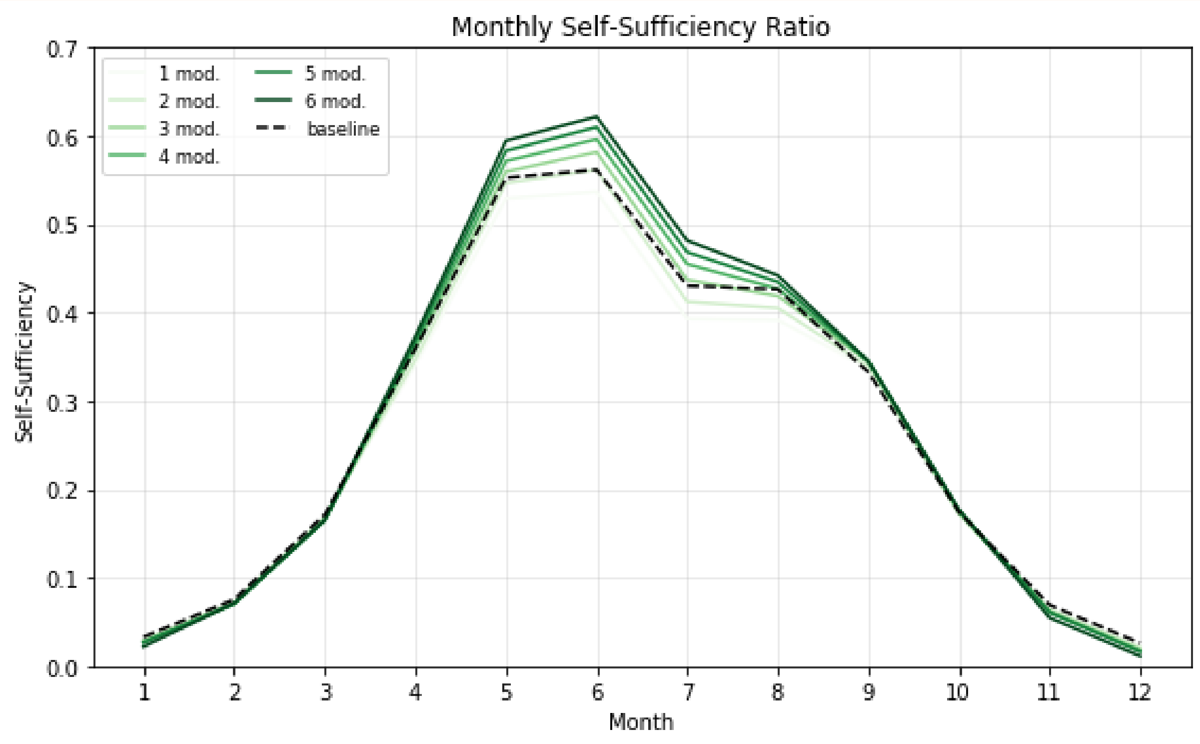


Figure 29*.* *Self-sufficiency ratio for the different BESS modules.*

LOCAL FLEXIBILITY MARKETS (LFM)

Besides optimizing the systems based on dynamic pricing, the battery system can be set to participate in local flexibility markets (LFM). Currently, the building is in an area where Elvia operates the EuroFlex LFM with NODES. Two types of products are offered in this market: ShortFlex and LongFlex. The ShortFlex product corresponds to a pay-as-bid contract, similar to stock markets. The second product, LongFlex, corresponds to a capacity contract, meaning that the building reserves in advance (weeks, months, etc.) capacity to be delivered when the distribution system operator (DSO) requires flexibility for decongesting the grid. In this work's scope, only the LongFlex product is contemplated in the analysis due to data availability.

For season 2025/2026 [1], the market requires turn-up capacity reserves in the months January to March, and from October to December, from Tuesday to Saturday between 7:00 and 10:00 and between 15:00 to 18:00. The reserved is paid with NOK 0.12 kWh/h, while the full activation is reward with NOK 4.00 kWh/h, around 6.5 larger than the average energy price in the NO1 zone for 2024. If the activation is not met, no payment or penalties are added. Aiming for an overall overview of the flexibility potential under this product, the BESS system is set to reserve the full capacity for the LFM (~8.45 kWh/h, during three consecutive hours per module). Similarly, as an extreme case, all the reserves are activated, marking the theoretical maximum flexibility that the BESS can deliver.

It is essential to note that the product has upward flexibility (export to the grid), and as the MILP model is developed, the reserves are always activated; thus, the results expressed in this section mark the theoretical maximum that might be achieved with this methodology. In total, 786 hours of activation are applied during the calendar year, equivalent to revenues of 799.83 [NOK/module] for capacity reservation and 26,661.12 [NOK/module] for the activation of flexibility.

