SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

Opportunities for Improved Workflows and Development Needs of Solar Planning Tools

IEA SHC TASK 63 | SOLAR NEIGHBORHOOD PLANNING

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Opportunities for Improved Workflows and Development Needs of Solar Planning Tools

This is a report from SHC Task 63: Solar Neighborhood Planning and work performed in Subtask C: Solar planning tools

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List of Abbreviations

AEC	Architecture, Engineering and Construction
BIM	Building Information Modeling
BPS	Building Performance Simulation
CAD	Computer Aided Design
DSH	Direct Solar Hours
DSM	Digital Surface Model
DSO	Distribution System Operators
IFC	Industry Foundation Classes
FME	Feature Manipulation Engine
GIS	Geographical Information System
KPI	Key Performance Indicators
LoD	Level of Detail
PV	Photovoltaic
ST	Solar Thermal
VSC	Vertical Sky Component

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1 Executive Summary

Harnessing incoming solar energy could mitigate the environmental impact of urban development while ensuring a sustainable energy future. This goal is attainable through both passive and active methods of solar energy utilization, including optimizing daylighting, facilitating direct sunlight access, and generating heat and electricity.

In the strategic planning of new urban areas and the expansion of existing ones, it is crucial to integrate solar energy early in the decision-making process. This can be effectively achieved using simulation tools. Recent advancements in simulation technology have empowered planners to make informed choices regarding solar integration in neighborhood design.

Consideration of the current use of tools clearly shows that throughout the different planning stages, the Level of Detail of all aspects -data availability, KPIs, and analyses- increases. During the first stage of the Urban Planning Process, there is little known about the planned (solar) neighborhood. Simple tools or even rules of thumb are often used to gain an understanding of how much solar energy could contribute to these goals. In the next stage of the Urban Planning Process, building volumes are known, enabling a deeper analysis of the role of solar energy to the neighborhood. As you progress to the Building Design Process, more details about the buildings and requirements from the building occupants are known. With the help of tools, details on a system level can be studied.

A large part of the building stock is already existing, and the planning strategies for solar deployment then relies on efficient mapping of the existing opportunities. To that aim, solar cadasters are tools used to evaluate the potential for solar installations on buildings, catering to various users including homeowners and city planners. They compile data on energy production, technical feasibility, economic viability, and environmental benefits using a range of indicators. Key metrics include potential electrical output, installation costs, and CO_2 savings. These tools support decision-making for solar projects by providing essential information on the economic and environmental impacts of solar energy, while also considering local constraints such as heritage preservation. Overall, solar cadasters are instrumental in advancing the adoption of solar technology.

There are increasing opportunities for using tools. Advanced tools can be of added value to improve living and working conditions in neighborhoods and buildings. It is, for instance, advantageous to be able to perform multiple types of simulations (e.g. daylight provision, irradiation analysis, direct solar access, energy performance) based on one geometric model. For key actors in the planning and building design process, advanced simulations could provide not only a set of design solutions to meet current legislation, but also assess solutions that go beyond what is legislatively mandated. Some advanced tools, however, still require a high proficiency of skills to master.

This report highlights opportunities for maximizing the use of tools for solar neighborhood planning by analyzing the current use of tools in the design process, the mapping of the solar potential and installed capacity, and by describing opportunities for an increase in use of tools.

2 Introduction

An increasing use of incoming solar energy can reduce the environmental impact of our built environment and secure future supply of energy. This can be achieved through the passive and active utilization of solar energy; by means of good daylight provision, access to direct sun, and the production of heat and electricity.

When planning for new city developments as well as for densification projects, it is important to take well-founded decisions regarding solar energy early in the planning stage. This can be achieved, amongst other approaches, by using simulation tools. In recent times, there has been a significant development of simulation tools capable of providing support in decision-making regarding solar neighborhoods. Report C1 of Task 63 titled 'identification of existing tools and workflows for solar neighborhood planning' has shown the large variety of tools available on different platforms (CAD, GIS, stand-alone) with different Levels of Detail (LOD) (Kanters et al., 2022). This was also shown within Subtask B on process, methods and tools of the previous Task 51 (Solar Energy in Urban Planning). The report from subtask B 'Approaches, Methods and Tools for Solar Energy in Urban Planning' showed also that many different approaches, methods and tools exist to support urban planners (Marja Lundgren & Johan Dahlberg, 2018).

