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Solar PV Potential on Site 4016 at Åsen and the Urban Fabric as the Future Solar Power Plant of Cities

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Abstract

With the urgent necessity for humans to take radical action to stop the impending climate crisis, it is necessary to cut carbon emissions as soon as possible to prevent further damage. Cities are one of the main sources of human-made emissions and considering the expected rise in urbanization in the upcoming years, sustainable urban development practices must be adopted to reshape cities around the world and be able to achieve the climate goals. The incorporation of positive energy districts (PEDs) and net-zero energy buildings (NZEB) into the urban centers by integrating renewable energy sources into the urban fabric to cover the energy needs of the city itself is a possible solution to the problem.

In this thesis, the solar potential of Site 4016—an existing area in Åsen, Stavanger, Norway that is planned to be further developed and densified in the next years into a modern regional knowledge and development center for the construction sector—will be analyzed to explore the possibility of transforming the site into a PED through the integration of photovoltaics (PVs) to generate electricity. The annual solar irradiance received by the surfaces of the buildings for both the existing development and the future 2030 development was analyzed using the DL-Light tool for Sketchup. The potential to generate power was calculated based on future PV efficiency estimations and balanced out with the energy consumption estimations to obtain a total energy balance. For the future development of the site two energy consumption scenarios were analyzed: a scenario where energy efficiency targets for the year have been met that resulted in the site having the potential to generate enough power to cover up to 70% of the annual energy consumed, and an ultra-high energy efficiency scenario where the site could potentially become a PED being able to cover 115% of the annual energy need and generating 1 390 000 kWh of excess energy annually. The characteristics of the urban fabric that could help increase the solar potential of an urban area were discussed as well as some efficiency practices that could lead to the low energy consumption that is needed to achieve a PED.

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List of Abbreviations

kWh	Kilowatt-hour
GWh	Gigawatt-hour
EPBD	Energy performance of buildings directive
IEA	International Energy Agency
SHC	Solar Heating and Cooling Program
PED	Positive Energy District
NZEB	Net/Nearly Zero Energy Building
PV	Photovoltaics
BIPV	Building integrated photovoltaics
BAPV	Building applied/attached photovoltaics
c-Si	Crystalline silicon
a-Si	Amorphous silicon
CdTe	Cadmium Telluride
GaAs	Gallium Arsenide
CIS	Copper Indium Selenide
OSC	Organic Solar Cell
DSSC	Dye-sensitized solar cell
PSC	Perovskite-structured solar cell
TPV	Transparent photovoltaics
STPV	Semi-transparent photovoltaics
LCCA	Life-cycle cost analysis
HVAC	Heating, ventilation and air conditioning
BEMS	Building Energy Management System
FAR	Floor-area ratio
SR	Solar reflectance

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) of the United Nations released a special report on global warming in 2018. The report determined that to achieve limiting the mean global temperature rise to 1.5°C based on pre-industrial levels, deep emission reductions and rapid, far-reaching and unprecedented changes are going to be needed in all aspects of society by at least the year 2030, as the negative consequences of the rise in global temperatures are already being perceived and if they are not stopped the further consequences will be possibly irreversible and extremely harmful to the environment and humanity (IPCC, 2018). As indicated in the report, action must be taken as soon as possible to cut these emissions, as the rise in temperatures is expected to be moving at a faster pace than thought before, and the 1.5°C temperature rise could even be expected to be reached in the next 5 years (WMO, 2020). The main solution to abruptly cut emissions is to eliminate the use of fossil fuels in the energy production process. To achieve this, the energy mix must be taken over by renewable energy sources like solar energy. As cities are responsible for a large share of the global energy consumption and they will continue growing, the urban fabric must be integrated with solar power and other renewable energy sources to meet the ever-growing energy demand in a sustainable manner.

Solar energy is an unlimited source of energy that provides cheap and clean power. With recent advances in technology and drops in prices, solar power alongside wind power are leading the future energy mix. With their exponential growth rates they are expected to eventually replace fossil fuels completely in the electricity producing sector by the mid 2030s, and by the 2050s push fossil fuels completely out of the energy sector, as it has been estimated that these renewable energy sources have the potential to meet the world energy demand 100 times over (Carbon Tracker, 2021).

1.1 Objective

The objective of this thesis is to have an insight into the use of the urban fabric as a solar power plant by determining the potential that the surfaces of Site 4016's buildings have to be used to generate solar power based on the local conditions, as well as pairing this with the energy consumption of the buildings to determine if a positive energy district (PED) can be achieved. The solar potential is analyzed for two main timeframe scenarios: the current existing buildings used as a baseline, as well as the proposed future development of the area under the name "Site 4016", where parameters like PV efficiency and energy consumption are also adjusted to such scenario taking place in the year 2030. The result of the research is linked to the impact that the solar design can have on an urban center, as well as analyzing the ideal design parameters and conditions of the urban fabric that will influence the future planning and reshaping of cities that will focus on renewable energies in the most efficient way possible. The feasibility of creating such developments and what is needed to achieve them is also looked upon to understand the possibility of integrating multiple solar designs into the urban centers.

1.2 Research questions

To fulfill the objectives of the thesis, two main research questions have been formulated:

- What potential does Site 4016 have to generate power from PV solar energy, and is it enough to achieve a positive energy district?
- Which characteristics of the urban fabric have the most significant impact on a solar power-focused urban development to ensure an efficient design that can lead to net zero energy or positive energy?

1.3 Area of study: Site 4016.

1.3.1 Concept

Site 4016 is an ambitious concept created by the Norwegian company Smedvig, being developed with the help of the architecture company MAD and other design companies. It is located in the neighborhood of Åsen in the city of Stavanger, the administrative center of Rogaland County, Western Norway (Figure 1). The objective of the project is to transform an already existing business and industrial area (Figure 2) into a regional and state-of-the-art knowledge and development center for the construction sector.

Figure 1. Location of Site 4016 (red) in the Stavanger/Sandnes urban area context. Screenshot from Google Earth.

Figure 2. Current state of Site 4016. (MAD Arkitekter, 2021)

Some of the construction sector related companies are already in the area, with the plan to have up to 70 companies together in the site. With the development of Site 4016, companies will be working together under the same roof, where they will be able to cooperate and share knowledge, at the same time facilitating accessibility on the client side. The site will be filled with co-working spaces, showrooms, meeting areas, warehouses and shared social spaces – sharing top of the line modern facilities that breathe innovation and sustainability (Smedvig, s.f.). The final plan will then be a beautifully designed area of medium rise buildings that will provide a pleasant environment not only to its employees and visitors but also people that will just be passing by the area (Figure 3).

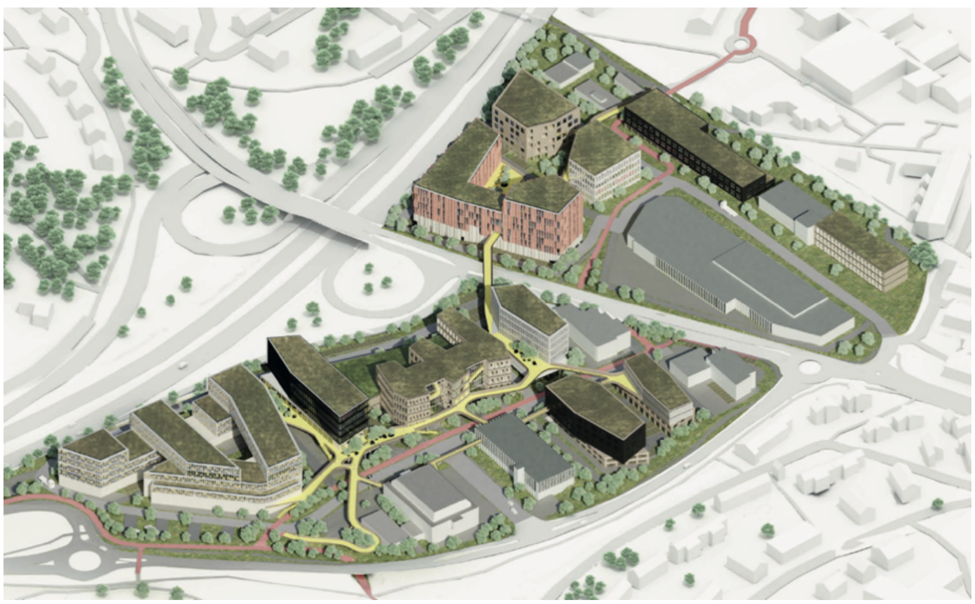


Figure 3. Future development proposal for Site 4016. (MAD Arkitekter, 2021)

Smedvig intends to develop this project throughout this decade, where they will replace some of the existing buildings with 6-8 story high buildings while also renovating some of the existing buildings to make them more modern and energy-efficient. The plan also considers renovating the common external areas, while also creating an elevated pedestrian and bike path that will pass through the heart of the project connecting each of the buildings (Figure 4). This path will promote sustainable mobility, while separating it from the lower zones that will be dedicated to storage and logistics where heavier machinery will need to operate; the pedestrian way will also create an easier connection between the northern area of the project where some residences and the high school are located to the southern residential areas and green areas.

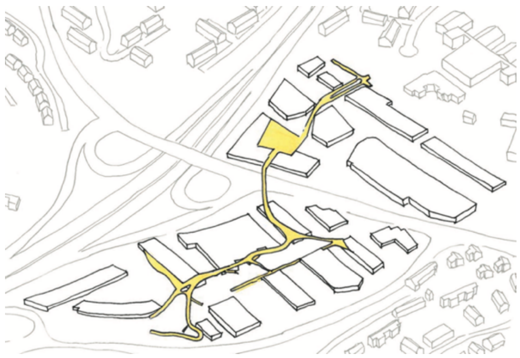


Figure 4. Sketch of the pedestrian way concept interconnecting all of the site (MAD Arkitekter, 2018).

1.3.2 Analysis of Site 4016 today

The site currently consists of 23 separate buildings, with very varied shapes, sizes and architectural style. The building nomenclature used in this thesis is the same that Smedvig utilizes, grouping some of the buildings together and numbering them KB1 to KB17, with a proposed new building that is to be named KB18 (Figure 5).

The area is currently divided into two clusters by an arterial road named Auglendsveien, the areas are connected by a small pedestrian tunnel that passes under the road. The main city highway, E39, passes directly West of the area, with exit ramps that connect to Auglendsveien.

Site 4016 is mainly a business and industrial area, which differs greatly from its residential surroundings (Figure 6). Besides the surrounding residences, the area is limited at south by a park, and directly north by Auglend High School.

Figure 5. Building nomenclature, adapted from (MAD Arkitekter, 2018).

Figure 6. Site 4016 surroundings. (MAD Arkitekter, 2018)

1.3.3 Site 4016 Development proposal

To achieve the development plans for Site 4016, some major changes would have to take place. First of all, some of the buildings are planned to be removed completely (Figure 7). Most of the buildings that will remain will undergo expansion, adding a significant amount of floor area to them (Figure 8).

While the final design and the building schedule is not completely clear at the moment, for the nature of this thesis it is assumed that the current proposal is the final design that will be accepted by Smedvig, characteristics of the buildings will be based on the models created by MAD, and that it will be completed approximately by or after the year 2030.

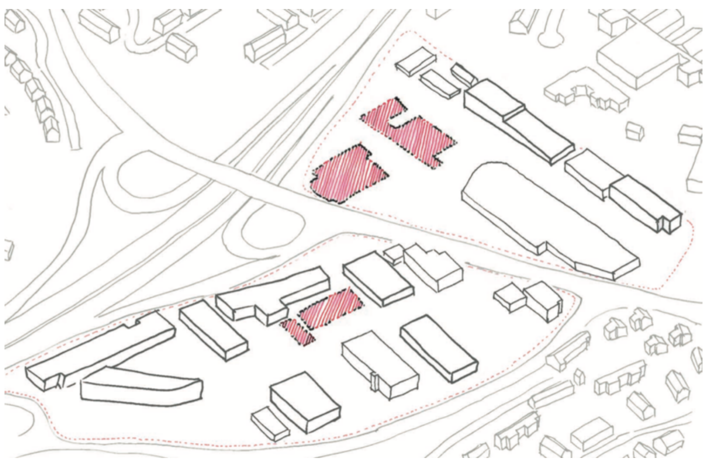


Figure 7. Sketch of the buildings planned to be removed (MAD Arkitekter, 2018).

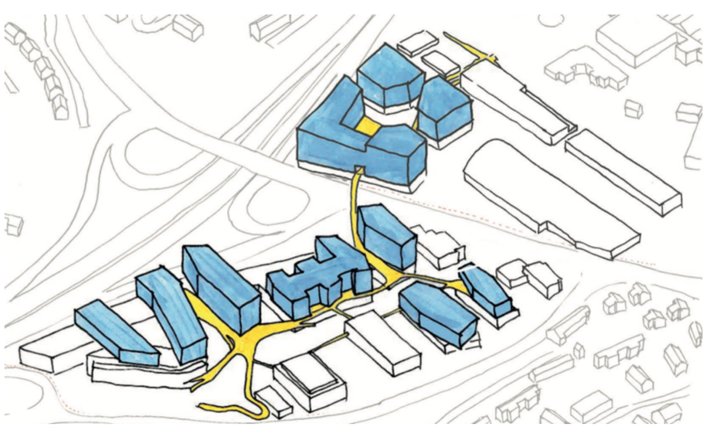


Figure 8. Sketch of the complete or partial buildings to be built (MAD Arkitekter, 2018).

1.4 Thesis structure

Chapter 2 presents a brief overview of theoretical concepts used throughout the analysis. *Chapter 3* describes the methodology used to conduct the solar analysis in addition to the input utilized for the final energy calculations. The results section in *Chapter 4* presents first the results obtained from the solar simulations run on DL-Light, then the results for energy calculations are presented. Results of further analysis elements are also included like the impact of interreflections and the role of the north-facing façades. In *Chapter 5,* the analysis takes place where the energy results and their feasibility are analyzed, further to this the relationship between the solar potential and urban planning and the variables that may affect it are discussed. Finally, the conclusion in *Chapter 6* gives a brief summary and concluding remarks of this thesis. At the end, *Appendix A* presents the detailed monthly render results obtained from DL-Light by analyzing both scenario models.

2. Theory

2.1 Solar irradiance

Basically, the sun is behind almost all energy fluxes on earth, it is a very valuable resource as we receive virtually an unlimited supply of energy. In just 10 minutes the surface of the earth receives from the sun enough energy to fulfill the primary energy needs of all humans for a year, as the earth receives 174 petawatts of energy on its upper atmosphere (Coley, 2008). This energy emitted by the sun in the form of electromagnetic radiation can be measured as the solar irradiance: the amount of solar energy that arrives at a specific area of a surface during a specific time interval, its unit is Watt/m^2, when this amount is measured over a period of time, the result is solar irradiation whose unit is Watt-hour/m^2 (NREL, 2021). For the nature of this investigation, the *total solar irradiation* on the surfaces of the buildings is considered, which results as a sum of the *direct normal irradiation* which considers the direct beam irradiance from the sun and the *diffuse horizontal irradiation* which considers radiation coming from light scattered in the atmosphere (NREL, 2021). Diffuse irradiance is stronger than direct irradiance in overcast and cloudy weather conditions and has been proven to provide significant amounts of energy to generate power from PV, especially in the west, east and north facing façades, while south-facing and horizontal roof surfaces receive a higher share from direct irradiance (Gholami & Røstvik, 2021).

2.1.1 Solar irradiance in Norway

As Norway is located between very up-north latitudes (Approximately 58˚N - 70˚N), its average solar irradiation is lower than the rest of Europe due to the inclination of the sun at these latitudes, especially during the winter months. As Norway is a very elongated country along the north-south direction this average irradiation may vary significantly. The southern part of Norway has similar amounts of average solar irradiation, with slightly less near the west coast in comparison to the south, east and inland areas (Figure 9) due to the climactic conditions of the western coast.

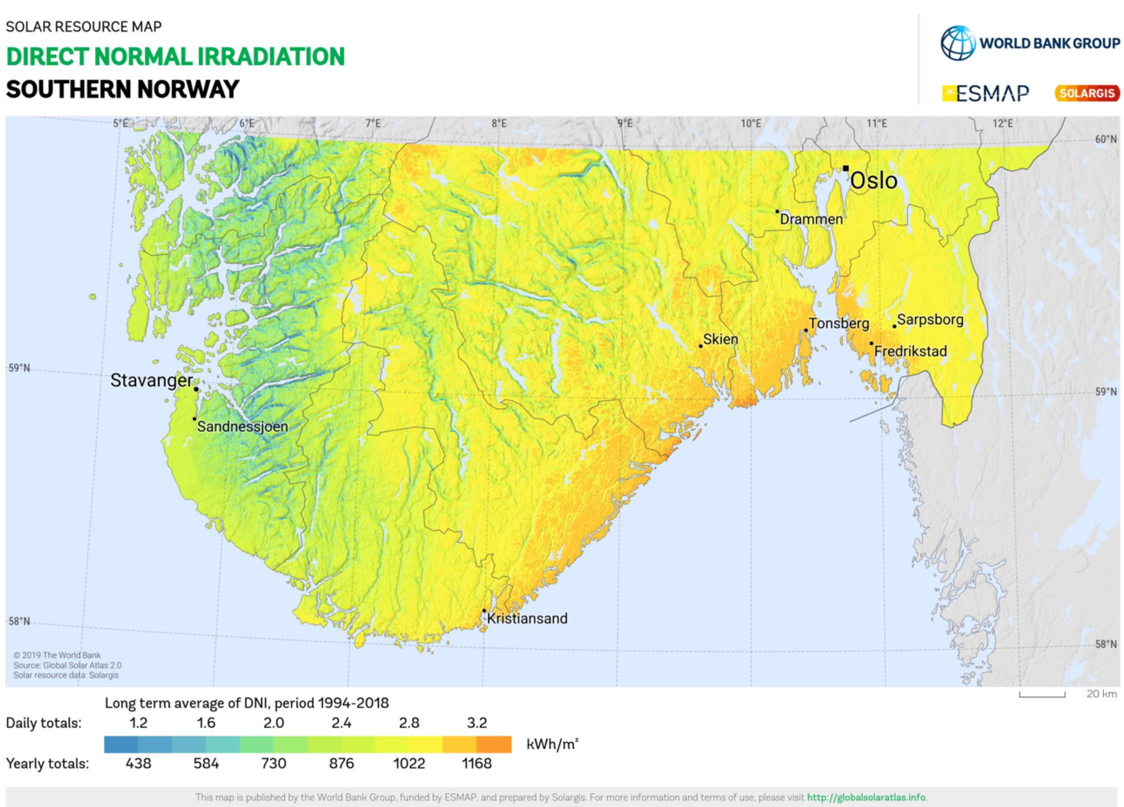


Figure 9. Average direct normal irradiation for southern Norway (SolarGIS, 2021).

According to Figure 9, the Stavanger region receives approximately 2.4 kWh/m^2 a day, or 876 kWh/m^2 a year; the solar analysis done in this thesis does result in similar average values as this one, supporting the accuracy of the results.

2.2 Photovoltaics

In the renewable energy mix, the use of photovoltaics (PV) is one of the best ways to take advantage of the almost unlimited supply of solar energy that we receive every day. To achieve the sustainable goals for Site 4016, the use of PVs is crucial as it is going to be the main source of energy to power the site. The basic function of a PV cell is converting solar radiation into electricity: layers of semi-conductors are placed in a solar cell, with the falling light releasing neutrons and creating an electric field across the layers causing the electricity to flow. This electrical power generated depends on the intensity of the light (V.V.Tyagi, A.A.Rahim, N.A.Rahim, & A./L.Selvaraj, 2013).

Nowadays there are a large variety of PV cell technologies being developed, some of them are on experimental phases yet, but a large variety are commercially available, they also have different efficiencies (the percentage of the solar energy received that is converted into electricity) that throughout the years have been improving thanks to research and development (Figure 10). These average efficiencies have been improving at a very high rate especially in the last decade as seen in the figure, at the current pace of growth the efficiencies will have a significant rise and efficiencies that are only achieved at labs will probably be commercially available and become more affordable. It is important to consider that the presented solar cell efficiency is not the final one for the system, as other losses have to be considered: mainly losses due to cables and wiring, losses due to inverter efficiency when converting the direct current (DC) into alternating current (AC) and losses due to the increase in the cell's temperature due to the sun exposure (colder climates have a reduced impact of this effect) (Coley, 2008).

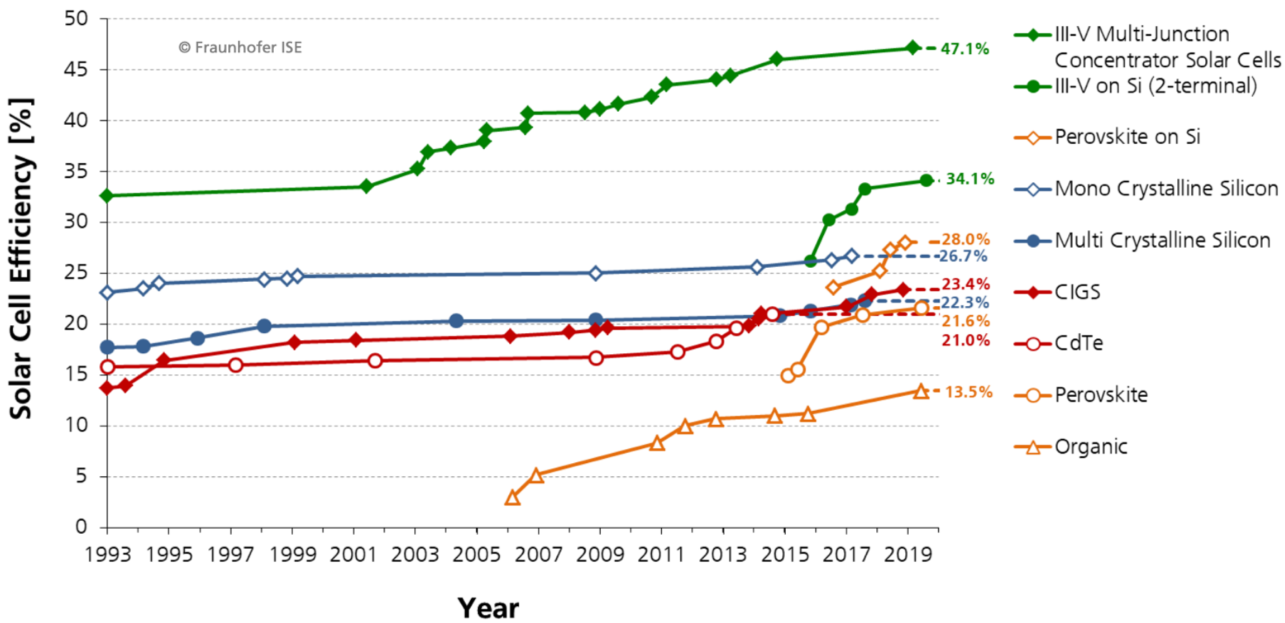


Figure 10. Solar cell efficiency development through the years (Fraunhofer Institute for Solar Energy Systems, 2020).

Of the many options that can be used, probably the most ideal technology to implement into the site's buildings would be crystalline silicon (c-Si) technology. These types of cells—often called first generation as they were the first to start to be commercially available—are the most convenient as they are very accessible commercially and present high efficiencies. There are two types of c-Si cells: monocrystalline and polycrystalline silicon cells. The two types of c-Si cells have similar durability and lifespans, however monocrystalline cells have a superior efficiency to polycrystalline cells but at a higher cost due to their higher complexity to manufacture (Marsh, 2021). Currently monocrystalline solar panels have some of the best efficiencies commercially available, as some of the best panels available have efficiencies of up to 20-22.6% (Svarc, 2021).

Another group of PV cell technologies that may be considered for Site 4016 are thin-film solar cells. These second-generation cells are composed of materials aligned in very thin films (35–260 nm), which create the opportunity to fabricate flexible and lightweight solar panels (ideal for BIPVs) which have also lower prices due to cheap manufacturing processes, the downside being that these type of cells have lower efficiencies (around 10-15%) and may have shorter lifespans (V.V.Tyagi, A.A.Rahim, N.A.Rahim, & A./L.Selvaraj, 2013). Some of the current thin-film PV technologies include: amorphous silicon (a-Si), Gallium Arsenide (GaAs), Cadmium Telluride (CdTe), Cadmium Sulfide (CdS) and copper indium gallium selenide/copper indium selenide (CIGS/CIS). Even though the efficiencies of thin-film are lower than c-Si, a comparative performance study conducted by Kumar, K.Sudhakar, & M.Samykano (2019) between c-Si, CdTe and CIS determined that even though CdTe has a lower efficiency compared to the most popular c-Si systems, it proved to be the most effective one at producing power due to having the lowest losses (Kumar, K.Sudhakar, & M.Samykano, 2019). Thin-film modules would be ideal to integrate into the buildings of Site 4016 if the design included curved surfaces, however as all building surfaces are flat, it is best to consider c-Si panels as they have higher efficiencies and lifespans.

A new group, the emerging and promising third-generation technologies are still mainly in experimental phase and not very commercially accessible. Some of these technologies include carbon nanotubes, copper zinc tin sulphide (CZTF), organic solar cells (OSC), dye-sensitized solar cells (DSSC) and colloidal quantum dot photovoltaics (QDPV). These technologies have promising results in durability and low-cost manufacturing, but their efficiencies still are relatively low (9-12%) in comparison to other technologies like c-Si (T.Ibn-Mohammed, et al., 2017). Perovskite-structured solar cells (PSCs) are another emerging technology that has proved to be one of the fastest growing technologies, with efficiencies currently proving to be higher than conventional c-Si and other technologies and at a lower cost, with a more sustainable life-cycle and a short payback period (T.Ibn-Mohammed, et al., 2017); therefore these solar cells combine the advantages of thin-film PV technologies with the good performance and sustainability of c-Si (Li, Ma, Yang, Lu, & Wang, 2020). If PSCs continue their current rate of improvement, they could be the ideal technology to be utilized in Site 4016 in a future development scenario, where efficiencies of 30% or more could be commercially available at an economically feasible price.

An important factor to consider when selecting the best PV technology for Site 4016 is the effect that the climate of the area will have on the efficiency, as Stavanger has a wet climate where high precipitation and an overcast or cloudy sky is usual throughout the year. Due to this climate, there is a reduced amount of direct irradiation that the PVs would receive, having to rely then on diffuse irradiation with lower levels of IR light for solar power generation; for Stavanger this share corresponding to diffuse irradiation can even get as high as 50-75% depending on the façade orientation (Gholami & Røstvik, 2021). A study conducted by Gholami & Røstvik (2021) concluded that for these cases where there is such a high amount of solar diffuse irradiation, technologies like mono/polycrystalline Si and CIGS would have their efficiencies greatly lowered, while GaAs and CdTe would be less impacted, and DSSC and OSC would be the most stable ones with relatively little impact on efficiency. This observed effect is due to the different technologies' capacity of absorbing different wavelengths, with DSSC and OSC having the higher tolerance to the light spectrum. It is important to consider however that DSSC and OSC have much lower efficiencies than the other technologies, so a detailed trade-off analysis could determine if the benefits of these cells outweigh the restricted output of technologies like c-Si and CIGS.

Photovoltaics not only can be integrated into solid surfaces of buildings, with emerging transparent and semi-transparent PV (TPV) technologies, PV cells can also be integrated into windows, making them and important tool to increase the solar power generation output. TPVs are mainly separated into two categories: non-wavelength-selective, which rely on spacing out conventional opaque PV cells to let sufficient light through, and wavelength-selective, which are transparent by utilizing materials that only absorb UV and/or IR light (Traverse, Pandey, Barr, & Lunt, 2017). One of the greatest challenges of TPV is to ensure good efficiencies while preserving the transparency of the windows to prevent that neither a solar passive design or the use of natural light get disrupted. This challenge to preserve transparency leads to lower efficiencies, however, in the last years thanks to research advances some technologies are giving promising results: in 2018 dye-sensitized cells with 60% transparency reached 9.2% efficiency while tandem semi-transparent Perovskite had a 77% transparency with 12.7% efficiency; those transparency values that are appropriate to be used in building windows with very reduced disruption of their functions, and can even help reduce excessive glare that may cause discomfort (Husain, Hasan, Shafie, Hamidon, & Pandey, 2018). With the current growth of TPVs, every time having better efficiencies, transparencies and getting cheaper, they could prove in the future to be valuable elements to consider integrating into Site 4016's windows.

2.2.1 BIPVs and BAPVs

Depending on the method of installation and characteristics of PV panels on a building, they can be categorized as building applied photovoltaics (BAPV) or a relatively new technology rising in popularity due to its convenience, building integrated photovoltaics (BIPV). In the case of BAPV, which has been the traditional or most common method of utilizing PVs, the PV modules are directly attached to the buildings with an additional mounting structure, they do not have any direct effect on the building structures or the way they function, and can be installed at certain tilt angles either on roofs or a façade (Kumar, K.Sudhakar, & M.Samykano, 2019). BAPVs are a better option for flat rooftops like the ones of Site 4016, as they can be installed with a tilt to take the best advantage of the solar irradiation, this tilt also permits more area to be covered. BAPVs require additional mounting systems, while BIPV are integrated into the building envelope and meet all of the envelope requirements like mechanical resistance and thermal insulation (Scognamiglio & Røstvik, 2012). By simultaneously serving as building envelope material and power generators, BIPV systems can provide savings in materials and electricity costs, reduce use of fossil fuels and emission of greenhouse gases, and add architectural interest to the building (Strong, 2016). The summary table of the main characteristics of both systems is provided by Kumar, K.Sudhakar, & M.Samykano (2019) is seen in Figure 11, where there seems to be a practical advantage for BIPVs; this may explain its current growing rise in popularity, and BIPVs should be the ideal system to be integrated into the façades of Site 4016's buildings to take advantage of their characteristics. Besides the physical advantage of BIPVs, a comparative performance study between the two systems conducted by Kumar, K.Sudhakar, & M.Samykano (2019) determined that the difference in energy performance between the two systems is negligible in tropical climates, with BAPVs having a very slight advantage, probably attributed to the capacity of BAPVs of being directioned at a more favorable angle towards the sun; this supports that considering BIPVs will not have a significant impact on the solar power generation.

Building integrated photovoltaics	Building applied photovoltaics
Integrated directly within the building structures like roof or facade	Indirect integration by using mounting hardware and roof perforations
Lightweight, and heavyweight	Heavyweight
Durable	Breakable
Highly resistance to winds	Lift or drag is possible
Aesthetically pleasing	Clunky looking

Figure 11. Comparison of characteristics of BIPVs and BAPVs (Kumar, K.Sudhakar, & M.Samykano, 2019).

2.3 Positive energy districts (PEDs) and Net Zero Energy Buildings (NZEBs)

To be able to achieve and even exceed the Paris Agreement goals and help mitigate the damage that has been exerted on the environment, decarbonizing buildings and the construction sector is a crucial step. Buildings are a main contributor to emissions and energy use, as buildings and the construction sector accounted for 36% of final energy use and 39% of energy and process-related carbon dioxide (CO2) emissions in 2018 (IEA, 2019). As Europe is one of the main actors in this global effort, one of the actions that the European Union has taken to reduce emissions is implementing the *Energy performance of buildings directive* in 2010*.* The EPBD requires that all new buildings from 2021 (public buildings from 2019) to be net or nearly zero-energy buildings (NZEB). According to them a NZEB is a building that has a very high energy performance, as determined in accordance to their parameters defined in the legislation. The nearly zero or very low amount of energy required should be covered to a very significant extent from renewable sources, including sources produced on-site or nearby (European Comission, 2021). The specific numbers are not actually defined by the EPBD and it was left open to interpretation by each European country to define what comprises a NZEB, this had to be done so every country can adapt to their specific climate conditions, primary energy factors, ambition levels, calculation methodologies and building traditions (European Comission, 2021).

Regardless of the open interpretation of what defines a NZEB, the core concept remains unchanged. Scognamiglio & Røstvik (2012) for example try to define it as "an energy-efficient building able to generate electricity, or other energy carriers, and from renewable sources to compensate for its energy demand, the building is connected to an energy infrastructure and not autonomous. The net ZEB balance is satisfied when weighted supply (the sum of all exported energy or generation, obtained summing all energy carriers each multiplied by its respecting weighting factor) meets or exceeds weighted demand over a period, nominally a year; the balance can be determined either from the balance between delivered and exported energy (import/export balance) or between load and generation (load/generation balance)". Additional to this, Sartori, Napolitano & Voss (2012) also argue that NZEBs are characterized by more than the mere weighted balance over a period of time, so two aspects of temporal energy match may be used: load matching which is the ability to match the building's own load, and grid interaction, the ability to work beneficially with respect to the needs of the local grid infrastructure (Figure 12).

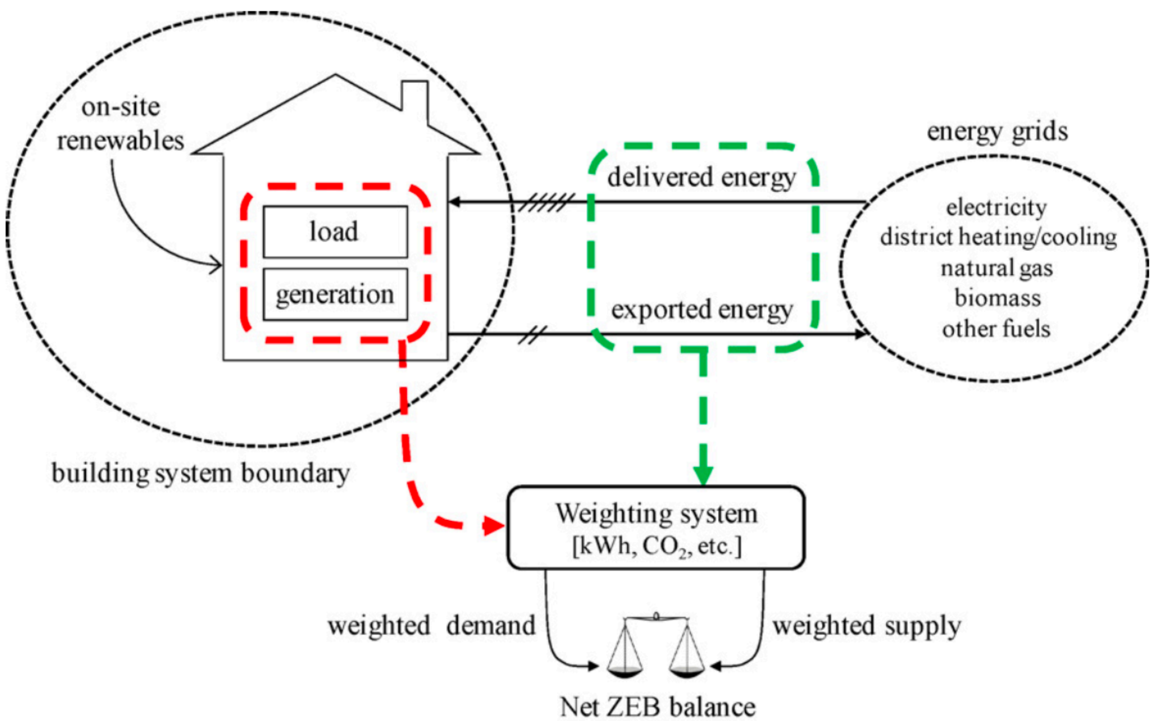


Figure 12. Weighted interaction between a building and the grid to determine NZEB balance (Sartori, Napolitano, & Voss, 2012, p. 222) .