In **Figure 30**, the cumulative cash flows and return periods are depicted for the baseline case, which only includes dynamic pricing, and the case for LFM. Comparing both scenarios, with 1 BESS module, the PB is reduced by 3.32 years. The reduction of PB goes even further when more modules are added, reaching the maximum difference of 9.28 years with 6 modules, obtaining a PB period of 7.15 years. As previously mentioned, larger cashflow slopes exist for larger battery sizes, meaning shorter payback periods. Comparing both cases, the LFM presents even steeper slopes, translating into the shorter PB mentioned above.

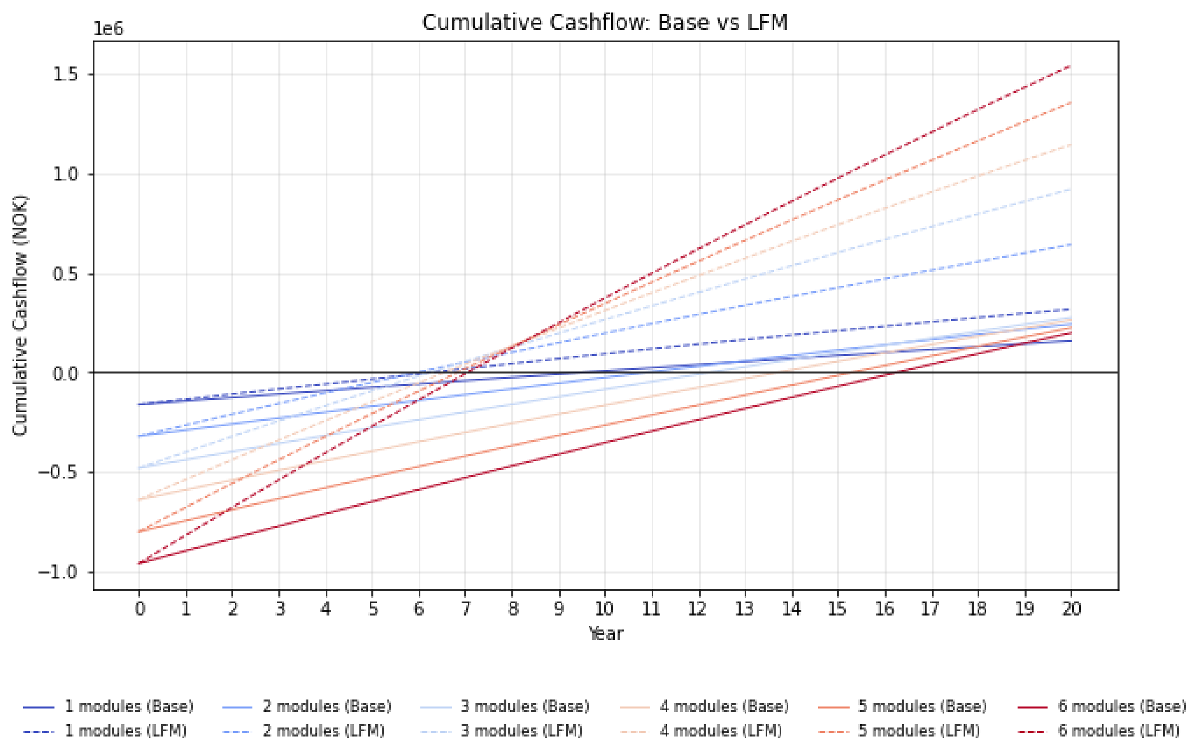


Figure 30. *Cumulative cash flow for the different BESS sizes and considering the baseline (solid lines) and LFM (dashed line) cases.*

Table 12 illustrates the subsidies required for the LFM case. When compared to the baseline case, the installation of a single BESS module decreased the subsidy needed by nearly 1,000 [NOK/kWh]. With six modules, this reduction increased to 1,500 [NOK/kWh]. These findings align with the shorter payback periods observed in the LFM case. Additionally, the proportion of capital costs is significantly reduced when compared to the baseline case, ranging from a minimum of 15.3% for two modules to a maximum of 28.1% for six modules.

Table 12. *Subsidy amount for reaching a 5-year payback in the LFM case. The results are shown normalized per NOK/kWh and in a fraction of the initial CAPEX.*

Modules	1	2	3	4	5	6
[NOK/kWh]	819.6	612.3	757.2	910.5	1032.5	1125.4
[%]	20.5	15.3	18.9	22.8	25.8	28.1

7.5. PERFORMANCE OF THE THERMAL SYSTEM

The energy use profile of the Voldsløkka CO_2-based GSHP in 2024 reflects a well-balanced and seasonally adaptive design that meets varying heating and cooling demands throughout the year. **Figure 31**shows the monthly average heat rate for different system components—namely, the gas cooler of the CO_2-based GSHP, electricity input to the compressor of the heat pump, and district heating. The results in **Figure 31** show that CO_2-based GSHP operate properly to maintain thermal comfort in a cost- and energy-efficient manner. The building exhibits a clear seasonal shift: winter months are dominated by heating demand, while summer operation emphasizes heat storing in the boreholes.