Key actors will rely more and more on advanced simulation tools that can provide significant decision-making support during the early design stages. For now, there are very few tools or tool environments that can both assess the active and passive solar utilization at different planning stages and with varying levels of detail since most tools are either focused on, or more suited to, a particular design phase.

Besides, the use of tools in the urban planning and building design process is gaining traction as more and more open data becomes available related to solar energy neighborhoods. The data could be a solar map but can also be the registered energy use of buildings or information about an urban heating network. Combining the outcome of tools with such open databases enhance decision-making resources.

This report aims to show opportunities for maximizing the use of tools for solar neighborhood planning. In Chapter 3, the current use of tools in the design process is discussed, followed by Chapter 4, which focuses on the mapping of the solar potential and installed capacity, while Chapter 5 describes opportunities for an increase in use of tools.

The target group for this report consists of the users of tools for solar neighborhood planning, relevant stakeholders in the design process, and legislators.

3 Current use of tools in the design process

Within Task 63 and Subtask C, the report C1 has identified existing tools and workflows (Kanters et al., 2022). Based on this report, it can be concluded that currently, a multitude of tools for solar neighborhood planning are available, all with advantages and disadvantages for users in meeting their needs.

Tools and tool workflows, when different tools are used in series or within a certain procedure, are normally developed to fit a certain planning process (the urban planning process or building design process) -all with a different purpose. There are, of course, exceptions as some tools allow the user to work at different scales. Often, at the urban scale, tools that can handle large amounts of data are prevalent and are often GIS-based. At the neighborhood and building scale, we identified tools that work either as a stand-alone product or within CAD environments. Important elements for correct modelling of a solar neighborhood are how to choose the weather data, how to model the geometrical model and energy consumption, and how to simulate micro-climates. Other important aspects of tools are if they can handle multi-objective optimization, which is the process of decision-making involving more than one objective. Furthermore, another aspect is if tools are free (open source) or commercial.

To optimize calculation times, tools often use simplified equations. One part of the Report C1 report analyzed how well different tools correlate with each other. One of the results found, with similar geometrical input and settings, the different tools were all within a very small range of error for predicting the solar irradiation on roofs. On façades, however, the tools varied in accuracy considerably.

Tools are used by their users with a certain aim and at a certain point in time. Their use is, therefore, highly connected to the design phase, the available data at this stage, key performance indicators (KPIs), different actors, and the type of analysis that is typically performed during those stages.

Stakeholders expect different outcomes from tools. Urban planners often see tools as a way of evaluating if their zoning plan meets at least minimum requirements under building codes (Kanters et al., 2021). On the building scale level, architects and engineers use tools to provide a good decision-making foundation for themselves and their clients.

In order to gain a better insight of the differences in tool use and related framework, experts from the different participating countries in this IEA SHC Task gathered specific national datasets. An earlier developed framework by Kanters & Wall, (2016) was used as a base and adapted to fit a consistent comparative approach. National frameworks from experts from Canada, Italy, Norway, Sweden, and Switzerland were compiled into one framework for the use of tools, data availability, Key Performance Indicators (KPIs), actors, and common performed analyses.

It should be noted that the framework compiled by the national experts and summarized version should not be seen as a representative framework for all participating countries, since not all experts are engaged in all aspects of planning solar neighborhoods.

The compiled framework is provided below in Table 1.

Table 1: Tool framework for solar neighborhood planning

	Urban Planning Process	
	Strategical planning	**Urban Design**
Available data	-Geometrical data -Local climate data -Legislative restrictions -Other relevant (energy-related) data	-Geometrical data -Local climate data -Legislative restrictions -Other relevant (energy-related) data
KPIs	-Geometrical KPIs (density, etc) -Energy KPIs (zero carbon, plus energy). Active production requirement (Switzerland only) -Liveability KPIs	-Geometrical KPIs (density, etc) -Energy use KPIs (zero carbon, plus energy) -Solar Energy production (DSH, sky view, daylight, peak solar radiation, VSC)
Actors	Local governments (politicians, urban planners), real estate developers, energy consultants, utilities, academy	Local governments (politicians, urban planners), real estate developers, architects, engineers
Tools / analyses	-Rules of thumb -Analogue tools (sketches, models, presentations) -Energy use simulation (low accuracy) <GIS, CAD (Sketchup), BPS tools (E+) >	-Possible solar energy production / irradiation -Daylight simulations -Energy modelling and load matching (production vs consumption) -3D modelling -Microclimate <Rhino / Grasshopper, ArcGIS, Autodesk Forma, Helioscope, PVSyst, LB/HB, E+-, hand calculations –python, excel, MatLab>