In 2016, the Norwegian research center ZEB: Research Center on Zero Emission Buildings released a definition guideline for zero emission buildings, which takes the NZEB definition further as the balance is measured in terms of associated greenhouse gas equivalent emissions during the lifetime of a building instead of on direct energy demand and generation (Fufa, Schlanbusch, Sørnes, Inman, & Andresen, 2016). The guide provides a comprehensive guide to understanding the definition from a Norwegian context plus the associated calculation methodologies. The guidelines presented include the operational energy calculations which involve concepts like CO_2 conversion factors, system boundaries and energy efficiency requirements. As the assessment involves the emissions from all parts of the process, a section for life-cycle emission calculations is also included, where all stages of the life-cycle of a building are assessed from an emission point of view. Finally, the guideline presents various case studies to be used as examples of how the assessment process should go (Fufa, Schlanbusch, Sørnes, Inman, & Andresen, 2016). This guide demonstrates the importance of creating a framework for each country to help designers integrate properly a sustainable design having predetermined parameters, methodologies and case examples to compare with.

With the necessity to accelerate the energy transition and radically cut carbon emissions, the concept of positive energy districts (PEDs) has gained popularity. In cities, the advancement of integration of renewable energies, electrification of mobility systems and urban growth call for the creation of flexible and stable grids, which can be better achieved by introducing changes at a district level rather than building level (Hedman, et al., 2021). The creation of PEDs creates a holistic approach towards sustainable urban development that integrates technological, spatial, regulatory, financial, legal, social and economic perspectives through the interaction and integration between buildings, the users and the regional energy, mobility and ICT system. PEDs can then be understood as urban areas with annual net zero energy import and net zero carbon emissions that have a positive production of renewable energy that is integrated into an urban and regional energy system (Urban Europe, 2021). If multiple PEDs can be created within a city, a *solar city* can be achieved, with the urban fabric of the city itself being a renewable energy sourced power plant.

3. Methodology

3.1 Solar Irradiation Analysis using DL-Light for Sketchup

In order to understand the amount of solar irradiance that buildings can potentially receive in a year, an advanced light analysis tool was chosen. The tool used to gather all of the data is *DL-Light*, an extension tool for the modeling software Sketchup, used to study natural light in urban and architecture projects. The tool was created by French company De Luminæ, which describes itself as "a technical and research office in natural and artificial lighting, its impacts on energy consumption and the improvement of comfort and pleasantness for sustainable buildings and cities." (De Luminæ, 2021).

The tool is very complete, as it comes with 19 different metrics to analyze light, including external exposure of the building as well as how light behaves inside the building itself, and the tool can be used to generate data compatible with sustainability certification systems like LEED and BREEAM (De Luminæ, 2021). The selected metric used in the analysis is *Watt*, this tool uses ray tracing technology to analyze the irradiation in Wh/m^2 that surfaces receive in a selected period of time, given the geographical location and climate data. Additionally, the tool has been validated by comparison with case base 600 of ASHRAE Standard 140-2011 (De Luminæ, 2021). The tool also analyses the solar irradiance received from the interreflections caused by other building surfaces, which is why it is important to carefully assign building cladding and roof materials for the surfaces that most accurately match the real reflectance of the surfaces. The tool is highly versatile as one can choose any given period of time to be analyzed, from hours to months to a whole year, and obtain different sets of data including average, maximum or total solar irradiation. After the analysis is run, that may take many hours of computation, not only does an output of a data sheet is created but a false color rendering is generated for the surfaces to have a visual understanding of the results.

In order to run the solar analysis, two models had to be created in Sketchup. The first and very important step was to learn how to use and model on the Sketchup modeling program, as I had no previous experience working with this program. MAD Arkitekter provided a baseline model, however, a lot of work had to be done on this model to be conditioned for the analysis. First of all, the model provided was for the future proposal only, so some of the current existing buildings had to be modeled from scratch for the current conditions model. To properly run the simulations many hidden and internal layers had to be removed so they didn't interfere in the analysis, when some of these were removed some of the external layers disappeared also as the geometry was merged, so many external faces had to be remodeled. Some reshaping had to be also done as some of the dimensions, heights and building shapes were inaccurate and the cardinal orientation had to be verified as it is crucial for the analysis to be accurate. The next step was to separate and sort all the layers based on each of the buildings and a different layer for each of the building materials had to be created so the reflectance number could be assigned. Figure 13 and 14 show the final models that were created to be able to run the simulations.

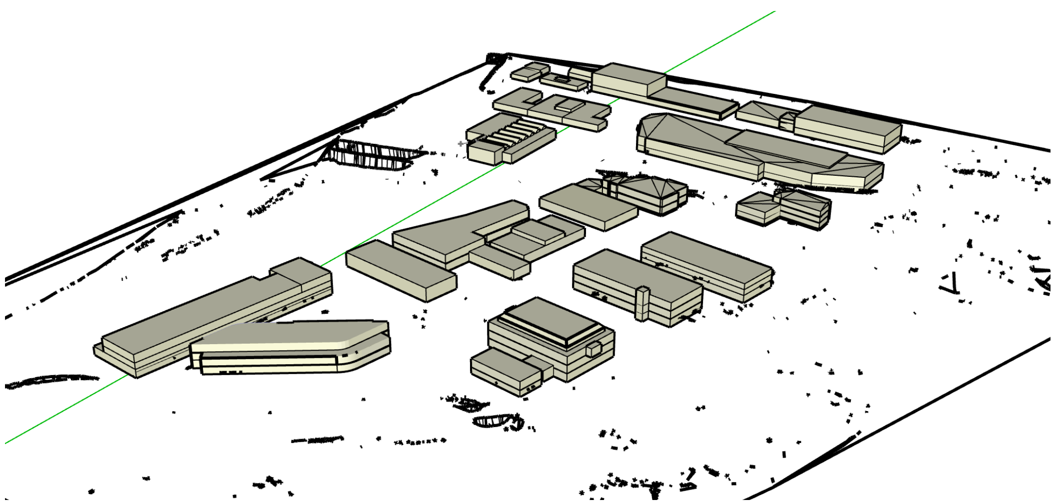


Figure 13. Sketchup model used for the analysis of the current Site 4016 conditions, view of the south and east-facing façades. The green line represents the north-south axis. Screenshot taken from Sketchup.

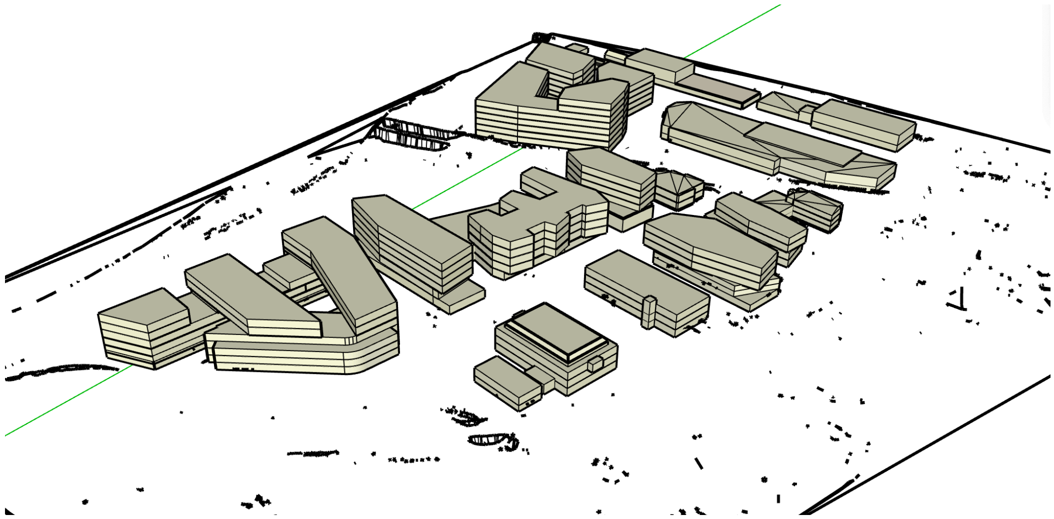


Figure 14. Sketchup model used for the analysis of the proposed development for Site 4016, view of the south and east-facing façades. The green line represents the north-south axis. Screenshot taken from Sketchup.

With the models ready to be analyzed, the inputs had to be added to the tool to be able to run the analysis properly (Figure 15). The exact coordinates had to be set for the project, for which a middle point was chosen with the coordinates 58.943993N, 5.727588E. An accurate climate datasheet has to also be input, a datasheet for the years 2004-2018 gathered from the Sola airport was obtained (climate.onebuilding.org, 2021), which is data gathered 8km from the project, making it an accurate weather representation of the area. The level of analysis detail must be chosen, for which the "Detailed" level was chosen, generating one light sensor per m^2, this level of detail also contributed to longer computation times.

As the analysis considers the interreflections of the buildings, each of the façade and roof surfaces of the model had to have a building material assigned (Figure 16). The materials chosen for the current model were based on analyzing the site's current conditions, while the materials for the proposal model were based on MAD's rendering of the project (Figure 3). Each of the selected materials were already included in tool's library, and each has a certain reflectance number assigned to them (Figure 17). Besides this the selected ground albedo chosen was of 40% that represents concrete.

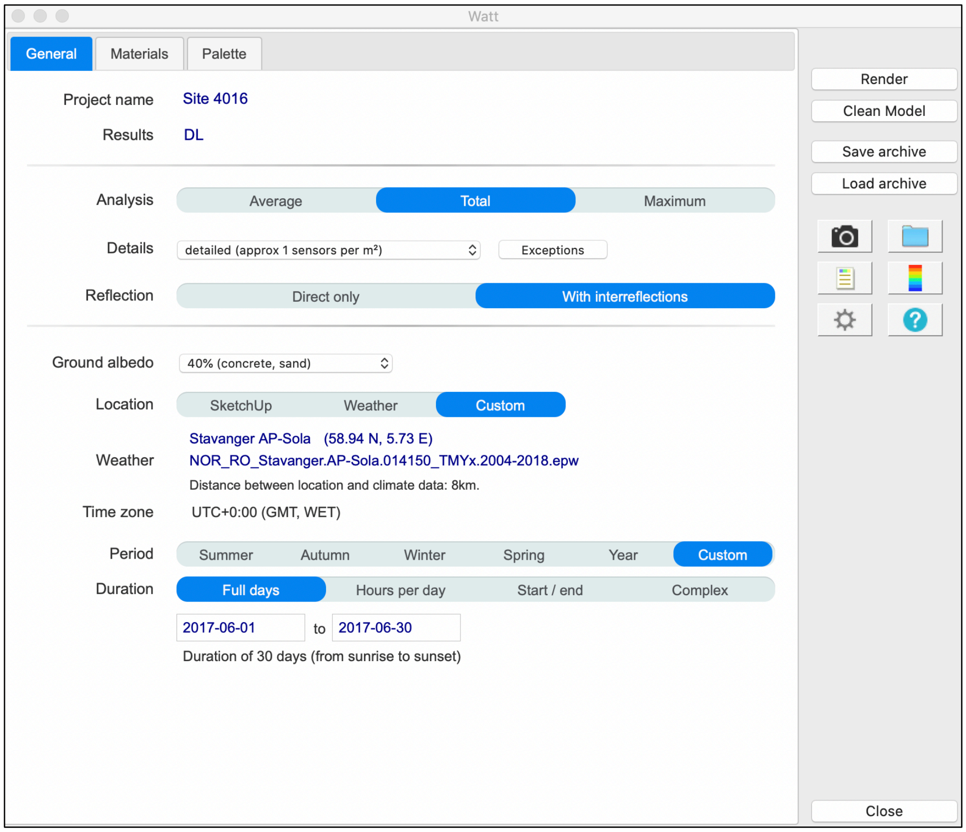


Figure 15. Sample of the input window for the DL-Light Watt tool. Screenshot taken from DL-Light on Sketchup.

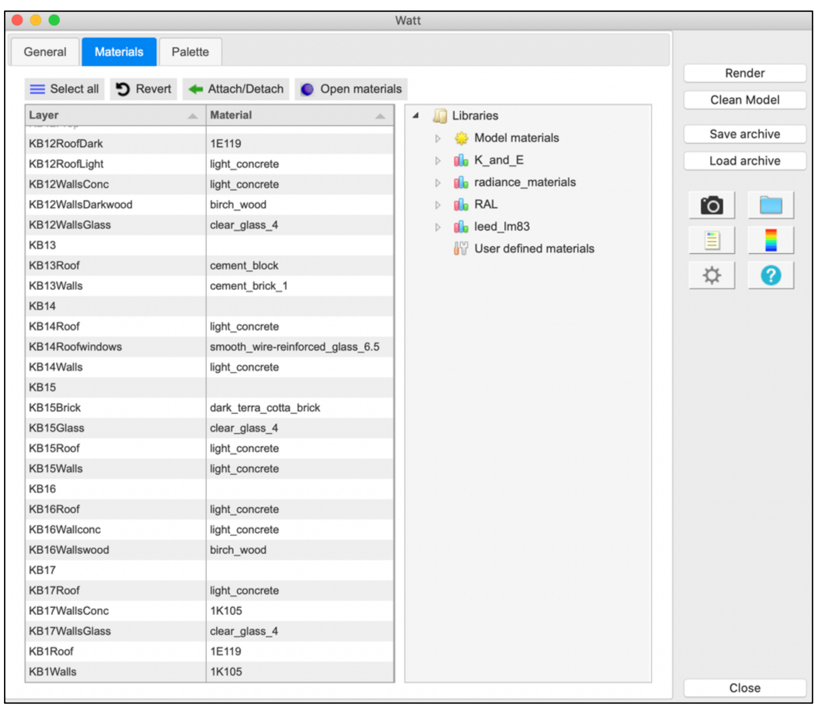


Figure 16. Sample of the materials assigned to the surfaces of the model. Screenshot taken from DL-Light on Sketchup.

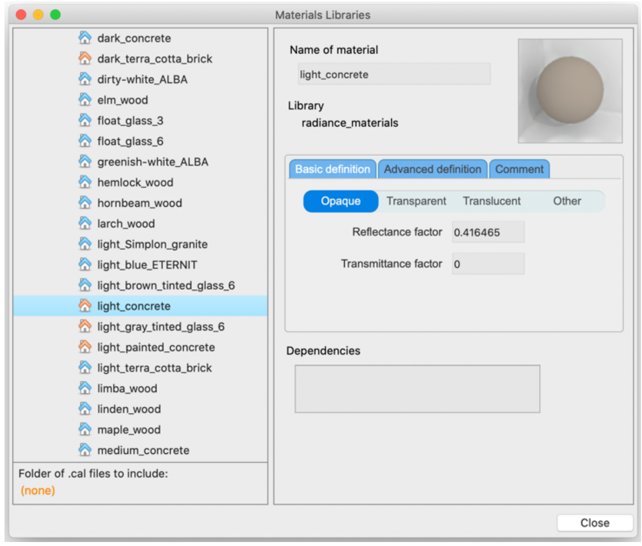
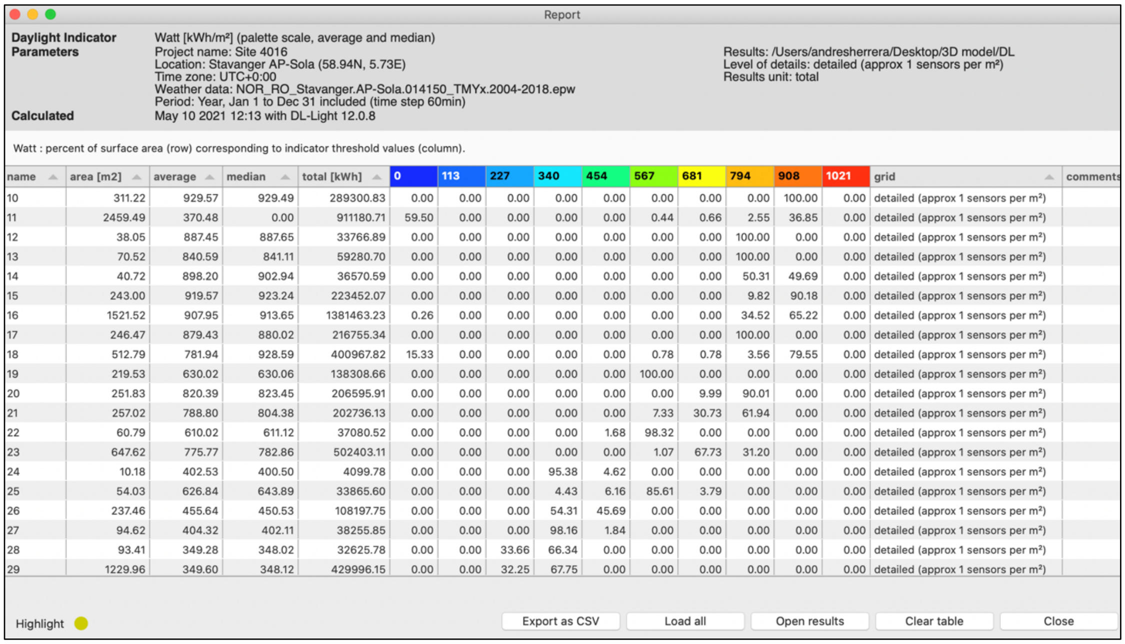


Figure 17. Sample of the characteristics of one of the materials assigned to the surfaces. Screenshot taken from DL-Light on Sketchup.

To be able to obtain the most detailed data possible, it was decided that for each model an irradiation simulation would be run for each month. The analysis was run on a laptop with fairly powerful computation power: a 2016 MacBook Pro with a 2.7 GHz Quad-Core Intel Core i7 processor, 16 GB 2133 MHz LPDDR3 memory and an Intel HD Graphics 530 1536 MB graphics card. Even with this power, each one of the simulations took a significant amount of time, on average 3-4 hours for each month, and for some reason some of the months even took nearly 12 hours to be analyzed. Besides this, many preliminary trial runs had to take place to detect minor mistakes in the model like a surface being inverted or erroneously not assigned to a corresponding layer. As the calculations were very intensive for the computer, a couple of times the software or the computer itself would crash without reason, sometimes hours into one of the calculations. The combination of all of these factors led to 120+ hours of total computation time, which further demonstrates the level of detail required for such calculations. After each simulation was run, the tool generated a datasheet report (Figure 18), the data includes the area of each surface analyzed, average irradiation received, median irradiation received, and total irradiation received. The tool also generates an automatic false color palette with 10 categories and determines the percentage of irradiation that the surface had in each of the categories generated. which can then be exported to Excel to be compiled.



Report

Daylight Indicator Parameters
Watt [kWh/m^2] (palette scale, average and median)
Project name: Site 4016
Location: Stavanger AP-Sola (58.94N, 5.73E)
Time zone: UTC+0:00
Weather data: NOR_RO_Stavanger.AP-Sola.014150_TMYx.2004-2018.epw
Period: Year, Jan 1 to Dec 31 included (time step 60min)

Results: /Users/andresherrera/Desktop/3D model/DL
Level of details: detailed (approx 1 sensors per m^2)
Results unit: total

Calculated
May 10 2021 12:13 with DL-Light 12.0.8

Watt : percent of surface area (row) corresponding to indicator threshold values (column).

name	area [m2]	average	median	total [kWh]	0	113	227	340	454	567	681	794	908	1021	grid	comments
10	311.22	929.57	929.49	289300.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	detailed (approx 1 sensors per m^2)	
11	2459.49	370.48	0.00	911180.71	59.50	0.00	0.00	0.00	0.00	0.44	0.66	2.55	36.85	0.00	detailed (approx 1 sensors per m^2)	
12	38.05	887.45	887.65	33766.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	detailed (approx 1 sensors per m^2)	
13	70.52	840.59	841.11	59280.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	detailed (approx 1 sensors per m^2)	
14	40.72	898.20	902.94	36570.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	50.31	49.69	0.00	detailed (approx 1 sensors per m^2)	
15	243.00	919.57	923.24	223452.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.82	90.18	0.00	detailed (approx 1 sensors per m^2)	
16	1521.52	907.95	913.65	1381463.23	0.26	0.00	0.00	0.00	0.00	0.00	0.00	34.52	65.22	0.00	detailed (approx 1 sensors per m^2)	
17	246.47	879.43	880.02	216755.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	detailed (approx 1 sensors per m^2)	
18	512.79	781.94	928.59	400967.82	15.33	0.00	0.00	0.00	0.00	0.78	0.78	3.56	79.55	0.00	detailed (approx 1 sensors per m^2)	
19	219.53	630.02	630.06	138308.66	0.00	0.00	0.00	0.00	0.00	100.00	0.00	0.00	0.00	0.00	detailed (approx 1 sensors per m^2)	
20	251.83	820.39	823.45	206595.91	0.00	0.00	0.00	0.00	0.00	0.00	9.99	90.01	0.00	0.00	detailed (approx 1 sensors per m^2)	
21	257.02	788.80	804.38	202736.13	0.00	0.00	0.00	0.00	0.00	7.33	30.73	61.94	0.00	0.00	detailed (approx 1 sensors per m^2)	
22	60.79	610.02	611.12	37080.52	0.00	0.00	0.00	0.00	1.68	98.32	0.00	0.00	0.00	0.00	detailed (approx 1 sensors per m^2)	
23	647.62	775.77	782.86	502403.11	0.00	0.00	0.00	0.00	0.00	1.07	67.73	31.20	0.00	0.00	detailed (approx 1 sensors per m^2)	
24	10.18	402.53	400.50	4099.78	0.00	0.00	0.00	95.38	4.62	0.00	0.00	0.00	0.00	0.00	detailed (approx 1 sensors per m^2)	
25	54.03	626.84	643.89	33865.60	0.00	0.00	0.00	4.43	6.16	85.61	3.79	0.00	0.00	0.00	detailed (approx 1 sensors per m^2)	
26	237.46	455.64	450.53	108197.75	0.00	0.00	0.00	54.31	45.69	0.00	0.00	0.00	0.00	0.00	detailed (approx 1 sensors per m^2)	
27	94.62	404.32	402.11	38255.85	0.00	0.00	0.00	98.16	1.84	0.00	0.00	0.00	0.00	0.00	detailed (approx 1 sensors per m^2)	
28	93.41	349.28	348.02	32625.78	0.00	0.00	33.66	66.34	0.00	0.00	0.00	0.00	0.00	0.00	detailed (approx 1 sensors per m^2)	
29	1229.96	349.60	348.12	429996.15	0.00	0.00	32.25	67.75	0.00	0.00	0.00	0.00	0.00	0.00	detailed (approx 1 sensors per m^2)	

Highlight

Export as CSV | Load all | Open results | Clear table | Close

Figure 18. Example of the report generated by DL-Light Watt after an analysis. Screenshot taken from DL-Light on Sketchup.

3.2 Solar Analysis Scenarios

The solar analysis covers three scenarios for this study (Figure 19): a current scenario that will set the baseline, plus two alternate future scenarios for the project proposal assuming that it will be developed by the year 2030.

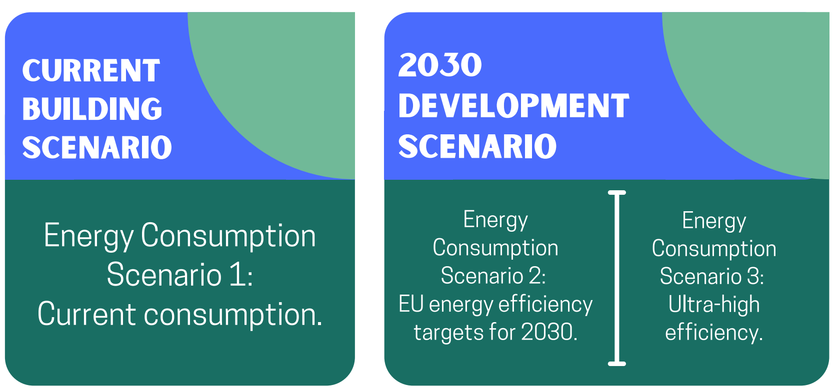


Figure 19. Scenarios used in the analysis.

The current scenario used as baseline, named **scenario 1,** considers the solar power potential that the project has in its current state with its existing buildings; its energy consumption and PV efficiency data is estimated based on existing data and current trends. The two future scenarios, **scenarios 2 and 3,** share most of their characteristics—considering that the design proposal is to be finished around the year 2030—meaning that the same solar irradiation estimations apply for both of them, plus they share the same PV efficiency estimations; they vary solely in the energy consumption of the buildings. The first of the future scenarios, **scenario 2**, bases its energy consumption on the assumption that the EU energy efficiency target minimum expected for the year 2030 has been met (European Union, 2021), this means that there is at least a 32.5% reduction on energy consumption. The last scenario, named **scenario 3**, considers that the buildings will be extremely efficient and passive buildings handling an extremely low energy consumption due to a solar passive design for heating and lighting, energy efficient technology and advanced insulation and sealing technologies that would lower the demand for energy-consuming heating to extremely low levels. The latter energy consumption scenario would be the ideal, radical change needed in future building developments to ensure that the climate action targets are met effectively and even exceed expectations.

Beside the mentioned scenarios, another solar irradiation analysis was run for the Site, based on the design proposal model, but this simulation only considers the direct radiation that the buildings receive, without considering interreflections. This simulation was run to analyze the impact that the buildings themselves have between each other to increase the amount of solar energy that they receive, demonstrating the importance of considering dense urban centers for the production of solar energy and creating PEDs.

3.2.1 PV efficiency

As mentioned in the theory, two types of PV systems are considered for this project: monocrystalline PV cells installed in the solid surfaces of the buildings and transparent PV cells for the windows. Besides the efficiencies chosen for the two types of PV cells, some multipliers are considered to make the efficiency of the cells more realistic (Coley, 2008). These multipliers or reduction factors (Table 1) are applied to consider the losses that are derived from cables, from the efficiency of the inverters and the loss of efficiency due to the temperature rise of the cells due to solar exposure (which is not considered a very high loss due to the relatively average cold temperatures of the area).

Multipliers	
Losses from cables	0.98
Inverter efficiency	0.98
Operating temperature	0.95

Table 1. PV efficiency reduction factors. (Coley, 2008)

By using the multipliers, the adjusted efficiency percentage for the current scenario was finally determined (Table 2). This adjusted number was ultimately used to determine the potential the project currently has to generate solar power.

PV Type	Current Efficiency	Current Adjusted Efficiency
Mono-crystalline	0.20	0.182
Transparent	0.07	0.064

Table 2. Current PV efficiency values used in calculations.

Assuming the same multipliers for the future scenarios, the adjusted efficiency percentage for was finally determined (Table 3). This adjusted number was ultimately used to determine the potential the project could have in 2030 to generate solar power.

PV Type	2030 Efficiency	2030 Adjusted Efficiency
Mono-crystalline	0.30	0.274
Transparent	0.13	0.119

Table 3. 2030 PV efficiency values used in calculations.

3.2.2 Energy Consumption

As mentioned before, three different energy consumption scenarios are used in the study. The baseline of annual energy consumption used in the calculations is of 228 kWh/m^2. This number is based on Norwegian statistical data obtained for the year 2011 for offices and business buildings (ssb.no, 2021), this is the last year that the statistic is available, nevertheless it works as the EU energy efficiency targets for 2020 and 2030 were set in the year 2012 (European Union, 2021).

For the number used to estimate the average energy consumption of scenario 1, it is assumed that the EU 20% energy efficiency target has been met. This could be achieved through various methods like replacing lighting to LEDs, using energy efficient office equipment, improvements in insulation and proper energy management. Based on this, the current average yearly energy consumption for the buildings has been estimated at **180 kWh/m^2** for scenario 1. Some exceptions have been applied to some of the buildings (see Table 9), for example building KB6 is a factory so a higher energy consumption is estimated, on the other hand KB1 is mainly a storage area so a lower energy consumption is considered.

For scenario 2, the EU energy efficiency target for the year 2030 indicates that a minimum of 32.5% improvement in energy efficiency must be met. Based on the 2011 baseline, this means that for scenario 2 the building average minimum yearly energy consumption for the year 2030 should be 155 kWh/m^2. However, for this scenario a more optimistic outcome has been determined based on Smedvig's vision of creating a highly sustainable project; it is assumed that high efficiency will lead to an improvement of 50% from the 2011 baseline, leading to an average yearly energy consumption of **120 kWh/m^2** for scenario 2.

Scenario 3, the second scenario for 2030, comprises an ultra-high energy efficiency scenario, which is considered to be the ideal one with current necessities for radical change. This scenario considers that the buildings would have very high energy efficiency, assuming also that the current necessities will lead to unprecedented related technological advancements and innovation in the next decade. This goal could be achieved through advanced insulation technologies, ultra-low energy consumption equipment, utilizing passive solar design and ventilation, smart energy management through Building Energy Management Systems (BEMS) etc. In this scenario, the new buildings (built with state-of-the-art building technology and materials) would achieve annual average energy consumptions as low as **70 kWh/m^2**. For existing buildings that will not be replaced, it is assumed that they will be renovated and retrofitted using the aforementioned advancements in technology, helping them achieve annual average energy consumptions as low as **90 kWh/m^2**.

To further support the possibility of achieving the high efficiency scenario 3, some energy simulations that were actually run by the company Veni were used as reference. The detailed simulations demonstrate that some of the new buildings could achieve annual energy consumptions as low as 60 kWh/m^2. The energy simulations for the new buildings were limited though, as they were only run for the buildings KB10, KB16 and KB18, resulting in annual energy consumptions of 68.9, 64.4 and 77.0 kWh/m^2 respectively. Besides this, a simulation was run for building KB14 (which is not in the plans to be expanded or replaced) where it could be retrofitted to achieve an annual energy consumption of 60.4 kWh/m^2. The report details many of the characteristics needed to achieve the low energy consumption, including data of the insulation values that would be necessary to reduce greatly the demand for heating in the cold months (Figure 20).

Dokumentasjon av sentrale inndata (1)		
Beskrivelse	Verdi	Dokumentasjon
Areal yttervegger [m²]:	1245	
Areal tak [m²]:	1330	
Areal gulv [m²]:	1366	
Areal vinduer og ytterdører [m²]:	510	
Oppvarmet bruksareal (BRA) [m²]:	6550	
Oppvarmet luftvolum [m³]:	20027	
U-verdi yttervegger [W/m²K]	0,23	
U-verdi tak [W/m²K]	0,18	
U-verdi gulv [W/m²K]	0,15	
U-verdi vinduer og ytterdører [W/m²K]	0,80	
Areal vinduer og dører delt på bruksareal [%]	7,8	
Normalisert kuldebroverdi [W/m²K]:	0,06	
Normalisert varmekapasitet [Wh/m²K]	79	
Lekkasjetall (n50) [1/h]:	0,70	
Temperaturvirkningsgr. varmegjenvinner [%]:	83	

Figure 20. Sample of the Veni report for input data to estimate a retrofitting that would yield a low energy consumption for building KB14, including U-Values and leakage number. (Bårdsen, 2021)

3.3 Energy calculations

3.3.1 Solar power generation potential

With the total solar irradiation data gathered for each building, and the PV efficiency estimation, the power generation potential for the project scenarios could finally be calculated, however some additional factors were first determined.

While the total solar irradiation was calculated for 100% of the external surfaces, logically this percentage cannot be considered to be completely covered in PV cells. A percentage of usable surfaces was estimated for each building, considering many factors like space needed for other HVAC and maintenance equipment, the accommodation of rooftop solar panels, and surfaces that could not be utilized like doors and first floor areas that never receive sunlight. Based on this, the surface percentage available for PV was estimated on average between 50% to 80% of the building surfaces. The total solar irradiation received by each building was then multiplied by this percentage to obtain an estimate of the true available solar irradiation.

Another important factor to determine is the percentage of windows that each building has. For the current state of the buildings, Google Earth was used to take exact measurements of the windows to determine the percentage from the total area. For the proposal model the estimates were taken from the realistic renders created by MAD, while comparing these numbers to the Google Earth obtained data to determine how realistic these percentages are.

With these two factors determined, the amount of solar power that can be potentially generated can finally be calculated. To obtain this number for each building, the area of solid surfaces is multiplied by the adjusted efficiency of monocrystalline PV cells and then added to the area of window surface multiplied by the adjusted efficiency of transparent PV cells. The formula used is the following:

$$P_S = (SI_A \times A_s \times E_m) + (SI_A \times A_w \times E_t) \quad (1)$$

Where:

- P_S : Total annual solar power generated (kWh)
- SI_A : Total available annual solar irradiation (kWh)

- A_S : Percentage of solid surfaces
- A_W : Percentage of window surfaces
- E_m : Adjusted efficiency of monocrystalline PV cells
- E_t : Adjusted efficiency of transparent PV cells

By using this formula, it was possible to obtain the potential solar power that each of the buildings could generate in a year.

3.3.2 Net energy balance calculation

Finally, with the total solar power generation potential as well as the energy consumption of the buildings estimated, it was possible to calculate the net energy balance for the buildings and the site as a whole. The calculation is pretty simple, as the energy balance for each building is calculated by subtracting the annual solar power generated total minus the annual energy consumption. If the result is negative it means that the solar power that the building generates is not enough to cover the annual energy needs, however, some of the other buildings with excess power production could compensate for the need of other buildings. By adding all of the energy balances a final number is achieved that will determine if it is possible for the whole site to be net zero energy or even better, a positive energy district.

4. Results

4.1 Solar irradiation results

After running all the necessary simulations, Table 4 summarizes the data gathered for each month for the whole Site 4016 for both the current and future scenario, then, the annual total and average solar irradiation on building surfaces were calculated. The table was color coded to compare the variation in the irradiation throughout the year.