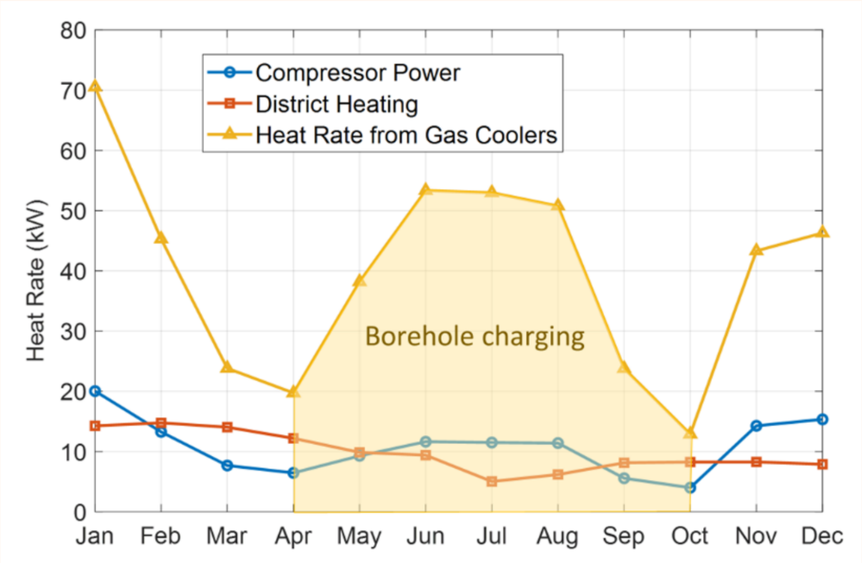


Figure 31. *Monthly average heat and power rate for the heat supply*

The CO_2-based GSHP delivers heat in colder months and heat for thermal storage in summer months. District heating plays a consistent but modest role across the year, supplementing the heat pump primarily in colder periods with slight reductions during summer. Electricity use by the compressor of the heat pump remains relatively stable (8–15 kW), signaling a continuously optimized operation. An average COP of the CO_2-based GSHP was 3.09, as shown in **Figure 32**. The regression equation indicates that for every kilowatt increase in compressor power, the gas cooler delivers approximately 3.1 kW of thermal output. This steady performance across diverse seasonal conditions underscores the efficiency and reliability of the LowEx system, effectively leveraging renewable and local energy sources to minimize energy waste and maintain thermal performance.

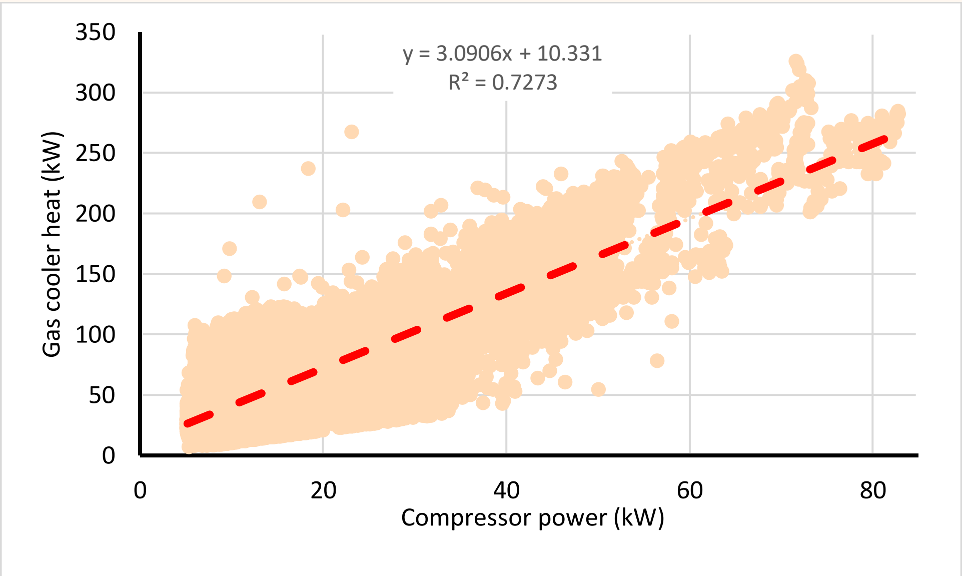


Figure 32. *Linear Relationship Between Compressor Power and Gas Cooler Heat Output in the CO_2 Heat Pump System (COP Trend Line)*