Table 2: Building design process

	Concept Design	Schematic Design	Detailed Design
Available data	-3D Volume studies -Requirements of project	-Interior layout -Exterior layout	-Detailed design (interior & exterior), with full 3D model
KPIs	-National regulations regarding passive solar utilization, energy, thermal comfort -Building certification assessment (WELL, BREEAM etc) -Legislative restrictions (height limitations)	-National regulations regarding passive solar utilization, energy (avg U-value), thermal comfort -Local energy production (RE) -Building certification assessment (WELL, BREEAM etc) -Legislative restrictions (height limitations)	-National regulations regarding passive solar utilization, energy (avg U-value), thermal comfort -Local energy production (RE) -Building certification assessment (WELL, BREEAM etc) -Legislative restrictions (height limitations)
Actors	Urban planners, Architects, Engineers, Real estate developers (clients)	Urban planners, Architects, Simulation specialists, Engineers, Real estate developers (clients)	-Urban planners, Architects, Simulation specialists, Engineers (HVAC), Real estate developers (clients), Electricians
Tools / analyses	-Energy use analysis -Solar energy production -Passive solar utilization -3D modelling <Simien, Rhino/GH, IDA ICE, Sketchup, Own developed tools, Dragonfly>	-Energy use analysis -Solar energy production -Passive solar utilization / daylight (climate-based KPIs) -3D modelling <Simien, Rhino/GH, IDA ICE, PVSyst, Sketchup, Own developed tools, ENVIMet>	-Energy use analysis (load matching) -Solar energy production -Passive solar utilization / daylight (climate-based KPIs) -3D modelling <Simien, Rhino/GH, IDA ICE, PVSyst, Sketchup, Own developed tools, ENVIMet, ClimateStudio>

The tool framework as shown in Table 1 clearly shows that throughout the different planning stages, the Level of Detail of all aspects -data availability, KPIs, and analyses- increases. This is logical since neighborhoods are developed throughout the urban planning and building process stage.

During the first stage of the Urban Planning Process, there is little known about the planned (solar) neighborhood. KPIs or goals, such as the planned density or achieving a Net Zero Energy Neighborhood will directly link to the use of solar energy. Simple tools or even rules of thumb are often used to gain an understanding of how much solar energy could contribute to these goals. In the next stage of the Urban Planning Process, building volumes are known, enabling a deeper analysis of the role of solar energy to the neighborhood. As you progress to the Building Design Process, more details about the buildings and requirements from the building occupants are known. With the help of tools, details on a system level can be studied.

Interestingly, some of the mentioned tools are used throughout all stages, while others are mandated to be used according to national legislation. The tools mentioned in the Tool Framework are often used in a more project-based approach and mainly for new buildings. For existing buildings, GIS tools have been used extensively.

4 Mapping the solar potential and installed capacity for solar neighborhoods

4.1 Mapping the solar potential on existing roofs

Solar maps, maps showing the potential of installing active solar energy production on existing buildings, are often used as a first step to acquire information about this potential. Nevertheless, the rapid expansion and availability of such tools make them more and more attractive to support local stakeholders such as authorities, citizens, industries etc (Thebault et al., 2022; Walch & Rüdisüli, 2023)**.** The data that is provided for solar maps differ from map to map and at a country-to-country level (Kanters et al., 2014). Moreover, similar data (for example, solar irradiance or investment costs) can be presented in various ways by means of using different types of indicators and/or thresholds (Lobaccaro et al., 2019). It is, therefore, important to study how different aspects of solar energy are being presented to the user, as well as how country-specific details are provided. Experts from the Task were asked to provide examples of solar maps in their country. Even though the list might not be comprehensive, it provides an indication of the data that is available for these solar maps.

A solar cadaster, in its simplest form can be defined as a map (usually a GIS representation) which represents how much irradiance (solar energy) is received on the buildings-roof of a specific region. To that aim, it is necessary to know at least the local typical weather conditions, as well as building shapes and locations.