	Current		Proposal	
	Total Solar Irradiation on building surfaces (GWh)	Average Solar Irradiation on building surfaces (kWh/m2)	Total Solar Irradiation on building surfaces (GWh)	Average Solar Irradiation on building surfaces (kWh/m2)
Annual	**44.95**	**714.7**	**65.22**	**548.9**
Jan	0.57	9.02	0.81	6.78
Feb	1.26	20.07	1.81	15.21
Mar	3.26	51.79	4.71	39.68
Apr	5.46	86.82	7.96	67.03
May	7.13	113.31	10.37	87.24
Jun	7.72	122.81	11.20	94.30
Jul	7.22	114.76	10.51	88.42
Aug	5.56	88.32	8.07	67.95
Sep	3.74	59.53	5.43	45.72
Oct	2.00	31.84	2.88	24.21
Nov	0.74	11.72	1.05	8.84
Dec	0.30	4.71	0.42	3.55

Table 4. Summary of the annual solar irradiation received by Site 4016 both currently and with the development proposal.

By observing the data obtained for each month, it is clearly concluded that the results for each month agree with the weather conditions that each of those months present: the winter months receive very little solar irradiation and the summer months receive much higher amounts of sun.

When comparing the data gathered for the current conditions against the proposed development, significant differences can be observed. First of all, there is a clear difference on the average solar irradiation received per m^2, the average amount is reduced significantly between the current conditions and the proposal, between 23-25% for each month. This can be deduced to be caused by the shade that the buildings with higher height cause on each other and on the smaller buildings. This effect demonstrates the importance that the building's orientation, height and position regarding each other has on the potential to generate solar power in denser urban areas, especially in northern latitude locations like in this case, making it an important urban planning and design parameter. This argument is further discussed in section 5.

Regardless of this reduction in average solar irradiation, the development proposal has a significantly higher surface area that may receive solar energy, thus it is clear that the total solar irradiation that it receives in a year is much higher. While the total surface area of the site increases by 88% with the proposal, the total solar irradiation calculated increased by 42-46% each month only. This information further supports the importance of building orientation, height and position regarding each other, as with less shading between each other there could be an even higher potential to generate solar energy.

A false color render was also generated for the average annual solar irradiation received by both the current (Figures 21 and 22) and the development proposal (Figures 23 and 24), from a southeastern and a northwestern point of view. The render generated for each month is presented in Appendix A. This render clearly demonstrates the obvious fact that in northern latitudes like Norway, the southern-facing façades receive most of the solar irradiation. The eastern and western façades receive less yet still significant amounts of irradiation, especially in the summer months. The northern façade is the less efficient one, receiving almost no solar irradiation, and relying mainly of that is received through reflectance from other buildings and diffuse irradiation.

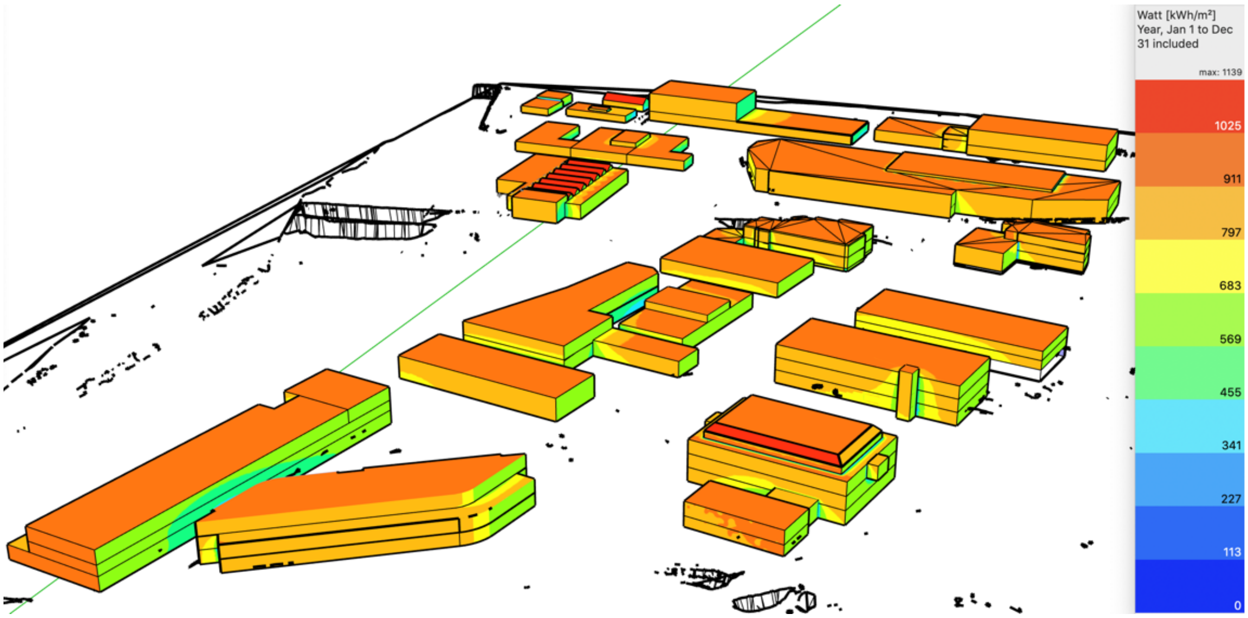


Figure 21. DL Light analysis results for the current scenario of Site 4016, average annual solar irradiance (kWh/m2), view of the south and east facing façades. Screenshot from Sketchup.

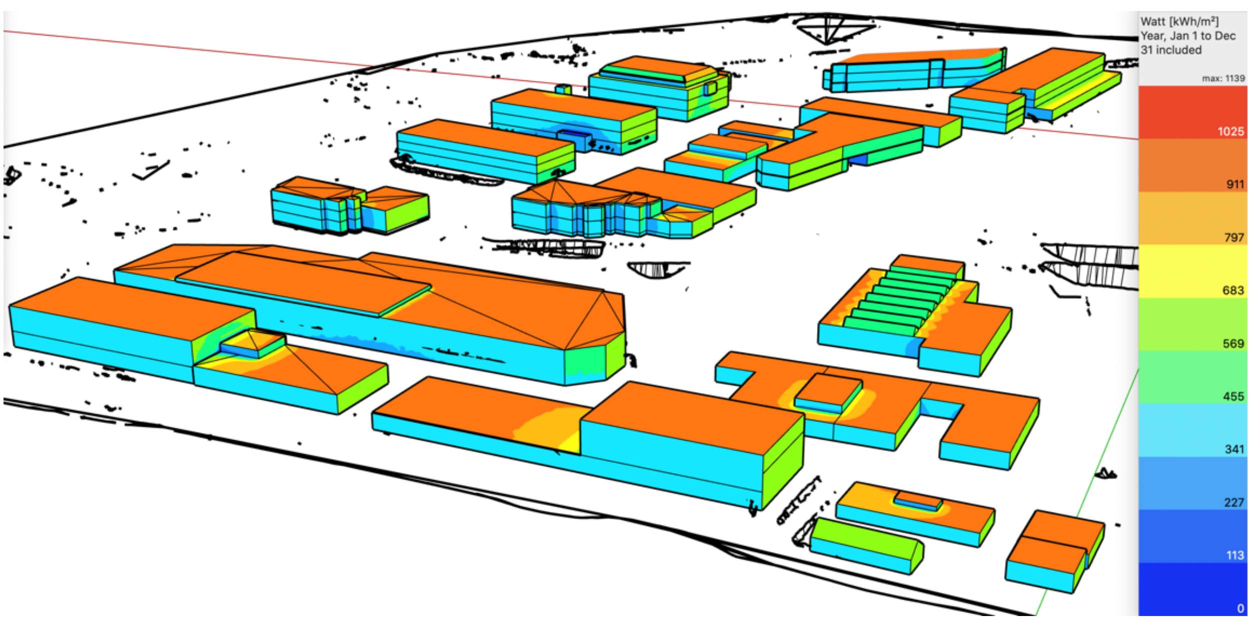


Figure 22. DL Light analysis results for the current scenario of Site 4016, average annual solar irradiance (kWh/m2), view of the north and west facing façades. Screenshot from Sketchup.

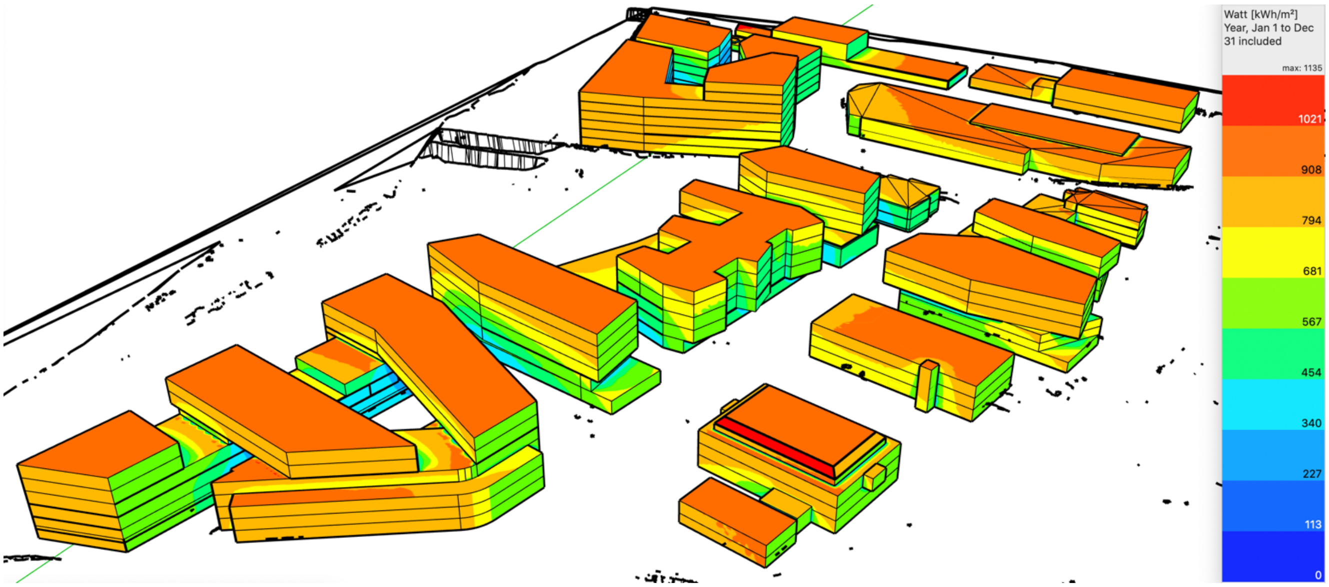


Figure 23. DL Light analysis results for the 2030 development scenario of Site 4016, average annual solar irradiance (kWh/m2), view of the south and east facing façades. Screenshot from Sketchup.

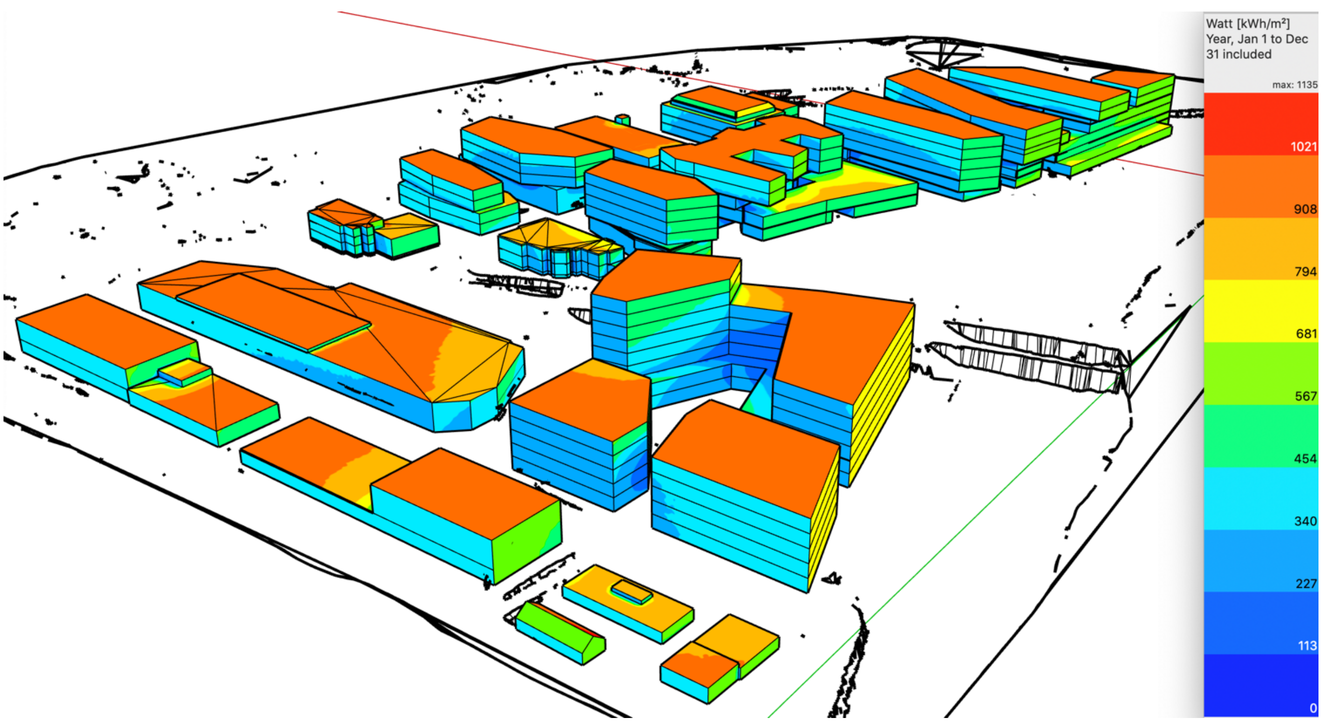


Figure 24. DL Light analysis results for the 2030 development scenario of Site 4016, average annual solar irradiance (kWh/m2), view of the north and west facing façades. Screenshot from Sketchup.

The data gathered was also organized by the irradiation that every building received for both scenarios. Table 5 shows this data, for each building presented in the table there are two values: the top value is for the current scenario and the lower value corresponds to the development proposal. The final column shows the difference between the average solar irradiation values between the current and the development proposal. It is clear that the buildings in the western section of the site are the most affected ones, as this section is where most of the densification would take place, and with the proposed alignment the buildings would cast a lot of shadow upon each other. KB9 is the building most affected by reduction in average irradiation, as it has a new building directly south and directly east of it that could block a significant amount of sunlight.

Building Name	Surface Area (m2)	Total Annual Solar Irradiation (kWh)	Average Annual Solar Irradiation (kWh/m2)	Percentage Reduction
KB1	1667.8	1183376	709.5	8.5%
	1667.8	1082619	649.1	
KB2	4044.7	3104899	767.6	5.3%
	4044.7	2940396	727.0	
KB3	1383.8	1036292	748.9	1.7%
	1383.8	1019015	736.4	
KB4	2959.4	2166161	732.0	0.4%
	2959.4	2157664	729.1	
KB5	3100.0	2485957	801.9	23.9%
	8109.0	4947478	610.1	
KB6	3672.8	2723506	741.5	35.9%
	16758.2	7962356	475.1	
KB7	10320.5	7095770	687.5	3.9%
	10320.5	6819304	660.8	
KB8	2268.9	1545251	681.1	22.2%
	2268.9	1201596	529.6	
KB9	1794.8	1459605	813.3	50.3%
	6805.1	2752437	404.5	
KB10	6017.9	4348437	722.6	33.7%
	12894.4	6176056	479.0	
KB11	2081.0	1616520	776.8	21.8%
	6511.1	3956655	607.7	

KB12	10070.1	7190076	714.0	24.6%
	22230.0	11966570	538.3	
KB13	916.7	673561	734.8	2.0%
	916.7	660275	720.3	
KB14	4763.1	2772153	582.0	3.1%
	4763.1	2686936	564.1	
KB15	3609.7	2455691	680.3	6.5%
	3609.7	2296774	636.3	
KB16	2580.3	1915613	742.4	14.0%
	5234.4	3340841	638.2	
KB17	2008.4	1392769	693.5	7.8%
	2008.4	1284277	639.4	
KB18 (New building)	-	-	-	-
	3964.7	1969904	496.9	

Table 5. Irradiation data for the site buildings, for each building the top blue value represents the current scenario and the lower white value the future development scenario.

4.2 Solar power generation

With the solar irradiation information compiled, and other factors estimated like percentage of windows and percentage of surfaces available, the total annual solar power generated was calculated by using formula (1) described in section 3.3.1. Table 6 presents the data calculated for the current scenario while Table 7 presents the date calculated for the future development scenario.

Building Name	Surfaces Available for PV (%)	Percentage of Windows (%)	Total Available Annual Solar Irradiation (kWh)	Total Current Annual Solar Power Generated (kWh)
KB1	50	5	591688	104460
KB2	80	20	2483919	394332
KB3	80	33	829034	118829
KB4	80	30	1732929	254555
KB5	50	5	1242978	219442
KB6	50	5	1361753	240411
KB7	70	5	4967039	876908
KB8	80	30	1236200	181589

KB9	80	10	1167684	199224
KB10	80	30	3478750	511005
KB11	80	30	1293216	189965
KB12	80	45	5752061	742601
KB13	70	30	471493	69259
KB14	80	20	2217722	352073
KB15	80	25	1964553	300230
KB16	70	40	1340929	181069
KB17	80	40	1114215	150455
Total			**33246163**	**5086409**

Table 6. Solar power generation calculations for the current scenario.

Building Name	Percentage of Surfaces Available for PV	Percentage of Windows	Total Available Annual Solar Irradiance (kWh)	2030 Total Annual Solar Power Generated (kWh)
KB1	50	5	541309	143966
KB2	80	40	2352317	497920
KB3	80	40	815212	172558
KB4	80	40	1726131	365374
KB5	80	45	3957982	807100
KB6	80	40	6369885	1348327
KB7	70	5	4773512	1269558
KB8	80	30	961277	218385
KB9	80	55	2201950	414862
KB10	80	45	4940845	1007522
KB11	80	60	3165324	571820
KB12	80	50	9573256	1877906
KB13	70	30	462192	105002
KB14	80	20	2149549	521681
KB15	80	30	1837419	417430
KB16	80	40	2672673	565730
KB17	80	40	1027422	217477
KB18	80	40	1575923	333579
Total			**51104179**	**10856195**

Table 7. Solar power generation calculations for the 2030 scenario.

Finally, Table 8 summarizes the total data results from the previous tables in GWh.

	Total Available Annual Solar Irradiance (GWh)	Total Annual Solar Power Generated (GWh)
Current Scenario	**33.25**	**5.09**
2030 Scenario	**51.10**	**10.86**

Table 8. Summary of solar power generation for both scenarios.

Both scenario results demonstrate that the potential to generate solar power is high, especially for the development proposal scenario, which could generate double the power than the current scenario. This is obviously attributed to there being much more surface area that can be taken advantage of to install PV cells. It is important to point out that this calculation considers the installation of PV cells in the northern façades too to take advantage of interreflection and diffuse solar irradiation, however it is important to analyze further if it is really viable to install PV cells in the northern façades, as from a cost-benefit point of view it may not be economically feasible.

4.3 Building energy consumption

To obtain the final net energy balance, the energy consumption of the buildings was calculated according to the method described in section 3.2.2 for the three energy consumption scenarios. Tables 9, 10 and 11 represent the energy consumption data for scenarios 1, 2 and 3 respectively.

Building Name	Average Energy Consumption for Scenario 1 (kWh/m2)	Total floor area (m2)	Total Annual Energy Consumption for Scenario 1 (kWh)
KB1	150	714	107100
KB2	180	3967	714132
KB3	180	2300	414000
KB4	180	3693	664740
KB5	180	1960	352800

KB6	215	2012	432580
KB7	180	10600	1908000
KB8	180	1479	266220
KB9	200	2288	457600
KB10	180	4035	726300
KB11	180	2090	376200
KB12	180	11961	2152980
KB13	180	640	115200
KB14	180	4866	875880
KB15	180	3791	682380
KB16	180	3723	670140
KB17	180	1691	304380
Total		**61810**	**11220632**

Table 9. Energy consumption data for scenario 1, based on the current state of the buildings.

Table 9 demonstrates that currently the site is an energy intensive site, as it is estimated to consume up to 11.22 GWh per year. This points out the importance of taking measures to furthermore increase energy efficiency, like improving insulation and promoting energy saving practices and technologies.

Building Name	Average Energy Consumption for Scenario 2 (kWh/m2)	Total floor area (m2)	Total Annual Energy Consumption for Scenario 2 (kWh)
KB1	120	714	85680
KB2	120	3967	476088
KB3	120	2300	276000
KB4	120	3693	443160
KB5	120	11820	1418400
KB6	120	21695	2603400
KB7	120	10600	1272000
KB8	120	1479	177480
KB9	120	6064	727680
KB10	120	11671	1400520
KB11	120	8362	1003440
KB12	120	23503	2820360
KB13	120	640	76800
KB14	120	4866	583920

KB15	120	3791	454920
KB16	120	7792	935040
KB17	120	1691	202920
KB18	120	3477	417240
Total		**128125**	**15375048**

Table 10. Energy consumption data for scenario 2, based on the proposed development of the buildings for 2030.

As seen in Table 10, for the energy consumption data for scenario 2 the energy consumption has been increased by 30%. Regardless of this obvious increase in consumption, the increase in energy efficiency is reflected, as the floor area of the project has been doubled in comparison to the current state of the site.

Building Name	Average Energy Consumption for Scenario 3 (kWh/m2)	Total floor area (m2)	Total Annual Energy Consumption for Scenario 3 (kWh)
KB1	90	714	64260
KB2	90	3967	357066
KB3	90	2300	207000
KB4	90	3693	332370
KB5	70	11820	827400
KB6	70	21695	1518650
KB7	90	10600	954000
KB8	90	1479	133110
KB9	70	6064	424480
KB10	68.9*	11671	804132
KB11	70	8362	585340
KB12	70	23503	1645210
KB13	90	640	57600
KB14	60.4*	4866	293906
KB15	90	3791	341190
KB16	64.4*	7792	501805
KB17	90	1691	152190
KB18	77.0*	3477	267729
Total		**128125**	**9467438**

*Table 11. Energy consumption data for scenario 2, based on the proposed development of the buildings for 2030. *Data obtained from energy consumption simulations ran by Veni.*

In the ultra-high energy efficiency scenario 3 seen in Table 11, it can be observed that a very low total energy consumption can be achieved for the site. Even in this scenario where the floor area is doubled from the current building scenario, energy consumption is 15% less than that scenario, showing the energy efficiency possibility.

Table 12 summarizes in GWh the annual energy consumption for the three presented energy consumption scenarios.

	Scenario 1	Scenario 2	Scenario 3
Total Annual Energy Consumption (GWh)	**11.22**	**15.38**	**9.47**

Table 12. Summary of energy consumption of the three scenarios.

4.4 Net Energy Balance

Finally, with all the data gathered and the calculations done, the net energy balance for each of the scenarios can be obtained. Table 13 summarizes the data obtained. It can be observed that Scenario 3 would be the ideal scenario, where a positive energy district can be achieved, covering the energy necessities for Site 4016 and generating an additional 1.39 GWh of solar power that could be returned to the grid.

	Current Scenario	2030 Development Scenarios	
	Scenario 1	**Scenario 2**	**Scenario 3**
Total Annual Energy Consumption (GWh)	11.22	15.38	9.47
Total Annual Solar Power Generated (GWh)	5.09	10.86	10.86
Net Energy Balance (GWh)	**-6.13**	**-4.52**	**1.39**
% of Energy Consumption Covered by Solar Power	45.3%	70.6%	114.7%

Table 13. Summary of the net energy balance for the multiple scenarios.

4.5 Solar irradiation analysis without interreflections

The Watt analysis tool from DL-Light also has the option to run simulations that only consider the direct solar irradiation that building surfaces may receive on a given time without the irradiance received by the interreflections caused by the surrounding other buildings. By running such an analysis on the future development design model, it is possible to compare the results to determine what share of the total solar irradiance is actually attributed to these interreflections. Table 14 compares the solar irradiance results obtained from the direct light analysis to the previous analysis results that do consider interreflections. For each building the top value considers interreflections and the bottom value only direct solar irradiance.

Building Name	Total Annual solar Irradiation (kWh)	Average Annual Solar Irradiation (kWh/m2)	Irradiation difference %
KB1	1082619	649.1	12.9%
	943257	565.6	
KB2	2940396	727.0	9.8%
	2651109	655.5	
KB3	1019015	736.4	9.5%
	921862	666.2	
KB4	2157664	729.1	10.9%
	1923341	649.9	
KB5	4947478	610.1	15.7%
	4173158	514.6	
KB6	7962356	475.1	15.2%
	6748535	402.7	
KB7	6819304	660.8	8.7%
	6226175	603.3	
KB8	1201596	529.6	18.4%
	980684	432.2	
KB9	2752437	404.5	17.9%
	2260329	332.2	
KB10	6176056	479.0	19.4%
	4980645	386.3	
KB11	3956655	607.7	19.7%
	3176851	487.9	
KB12	11966570	538.3	20.7%
	9494849	427.1	

KB13	660275	720.3	17.0%
	547941	597.7	
KB14	2686936	564.1	16.4%
	2245844	471.5	
KB15	2296774	636.3	15.3%
	1945082	538.9	
KB16	3340841	638.2	16.5%
	2787981	532.6	
KB17	1284277	639.4	17.5%
	1060026	527.8	
KB18 (New building)	1969904	496.9	17.1%
	1633953	412.1	
Total	**65221153**		**16.1%**
	54701623		

Table 14. Comparison of solar irradiance analysis for Site 4016. For each building the top value considers interreflections and the bottom value only direct irradiance.

From the analysis there is clear evidence that building interreflections represent a significant amount of the solar irradiation that the surfaces receive, between 8-20% for the different buildings and 16.1% in total for the whole project. Such percentage, depending on the development, could mean the difference of the site achieving net-zero energy or even a positive energy status.

This hypothetical case of not considering interreflections could also be interpreted by analyzing how the solar power production could change without interreflections. Table 15 summarizes the result of the hypothetical energy production and energy balance, based on the scenario 3 annual energy consumption estimation of 9.47 GWh. It can be determined then with the energy balances that for this case interreflections do indeed have an important place in helping achieve a positive energy district, making it an important design parameter to consider.

	Total Annual Solar Power Generated (GWh)	Net Energy Balance (GWh)
With Interreflections	**10.86**	**1.39**
Direct Irradiation Only	**9.12**	**-0.34**

Table 15. Energy balance comparison between only direct irradiance and considering interreflections. Energy consumption data based on scenario 3.

4.6 Solar irradiation on the north-facing façades

It is a well-known fact that in northern latitude locations, north-facing façades receive a minimal amount of direct sunlight most of the year, especially in the winter months, and this was further confirmed through the solar irradiation analysis (Figure 25). As seen in the figure, for this analysis only façades that were completely facing north were considered, as some that were somewhat inclined to the east or west still have more potential to receive a higher solar irradiation amount.

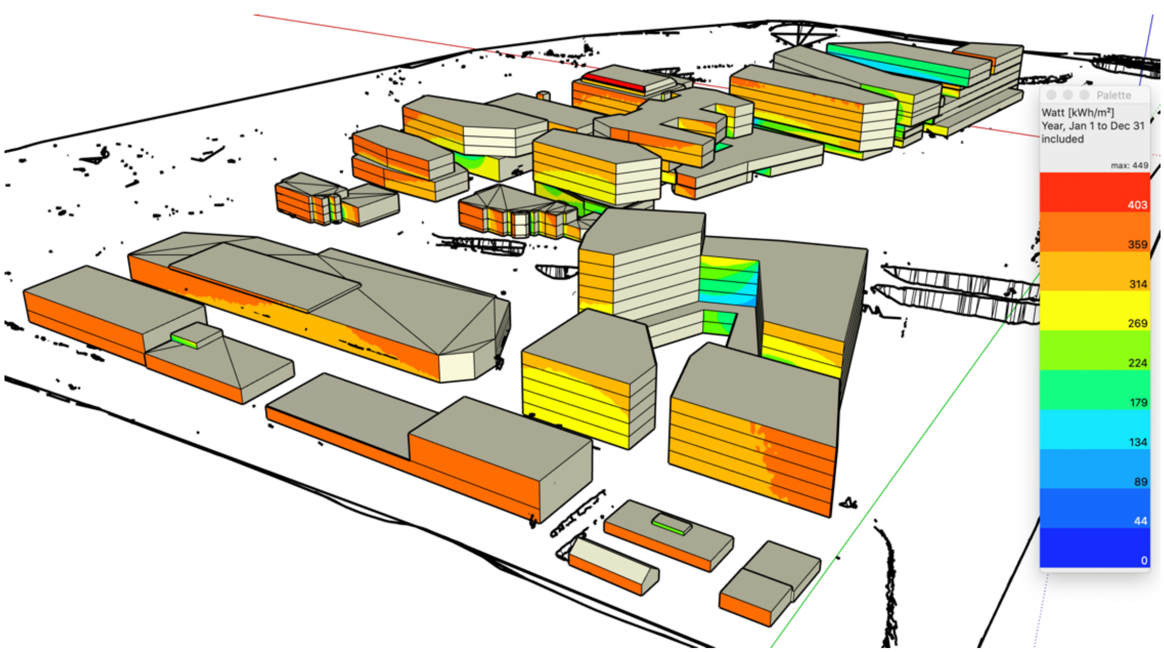


Figure 25. North-facing façades considered in the analysis. Screenshot taken on Sketchup.

Through the analysis it was determined that in a year these north-facing façades only receive 5.28 GWh of solar irradiation, this only represents 8% of all the solar irradiation that the whole site would receive in a year. Based on the results from section 4.5, this amount of solar irradiance probably is facilitated by interreflections from other buildings that can facilitate for the solar light to reach the north façades. Table 16 summarizes and compares the energy data for the whole site vs not considering the north-facing façades, with energy consumption data being based on scenario 3.

	Total Annual Solar Irradiation GWh	Total Annual Solar Power Generated (GWh)	Net Energy Balance (GWh)
All Façades	**65.22**	**10.86**	**1.39**
Without North-facing Façades	**59.95**	**9.99**	**0.52**

Table 16. Energy data comparison for the north-facing façades, energy consumption based on scenario 3.

It can be observed from the table that even without considering the north-facing façades for solar PV power production, the site can still achieve a positive energy status. This is an important factor to consider in the design, as this data demonstrates that it would not be cost-effective to install PV panels in these north-facing façades with such a low yield. This case may not always apply to other situations, as this minor difference in solar power production could define if a development could achieve a positive energy state or not.

5. Analysis

5.1 Energy calculations result analysis

As seen in the results section, the future energy estimations for Site 4016 show that there is potential for the project to become a PED with an efficient solar PV integration and highly energy efficient buildings. It was estimated that the site currently has a potential to generate up to **5 GWh (5 000 000 kWh)** of solar power in a year, however, by densifying the area and with the future expected increase in PV efficiencies, the possibility of generating double that power can be achieved, up to **10.9 GWh (10 900 00 kWh)** of solar power could be generated in a year by 2030. By considering a minimum of expected energy efficiency for the site by 2030, this solar potential could be enough to cover 70% of the site's energy consumption, which is a very high percentage, resulting in a net annual energy consumption of **4.5 GWh (4 500 00 kWh)**. If the energy consumption is further expanded to an ultra-high energy efficiency scenario, the energy needs of the site would be completely met by the locally produced solar power and would additionally generate up to **1.4 GWh (1 400 000 kWh)** of energy that would be returned to the energy grid, effectively proving the possibility of achieving a positive energy district for Site 4016.

For the development scenario, the amount of power generated per m^2 was calculated to verify how realistic the data result is. It was determined that this potential resulted in 93 kWh/m^2, however the northern façades could prove to create a disbalance as the energy generated per m^2 proportion is relatively low. By calculating the value only for the south, east and west facing façades, the resulting value is of 141 kWh/m^2. This potential value seems on an acceptable range if compared to results from other case studies in Norway, for example a result of 132 kWh/m^2 in Oslo (Gholami & Røstvik, 2020).

5.1.1 BIPV Economic Feasibility

The energy analysis demonstrates that building integrated photovoltaics in Site 4016's façades play a major role in achieving these energy results, and the site cannot solely rely on PVs installed on the roofs. From the solar analysis data, it was determined that there is a 50-50 share of the solar irradiance that the buildings received between horizontal surfaces and façades, this ensures that the project design must consider without a doubt integrating BIPV into the façades if a positive or net zero energy design is meant to be achieved.

Integrating PVs into most of the façades would consequently result in much higher project costs, however, a methodology that has been created to perform a life-cycle cost analysis (LCCA) on BIPV systems proves through some case-studies that integrating PV systems into façades can prove to be economically advantageous, even considering environmental and societal consequences (Gholami, Røstvik, & Müller-Eie, 2019). Furthermore, the methodology has been also applied on a case from Norway, and the results determined that BIPV systems replacing traditional construction materials could reimburse not only all the investment costs but also become a source of income for the buildings (Gholami H. , Røstvik, Kumar, & Chopra, 2020). This case study gives further support to the idea that creating a PED can be economically feasible for Site 4016, however, to have the true results a detailed economic feasibility analysis should take place.

The results presented in section 4.6 show that the solar power generation from PVs installed in the north-facing façades only represents 8% of the whole site's potential to generate power. This low yield compared to the significant surface area that it represents means that it is probably not economically feasible to install BIPVs in the north-facing façades. This is not always the case, as some economic analyses using the LCCA methodology have demonstrated that the north façades of buildings in some European countries have proven to be able to refund the investment (Gholami & Røstvik, 2020). This affirmation includes Norway; however, Norway's total income from electricity production minus O&M and inverter replacement cost for northern façades is relatively low (€11/m^2) compared to other European countries like Belgium (€150/m^2) and Denmark (€143/m^2) (Gholami & Røstvik, 2020, p. 11), this could result on the investment being an unnecessary risk as the PED goal is still achieved when excluding the north-facing façades. Nevertheless, some select sections of the north-facing façades could be considered to include BIPV systems based on studying the solar analysis results for sections with higher than average solar irradiation, like KB5's western building and KB12's top sections. These select sections could help compensate for moments when the sun is positioned to the east or west and the opposing façades will receive very little sunlight. Another factor to take into consideration is diffuse radiation and interreflections, as most of the light that these north-facing façades would receive would come mainly from these two sources, so areas that could be prone to receive more reflected sunlight could be considered.