The CO_2-based GSHP system installed at Voldsløkka school demonstrates dynamic and seasonally adaptive thermal performance across its components—namely the high temperature (Thigh) gas cooler, low temperature (Tlow) gas cooler, and district heating interface, as shown in **Figure 33**. During the winter months (January–March), the Thigh gas cooler operated with high median heat rates of approximately 40–50 kW, providing essential heating, but showed significantly diminished activity through the warmer months (May–October), where the median approached near-zero values, indicating a strategic operational shift. Conversely, the Tlow gas cooler exhibited a complementary performance profile, with its highest activity observed during the summer (May–September), where median heat rates ranged around 40–60 kW, aligning with the system's cooling demands. These measurements show a good fit with the design data given in **Figure 14**. The evaporator showed consistent heat extraction primarily from March to October. However, measurements from the evaporator were not in good quality and are not presented here. District heating remained the most stable heat source, supplying relatively consistent thermal energy year-round, with mild peaks in colder months and notable support again during autumn (September–December), suggesting it functioned reliably as a peak load and supplemental source during shoulder seasons.

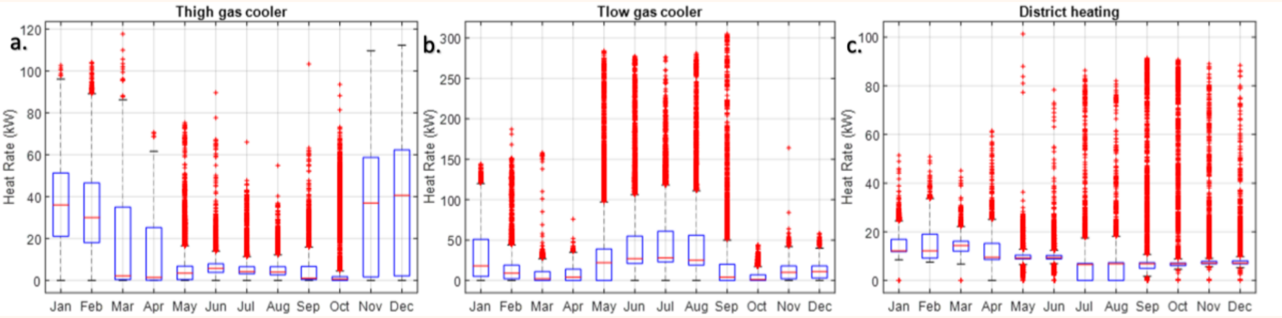


Figure 33. *Monthly box plot of heat exchange for the CO_2-based GSHP and district heating*

Overall, this heat rate distribution validates the design intention of the LowEx system, effectively using temperature-tiered components and integrated seasonal switching to optimize thermal efficiency. The interplay among the heat pump components not only reduces reliance on external sources but also maximizes the use of onsite renewable electricity for thermal services, demonstrating a well-calibrated and high-performing energy system tailored to Oslo's climatic variations.

8. SCALABILITY AND REPLICATION OF THE INNOVATIVE SOLUTION

8.1. SCALABILITY PROCESSES

The Voldsløkka project builds on experiences and lessons learned from previous projects by the city of Oslo. The combination of BIPV with BAPV as a renewable energy resource has been successfully implemented previously. Nevertheless, the energy ambitions and targets for previous projects were mostly set to nZEB and not plus-energy building, which are lower ambitions than those of Voldsløkka school. The PV systems of the demo case have an energy production performance that is similar to that of the estimations of the design phase. However, the primary energy demand of the school is still higher than the design estimates (49 kWh/m² per year instead of 19 kWh/m² per year). Nonetheless, this demo case has a low primary energy demand when compared to other recently built schools in Oslo, and thereby, further operation improvement will enable lower energy use and reach the desired targets. This section gives some examples of how the Voldsløkka school operation can be improved and how the results may be scaled for other projects.

Consequently, neither the BIPV nor the BAPV systems on their own are currently enough to generate enough electricity and enable the demo building to reach the *Plus-Energy* requirements. The extension of the PV deployment on the demo building presents some limitations. Regarding BIPV, the limitation is due to the orientation of the building, with its long axis oriented from North to South. Because of this, the South façade is smaller than the East and West façades. This meant that there is limited space for the installation of BIPV on the South façade, which is the optimal orientation for generation from solar PV in Norway. As for the BAPV, the area of the rooftop of the building is not large enough for the number of PV modules required to reach the necessary generation. Despite the nearly optimal generation capacity of BAPV in Voldsløkka school due to the orientation of the panels, a larger installed capacity would be needed to cover the additional primary energy needs of the latter.