Numerous approaches have been developed in order to calculate and create solar cadasters. Reviews of such approaches can be found in (Gassar & Cha, 2021; Melius et al., 2013)**.**

When data presents insufficient detail, a statistical approach can be used to aggregate and fill data gaps. For example, when the roof slope and orientation is not known, roof orientation can be deduced from the building footprint and the slope can be taken as an average representative slope for a given type of building (Wiginton et al., 2010). On the other hand, the availability of detailed 3D models (obtained by LiDAR or photogrammetry) enables the calculation of detailed solar cadaster maps with high levels of detail (Desthieux et al., 2018).

Note that there also exist solar maps, which cover the entire world or at least a large part of it, such as the NSRDB: National Solar Radiation Database[1], the Global Solar Atlas[2] or PVGIS[3]. These maps only consider the local topography without considering the elements such as buildings or trees. These maps provide an excellent input in order to evaluate the local irradiation, which would be received on a flat unshaded roof. However, in other cases, some maps are unable to provide direct information about solar radiation received on a roof surface. These solar maps are out of the scope of this report.

4.2 Global overview of existing solar cadaster

Since solar cadasters are made for citizens or local decision makers, they are often available in the local language. Therefore, the Task 63 experts were asked to identify solar cadasters available in the language they knew.

This resulted in a list of 56 solar cadasters from 30 countries. The location of the reviewed solar cadasters is presented in Figure 1. Recently, it appeared that some countries developed solar cadasters that would cover nearly all their territories as it is the case in the USA or in Australia or based on SolarCity Calculators of IRENA (IRENA, 2023). Whereas historically solar cadasters were mostly located in Europe, North America and Australia, an increasing number of cities located in Africa, central Asia or central America can now also have access to a solar cadaster.

[1] https://nsrdb.nrel.gov/

[2] https://globalsolaratlas.info/map

[3] https://re.jrc.ec.europa.eu/pvg_tools/fr/

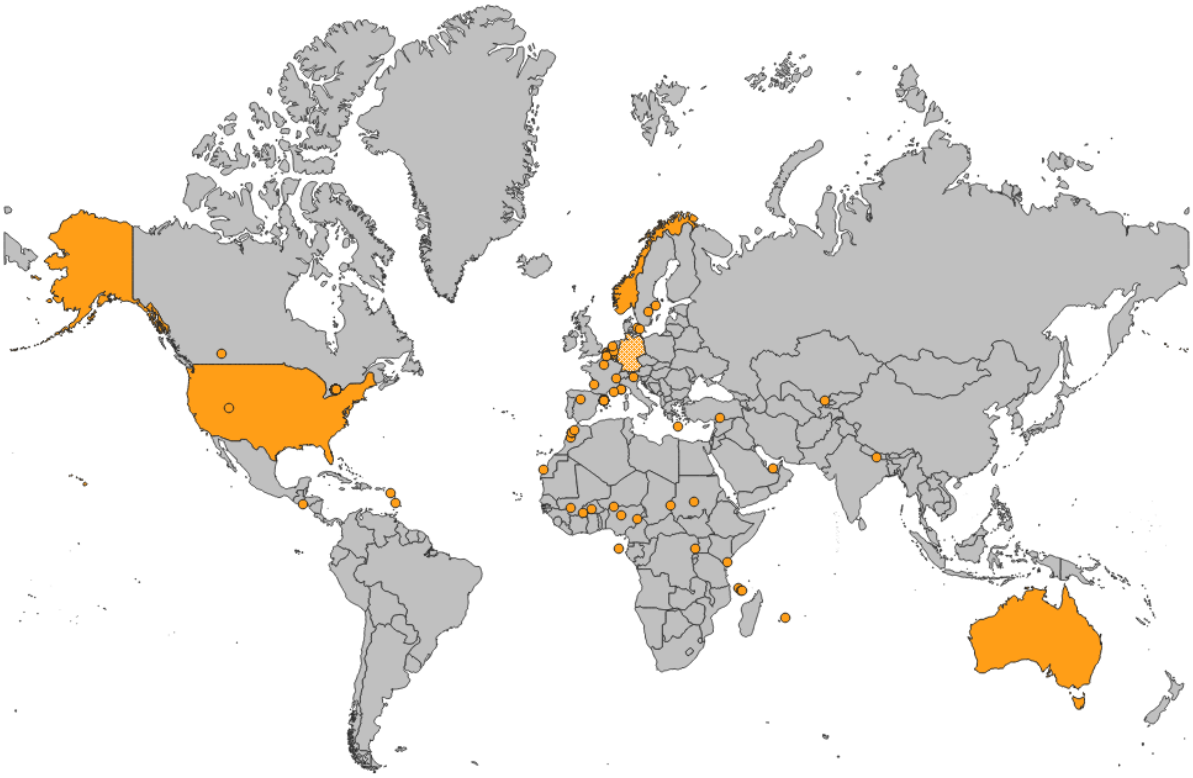

Figure 1: World maps of the area covered by the solar cadasters listed

As a further activity, these cadasters were analyzed in terms of the features they proposed, the indicators they use or, where possible, how they have been used by local actors.