5.1.2 Building energy efficiency

A crucial factor in achieving the energy goals for the project is the efficiency in the consumption of energy in the buildings. As mentioned before, in order to be able to achieve a net-zero or positive energy balance, the buildings must be designed in a way to achieve energy consumptions low enough for the on-site solar power production to be able to cover this energy demand. There are multiple characteristics that can be adopted for buildings to achieve these very low energy consumptions, they can be mainly catalogued into prescriptive and performance characteristics, where prescriptive properties refer to properties of envelope components (e.g. U-values of walls and windows, air-tightness in pressurization test) and of HVAC systems (e.g. specific fan power, COP of heat pumps), while performance properties apply to energy needs (e.g. for heating, cooling, lighting) or total (weighted) primary energy demand (Sartori, Napolitano, & Voss, 2012).

It is crucial to ensure that the physical properties of the building envelope will help reduce the demand for heating or cooling. This can be achieved by using insulating materials for walls, roofs and windows with very low U-values (low thermal transmittance factors), as well as insulation for pipes and other technical equipment. Proper sealing will also ensure air-tightness of the building and will reduce heat losses through air leakage or prevent cold air from entering. Other strategies like well managed ventilation and treatment of thermal bridges can improve the conditions too (Isover, 2021).

As solar energy is the main driving force of this study, it is important to consider other uses it can have that can contribute to the energy goals besides PV power generation by considering how it can contribute to energy efficiency. A very important strategy that has to be integrated into the design of buildings is the utilization of a passive solar design to reduce the use of mechanically-aided and energy-dependent HVAC. The proper orientation and number of windows, especially in the southern-facing façades, would ensure that the sun can contribute as much heat as possible to the building through the greenhouse effect; this can be further taken advantage of through strategies like proper heat flow management and using thermal masses inside the building that can absorb the heat. A case study focused on bigger buildings (D'Agostino, Daraio, Marino, & Minichiello, 2018) determined that through a proper and cost-optimal passive design strategy, an energy saving between 7-13% can be achieved; another study is even more optimistic as it estimates that possible energy savings in Norway can reach up to 27.95% through passive design (Valladares-Rendón, Schmid, & Lo, 2017).

Solar energy can also be used in the project through solar thermal collectors, these could be used to warm water and air, further reducing energy demand. There are many types of solar collectors that can be used like flat plate, evacuated tube, line focus and point focus collectors (Energy Education, 2021). The main issue with using these collectors is the necessity for space to install them, usually in the roofs, which would mean sacrificing area that could be dedicated to PV panel installation. A way to solve this issue is considering the use of district heating for the site. The size of the site and the amount of buildings could mean that building a small district heating plant for the site could ensure a reduction in the energy demand for each individual building by centralizing the supply of HVAC, this would also reduce the cost and demand for HVAC equipment. This plant would of course have to base its generation of heat for the site on renewable sources, this is where the implementation of solar thermal collectors could prove useful. The thermal collectors would probably not be enough as the space is still limited but other renewable energy strategies could be implemented, like a combined heat and power generator that runs on biofuel and could also contribute to the site's renewable energy mix and energy grid stability. Another strategy would be to implement heat pumps that could take advantage of the nearby lake water, as Vannassen lake is located just 300 meters away from the site. Piping could be installed that would connect to the lake and utilize the water to create an efficient heat exchange, this is a strategy that is going to be implemented to the new government quarters in Oslo, where water from the fjord 1 km away is going to be used for the heat exchangers (Solberg, 2017). An environmental impact assessment would have to be considered for this strategy, as well as an overall detailed economic feasibility study would have to take place to consider the option of district heating for the site.

Another strategy to contribute to lower energy consumption on the site is the implementation of energy efficient technologies. This may be achieved by taking advantage of the very varied array of options available nowadays; this can include low energy consumption LED lighting that uses motion sensors and timers (using passive solar design would also reduce significantly the demand for artificial lighting), the use of energy efficient office equipment and replacing the use of desktop computers with laptops. A smart building energy management system (BEMS) could also be implemented to control efficiently building elements like HVAC, lighting, ventilation etc.

A proper utilization of a smart BEMS has been proved to lead to very significant savings in energy consumption, especially by managing the need for HVAC in the most efficient way (Rocha, Siddiqui, & Stadler, 2015).

As mentioned on section 3.2.2, through Veni's energy consumption simulations it was proven possible to be able to condition a building to have ultra-low energy consumption, even down to 60 kWh/m^2/year. To achieve this number, it was observed that in some cases some of the inputs used are somewhat extreme values. As an example, for the retrofitting of building KB14, the U-values used for the roof, floor, walls and windows were 0.18, 0.15, 0.23 and 0.8 W/m^2K respectively. These values, when compared to typical U-values for insulated materials from other sources (Aspire Bifolds, 2021) (DIY Data, 2021) (Designing Buildings Wiki, 2021), may seem very low though still relatively realistic to achieve, but could mean a very high cost to be able to achieve them, especially in an existing building being retrofitted. For example, the U-value of 0.8 W/m^2K used in the input for windows means that to reach this low value all the windows would probably have to be triple-glazed, low-E coated and with an argon or krypton cavity; windows with these characteristics are very expensive and considering the amount of windows in these buildings it could not be economically feasible, a more moderate solution could be considered like double-glazed windows that usually have a higher U-value of around 1.2 W/m^2K. The U-value of 0.06 W/m^2K for cold bridges seems to be realistic and achievable through adequate cold bridge treatment (Whale, 2016).

Based on the aforementioned factors it was determined that for Scenario 3 annual energy consumption estimations, a higher average value was going to be used: 70 kWh/m^2 for new buildings and 90 kWh/m^2 for retrofitted buildings. These values are still relatively low, but they are estimated considering the possibility that in the upcoming years insulation technology will improve and energy efficiency technologies in general will also improve and become more accessible.

5.2 The urban fabric and solar power

5.2.1 The solar city and the decentralized grid

By the year 2050 it is projected that two-thirds of the world population will be living in urban areas (UN, 2018), this will lead to a significant rise in the necessity for cost-effective renewable energy solutions. To help solve this, the urban fabric presents itself as a valuable resource that if carefully planned can become itself the energy source needed to sustain its growth with a reduced impact. This reshaping is a challenging approach that would take time to achieve, where implementing careful planning and the proper policies to push the change are crucial to its success. If this is successful, a city can be reshaped following the *solar city* model*,* a concept proposed by Byrne & Taminiau (2018): the city itself would be the power plant generating most of its energy based on a grid composed of positive energy districts, while still relying on the main grid and maintaining energy exchange with other solar cities to maintain grid stability. Given that the city would then consist of interconnected but independent parts that can continue operation, even when in-city connections fail, or when connection to the larger grid fails (Figure 26) (Byrne & Taminiau, 2018).

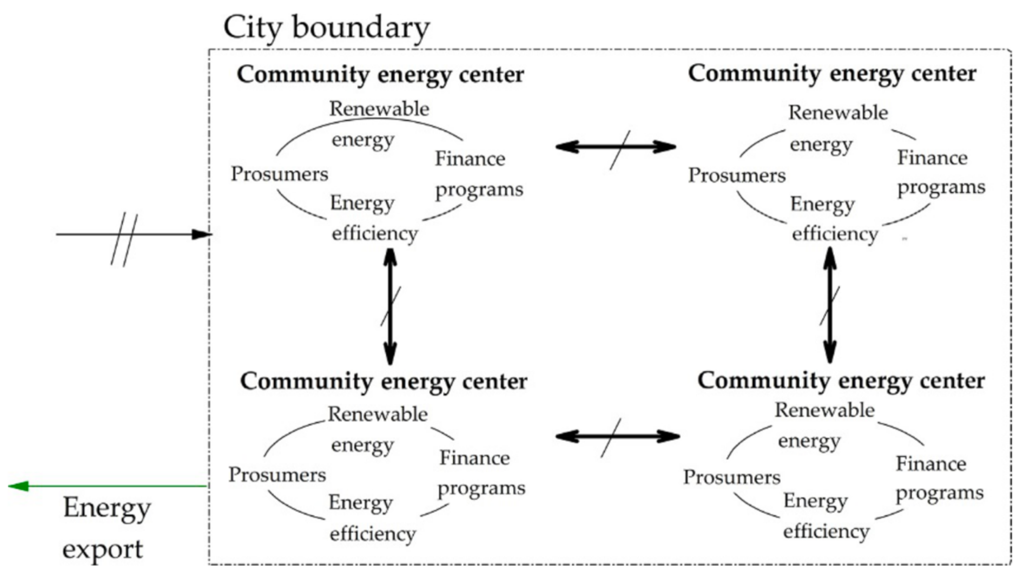


Figure 26. Simplified representation of the solar city concept, crosslines represent that disconnections could occur without disruption to function (Byrne & Taminiau, 2018).

Due to the intermittent nature of solar power generation, which may vary depending on the weather, the time of the day or year, it is important to ensure grid stability in this network of PEDs or NZEBs. This emphasizes the important of the necessity to create as much of these PEDs as possible to ensure a more reliant grid, its reliance due to the different districts that would have a constant energy exchange, as different parts of the city could have different moments where their performance is better due to the position of the sun at the moment as well as the energy demand of each of the districts varying at different moments. Further than that, an adequate integration of energy storage technologies like batteries and supercapacitors helps ensure supply and helps stabilize the intermittence. Stability could further be ensured by adapting other renewable sources of energy, for example a combined heat and power biofuel generator as mentioned in the previous section, or wind turbines. If the grid stability is not able to be covered solely by the aforementioned elements, the exchange of energy with other solar cities or the main grid (energy coming from renewable sources) would help ensure this grid stability. Thanks to the current advances in smart grid management complemented by data mining and machine learning technology, the management of this complex network of energy exchanges can be facilitated and pushed to higher efficiencies.

This transformation model does not only focus on sustainability but also on the improvement of the social situation of cities by answering for the lack of energy justice in most modern cities. The city reshaping would rely on active citizen participation, as citizens would be in charge of the generation and conservation of the energy (Byrne & Taminiau, 2018), the concept diagram on Figure 26 calls them prosumers, a portmanteau between consumers and producers. This active participation helps fight for energy justice in cities by integrating energy and due process into the system and helping fight energy poverty by making energy more accessible and affordable to its citizens (Sovacool & Dworkin, 2015).

5.2.2 Architectural and cultural considerations

With the resulting necessity to cover large percentages of surface areas of the buildings to achieve the positive or net-zero energy goals through solar power, a visual aspect comes into play that may impact architectural and sociocultural harmony in the area of the PV installations.

The visual impact of PV panels has become an issue when designing new PV-integrated buildings, and a bigger challenge when integrating them to existing buildings, as architects worry that a negative impact cannot make the design feasible. To address this issue, the IEA Solar Heating and Cooling Program has done extensive investigation into the topic through Task 41: Solar Energy and Architecture, where they have defined criteria and guidelines for a proper architectural integration of PV systems (IEA SHC, 2021).

To consider a proper solar design for Site 4016, the architectural integration aspects must be taken into consideration to ensure that the multiple stakeholders will approve and support such integration into the design. A way to assess this is through a two-part evaluation of architectural visibility, sensitivity and quality as proposed by Lobaccaro et al. (2019), who themselves based the criteria on IEA SHC Task 41. The first part of the evaluation consists of *Architectural integration quality* where the coherency of system geometry (PV field size and position), system materiality (visible materials, surface texture and colors) and system modular pattern (module shape and size, joints) are evaluated on a scale of “fully, partly or not coherent” (Lobaccaro, et al., 2019, p. 214). The second part of the evaluation considers *Urban context criticity*, where two aspects are considered: the context sensitivity that reflects on the socio-cultural value of the area (e.g. if the area is in a historical district or an industrial zone), and the system visibility that evaluates how visible the PV systems are from a close and remote proximity (Lobaccaro, et al., 2019, p. 214). Figure 27 shows an exemplary summary of 7 of the 34 evaluated case studies by Lobaccaro et al. (2019) based on their defined criteria.

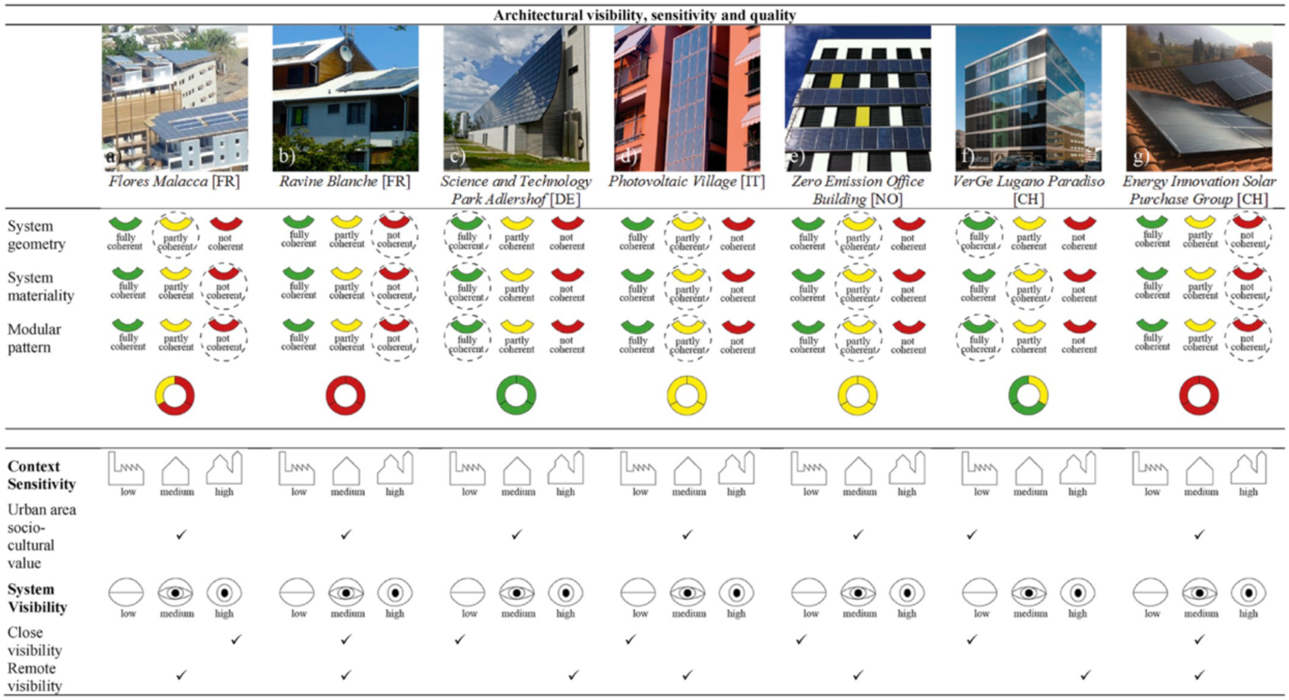


Figure 27. Architectural integration quality, context sensitivity and system visibility of case studies in existing urban areas (Lobaccaro, et al., 2019, p. 220).

The examples presented on Figure 27 can give an idea of what level of integration quality can be achieved for Site 4016. Regarding architectural integration quality, a carefully planned design for the new buildings could aim for a design similar to what is seen in (c) and (f), where there is high coherence and the PV panels are an integral part of the building and the façades; this also gives as a result a high aesthetic value that could prove valuable towards the area and the approval of stakeholders. For existing buildings that will only be renovated there is a higher challenge to achieve full coherence as the buildings would have to be adapted from their current state, but still with proper strategy a partly coherent design could be achieved, something similar to what is seen in (d) and (e).

Regarding the urban context, the location of Site 4016 may be considered to have a medium urban socio-cultural value, as this is a residential area that is not located within the wooden house area (Figure 28). The wooden house area is a protected zone within the city of Stavanger where the historic wooden houses are under strict aesthetic guidelines to preserve the socio-cultural historical identity of the area, this makes the installation of PV panels a challenge as they must be submitted for approval and must follow a set of rules (Stavanger Kommune, 2021). This protected area is similar to other historical areas found in other cities around the world, where a solar design is a challenge as it must help preserve the socio-cultural and historical identity of the area where it is located. This obstacle leads to challenging solutions to achieve a proper design and a probable reduction of the amount of PV panels that can be installed, making it more complicated to achieve positive energy districts.

Figure 28. Wooden house protected areas in Stavanger (orange), Site 4016 (red) is not in one of these areas (Stavanger Kommune, 2021).

Regarding the visibility of PV panels, the situation may be varied for Site 4016. For the new buildings, a close distance would have low visibility of PV panels, as the height of the buildings would lower the visibility, however this is achievable for façades if a highly coherent integration is achieved; for the existing buildings with lower height the visibility will be medium to high on the close range. The remote visibility of PV panels would be medium-to-low for the site due to the surrounding topography, which is relatively flat. As a result, there would be an expected medium-to-low impact on stakeholders based on PV visibility for Site 4016, considering that visibility is also important as it helps promote a general awareness of energy and the fundamental role it plays in society (Scognamiglio, et al., 2017).

Overall, if a successful and positively perceived solar design is to be achieved for Site 4016, the most important aspect to consider generating a positive impact and approval from stakeholders would have to be a coherent architectural integration. This is especially important for this site as a high percentage of surface areas should be integrated with PV panels to achieve a positive energy or net zero energy district. The effective architectural integration should not only consider the aesthetic aspects, but also other design parameters discussed in this analysis.

5.2.3 Design parameters in city planning to maximize solar power efficiency

To be able to reach positive or net-zero energy goals for clusters of districts, many factors have to be taken in consideration in the planning process. The ideal situation would be to shift the city planning process to consider solar design as one of its main design parameters, taking decisions that would favor an efficient design that could ensure higher production of solar power. Some of the planning factors that would be analyzed that should consider solar power production into consideration are: building location, orientation, position and height, area density and physical characteristics like albedo and surface reflectance.

5.2.3.1 Location and territorial planning

If the potential for solar power production is to be considered as a design parameter in the urban planning process, a useful strategy would be to create solar potential maps and integrate them into zoning plans. There are multiple solar analysis tools available that could help create these maps based on the current conditions of an urban area; these solar analysis tools can be applied on 3D representations of urban areas obtained through terrain analysis (for example from LiDAR terrain analysis). The created solar potential map would facilitate the visual understanding of which areas of an urban center could have the highest potential to generate solar power based on the existing urban fabric conditions, and which could probably not be economically feasible to develop. When planning on the expansion or reshaping of an urban area, one of the main elements that come into place is the use of a zoning plan; by using a solar potential map, a zoning plan could be modified to take the best advantage possible of the solar conditions. Zoning plans usually define the land uses, the use requirements, the maximum height and size of buildings, where land is to be left unbuilt, or where public services, open green spaces, or infrastructure facilities are to be sited (Radzi, 2008); all of these conditions and parameters could be modified to adapt to the ideal conditions to obtain the most out of solar power production on the urban fabric. These practices are being already adopted by some local governments, for example, the city of Frankfurt has an online solar cadaster that allows the public to not only find out the solar energy potentials of their roofs and open spaces, but also calculate the payback time, return on a planned solar installation and optimum module size (Radzi, 2008). A similar but private project on a country-wide scale has been developed for Norway called Solkart, though it is still in its Beta phase (Strømberg, 2021). The project developers have mapped and color coded all rooftops in the country according to solar potential, the user can click any rooftop, choose the type of roof material and PV panel, and the program will give an estimation of the cost of installation plus the annual power produced for different installation options (Figure 29). This initiative is ideal to promote citizen education on solar power and can incentivize them to invest on it.

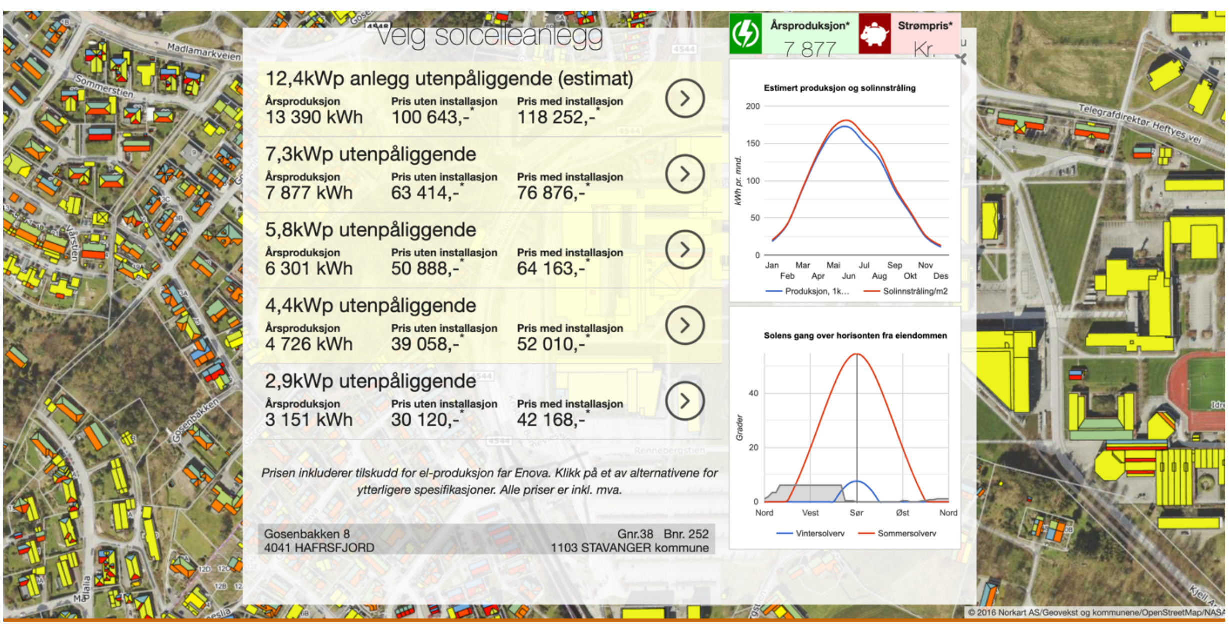


Figure 29. Example of Solkart interface, showing annual production plus installation cost for different options. The different solar potentials can be seen in the houses around (Strømberg, 2021).

This kind of open access information does not only help city planners integrate renewable energy into the planning process but lets the citizens take part in this planning, as their decisions can be better guided by understanding the potential that an area has for being developed with renewable energy integrated and the economic implications of it.

5.2.3.2 Building characteristics: orientation, shape, density, height and position

In positive energy districts the building orientation, shape, position, density and height play an important effect on how efficient the production of solar power can be. The orientation of buildings determines how much they can take advantage of the sun's position throughout the day, especially on non-tropical latitudes where the sun path is located to the north or south. A proper orientation and shape of a building would influence both its solar power generation through a better sun coverage as well as its energy demand through a solar passive design, as it has been discussed in previous sections of this analysis; however, as these both depend on the same façades (most importantly the south-facing façade for Norway), a balance must be found between the utilization of the façade both for PV installation as well as passive design techniques.

The shape and height of buildings are important factors to consider in a solar design as they influence energy consumption as well as the generation itself of solar power, especially for the case of BIPV systems. A more compact building design, where low surface area to volume ratios (ideally equal to or less than 0.5 m^2/m^3 or even 0.3 m^2/m^3) has been observed to be more effective at achieving zero or positive energy status, as the heat transmission losses are lowered (Scognamiglio, et al., 2017), even though the surface area that can be used for BIPVs can be reduced. Most of the buildings for the Site 4016 proposal have low AV ratios: for example, planned buildings KB5 and KB11 have an AV ratio of 0.15 and 0.17 m^2/m^3 respectively, while existing buildings that will not be expanded KB14 and KB15 both have an AV ratio of 0.23 m^2/m^3 as the former pair are medium rise buildings with significant length and width leading to a compact design and a possible reduction in heat loss. It can be observed that by densifying the buildings, like in the case of KB5 and KB14, a lower ratio is achieved than with KB14 and KB15, as these buildings would preserve their current shape for the 2030 plan.

The shapes of Site 4016's buildings are pretty basic; its façades are all straight vertical surfaces while the rooftops are horizontal surfaces. This design will not always be the most efficient one, especially when considering the integration of BIPVs; the horizontal roof would not allow such installation, BAPVs would have to be considered, reducing the effective area that could be taken advantage of, while vertical façades don't have the ideal angle to take advantage of the sun. To maximize the production of solar power, an inclined roof facing towards the southern façade and with BIPVs could result in an improved production; an extended roof overhang can even be considered to increase the area covered in PV, while providing additional rain protection and protecting against the sun during summer when its elevation angle is at its highest. On the same concept, designing a building with upwards curved BIPV façades could maximize the amount of solar energy received, an example of this is seen in Figure 27 example (c) where the Adlershof Science and Technology buildings incorporates a curved BIPV façade that maximizes the efficiency. The aforementioned characteristics are not always achievable as they are complex and can potentially interfere with its functions and increase construction costs; it is important to consider that building shapes not only are built to consider energy efficiency but must also take into consideration functional demands, quality of living, social, cultural aspects, government regulations and cost effectiveness (Scognamiglio, et al., 2017).

One of the objectives of sustainable urban planning is to reduce urban sprawl, as urban sprawl has been linked to negative environmental and social impacts like increased air pollution, overconsumption of water and its pollution, loss of wildlife habitat, loss of farmland and agricultural capacity, increased storm water runoff, increased socioeconomic disparity, increased health risks, and many more negative impacts (Grabkowski, 2018) (EverythingConnects, 2013). One of the strategies to fight sprawl is by densifying cities and increasing buildings' floor area ratios (FAR), this densification should also be limited as it should be a balance nevertheless. The challenge in this strategy is that by increasing the FAR of buildings (thus their heights), it becomes more difficult to achieve a net zero or positive energy status.

The main factor that will influence this is the obvious increase of energy demand that will result from increasing the amount of floor area concentrated on the same footprint. By densifying a building in temperate climates, energy demand also increases due to the increased thermal mass that demands heating as well as creating an increase in possible thermal transmission losses (Trepci, Maghelal, & Azar, 2020), however, the opposite has been proved for warm climates where densifying may reduce the energy demand needed for cooling (Liu, Wang, & Ge, 2020) (Lima, Scalco, & Lamberts, 2019). Another impact resulting from densification is the shadow that buildings may cast upon each other, reducing the amount of solar irradiation received; this is an impact that can be perceived in the results from the analysis on Site 4016, as the average irradiance per m^2 that the buildings received is reduced on average by 25% in the more densified proposal. Possible solutions to reduce this impact could be implemented by correcting the spacing between the buildings so they are not directly lined up in the north-south axis by spreading them across the west-east axis. The buildings in the southern area of Site 4016 already have an alignment that may be favorable, as they are slightly aligned in the southwest-northeast direction; there is still a perceived impact as the average solar irradiance per m^2 is reduced by 23% between current conditions and the more densified proposal. By defining different heights for multiple buildings, especially by choosing increasing heights in the south-north direction may help increase the solar coverage for the buildings that stand further north too. These solutions however are dependent on the surroundings of a development and there may not always be the necessary space to implement a proper separation, also in dense areas the other surrounding buildings will also inevitably contribute to the reduced solar coverage. Site 4016 does not suffer from this disadvantage as it is located in a low-density area surrounded by green spaces and single-family units, giving the site an extensive solar viewshed not interrupted by its surroundings.

Scognamiglio et al. (2017) present an image that summarizes different building typologies and determines its relationship with the potential to be ZEB (Figure 30), it can be clearly seen that more densified and higher height options throw off the energy balance greatly as their energy demand is too high (however only the south façade and roof are considered in the image for PV integration, the energy disbalance could be further reduced by integrating the east and west façades too); the building typology that best meets the potential is two-story row housing, that may not be the most dense option but it is an improvement both on density and energy production potential over single family housing (even though single family housing still has the potential for positive or zero energy) which is attributed to be the main type of housing responsible for urban sprawl. According to the figure, the type of building with the lowest potential for positive or zero energy is the high-rise building, as its energy demand exceeds its capacity to produce solar power.

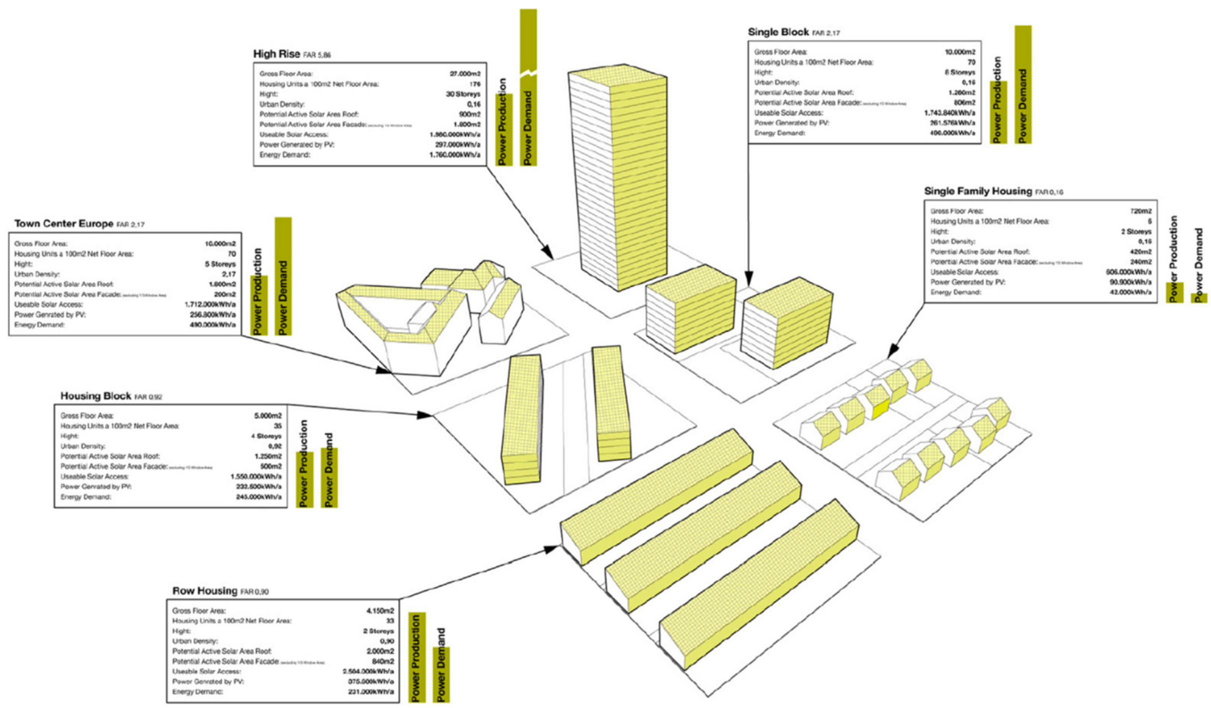


Figure 30. Relationship between urban density and zero energy potential (Scognamiglio, et al., 2017).

Further investigating how building geometry and different typologies influence the potential to achieve positive or zero energy, Kanters & Horvat (2012) studied this impact by running solar irradiation simulations on multiple scenarios (Figure 31). The analysis included four different typologies in five levels of floor area ratio (Floor Space Index (FSI) in the study), simulations were run on these 20 cases for three scenarios: a single block in north-south orientation, a single block in east-west orientation and a cluster of similar blocks; an additional analysis was run for a scenario where the block was located in a dense area like a city center (Kanters & Horvat, 2012). Figure 32 shows the annual electricity coverage that every analyzed case has, from the results it is clear that type A1 would be the ideal type (even on an east-west orientation), which is a very similar scenario to the row housing case presented by Scognamiglio et al. (2017). According to the analysis results (Figure 32), the only density scenario that is capable of having positive energy is scenario 1, where the four typologies are 2-3 stories high (6 - 9m). Type C (the highest FAR case) however, is not even able to reach net zero in scenario 1, demonstrating that it is the least efficient design to try to achieve positive or zero energy; besides this poor result, it seems that this type is the most sensitive to being placed in a dense urban center, as its coverage drops by 74% in this case. It would be recommended that the design for Site 4016 should be reconsidered to have less stories, effectively lowering their density and creating more potential to achieve a positive or net zero district, the height could be varied in an escalated way in the south-north direction to take better advantage of the solar irradiation throughout the year.

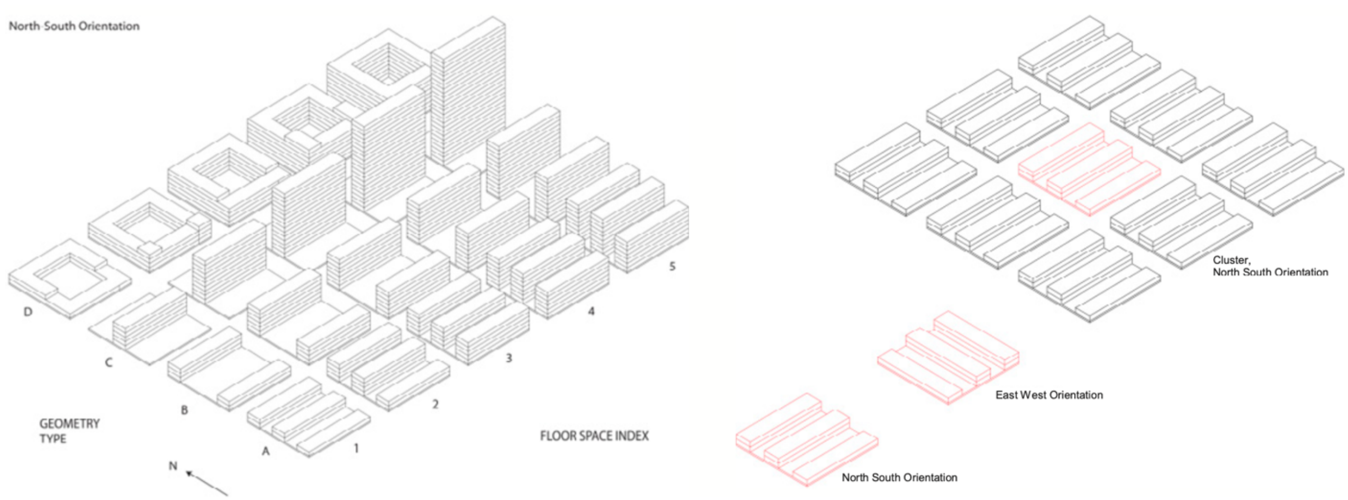


Figure 31. Geometry types and scenarios analyzed for PV potential (Kanters & Horvat, 2012).