Regarding the implementation of electrical battery storage units, the key limitation at Voldsløkka school is the high upfront capital cost, which results in long payback periods. This does not improve with increasing the number of BESS modules installed; on the contrary. However, participation in a local flexibility market significantly improves economic viability by reducing payback times and required subsidies. Without such market mechanisms or financial support, investment remains economically challenging for scaling up the implementation of BESS.

The thermal system consisting of the CO_2 based GSHP with boreholes and water tanks has been implemented on several projects in Norway. Some projects may have different types of heat pumps, or the substation configuration may be a bit different. The most important issues in the scalability of this type of thermal system are the size of the heating and cooling load and the performance of the borehole. There is a good match between the heat sent to the borehole and the extracted heat, meaning that the boreholes would not be cooled down over time. This shows good thermal balance in the system. The suggested thermal system can be scaled up to some level if there is a good match between the heating and cooling load and the heat pump has the possibility to work properly.

8.2. REPLICATION POTENTIAL

The Voldsløkka school demo provides a valuable reference model for other EU member states aiming to integrate decentralized onsite renewable energy sources, flexible storage, and energy-efficient design in public buildings. This demo case demonstrates strong replication potential for renewable energy integration in non-residential buildings across Europe, particularly in regions with similar climatic and regulatory conditions. The project's innovative use of BIPV, coupled with investigations on second-life BESS, provides a comprehensive and transferable framework for achieving Plus-Energy performance in school buildings and other public facilities.

A key replicable feature is the successful integration of BIPV as both an energy-producing and architectural element. The project showcases how PV can be embedded into the building façades with non-standard color schemes, expanding aesthetic options for architects without compromising energy production goals. This approach can be adopted by new or renovated buildings seeking to balance design requirements with renewable energy targets, thereby enhancing architectural flexibility while contributing to climate goals. The replication of BIPV systems, however, requires a multidisciplinary approach, involving coordination between architects, engineers, procurement experts, and installation contractors. Effective replication thus depends on the availability of technology but also on the establishment of integrated planning and procurement frameworks capable of accommodating cross-sectoral collaboration.

The study's detailed analysis of PV system orientation and its impact on energy performance is highly transferable to other Nordic or temperate-climate regions. Specifically, the combination of roof- and south-façade-mounted PV systems achieved a good alignment with the building's daily electricity demand, resulting in a satisfactory self-consumption rate. These insights can inform PV system design in other educational or public buildings with similar load profiles.

Moreover, the integration feasibility study of a second-life BESS demonstrated improvements in self-consumption and grid independence (self-sufficiency). However, the economic viability of battery systems remains sensitive to capital costs and market participation levels. With the present conditions, the return on investment is lengthy, but this payback period can be nearly halved if participating in local flexibility markets and performing demand response control strategies. This illustrates the added value of coupling renewable generation with building-to-grid service provisions. This is particularly relevant for municipalities and public institutions across the EU seeking to optimize operational expenditures and energy resilience while aligning with sustainability targets. Widespread replication will require either targeted subsidies or the development of local energy markets that reward flexibility and capacity services. Nonetheless, the use of second-life batteries, which reduce environmental impact and hardware costs, enhances the feasibility of replication in cost-constrained public sector projects.

The thermal system at the Voldsløkka school demo consisting of the CO_2 based GSHP with boreholes and water tanks has been implemented on several projects in Norway. Similar thermal systems can be implemented in other EU countries. However, the most important issues in replicating this type of thermal system are the size of the heating and cooling loads and the performance of the borehole. To achieve the desired performance of the borehole, sizing the borehole is critical. There is a need for a good match between the heat sent to the borehole and the extracted heat to get good thermal balance in the system and thereby good system efficiency. To achieve this and make the system replicable at other places in Europe, the following must be considered:

- A good match between heating and cooling load should be achieved;
- The heat pump sizing should be done properly, so that the heat pump can operate properly;
- Sizing of the boreholes should be done properly to enable good annual thermal balance.

8.3. READINESS FOR FUTURE AND NEW TECHNOLOGIES

Future grid-integrated smart buildings capable of providing demand response and building-to-grid services rely heavily on advanced control strategies, such as model predictive control (MPC). These intelligent algorithms optimize building operations and energy usage by integrating forecasts of external signals from the energy grid, outdoor weather conditions, and onsite energy use, production, and storage.

In the present demonstration case, a key forecasting input is the predicted photovoltaic (PV) production, which is supplied via an API from an external service provider. While the forecasting model performs adequately overall, its accuracy is reduced during low-production periods in winter. Moreover, the reliability of the forecasting service is critical: two outages were recorded over a six-month period, both requiring manual intervention and contact with the provider to restore service and data flow. Implementing automated downtime detection or running a local PV forecasting model on the building management system (BMS) could help improve resilience.