4.3 Solar cadasters and indicators

Since solar cadasters are visual tools which aim to be used by different types of actors, from the building owner curious about the solar potential of a roof, to a city investigating which of their buildings may have the best potential for a PV installation, the information provided must be intelligible. To that aim, the choice of indicators is crucial. Figure 2 displays the choice of various indicators related to technical, energy or economical aspects of the PV project.

Figure 2: Different indicators displayed in the cadasters provided by the IRENA SolarCity Simulator. City of Khartoum - Sudan

In total, 70 metrics were referenced in the 56 solar cadasters. These metrics were classified in five categories:

I) Energy, II) Technical, III) Economical, IV) Environmental, and IV) Other.

4.3.1 Energy indicators

Energy indicators of solar cadasters were related to the solar energy potential production (electrical and/or thermal), or the energy consumption of the building. Energy indicators are the core indicators in solar cadasters and is presented in Table 3.

Table 3: Summary of energy indicators

	Energy Indicators	Unit	Occurrence
Irradiance	Yearly irradiance	kWh/m²/y	**16**
	Monthly irradiance	kWh/m²	2
	Instantaneous irradiance (plane of array)	W/m2	1
PV production	PV production over T years (20/25/35 years)	kWh	4
	Annual potential PV power production	kWh/y	**44**
PV energy use	PV self-sufficiency	%	7
	PV self-consumption	%	**28**
Thermal	Annual potential heat production	kWh/y	4
	Production per year per district/postcode	kWh/y	1
Other	Thermal self-sufficiency	%	3
	Roof Sunlight	h/year	2
	Amount of Sunlight	%	1
	Optimal Storage Capacity	kWh	3

The most used indicator is the **Annual potential PV power production**. This metric indicates the annual production of electricity in terms of kWh/year from the system that would be installed. Most solar cadasters calculate the potential production by taking the **Yearly Irradiance**, multiplied by the potential area of the PV system (**Total PV installation capacity, Optimal sizing for PV** or **Optimal area for PV**) and the system's performance (between 15 % and 20 % depending on the technology considered and the last update of the calculation methodology). This calculation is typically simplistic and does not account for operating conditions which impact the PV performance, such as the PV system (ambient) temperature, and the PV installation type (integrated, rack-mounted, …). This information can provide a rough estimate on the ratio between potential PV production and the building's annual energy consumption. It is also a necessary value for the calculation of numerous economic, technical or environmental indicators. However, this information can, for some users be difficult to apprehend since a "kWh" is not as straightforward to understand as some economic indicators like payback time (in years) or the investment cost. Similarly, in some countries the PV power that may be generated during afternoon periods, especially in the summer, may be of greater grid value at that time due to demand for air conditioning.

One of the primary challenges faced by tools addressing large spatial scales is providing detailed spatial and temporal resolution. Some of the more recent cadasters offer metrics at lower resolution. For instance, the solar cadaster of Geneva provides only irradiance data for a typical day each month (*Cadastre Solaire Du Grand Genève*, 2024). This information provides valuable input, especially in understanding the expected differences in PV production between summer and winter periods. A higher temporal resolution allows for estimating ***PV self-consumption*** *(rate of electricity produced by the PV system which is consumed locally)* and ***PV self-sufficiency*** *indicators (rate of self-consumed PV electricity and total electric consumption)* (as defined by (Luthander et al., 2015). However, calculating self-consumption indicators is highly challenging. It involves knowing the electrical energy consumption of each building at a frequent temporal resolution. This task is more complex than estimating potential PV production for each building, as it is difficult to model precisely. Factors such as residents' behavior, the amount of installed electrical equipment, building characteristics, etc., make it challenging. Additionally, electrical energy consumption is not always measured at a lower temporal scale (at least hourly), and when measured, the data is often private and intrusive, making it difficult to access due to privacy concerns. In some instances, users can provide their own consumption data directly to the online tool for self-consumption evaluation.