	Type A					Type B					Type C					Type D				
FSI	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
NS	169	93	65	54	46	134	81	63	47	43	90	68	60	57	54	149	85	59	48	43
EW	141	75	53	42	35	97	53	39	31	27	53	31	24	20	18	154	80	61	47	43
Cluster	159	79	53	40	32	115	57	44	29	23	71	36	24	18	14	139	73	47	36	30

Figure 32. Results from the solar analysis, annual electricity coverage of PV cells in the buildings in %

5.2.3.3 Building façade surface reflectance

The physical characteristics of a building's façades, like its surface reflectance (SR), are important factors to consider that may contribute to the solar PV potential of a site. SR, or albedo, measures the ability of a material to reflect incident solar radiation without absorbing it (Casini, 2016); a completely black surface that absorbs all radiation would have a value of 0, while a white surface that reflects all the light would have a value of 1. Through the analysis it was determined that interreflections between building surfaces were responsible for 16.1% of the solar irradiation that the surfaces of Site 4016's future proposal received, which represents a significant amount of PV generation potential that could be crucial in defining if the district is positive or net zero energy. The result obtained through DL-Light is based on estimations of the SR of the buildings' surfaces, this SR had to be manually assigned to every surface. These materials were estimated by observing the proposal renders created by MAD and choosing the most similar material possible from DL-Light's material library, which are materials that follow sustainable certification standards and have a SR number assigned already. The materials used on the surfaces of the simulation had a SR of 0.31 on average, meaning that they are not very reflective surfaces, so it would be recommended that for the final design materials with much higher SR numbers should be chosen, this could lead to increased solar power production thanks to interreflections. Besides increasing the solar potential, using materials with a high SR (especially roofs) can help reduce the urban heat island effect, which causes abnormal high temperatures in urban areas in contrast to surrounding rural areas leading to a reduction in air quality and unstable weather like increased precipitation. Materials with SR higher than 0.65 are considered *cool materials* (Casini, 2016) and would be ideal for a more sustainable design of Site 4016 and could lead to increased solar power production.

5.2.4 Shared spaces and external areas

To achieve net zero or positive energy, the energy supply options can usually be divided into three boundary-wise categories: within the building footprint, on-site and off-site (Scognamiglio, et al., 2017). This study has been focusing mainly on the first category, however given the context of the area the second option of on-site generation could have potential to contribute a significant amount of energy too. This option would explore considering the shared spaces around the buildings to generate energy too.

The concept that Smedvig envisions for the site is to create shared external spaces where not only people who work and visit the site, but nearby residents too could go to and enjoy; these spaces should be aesthetically pleasing and integrated with greenery, making them attractive to visit and where commerce like cafes and restaurants could cater to the visitors, creating a pleasant experience. This poses a challenge as not all solar PV designs are aesthetically attractive, so a balance must be found where the elements can be integrated to the natural spaces attractively but a certain degree of visibility of the solar panels could also help promote awareness and the importance of solar power. Luckily this has become a popular trend, where architects and artists can come together to design structures with the needed characteristics that would have also usefulness by providing protection from the sun or the rain, while adding aesthetic value to the place, these structures could even come to become an icon and representative of the site or city where they are located (Figure 33 shows an example of a popular solution for this "solar trees").

Figure 33. Solar trees may not only provide shade and energy, but aesthetic value and awareness for solar power (Spotlight Solar, 2021) .

Not all the shared spaces could be integrated with solar panels however, the height and configuration of the buildings would create a lot of shade for most of the areas between the buildings, though certain areas with less obstruction and more open space could provide useful (e.g. the areas directly south from buildings KB7, KB12 and KB13). The element that could result to be more useful is the elevated pedestrian way planned for the site, where its elevated sections and some of its sections passing through the middle area in between buildings have the potential to receive a significant amount of sun exposure. The design for this pedestrian way could consider integrating a tilted solar roof facing towards the south, this way it will not only contribute in the generation of power but also provide protection from rain (especially in such a rainy city as Stavanger) and provide shade in the summer months for people moving between buildings, transiting through the area or attending one of the planned cafes or restaurants located on the pedestrian way (Figure 34). An estimate of the potential for this path to generate solar power determined that its approximate 3700 m^2 of pedestrian ways could have the potential to generate in 2030 around 0.50 GWh in a year based on an average irradiation of 550 kWh/m^2, which would be a significant amount to contribute to the energy balance. This value of potentially generated power could increase even more if a sloped roof design could be adopted where the area of PV array could be greater than area of the pedestrian way, what can be sometimes known as a "hat" design.

Figure 34. This depicted section of the pedestrian way next to KB11 and the connecting bridge seen in the background could be ideal to be integrated with a solar roof (MAD Arkitekter, 2018).

Other not-so-visible areas of the site where pedestrians don't transit, for example the eastern façade sections of buildings KB 13-18, could also take advantage of the space to install PV panels. These areas could prove useful as they are mostly dead spaces and could help overcome the shading that the buildings create on each other by installing protruding "wing" structures for solar PV arrays. An example of this concept, applied on the Rainbow Headquarters in Loreto, Italy is seen in Figure 35; the example shows how these tilted wings would protrude from the building boundaries to help produce additional solar power and take advantage of the space (Scognamiglio & Røstvik, 2012).

Figure 35. Protruding "wing" PV structures in the Rainbow Headquarters in Loreto, Italy (Scognamiglio & Røstvik, 2012, p. 12).

The external areas of the site could also be contributing to the renewable energy production by using the space to implement other energy generating technologies. A practical and aesthetically pleasing solution could be the implementation of vertical axis wind turbines all around the site. These turbines have minimal impact and require very little space to be installed and would take advantage of the windy conditions of the area to contribute a share of the energy to the site's production. Besides that, these turbines are usually aesthetically pleasing and would help promote and raise awareness for clean energy production. As mentioned in section 5.1.2, another proposed solution to complement the production of renewable energy and reduce energy demand for the site would be installing a district heating plant to cover the heating necessities of the project. This plant would take advantage of natural elements like using lake water heat exchange or ground based heat pumps and could also include solar collectors to contribute. This plant could even be taken further by considering installing a biofuel combined heat and power generator, a concept that maximizes energy efficiency by not only producing heat for the buildings but also generating clean electricity that could contribute to the grid stability of the site.

6. Conclusion

The first question that was asked on this thesis, which had a more technical approach—the solar PV potential of Site 4016 and the possibility of achieving a PED—was answered based on the supposition that this project will be developed close to the year 2030, with calculations taking into consideration factors like future PV efficiencies values, low building energy consumption and the integration of PVs into a majority of the area of the buildings' surfaces including façades and rooftops. To answer the question, simulations of the solar irradiance that the building surfaces receive throughout the year were run for the site. The subsequent calculations determined that the site can potentially generate enough power to cover up to 70% of the annual energy consumed by the buildings in an energy consumption scenario that complies with the EU energy efficiency goals for 2030, however, being optimistic that the site development could take their energy consumption goals even further, Site 4016 could potentially become a positive energy district being able to cover 115% of their annual energy need and generating 1 390 000 kWh of excess energy annually.

Through the data obtained in the solar analysis it was possible to draw further conclusions on the relationship between using buildings for solar power generation and the urban fabric, and which characteristics can help ensure a more efficient solar design that can reach zero or positive energy. It was concluded that the location, shape, height, density and position of the buildings are crucial and should be used as parameters when designing a development or reshaping parts of the city while considering integrating solar power. One clear example found in the analysis of the impact that these characteristics could have is the reduction in the average solar irradiation between the current and the future development scenario, where increasing the FAR of the buildings resulted in a reduced average annual solar irradiation from 715 kWh/m^2 to 549 kWh/m^2 due to the buildings casting shadows upon each other. This could be mitigated by modifying the design to accommodate for a better solar coverage. The data also demonstrated the importance of interreflections, as they are responsible for 16% of the solar irradiance that the surfaces receive, so having a high surface albedo for the project can ensure a higher energy generating potential and help fight negative impacts like the heat island effect.

Even though the analysis demonstrates the solar potential that Site 4016 has, actually being able to create a PED depends on a series of factors discussed in this study. A solar design has multiple constraints to take into consideration that could create challenges: the architectural/cultural sensibility and local regulations for example could completely prevent a solar design of being developed. Also, the economic feasibility has to be analyzed carefully through a LCCA and incorporating cost-effective measures could help make it possible: only integrating PV on a few select areas of the north-facing façades that receive the highest amount of light could prove useful as these façades were calculated to only contribute to 8% of the power generated. Integrating BIPVs to the building façades could also prove useful as building envelope material costs are reduced and have been proved to have relatively short payback periods, as well as taking advantage of the external areas of the site to install PV panels too and maximize the generation of power.

The other main aspect to consider to be able to achieve the energy goals for the site is the energy use of the buildings. A high energy efficiency through different methods discussed in the analysis will ensure that the energy consumption is low enough to be covered by what is generated on-site. Besides the low energy use, and on-site generation, grid stability and coverage for periods of low solar irradiance must be considered; the site then must still rely on the main grid and other sources of renewable energy like wind and biofuel, and in a more optimistic scenario, other future PEDs in the city could help contribute to a stable grid through energy exchange.

Though ambitious, the idea of turning a planned future development like Site 4016 into a solar-powered positive energy district could become a reality through careful planning. Such a development could set the example and, in the future, create inspiration for other parts of the city to be reshaped into PEDs too, creating a solar city where the city itself becomes a solar power plant through the use of its urban fabric. The challenge to create these areas goes further, as the process not only involves integrating sustainable production and consumption but must also consider other elements like a proper mobility to further reduce energy use and emissions, all while also ensuring a high standard of living for its inhabitants within an affordable range. If we plan to successfully cut emissions in such an unprecedented way so that the climate goals agreed on the Paris Agreement are met, decisions like integrating solar power plus other renewable sources and its related elements as design parameters of urban planning can then prove to be crucial, as cities and their constant evolution are one of the main actors in the climate change struggle, and guiding this process through the correct path will ensure a better outlook for current and future generations.

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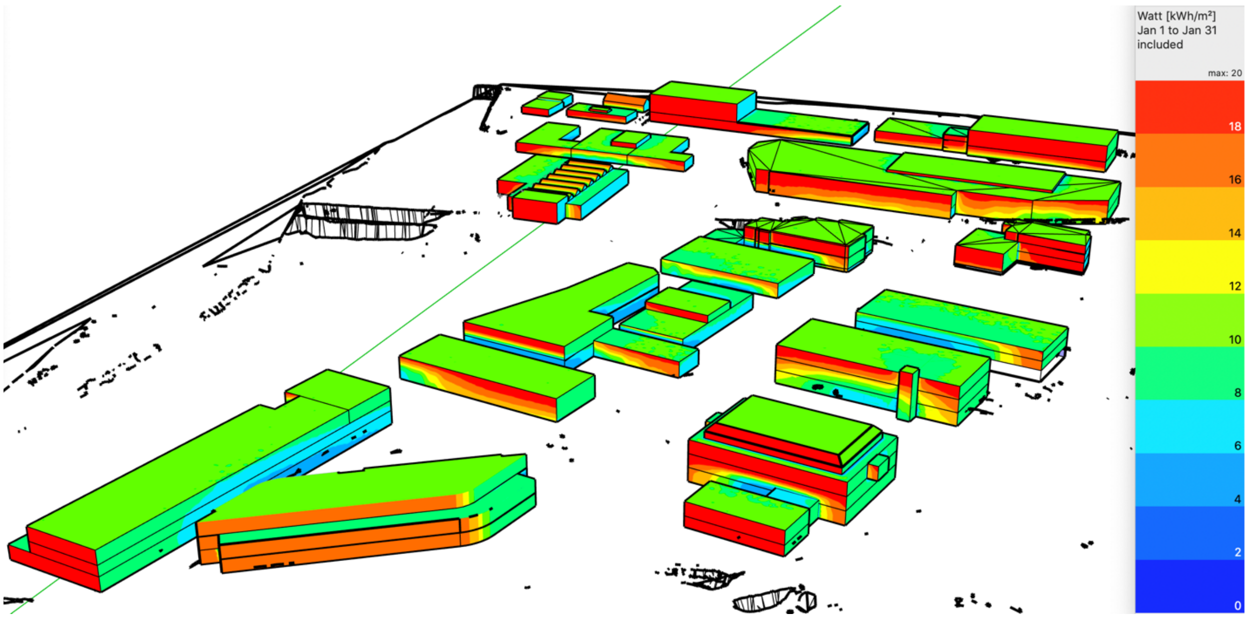
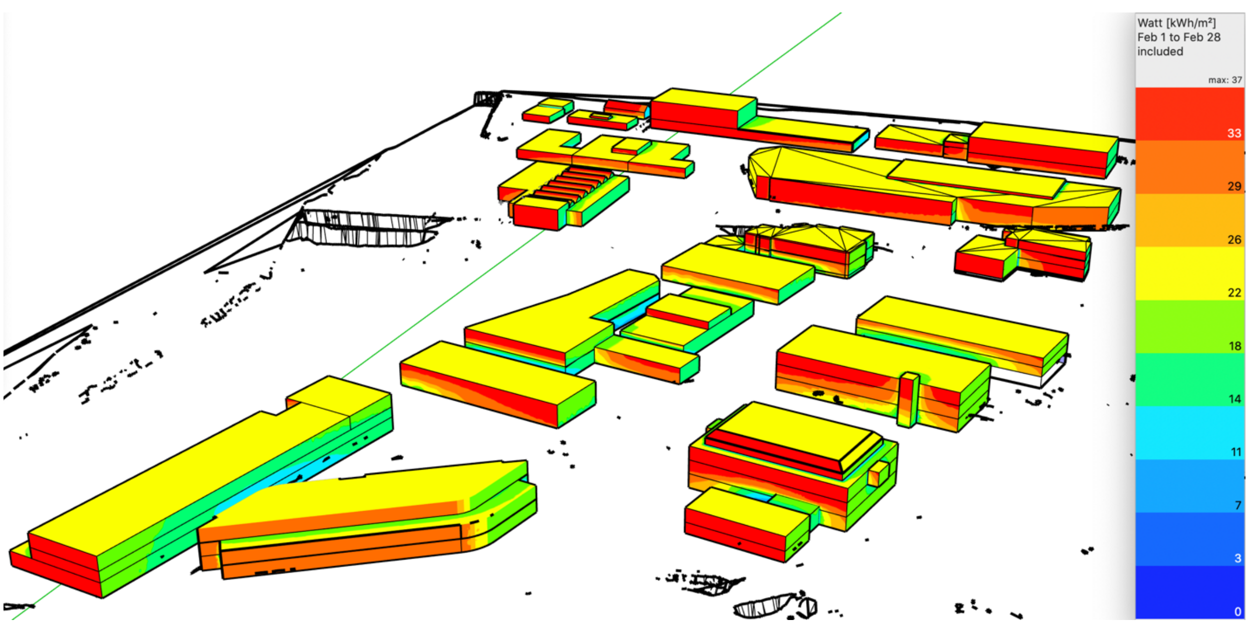
Appendix A – Detailed Solar Analysis Results