Implementing smart control strategies like MPC also presents challenges. Currently available commercial building management and automation systems do not natively support advanced predictive control features such as optimization routines and integrated building models. As a result, a common workaround involves deploying an additional computing setup to handle data acquisition and control computations in parallel to the BMS, which then overrides the default control signals of the BMS. While technically feasible, this approach introduces added complexity, demands programming expertise, and incurs additional costs. It can also raise concerns regarding system robustness and cybersecurity vulnerabilities.

A comparative analysis of control strategies for the CO_2 based GSHP shown in **Figure 14** demonstrates the operational characteristics of the MPC approach. **Figure 34** shows the results comparison for the performance of MPC, PI, and the baseline control strategies in controlling a heat pump and thermal storage system. The tank temperature of MPC controller (the blue line) remains consistently within the defined limits, exhibiting smooth and responsive behavior. The heat pump outlet temperature (the purple line) of the MPC controller adjusts dynamically, particularly reducing output during periods of high electricity prices (e.g., after 400 hours). In contrast, the PI-controlled tank temperature (magenta) remains close to the upper limit, indicating fixed setpoint tracking without consideration of the economic signal. The baseline controller (the green line) operates in a stepwise manner with frequent switching and lacks adaptability during price fluctuations. Despite similar average power inputs, MPC demonstrates more flexible and efficient temporal allocation, adjusting output according to price disturbances. The power compressor input, the middle figure in **Figure 34**, shows that the MPC varies the compressor input to avoid high electricity price periods, while PI maintains relatively steady input, and the baseline follows a rigid, unresponsive pattern. The disturbance plot, the bottom plot in **Figure 34**, confirms that the dominant challenge in the latter half of the observed period is economic (price spikes), and not thermal demand. MPC responds effectively to this electricity price disturbance by shifting energy use, whereas PI and baseline continue full operation regardless of cost, potentially increasing operational expense. This example in **Figure 34** shows that there is a need for advanced control such as MPC for the thermal system in this demo.