It appears that there is much less information related to thermal solar systems than PVs. This may seem surprising since the calculation of indicators regarding the thermal produced energy, the investment costs are not more complex than for PV systems. PV systems have benefited from extensive market and policy support globally, including feed-in tariffs, tax incentives, and subsidies. These policies have encouraged investment in PV technology, leading to economies of scale and further cost reductions. However, it is often not the case for solar thermal systems.

Finally, in some cadasters, information is provided on daylight with indicators such as for '***Amount of direct sunlight'*** or '***Roof sunlight'***. Nevertheless, this information is limited because the indicators used are not explicitly defined, and therefore it is not clear how they compare with more classical indicators related to daylight.

4.3.2 Technical indicators

Technical indicators of the analysed solar cadasters were related to areas or dimensions of potential PV / ST systems (such as area available, type of technology, capacity installed, height of the building etc). A summary of the technical indicators, as well as their occurrence, are presented in Table 4. These indicators do not involve any direct link with energy. However, they are involved in the calculation of the energy indicators. As an example, the capacity of a system, usually expressed in kWp, is actually a theoretical value obtained by a specific technology under standard conditions. However, this value only depends solely on the technology used and the size of the system, it is not influenced by the local irradiance nor the building's energy consumption.

Table 4: Summary of technical indicators

	Technical Indicators	Unit	Occurrence
PV features	Total PV installation capacity	kWp	**36**
	Optimal sizing for PV	kWp	**14**
	Optimal area for PV	m²	**43**
	Number of modules that could be installed		4
	Optimal number of modules		7
	Technology recommendation		7
	Choice of the PV technology		1
	Layout personalization		2
Existing PV	PV capacity already installed in the district/postcode	MWp	1
	Surface of the existing PV system	m²	2
	Production of the existing PV system	kWh	1
	Number of PV systems installed in the district/postcode		1
	Number of PV plant being/to be installed		1
	Location of existing PV system	kWp	4
	Location of Thermal system		1
Roof and Building features	Area of the roof	m²	**15**
	Area of the Floor	m²	3
	Slope of the roof		6
	Orientation of the roof		5
	Building's height	m	1
	Choice of the roof type		1
	Installation Type (Integrated or mounted)		1
Other	Optimal area for thermal system	m²	8
	Thermal capacity already installed (in unit)		1

Total PV installation capacity: This indicator is sometimes used but may have limited relevance. On a roof, the total area often does not align with the optimal area for a PV system. Some parts of the roof may be oriented east, west, or even north, resulting in lower annual energy production per surface unit. Therefore, metrics related to the total PV installation capacity should be approached with caution, especially in the context of design strategies. An alternative indicator occasionally proposed is the total ***number of modules*** that can be installed.

Optimal sizing for PV and ***Optimal area for PV*** are very similar. Indeed, for a specific PV technology and performance, the PV capacity is directly proportional to the area. Some cadasters offer the capacity to select the technology or to directly enter the capacity per square meter. The cadaster that covers several cities in Norway (Solcellespesialisten AS, 2024) even proposes a PV technology recommendation. As an example, nowadays an industrial monocrystalline panel can have a capacity factor of nearly 200-250 Wp/m². Despite these two indicators expressing roughly the same thing they both are interesting. Whereas the ***Optimal PV Capacity*** gives a direct idea of the energy sizing of your installation, the ***Optimal Area for PV,*** expressed in m² allows to directly imagine the spatial dimension of the system. The *'**Optimal number of modules'*** indicator proposes an alternative, but is directly proportional to the sizing (in kWp) or the area (m²) for a standard technology.

Nevertheless, 'optimal' can have several meanings. Indeed, a PV design can provide the optimal "Net Present Value" (here the highest) or the optimal Payback Period (lowest). Sometimes the optimal conditions are actually just a threshold, in terms of irradiance, above which the roof sections are considered as good for a PV system. For example, the solar cadaster of Geneva proposes an optimal area which corresponds to the area offering the lowest payback-period which means that not all the roof is considered for a PV installation, only the roof sections providing the lowest Payback Period is considered. One of the consequences is that occasionally only a small portion of the entire roof is considered as suitable, whereas if another indicator was chosen, maybe a greater portion of the roof would have been considered. However, most of the time, solar cadasters propose an "optimal" design without defining which criteria it is optimal for.