Current Scenario Analysis – View of South and East Façades

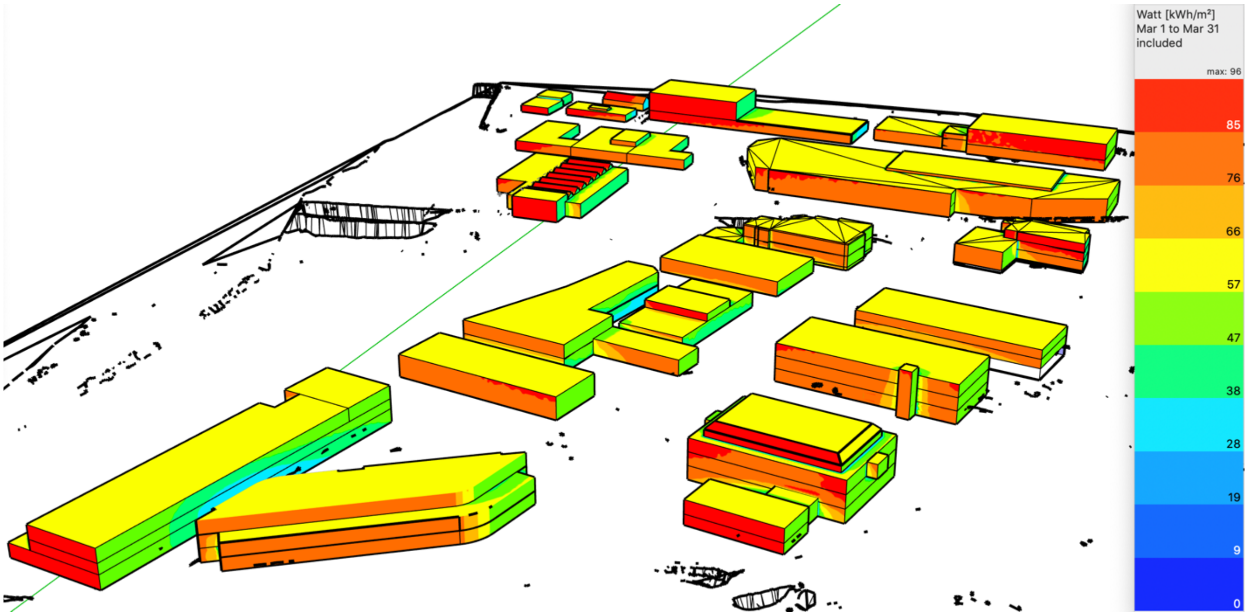
January



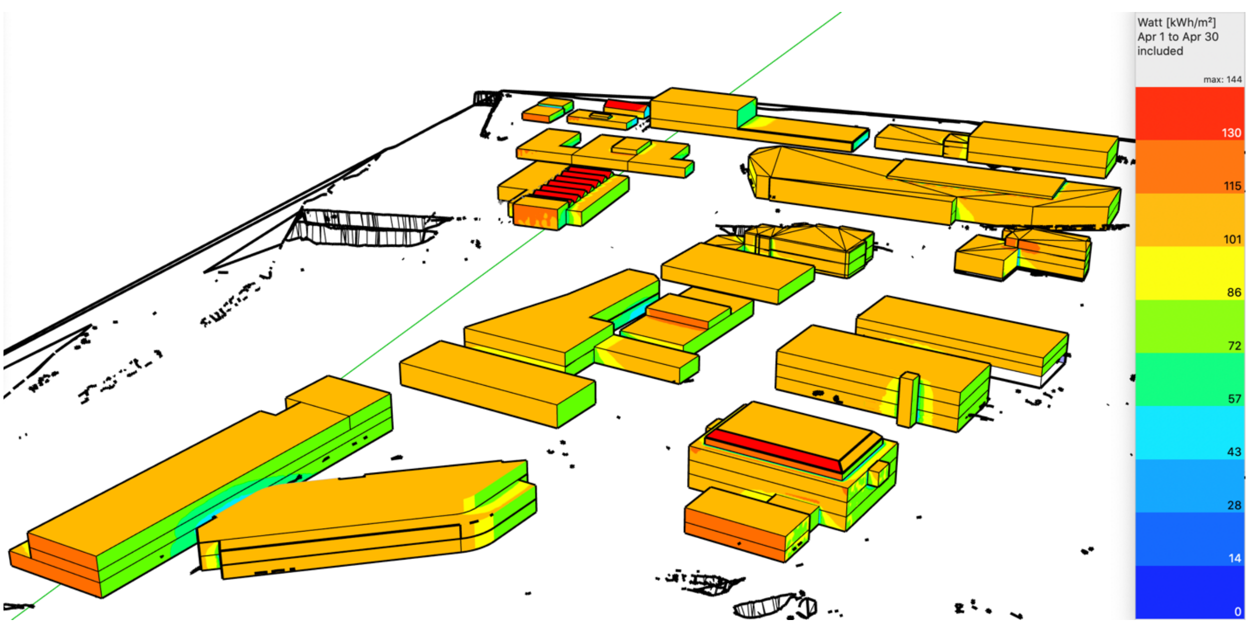
February



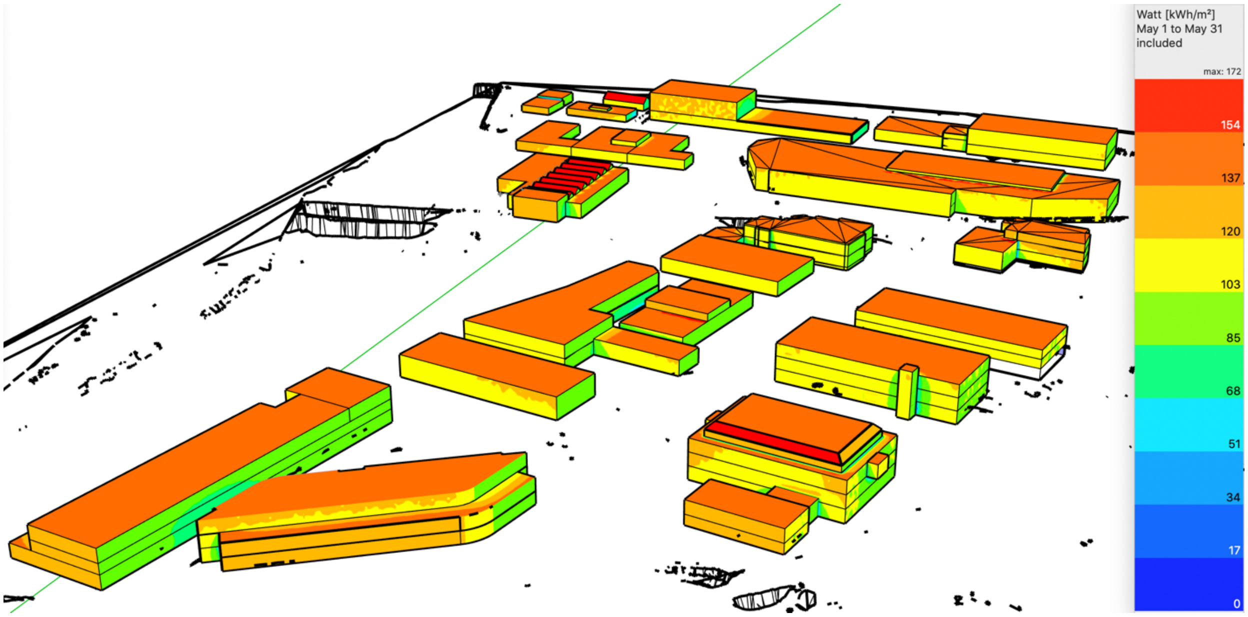
March


Watt [kWh/m²]
Mar 1 to Mar 31
included
max: 96
85
76
66
57
47
38
28
19
9
0

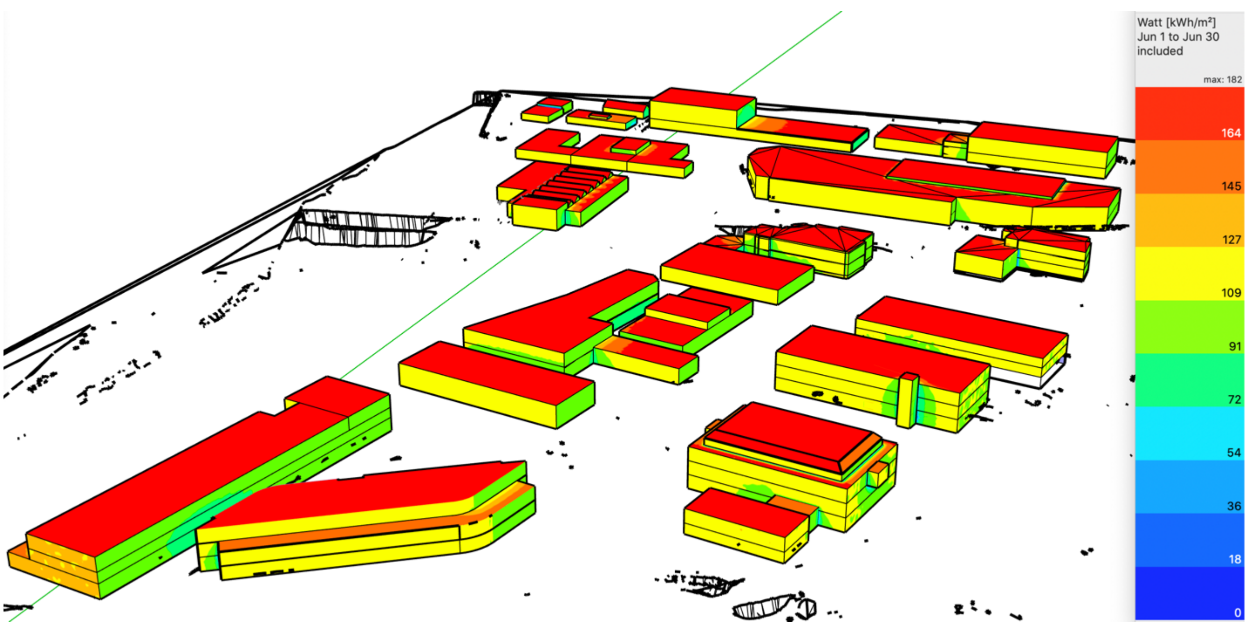
April


Watt [kWh/m²]
Apr 1 to Apr 30
included
max: 144
130
115
101
86
72
57
43
28
14
0

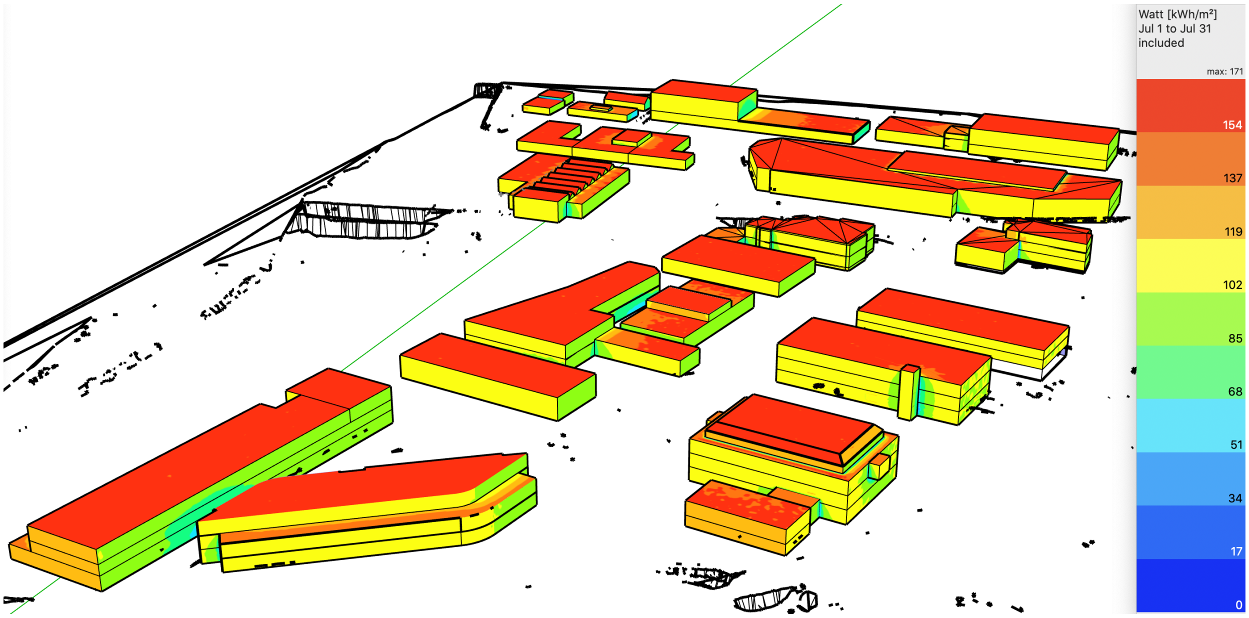
May


Watt [kWh/m²]
May 1 to May 31
included
max: 172
154
137
120
103
85
68
51
34
17
0

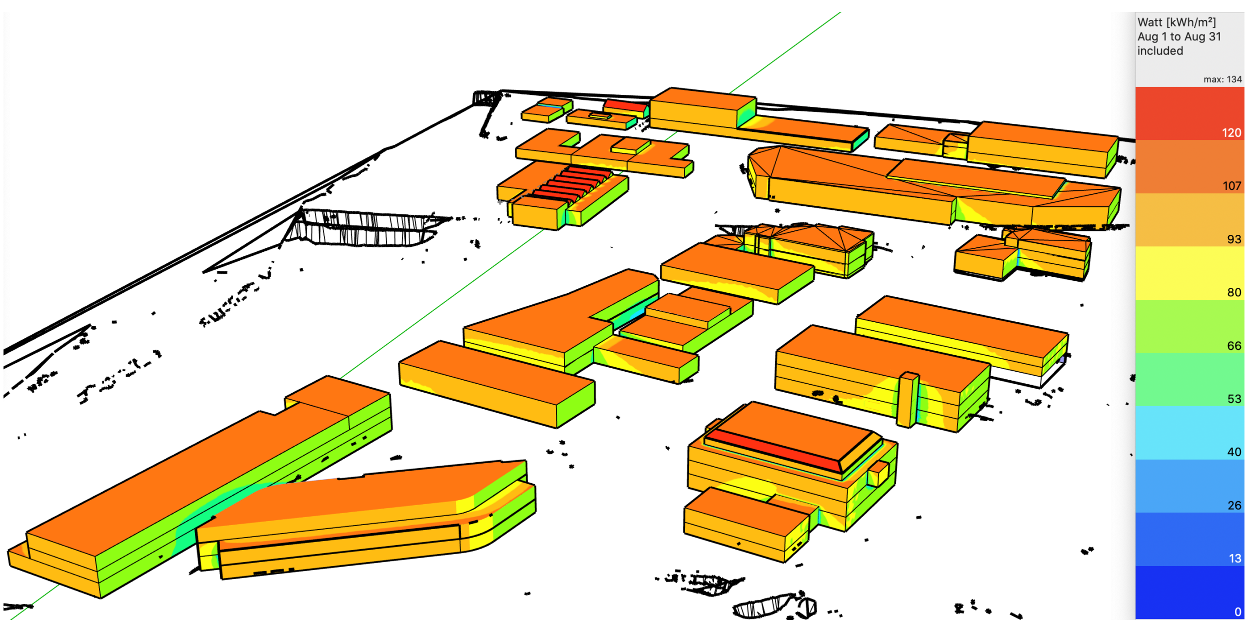
June


Watt [kWh/m²]
Jun 1 to Jun 30
included
max: 182
164
145
127
109
91
72
54
36
18
0

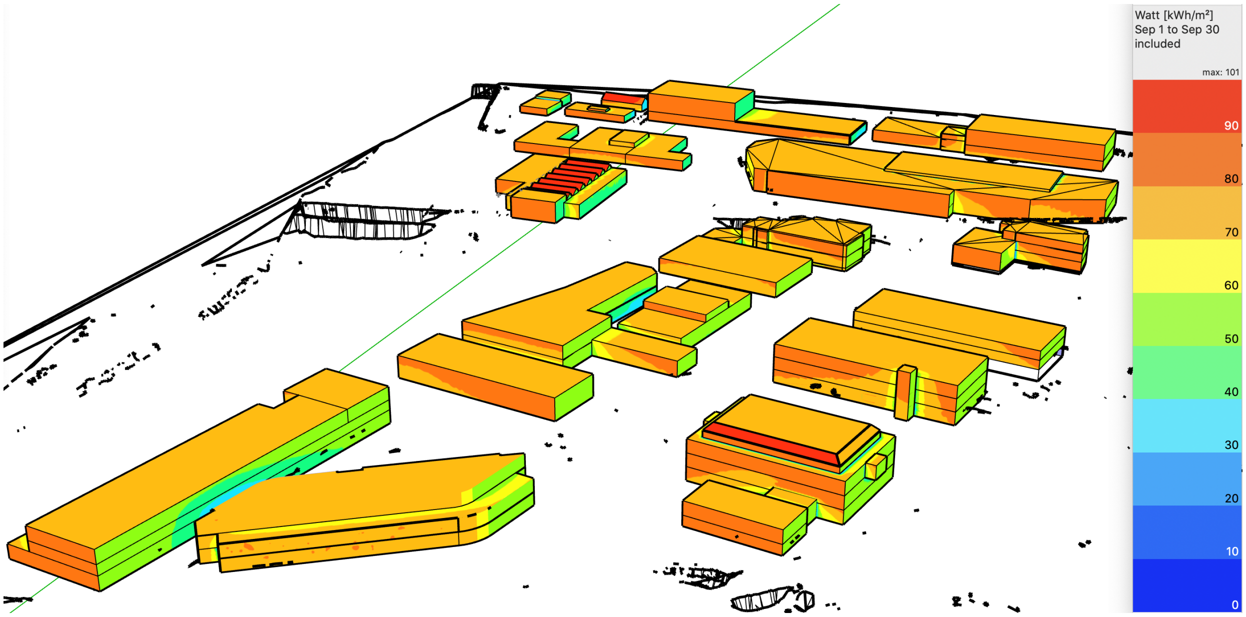
July


Watt [kWh/m²]
Jul 1 to Jul 31
included
max: 171
154
137
119
102
85
68
51
34
17
0

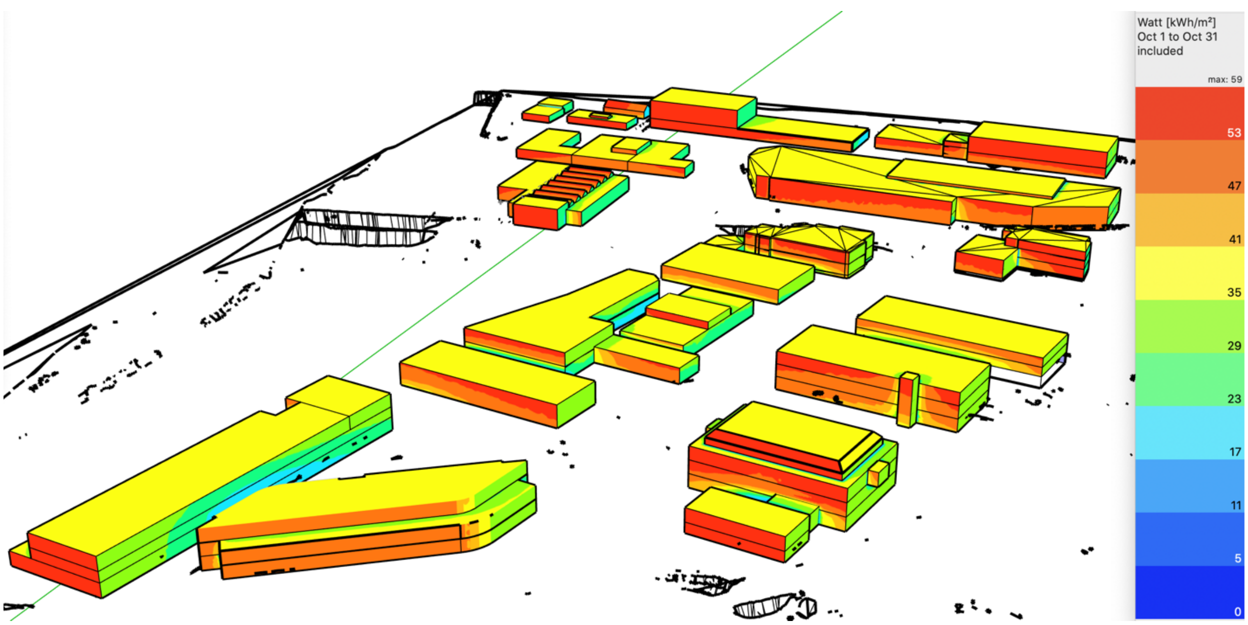
August


Watt [kWh/m²]
Aug 1 to Aug 31
included
max: 134
120
107
93
80
66
53
40
26
13
0

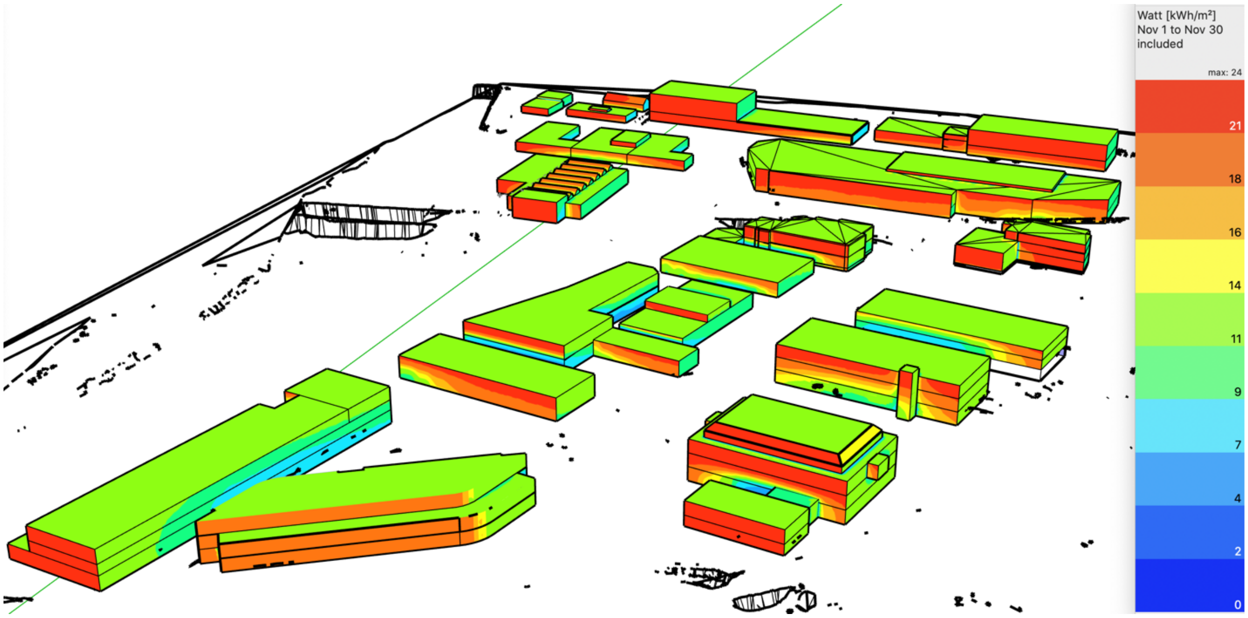
September



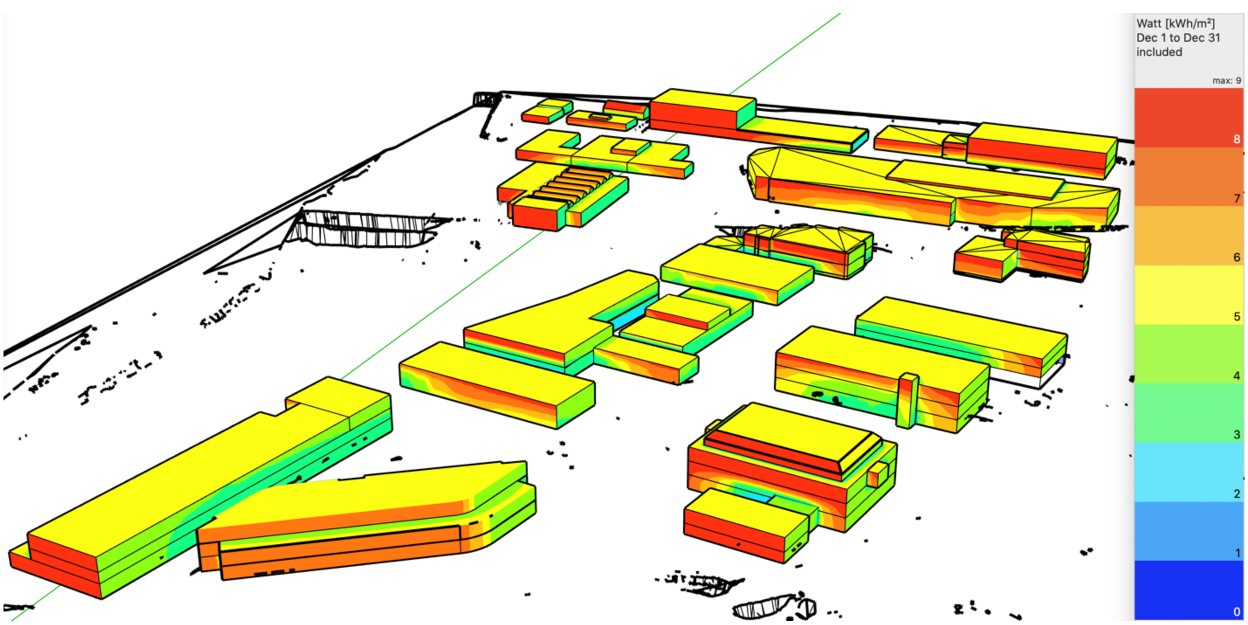
October



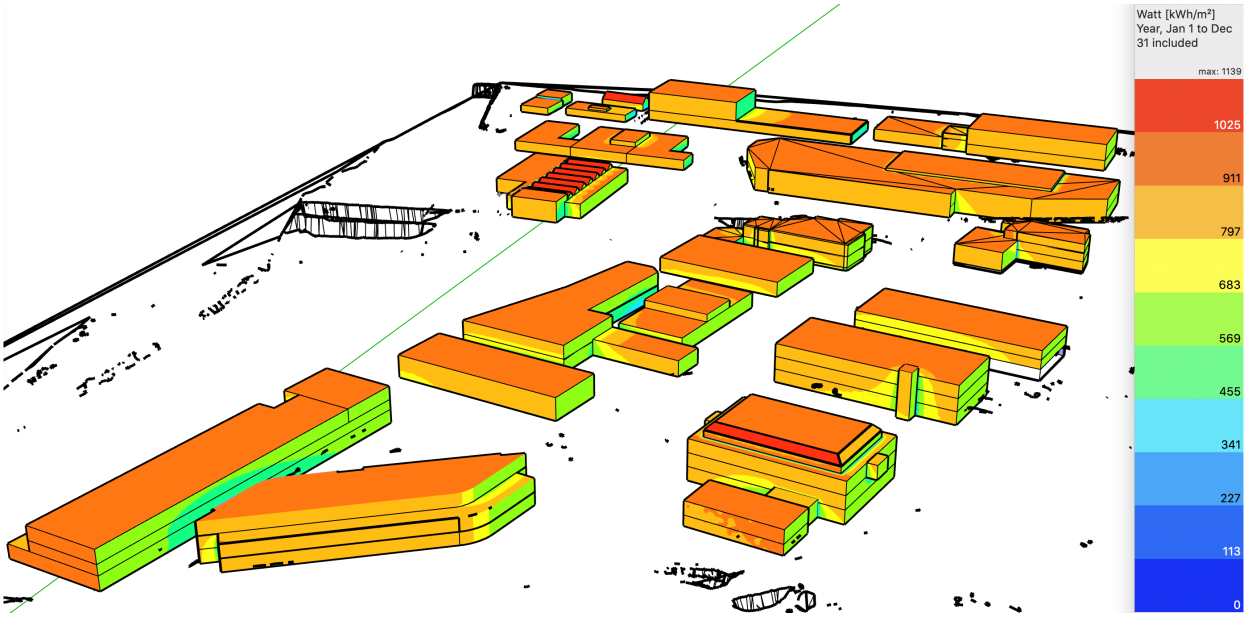
November



December

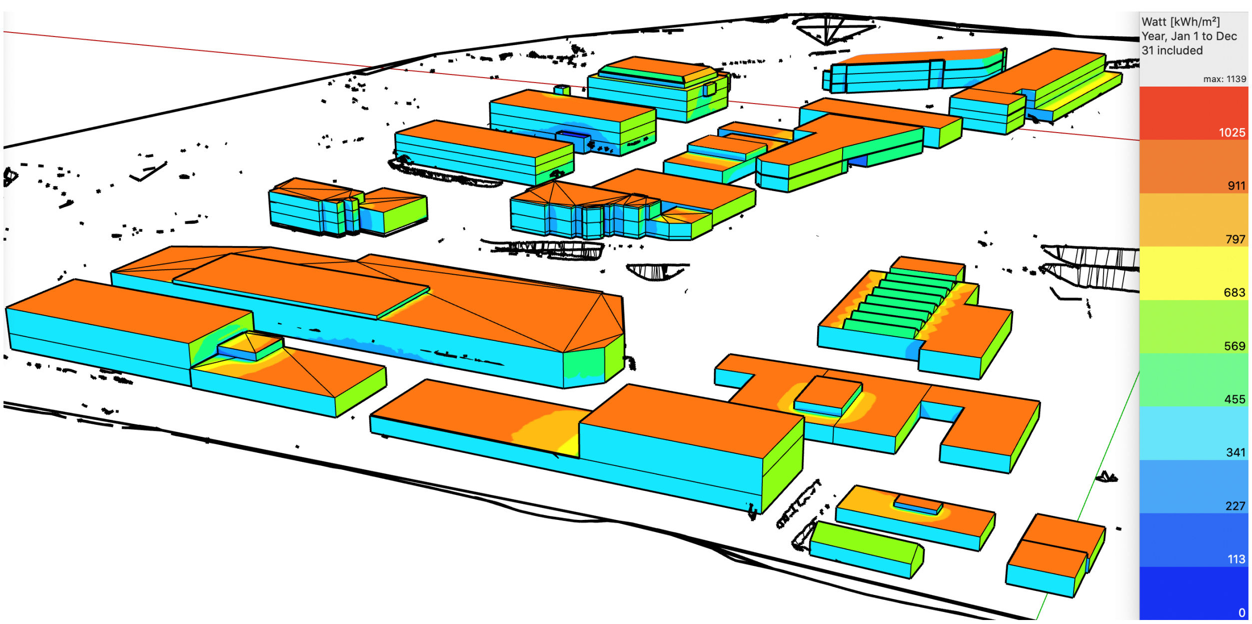


Annual Average

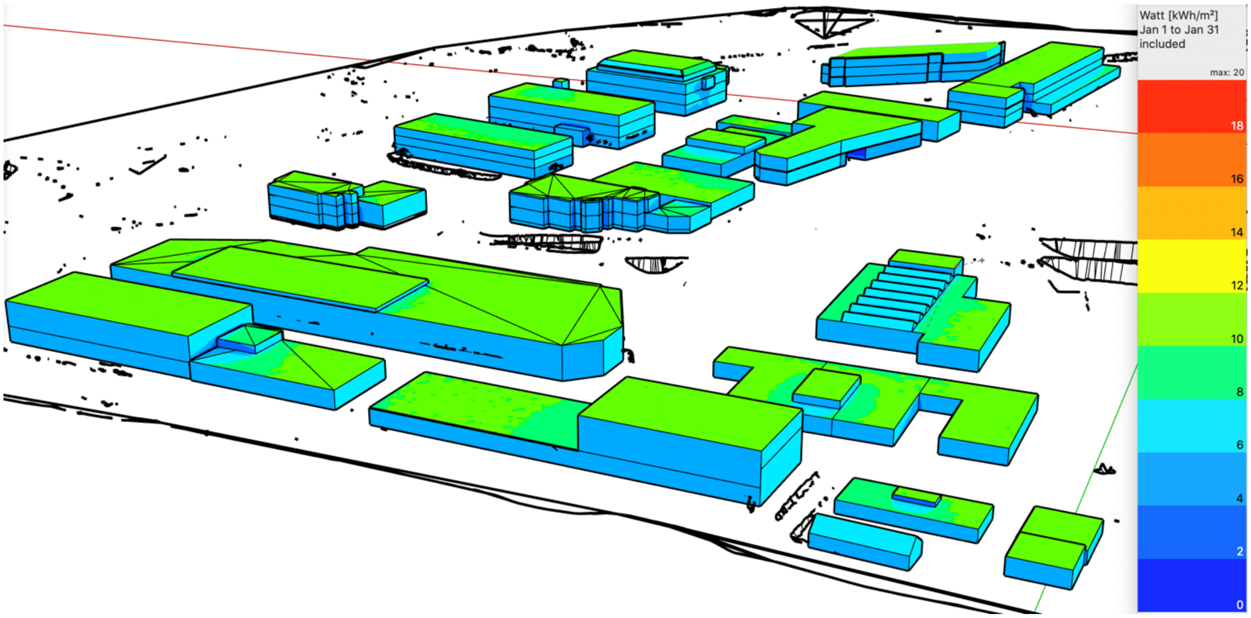


Current Scenario Analysis – View of North and West Façades

Annual Average



January



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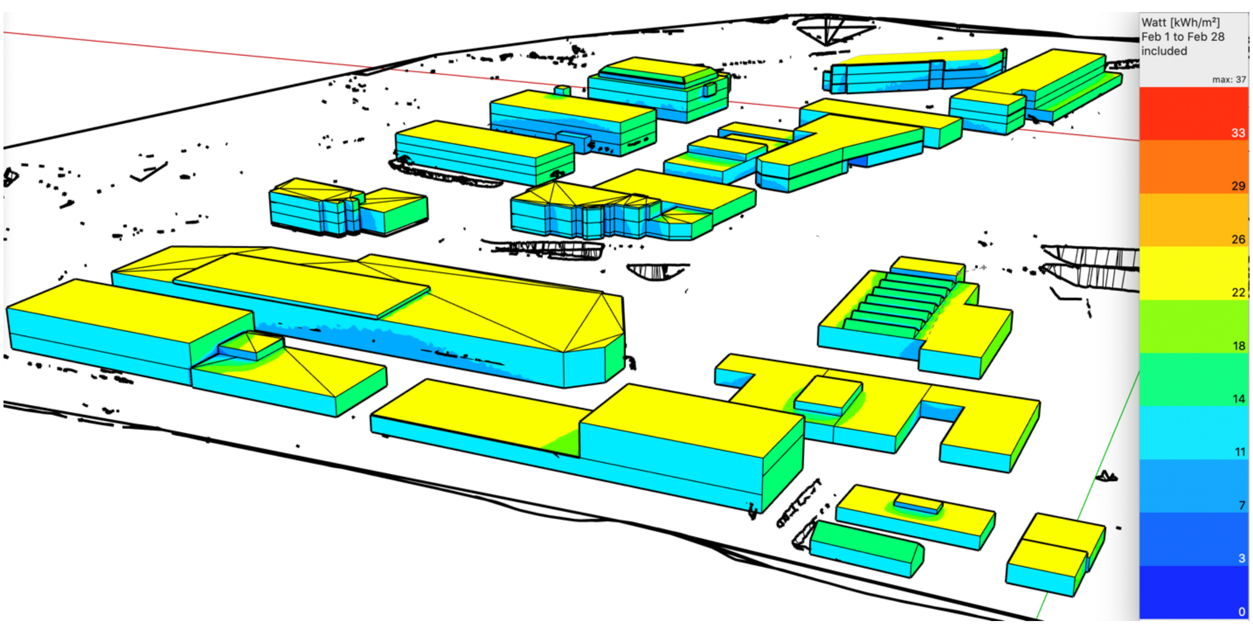

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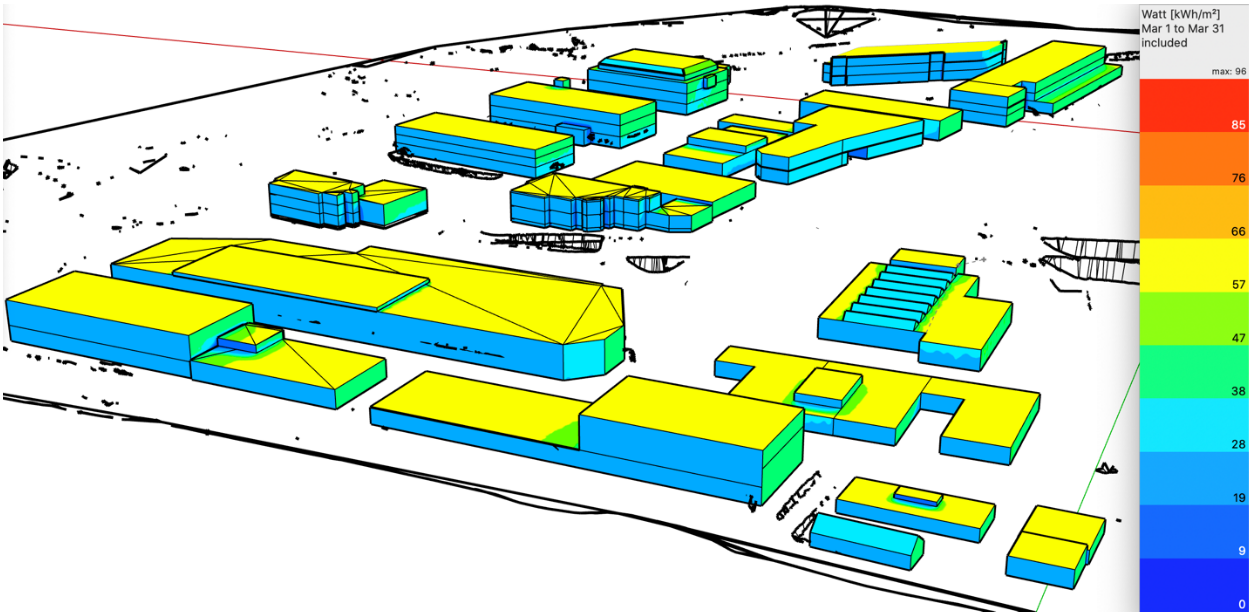
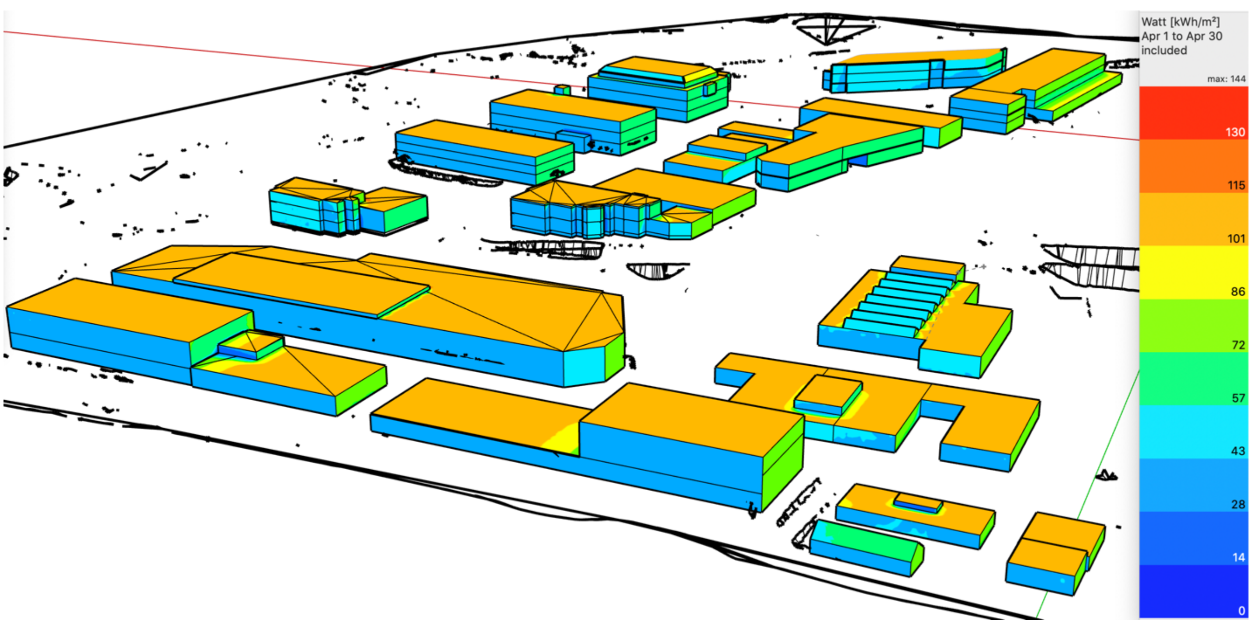
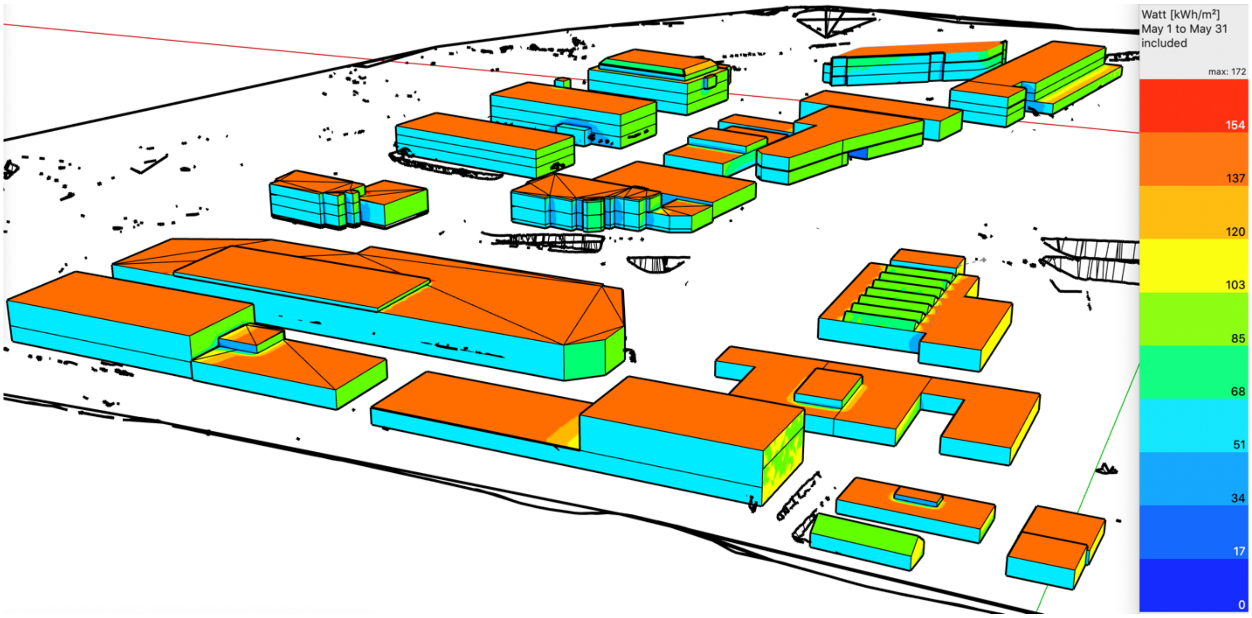

Watt [kWh/m²]
Mar 1 to Mar 31
included
max: 96
85
76
66
57
47
38
28
19
9
0

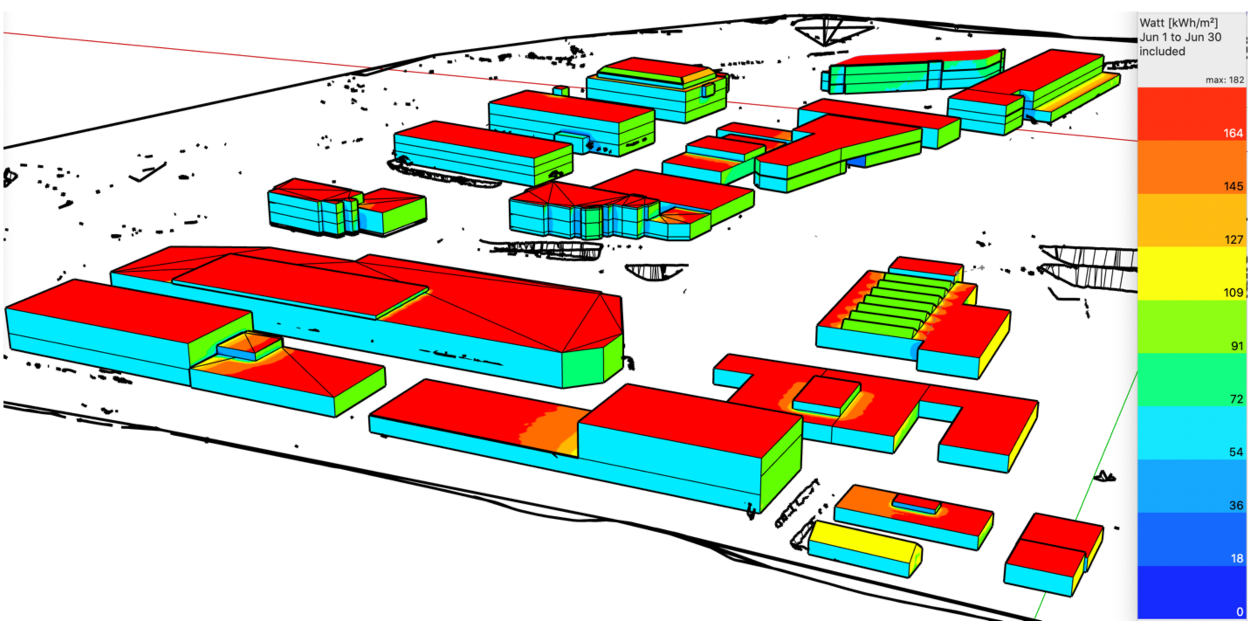
April


Watt [kWh/m²]
Apr 1 to Apr 30
included
max: 144
130
115
101
86
72
57
43
28
14
0

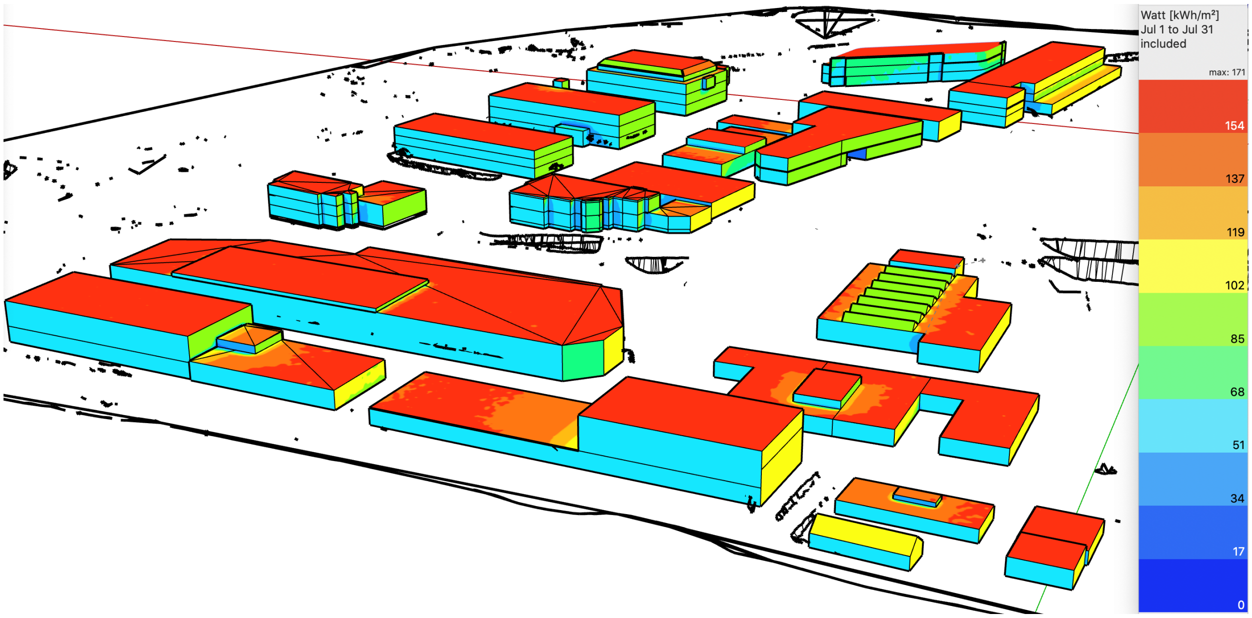
May


Watt [kWh/m²]
May 1 to May 31
included
max: 172
154
137
120
103
85
68
51
34
17
0

June


Watt [kWh/m²]
Jun 1 to Jun 30
included
max: 182
164
145
127
109
91
72
54
36
18
0

July



Watt [kWh/m²]
Jul 1 to Jul 31
included
max: 171
154
137
119
102
85
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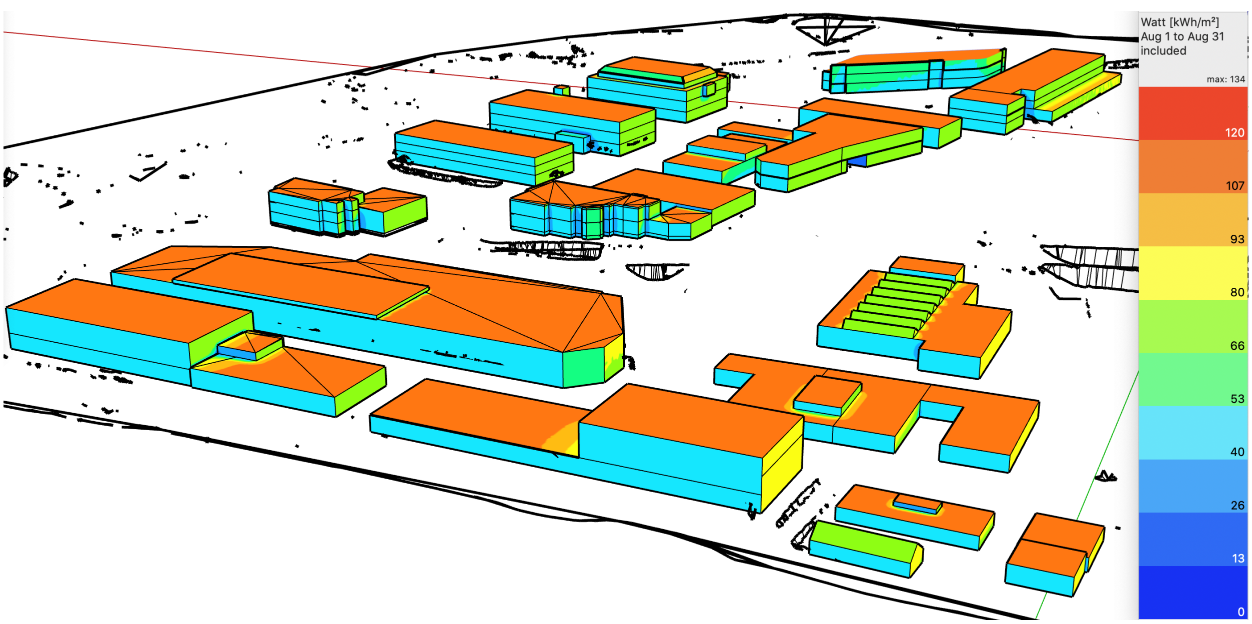
51
34
17
0

August



Watt [kWh/m²]
Aug 1 to Aug 31
included
max: 134
120
107
93
80
66
53
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26
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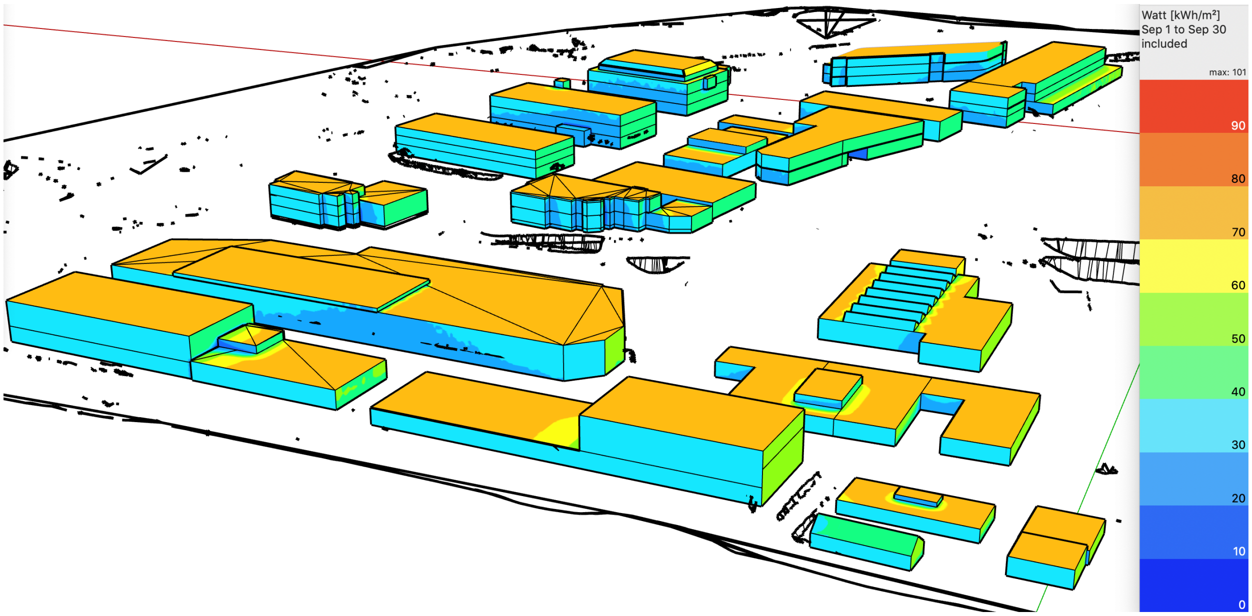
September