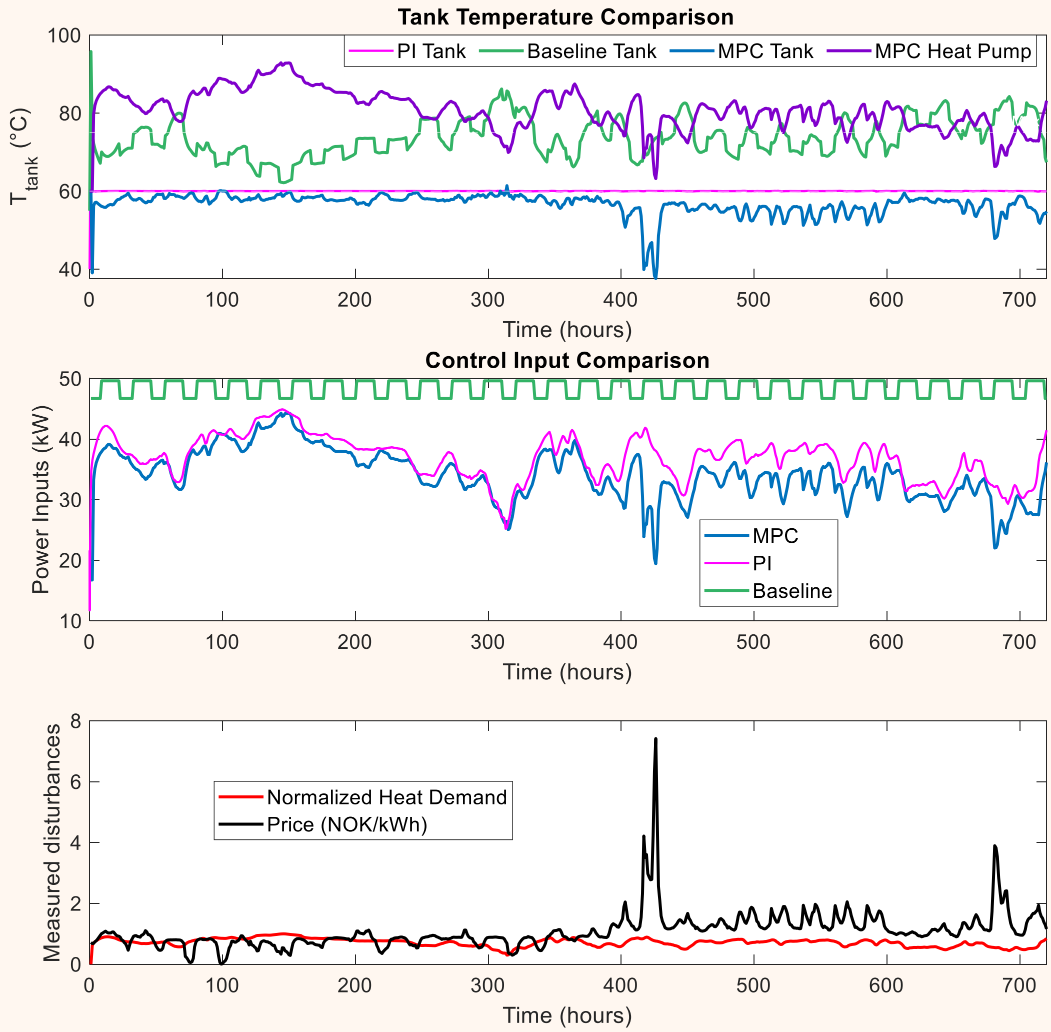


Figure 34. *MPC vs. PI control for heat pump operation*

9. LESSONS LEARNED

The monitored energy performance of the case study building is higher than the design value. This is a common situation in the building sector and may arise due to the starting phase and a lack of optimal control of all the components. However, in the present case, this school building remains fairly efficient compared to the rest of the school building stock in Oslo.

The detailed study of PV production as a function of orientation and implementation configurations helps to better understand how to optimize the design of such systems to maximize onsite PV production and self-consumption (matching peak demand and peak supply) while limiting electricity exports to the local grid.

Previously, OBF implemented PV installations on the roof combined with batteries for energy storage. This was done due to the stricter requirements for energy efficiency and to increase the renewable energy production. These projects took place during a period when there were incentives for investing in the combination of PV with batteries, thus reducing the costs of the building owner significantly. Based on the interviews with OBF regarding projects where PV is combined with BESS, the following lessons learnt can be drawn:

- In Oslo municipality, there is a strong focus and commitment to installing PV, but not combined with battery storage. The construction and rehabilitation projects have many requirements in relation to climate, environment, and their functions, but currently not in relation to energy flexibility. If in the future, energy flexibility and demand-side flexibility are prioritized, and there is a political target, there will be a higher incentive to invest in batteries.
- There is a lack of knowledge of how to make full use of the different technical systems that are implemented in the different projects. The building managers or relevant personnel don't get the necessary training in understanding and maintaining the technical systems.
- Generally, little follow-up on the projects where BESS combined with PV systems have been implemented, for example, whether the control system of BESS is operating according to specification or not.
- Access to data is needed to fully utilize the potential of energy systems. There are difficulties accessing the data as the BESS system is not incorporated into the building management system (BMS) or energy management system.
- To lower the payback time, there are suggestions for alternative uses of the BESS other than energy storage, including using it for fast charging of EVs.

The simulations showed that implementing the BESS in Voldsløkka school leads to an increase in self-consumption as well as a reduction in the electricity imports from the grid. However, the still high capital cost of the system leads to extensive payback periods. Participation in a local flexibility market significantly improves economic viability by reducing payback times and required subsidies. Without market mechanisms or financial support, investment remains economically challenging for scaling up the implementation of BESS.

There is a need to develop a BMS that can directly integrate smart control algorithms. In the meantime, it is important for the BMS to include easy and safe two-way communication possibilities with an external computing device with an adequate actuation priority system, to enable the flexible integration of an external smart controller.

External service to provide PV production forecast is adequate in terms of accuracy for the MPC application. However, forecasting service outage can be challenging if there is no automated detection of such an event and no automated response mechanism on the service provider side.

Although a complex endeavor, it was possible to implement a smart MPC algorithm to optimize the operation costs of the building systems based on internal monitoring data and external forecasting services (onsite PV production, weather conditions, energy spot price).

Lessons learned related to the thermal energy system are related to the sizing and control of the system. The results achieved until now have shown clearly that heating and cooling loads should match each other. Further, sizing the heat pump and the boreholes is critical to provide good performance on the annual level. Finally, to tackle variation in heat demand and electricity pricing, the use of advanced control, such as MPC, is needed.

REFERENCES

[1] NVE (2025). https://www.nve.no/energi/energisystem/solkraft/oversikt-over-solkraftanlegg-i-norge/

[2] IRENA (2024). Renewable power generation costs in 2023, International Renewable Energy Agency, Abu Dhabi.