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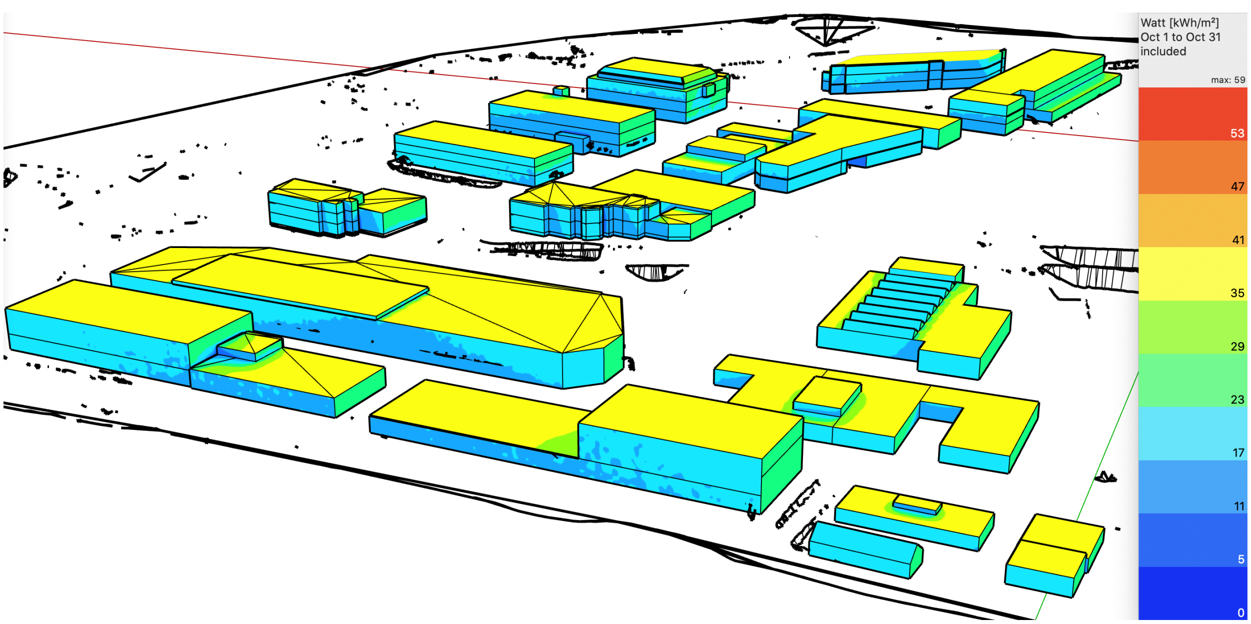

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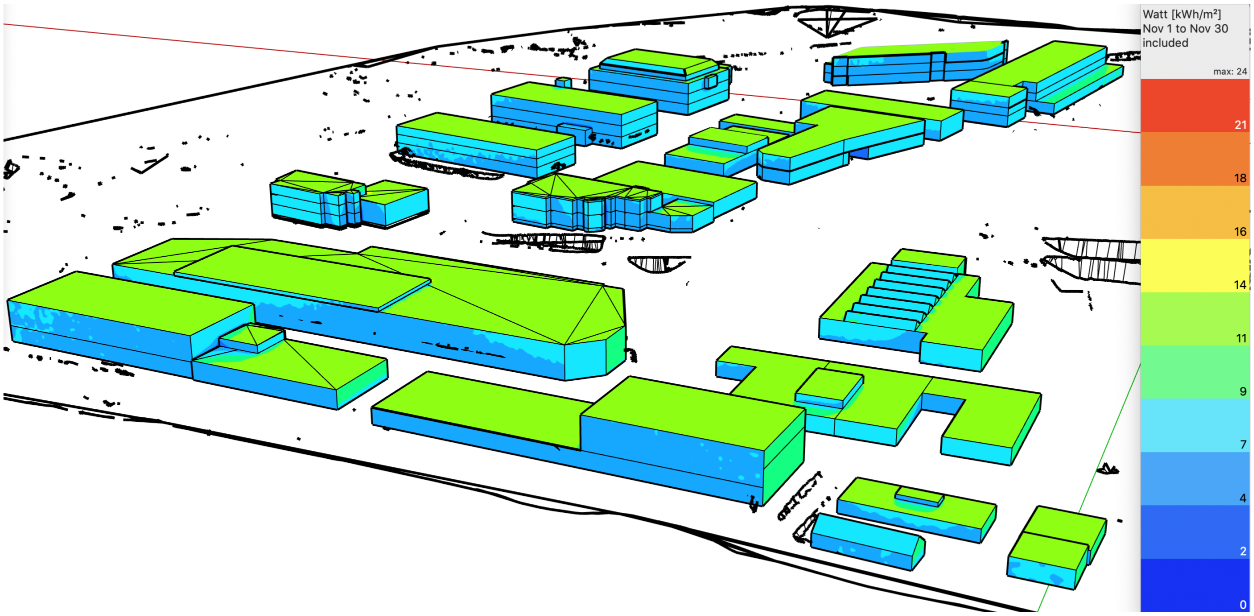
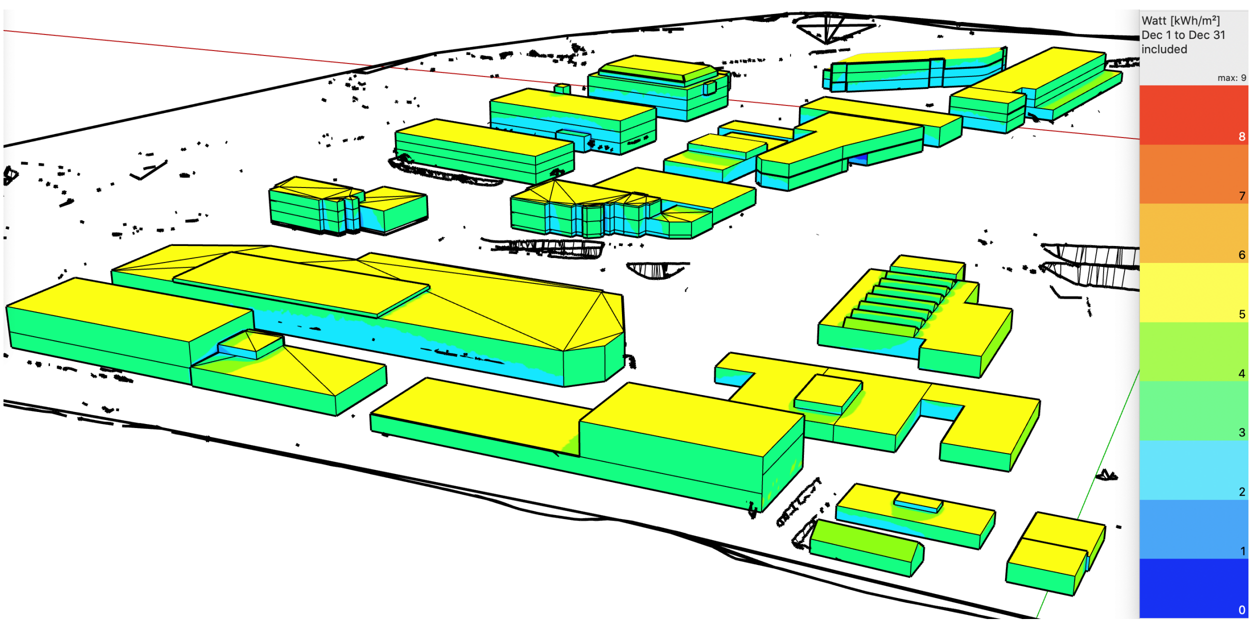
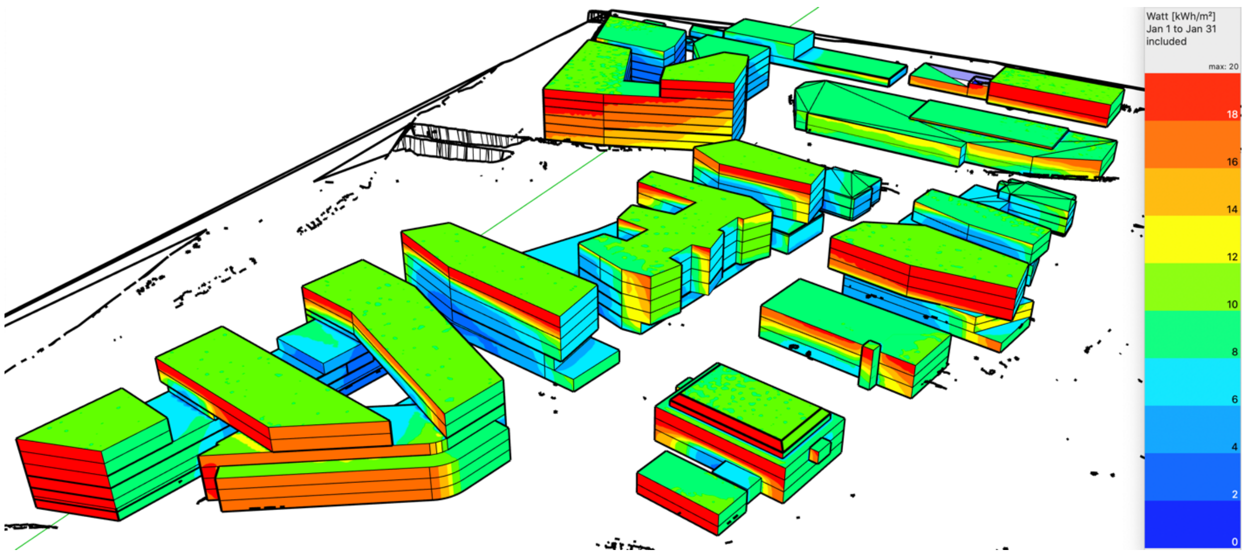


December



2030 Development Scenario Analysis – View of South and East Façades

January



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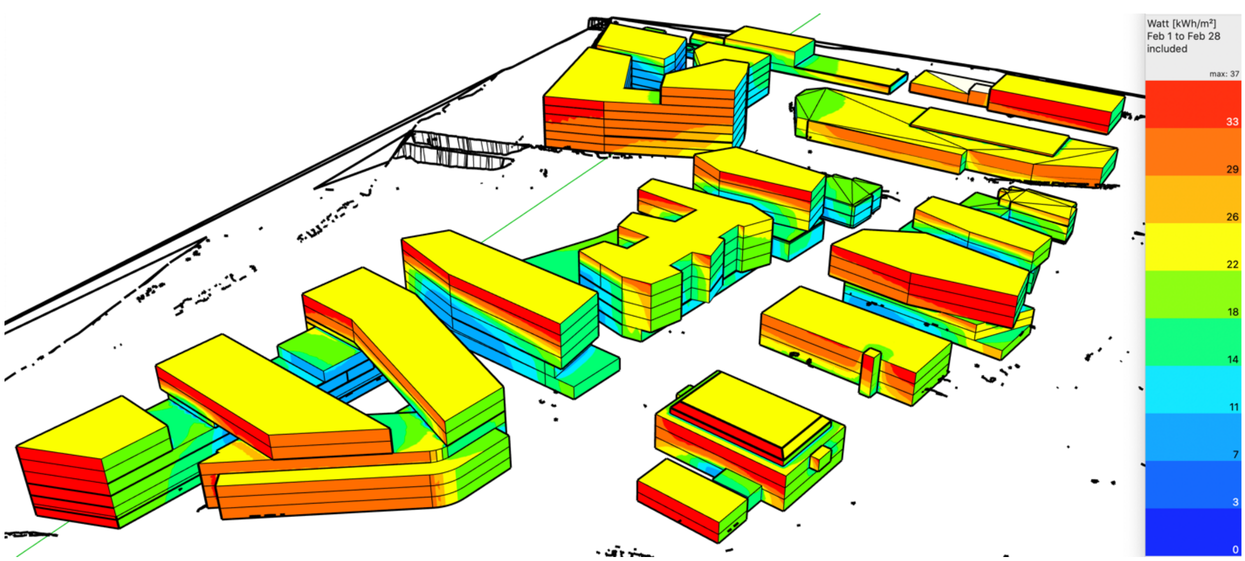

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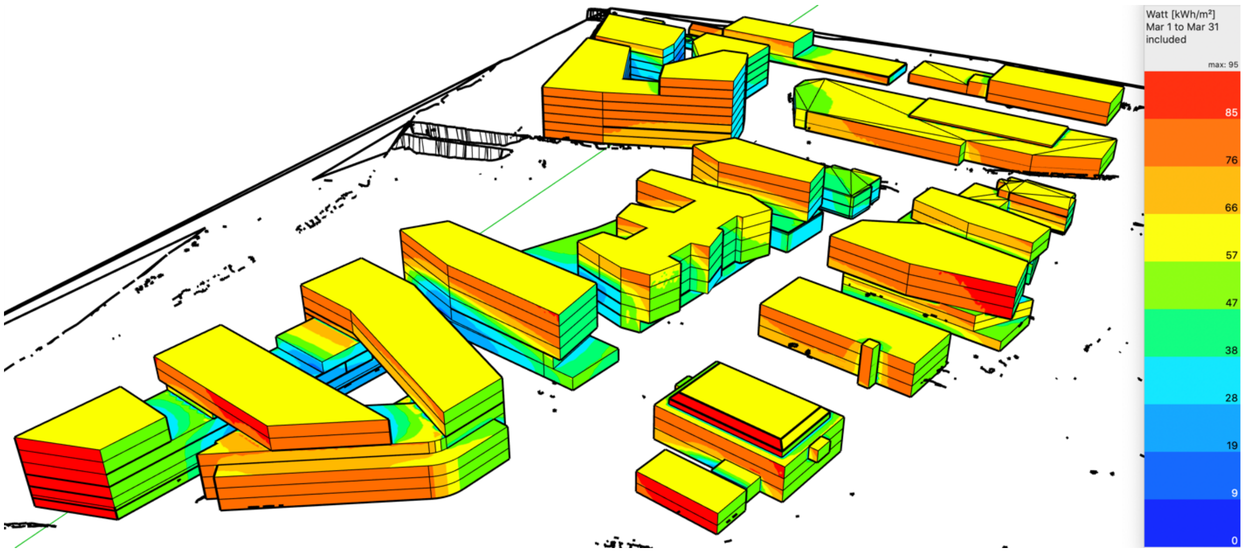
Watt [kWh/m²]
Mar 1 to Mar 31
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max: 95
85
76
66
57
47
38
28
19
9
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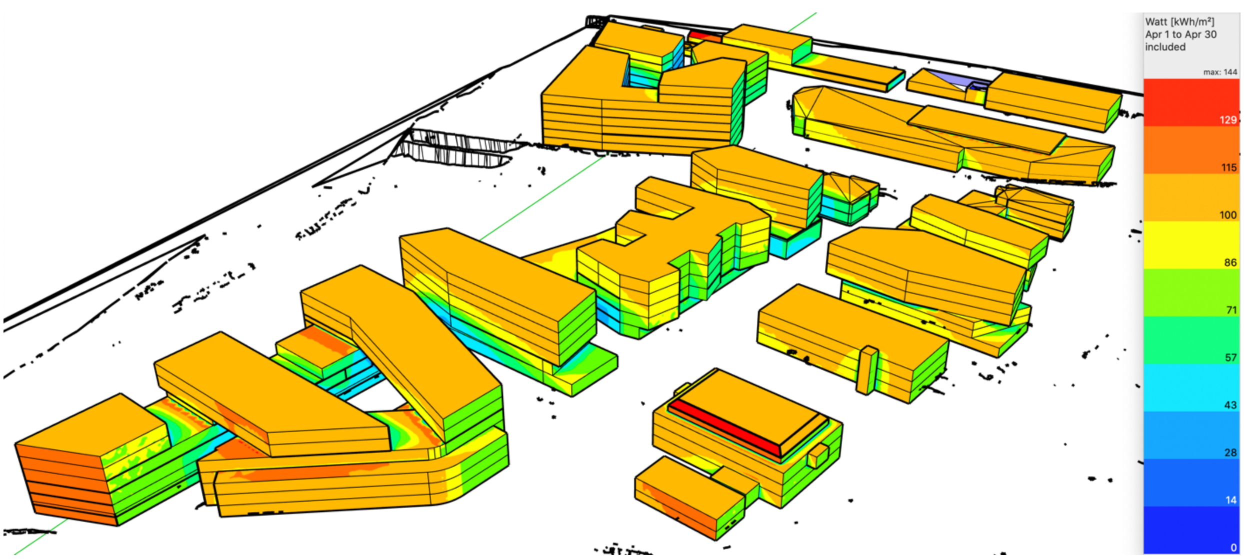
April


Watt [kWh/m²]
Apr 1 to Apr 30
included
max: 144
129
115
100
86
71
57
43
28
14
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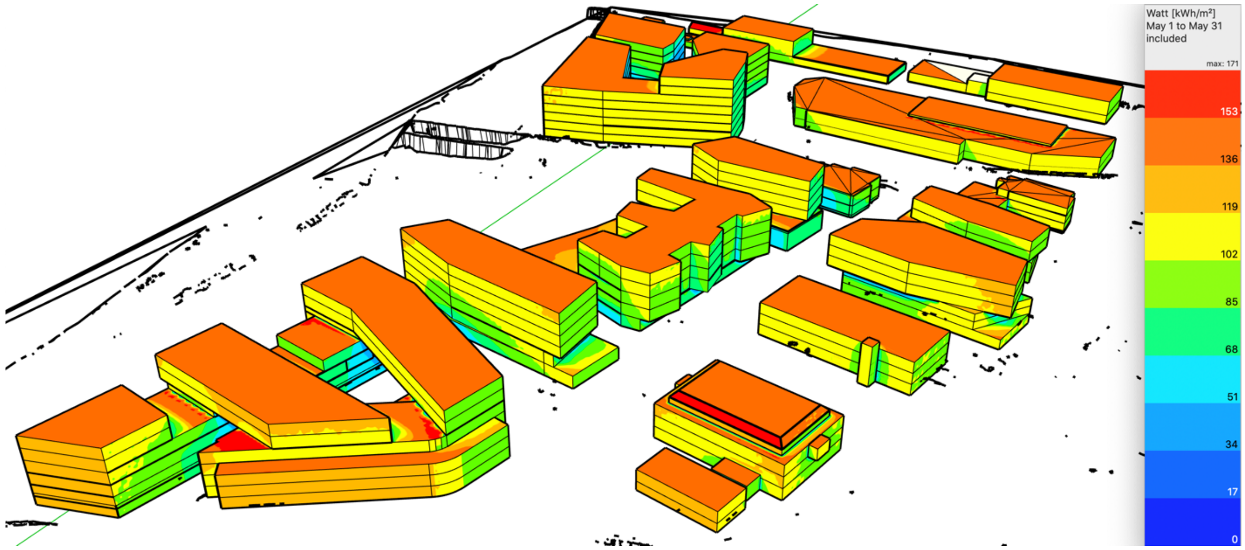
May


Watt [kWh/m²]
May 1 to May 31
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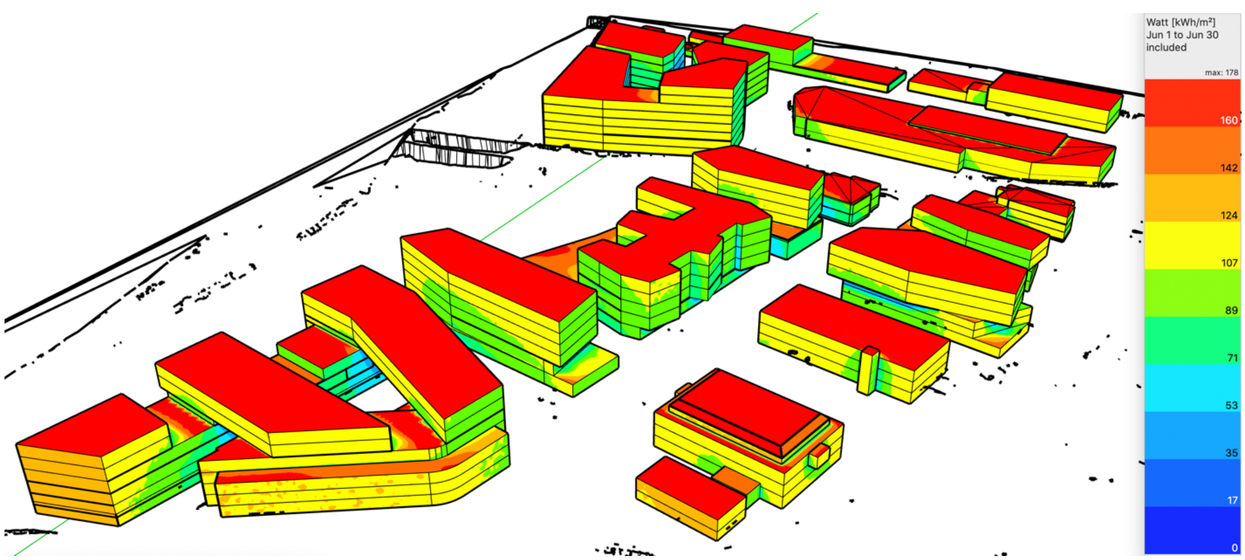
max: 171
153
136
119
102
85
68
51
34
17
0

June


Watt [kWh/m²]
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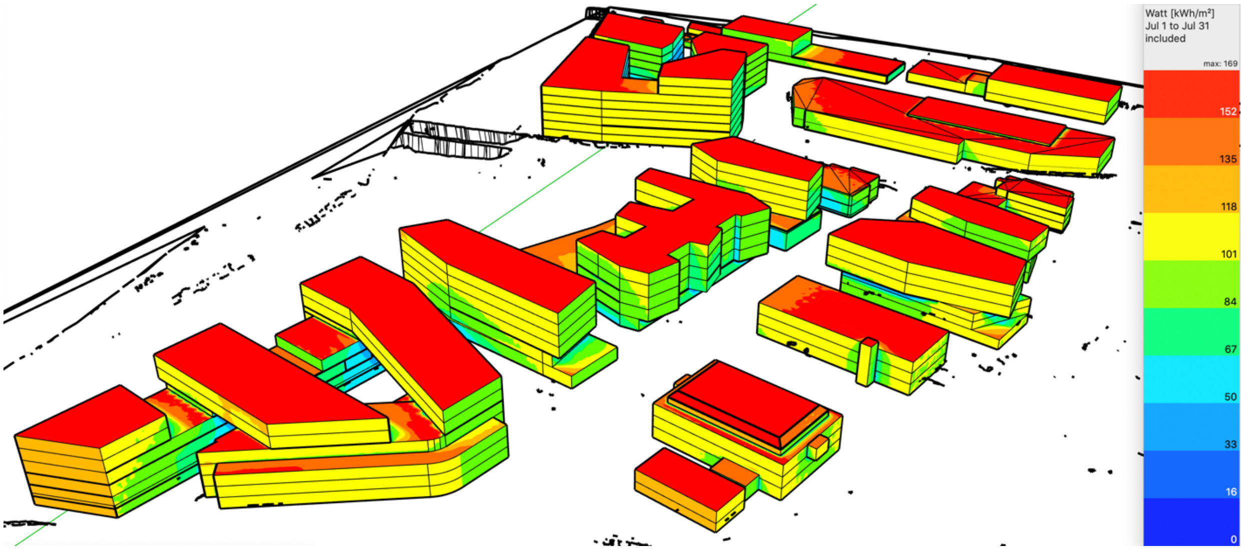
July


Watt [kWh/m²]
Jul 1 to Jul 31
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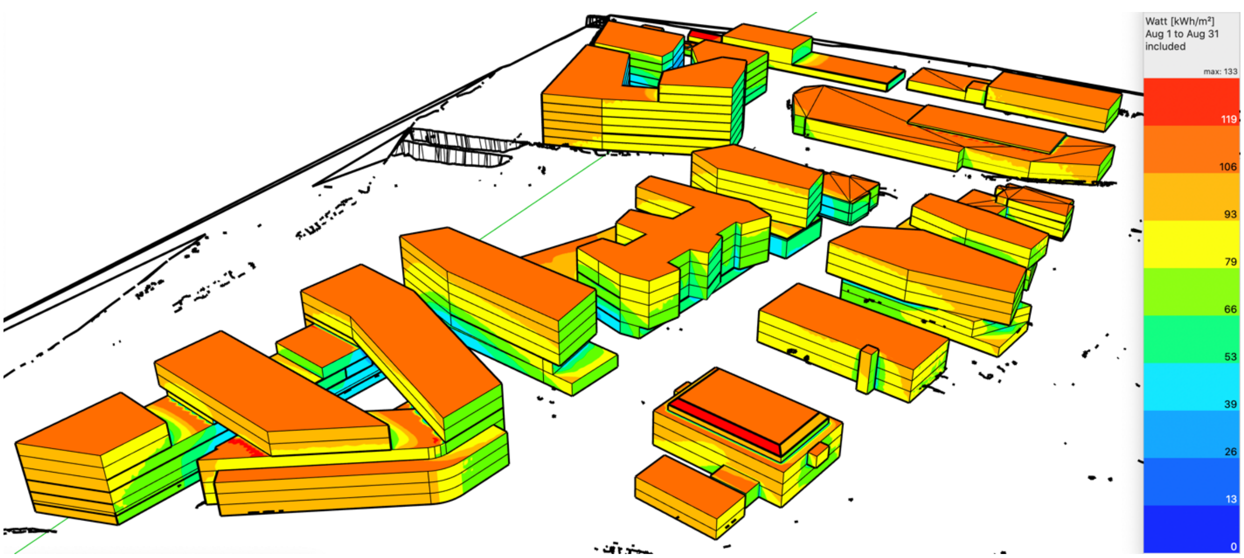
16
0

August


Watt [kWh/m²]
Aug 1 to Aug 31
included
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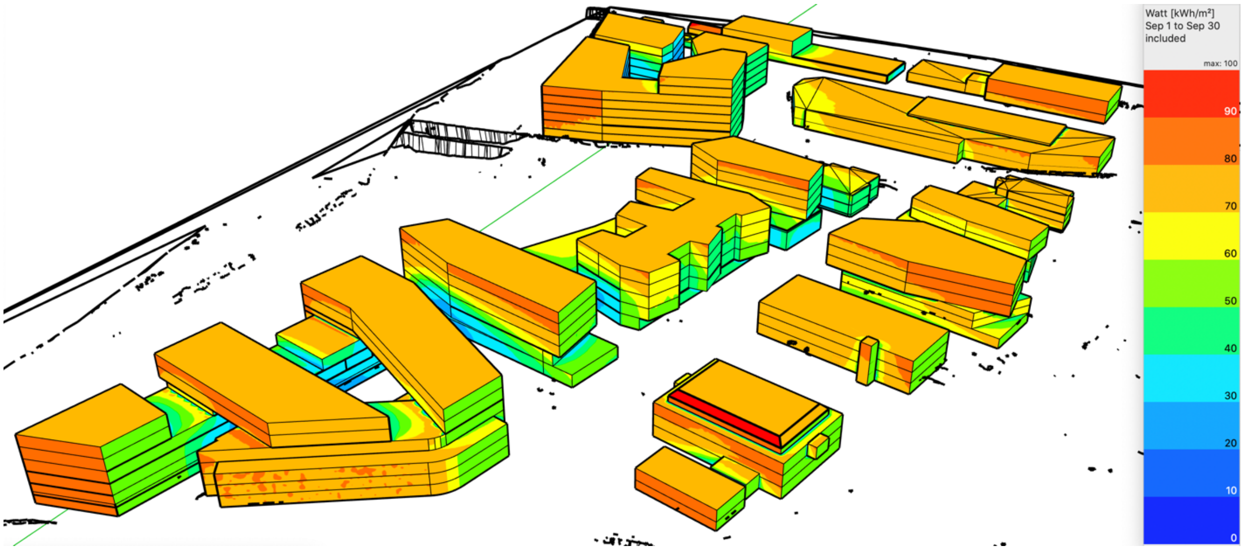
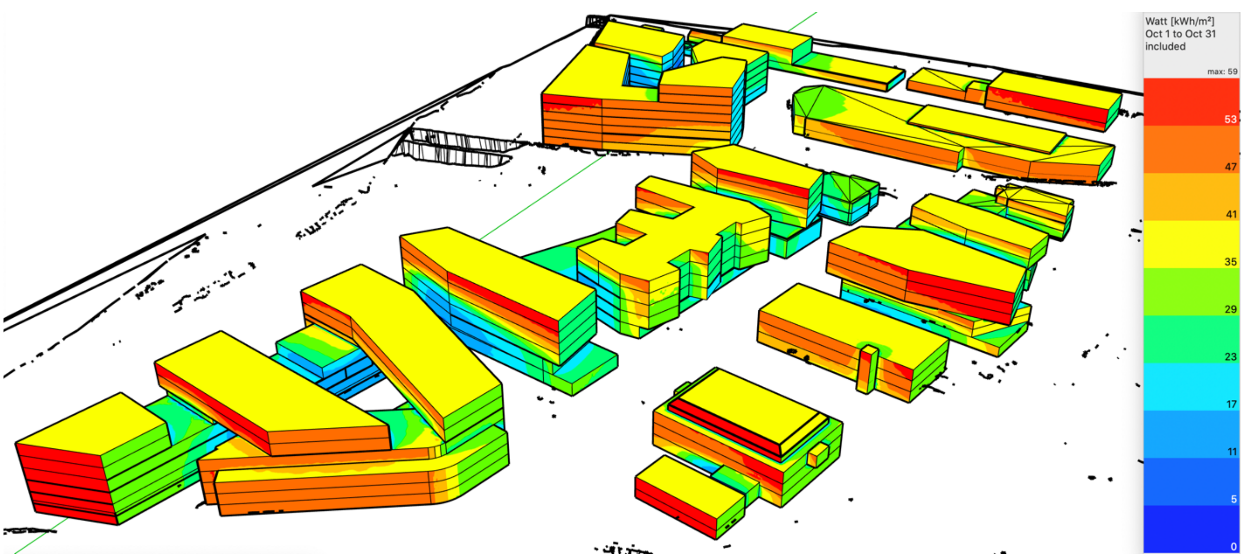
26
13
0

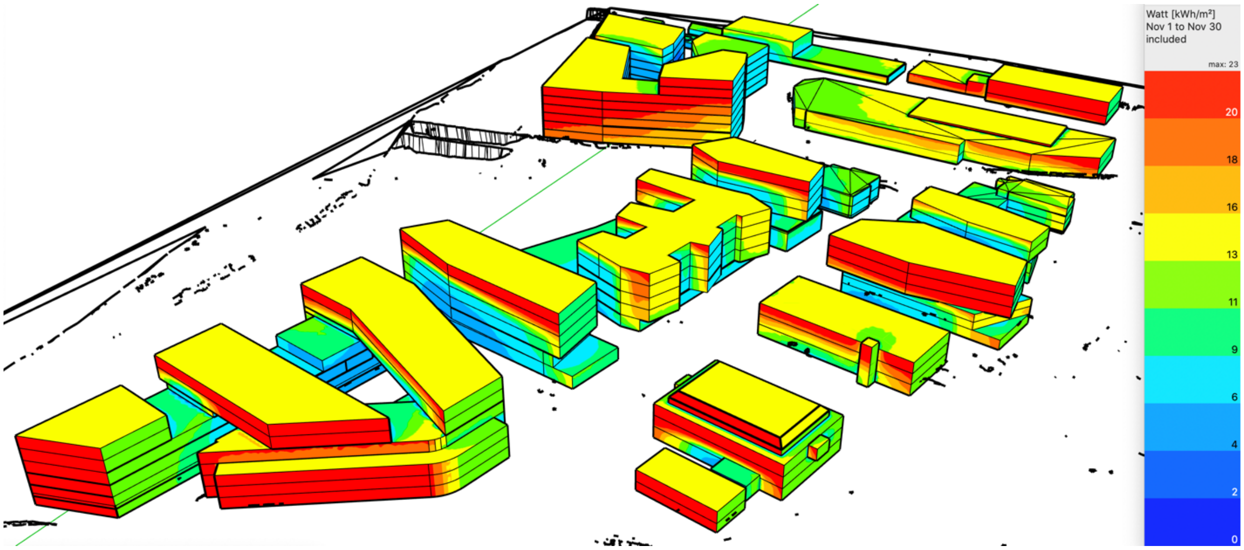
September



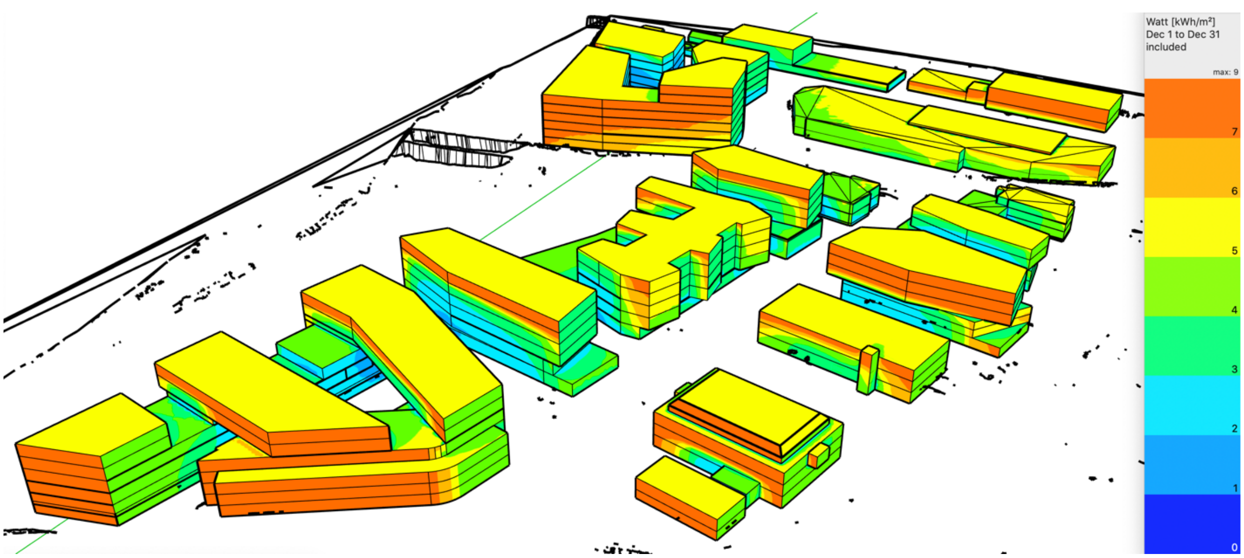
October



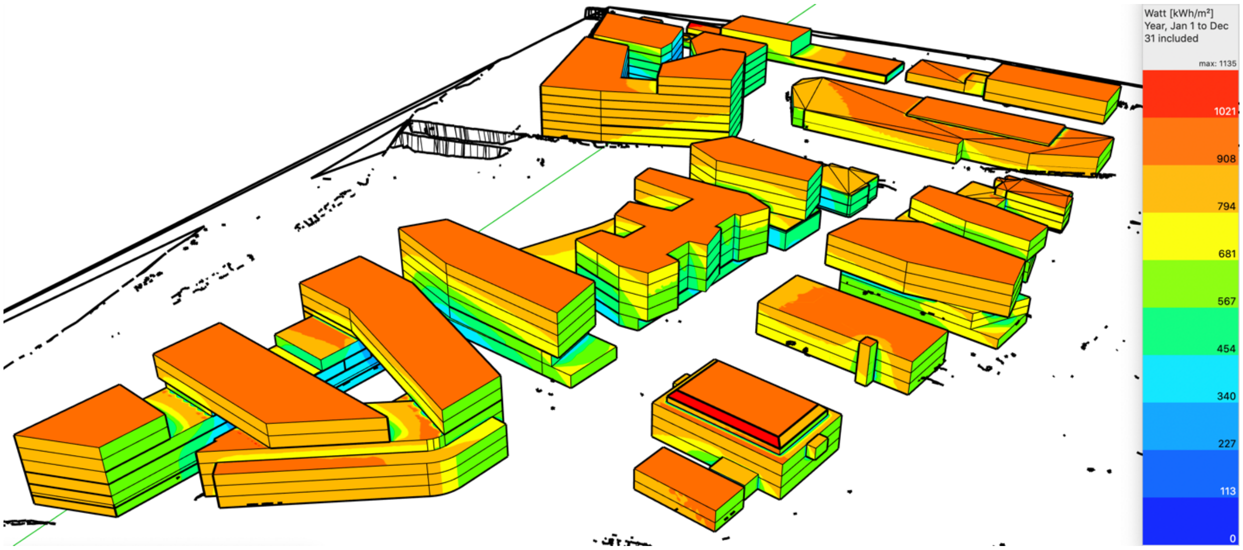
November



December

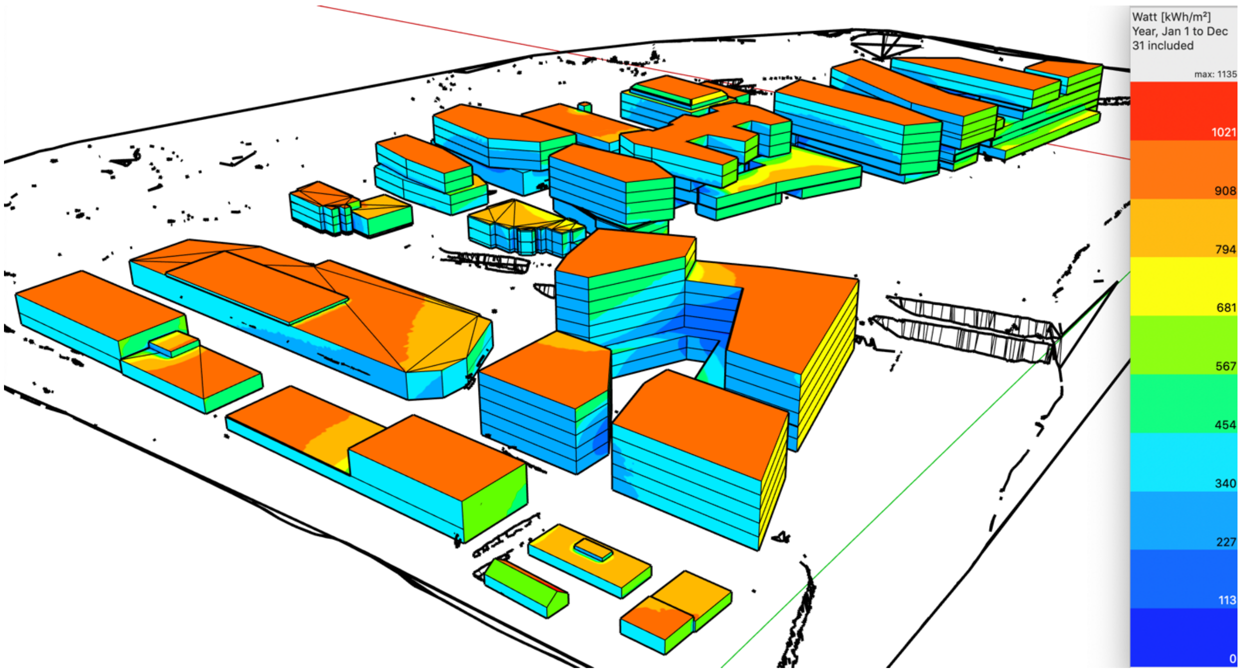


Annual Average

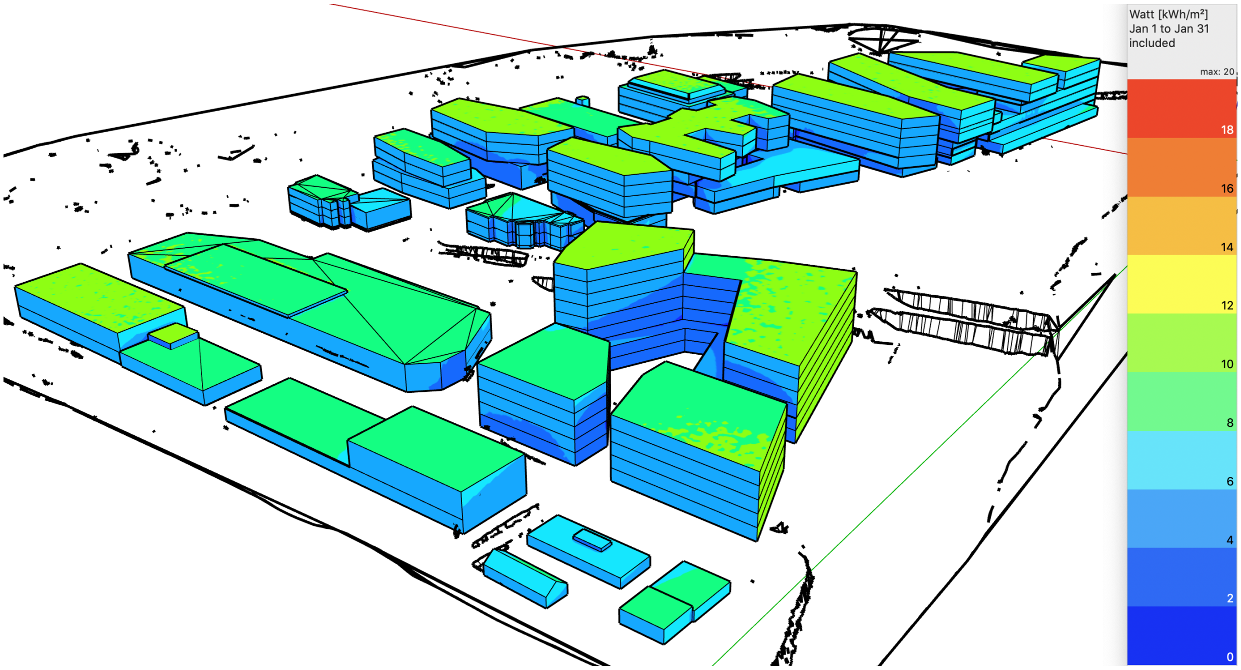


2030 Development Scenario Analysis – View of South and East Façades

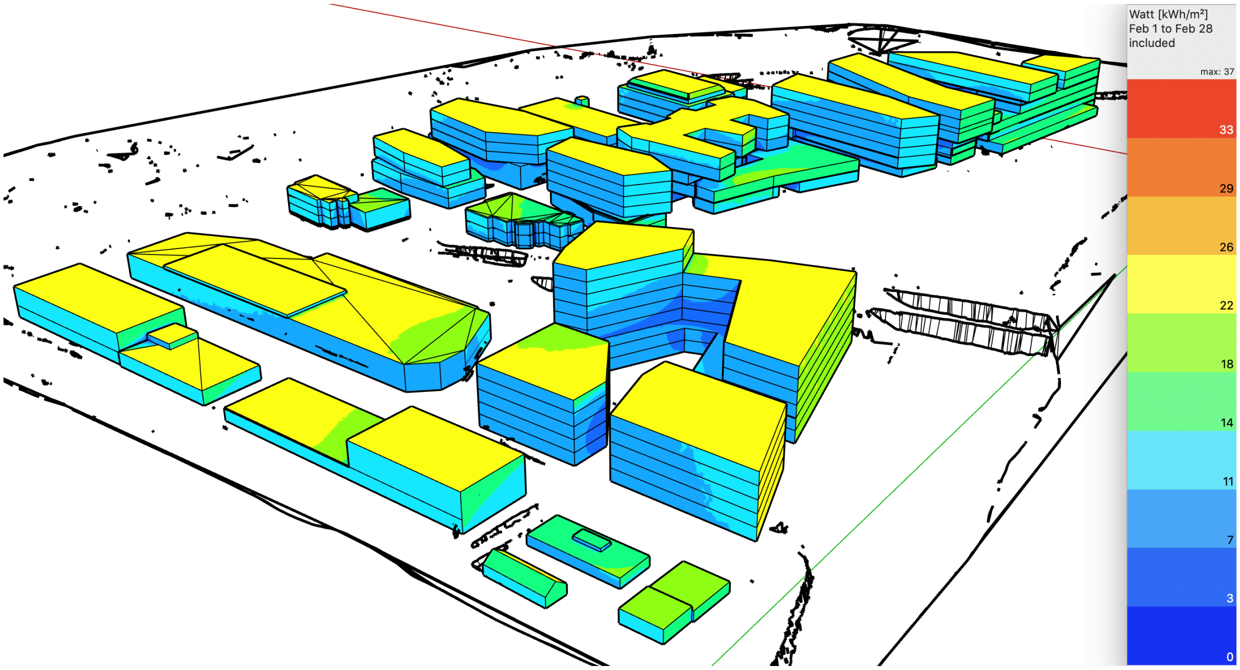
Annual Average



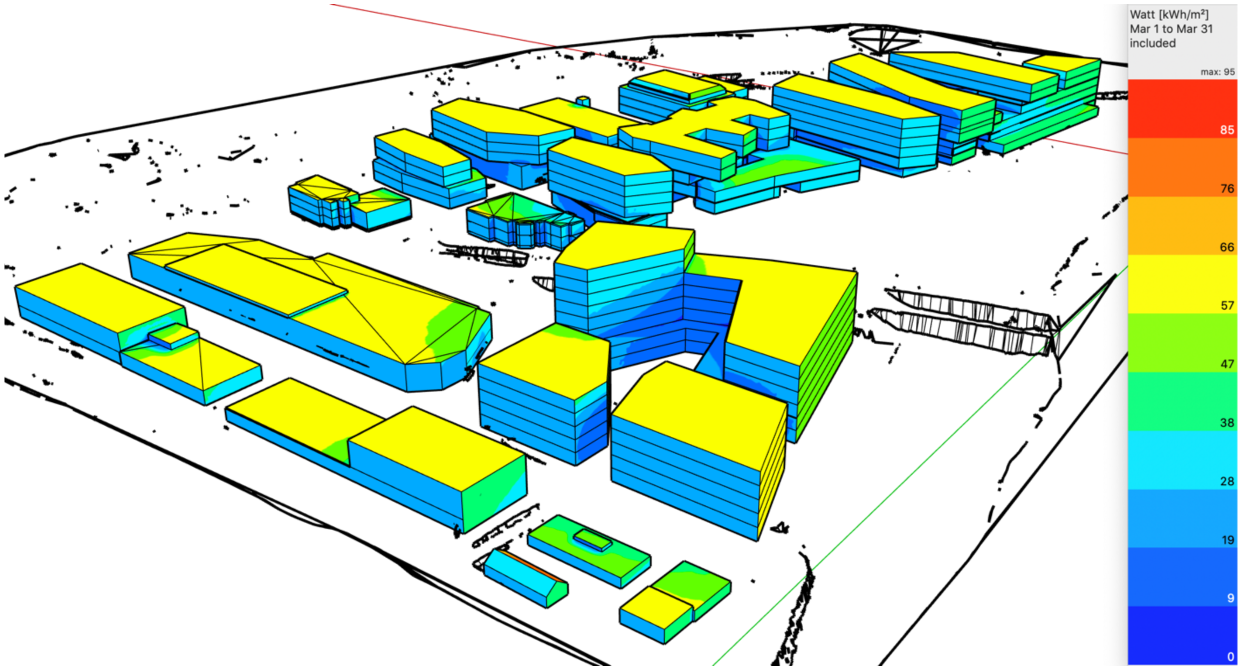
January



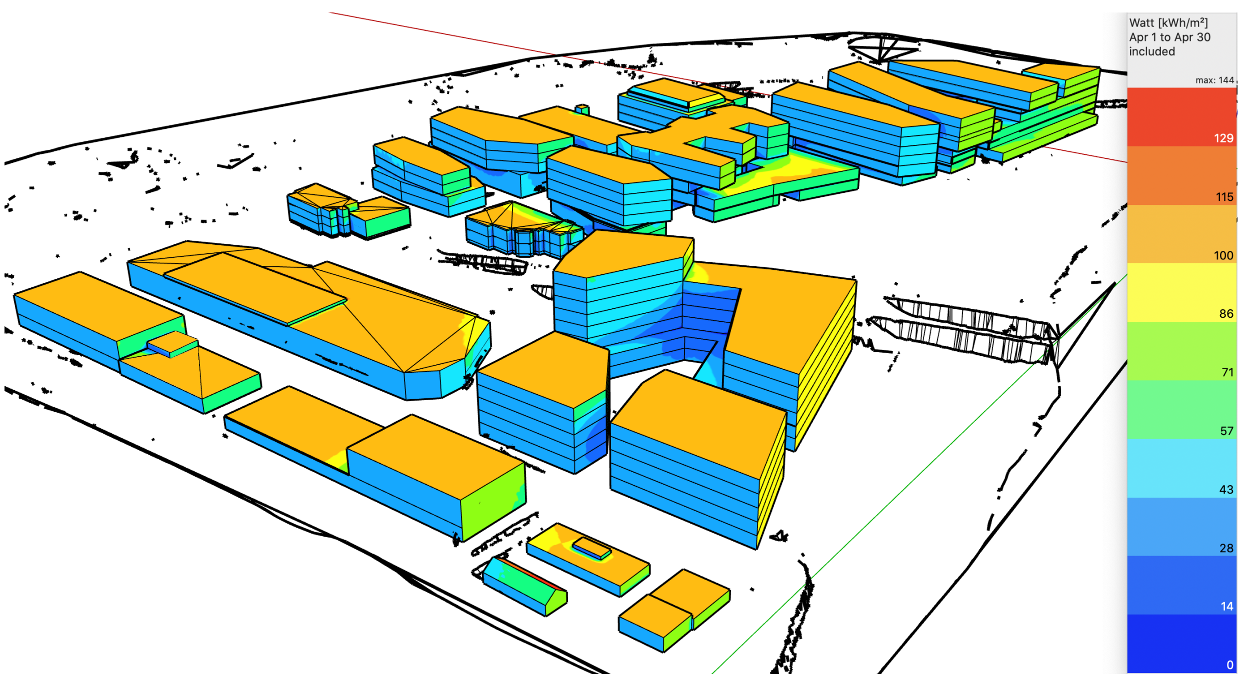
February



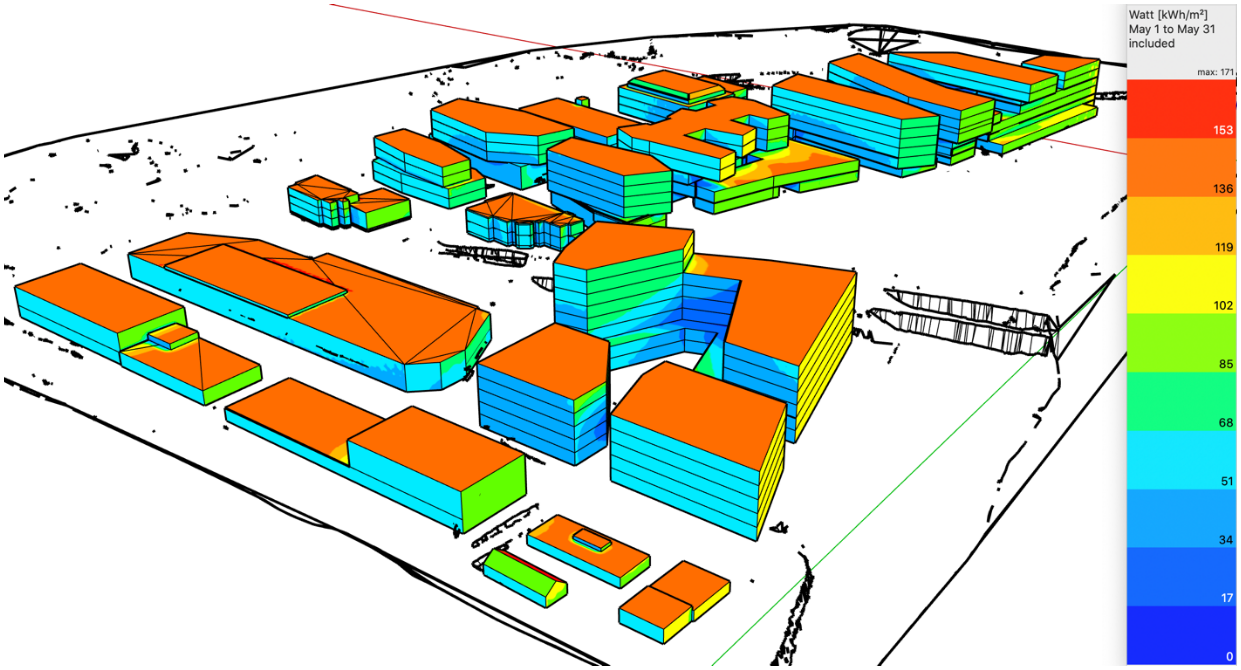
March


Watt [kWh/m²]
Mar 1 to Mar 31
included
max: 95
85
76
66
57
47
38
28
19
9
0

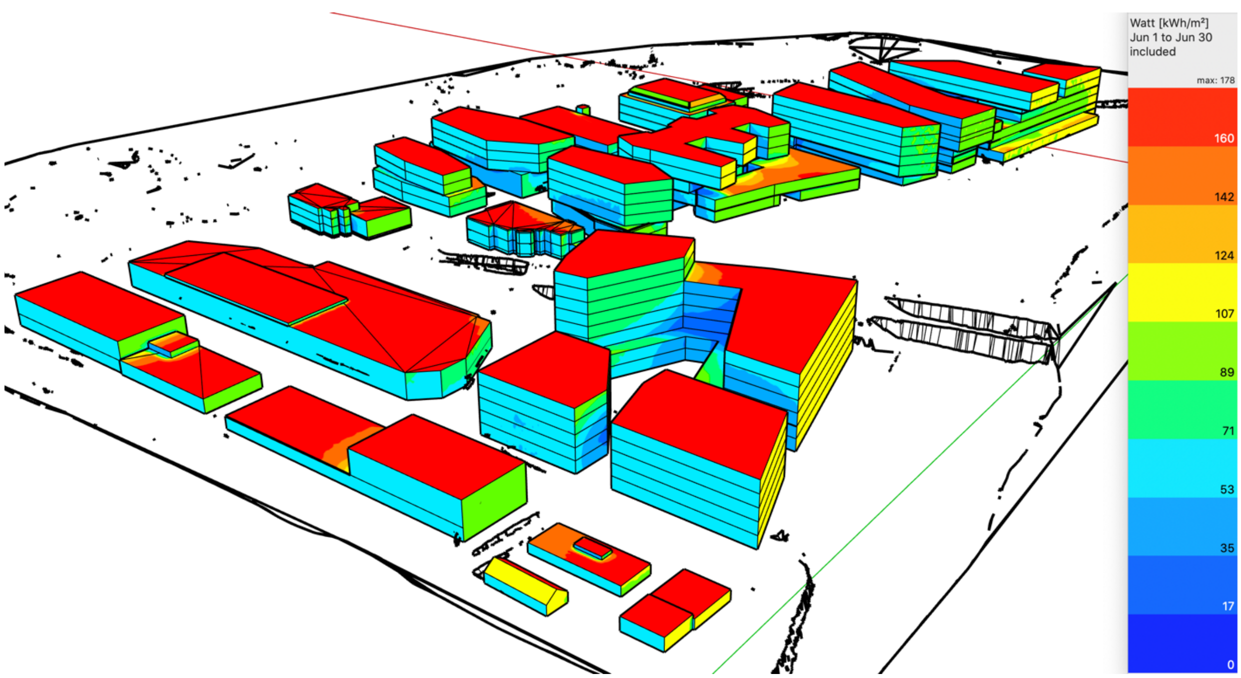
April


Watt [kWh/m²]
Apr 1 to Apr 30
included
max: 144
129
115
100
86
71
57
43
28
14
0

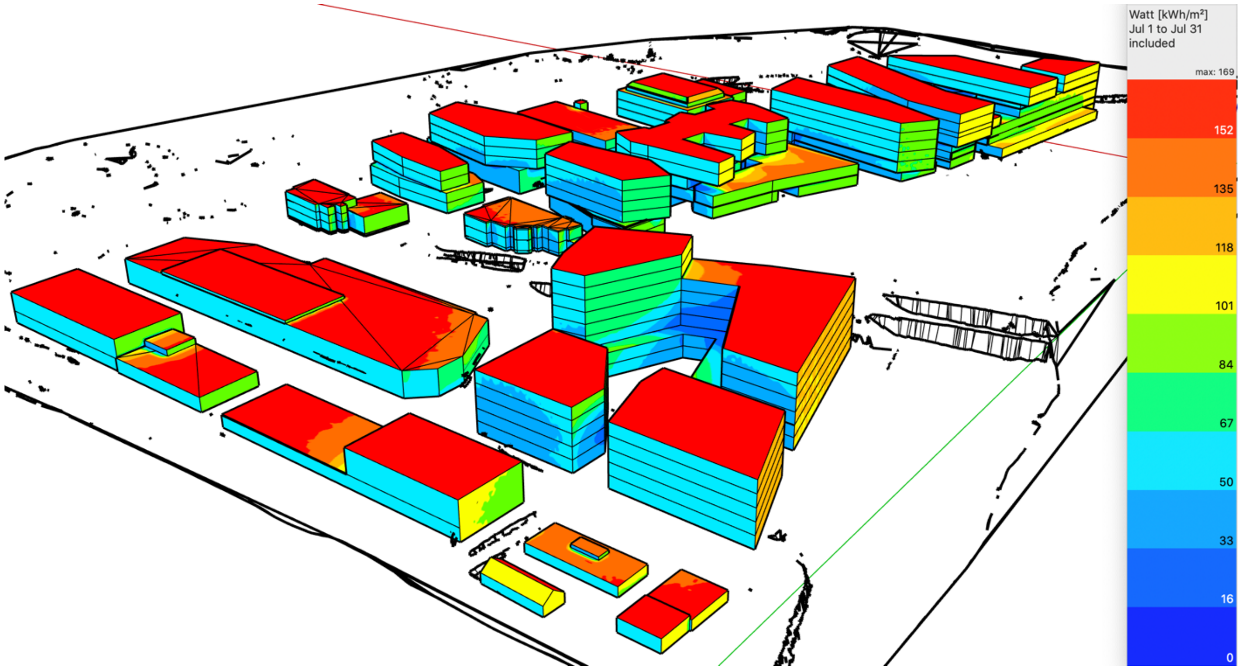
May


Watt [kWh/m²]
May 1 to May 31
included
max: 171
153
136
119
102
85
68
51
34
17
0

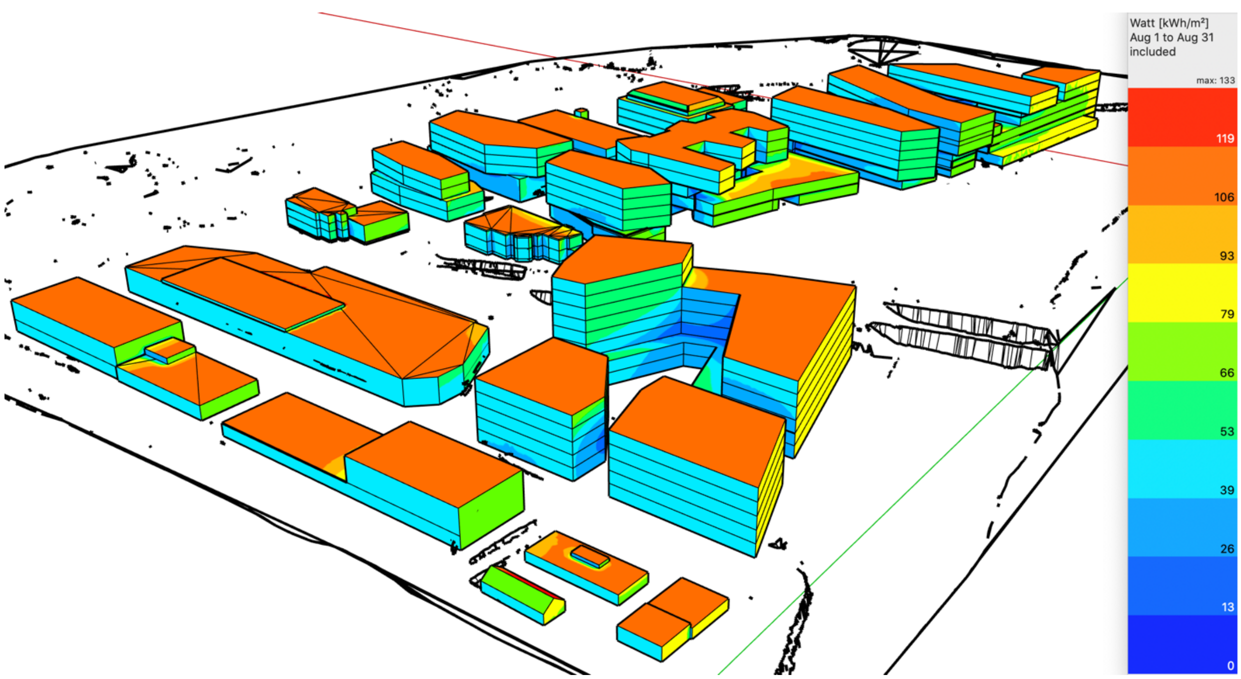
June


Watt [kWh/m²]
Jun 1 to Jun 30
included
max: 178
160
142
124
107
89
71
53
35
17
0

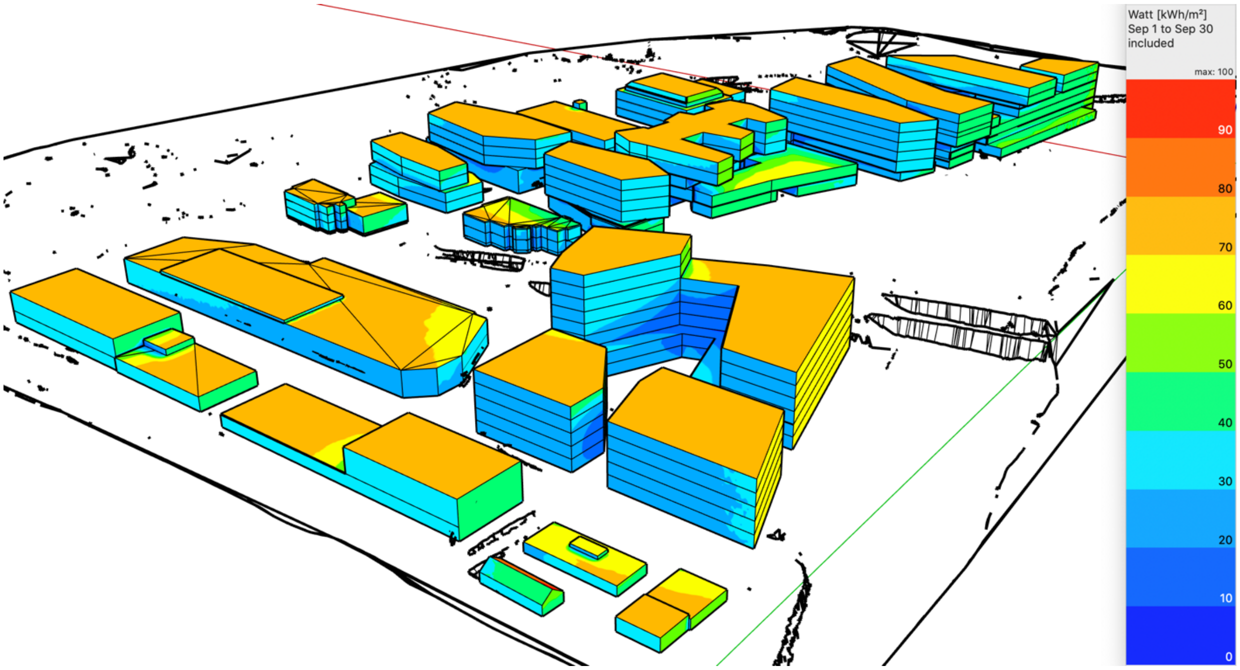
July


Watt [kWh/m²]
Jul 1 to Jul 31
included
max: 169
152
135
118
101
84
67
50
33
16
0

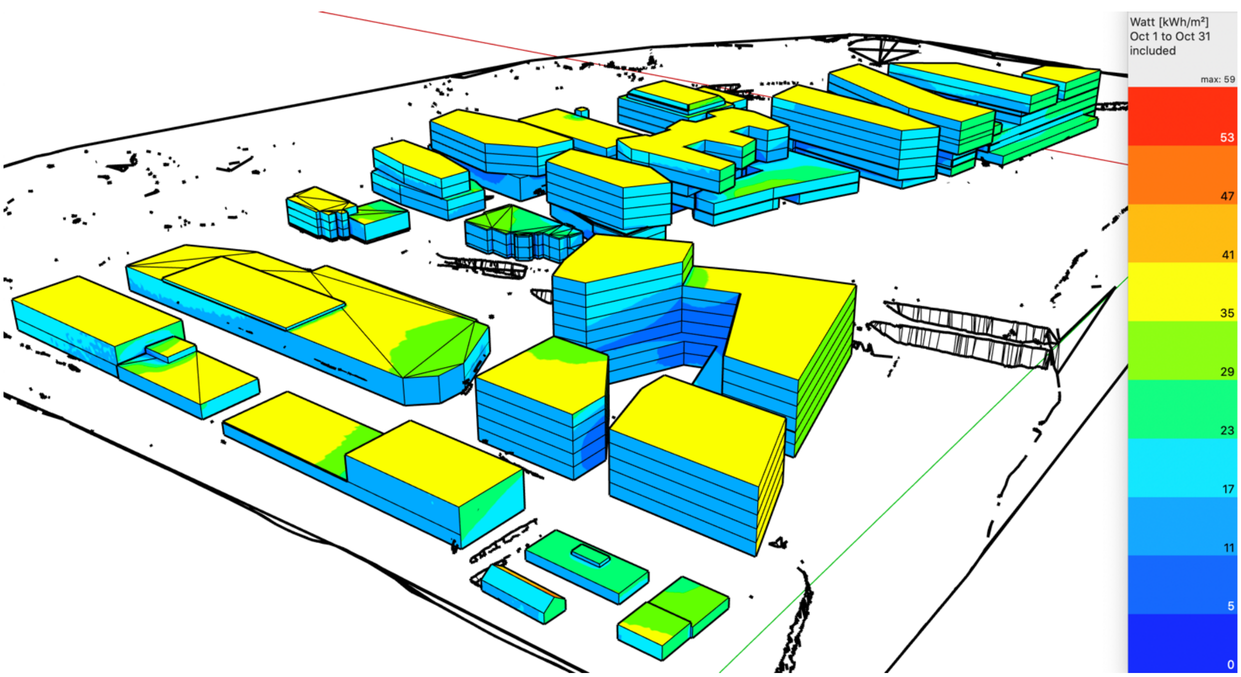
August


Watt [kWh/m²]
Aug 1 to Aug 31
included
max: 133
119
106
93
79
66
53
39
26
13
0

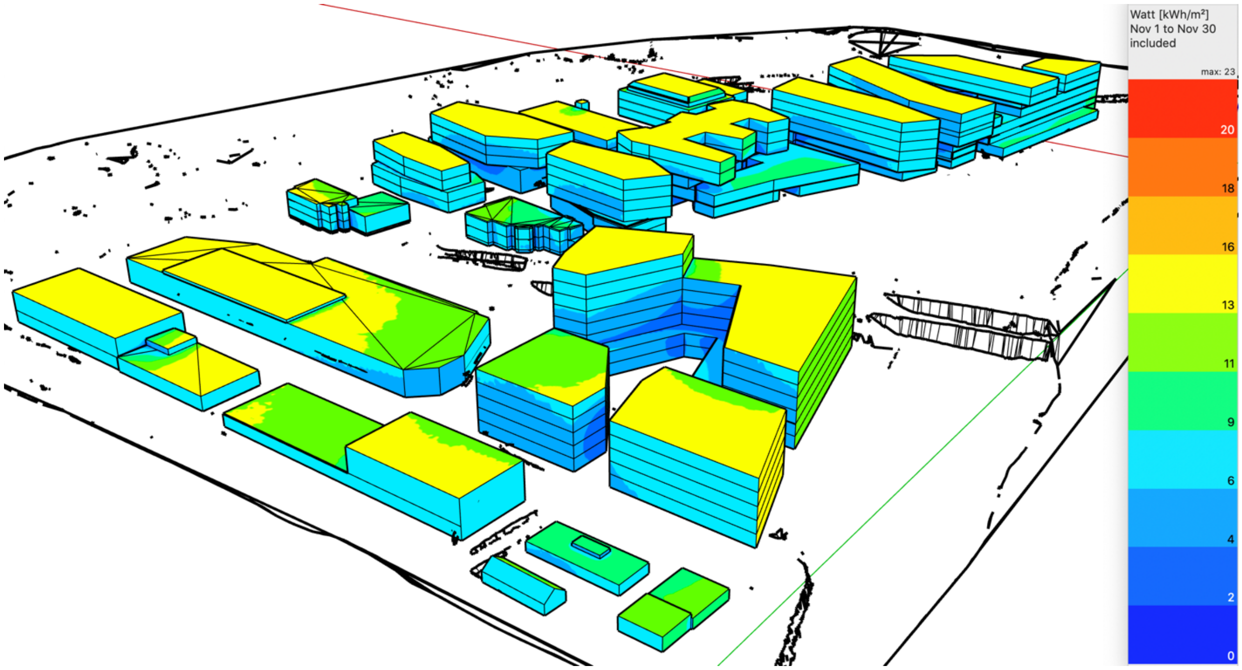
September



October



November



December