[3] Standard Norge (2014). NS3031:2014 – Calculations of energy performance of buildings – Method and data

[4] NVE (2025). https://www.nve.no/energi/energisystem/#

[5] Energiaktuelt (2024). Gjennomsnittlig klimagassutslipp knyttet til bruk av strøm: 15 gram CO2 -ekvivalenter per kWh. https://www.energiaktuelt.no/cppage.6673552-575505.html

[6] Frischknecht R. et al. (2021). Environmental life cycle assessment of electricity from PV systems. 2021 Data update. https://iea-pvps.org/wp-content/uploads/2022/11/Fact-Sheet-IEA-PVPS-T12-23-LCA-update-2022.pdf

[7] Epd-norway (2025). https://www.epd-norge.no/epder/byggevarer/solcellepaneler-og-komponenter/

[8] 4RinEU project. http://www.4rineu.eu/

[9] Xiang et al. (2021). Pixelization approach for façade integrated coloured photovoltaics-with architectural proposals in city context of Trondheim, Norway, *Solar Energy, 22,1222-1246*.

[10] Kallhovd M. (2018). Brynseng skole. *Solenergidagene 2018*, Oslo, Norway.

[11] Metsolar (2022). How much does really BIPV cost? https://metsolar.eu/blog/how-much-does-really-bipv-cost/

[12] Røyset A., Kolås T, Jelle B.P. (2020). Coloured building integrated photovoltaics: Influence on energy efficiency. *Energy and Buildings, 208,* 109623

[13] Granås S. (2023). Solenergi FUSen vant solenergiprisen «Årets anlegg 2022». https://www.energiaktuelt.no/solenergi-fusen-vant-solenergiprisen-aarets-anlegg-2022.6597321-575508.html

[14] Format Engineers Ltd (2025). Https://formatengineers.com

[15] Andresen, I., Thyholt, M. & Dokka, T.H. (2014). Kriterier for Futurebuilt Plusshus, 1–3.

[16] Sørensen, Å.L., Johra, H., Lolli, N., Walnum, H.T., Høiaas, I.E., & Andresen, I.(2025). Influence of PV system orientation and design on energy self-consumption and cost savings: A Norwegian case study. In Journal of Physics: Conference Series (under review)

[17] Campodonico-Avendano, I.A, Moazami, A., Yang, A. & Johra, H. (2025). Optimization of Second-life Battery Energy Storage System in Buildings with Photovoltaic Panels: A Norwegian Case Study. In Lecture Notes in Computer Science (LNCS) (under review).

[18] Elvia (2024, January 1). Dagens og historiske priser innenfor Elvias nettområde. https://www.elvia.no/nettleie/alt-om-nettleie/dagens-og-historiske-priser-innenfor-elvias-nettomrade/, last accessed 2025/05/01

[19] Thomas, C. E. (2009). Fuel cell and battery electric vehicles compared. *international journal of hydrogen energy*, *34*(15), 6005-6020.

[20] Viswanathan, V., Mongird, K., Franks, R., Li, X., Sprenkle, V., & Baxter, R. (2022). 2022 grid energy storage technology cost and performance assessment. *Energy*, *2022*, 1-151.

[21] Salek, F., Resalati, S., Babaie, M., Henshall, P., Morrey, D., & Yao, L. (2024). A review of the technical challenges and solutions in maximising the potential use of second life batteries from electric vehicles. *Batteries*, *10*(3), 79.

[22] Dong, C., & Sigrin, B. (2019). Using willingness to pay to forecast the adoption of solar photovoltaics: A "parameterization+ calibration" approach. *Energy Policy*, *129*, 100-110.

[23] Xu, B., Oudalov, A., Ulbig, A., Andersson, G., & Kirschen, D. S. (2016). Modeling of lithium-ion battery degradation for cell life assessment. *IEEE Transactions on Smart Grid*, *9*(2), 1131-1140.

[24] NODESmarket. (2025, March 14). *NODESTM platform*. NODESmarket. https://nodesmarket.com/nodes-platform/

ACKNOWLEDGEMENTS AND DISCLAIMER

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101036723.

We would like to acknowledge Oslobygg KF for their contributions, and Eco-store for providing information about their battery systems.

APPENDIX A – GLOSSARY OF TERMS

Table A.1 *Abbreviations used in the report.*

Abbreviation	Description	References
CPCC	Climate Positive Circular Communities.	See ARV Deliverable D2.1 for a detailed definition of CPCC
BAPV	Building Applied Photovoltaics	
BIPV	Building Integrated Photovoltaics	
BESS	Battery Energy Storage System	
BMS	Building Management System	
OBF	Oslobygg KF, the demo building owner.	
GSHP	Ground source heat pump	
PV	Photovoltaics	
MILP	Mixed-integer linear programming	
CO_2e	Carbon dioxide equivalent, a metric measure used to compare the emissions from various greenhouse gases on the basis of their global warming potential (GWP).	
NZEB	Near zero energy building	
RESs	Renewable energy sources	
ESSs	Energy storage systems	
MPC	Model predictive control	
LowEx	Low-temperature thermal heating and high temperature thermal cooling	

PARTNER LOGOS

WWW.GREENDEAL-ARV.EU