Some solar cadasters provide information about existing solar energy installations, that could either be PV (Stockholms stad, 2024) or thermal (*Cadastre Solaire de Paris*, 2023) systems. This type of indicator remains rare in reviewed cadasters. Typically, it is the location of the PV system that is provided, but in one of the reviewed cases the capacity installed is mentioned (Stockholms stad, 2024).

Apart from energy related information, some cadasters provide information about the roof itself. The level of information and the accuracy is highly dependent on the Level of Detail (LoD) and building geometry. Some solar cadasters such as the one in Geneva (*Cadastre Solaire Du Grand Genève*, 2024) were generated using a high-accuracy digital surface models (DSM), from recent Light Detection and Ranging (LiDar) measurements. Therefore, this cadaster can identify not only slope, orientation and height data for each building surface but also the presence of superstructure elements (for example, chimneys, windows, HVAC) that can reduce the available roof area for PV modules. Access to detailed topographical data, however, can be limited and consequently roof area calculated using simplified estimations.

4.3.3 Economic indicator

Economic indicators provide information about the financial performance of ST /PV systems. A good choice of economic indicators is of primal importance. Indeed, one of the main goals of these cadasters is to provide a tool for citizens and decision makers in order to support them in the decision-making process. Nowadays, economic indicators remain the main driver guiding most PV installation projects.

Table 5: Summary of Economic indicators

Economic Indicators	Unit	Occurrence
Benefits ($) (Subventions + Selling + Savings)	$	7
NPV - Net Present Value (Benefits – Costs =Investments +OM))	$	**32**
Investment (Installation Cost) - PV	$	**34**
Investment - Thermal ($)	$	8
Operation and maintenance costs	$/y	5
Payback Period	y	**37**
Internal Rate of Return		6
Subsidies	$	5
Annual electricity bill with solar	$	1
Annual savings on energy bills with PV	$	6
Annual savings on energy bills with thermal	$	3

In the reviewed cadasters (see Table 5)***, the Internal rate of return*** and ***Payback Period*** were among the most present. In the case of a PV system, these two indicators are nearly proportional. The Internal Rate of Return, however, expressed in %, may not be the most user-friendly indicator for an average user of the tool. In the latter case, the Payback Period, which expresses the number of years required to refund the initial investment and the operation and maintenance costs, is probably more related. Whereas these two metrics are mathematically proportional, the first places the investment in a PV system on the same level as a financial product, whereas the PP is more a reassuring indicator in order to ensure that the system will not be a loss-making venture.

Most of the cadasters also identify the ***Investment Costs,*** the expected ***Benefit*** and the ***Subsidies.*** These indicators are at least national, since price of installation and feed-in tariffs of exported solar electricity including subsidy schemes are typically localized. The Net Present Value is also one of the common cadasters and represents the sum, over the system lifetime of the Benefit and Subsidies minus the Investment and the Operation and Maintenance cost.

The ***Investment*** indicator is also a key indicator in decision making. Indeed, with the decreasing price of PV most of the current PV systems are profitable within their lifetime. The upfront cost can still be high and be a barrier for the deployment of PV (Eric Wilczynsk et al., 2024).

4.3.4 Environmental indicator

The use of environmental indicators has become extremely common in recent cadasters. Indeed, they offer an alternative perspective to classical energy and economic indicators and can be more engaging or appealing to common users. These indicators were summarized in Table 6. One of the most prevalent environmental indicators is ***CO_2 savings.*** It is often calculated as the difference between the CO_2 emissions associated with the electricity production from the grid and the CO_2 emissions from PV production.

$$CO_2\ savings = E_{roof}(y)\frac{e_{CO2,grid}-e_{CO2,PV}}{A_{roof}} \quad (1)$$

Where A_{roof} is the area of the potential PV system, E_{roof} is the potential PV production, and $e_{CO2,}$are the emission factors of the grid and of the PV system. Regarding the PV panels the emissions can be evaluated between 32 gCO_2/kWh (Fthenakis & Leccisi, 2021) and 50 gCO_2/kWh (NREL, 2012). Nevertheless, there can be major differences in terms of CO_2 emissions from the grid. For example, in Norway, the average CO_2 emission per kWh of electricity produced was equivalent to 29 gCO_2/kWh, making the installation of a PV system theoretically more 'polluting' than the existing system (mostly based on hydropower). However, this is an isolated case, and the vast majority of countries have much higher CO_2 emissions. In 2021, for instance, the average CO_2 emissions of the electricity mix were around 277 gCO_2/kWh in the European Union, 379 gCO_2/kWh in the USA, or 533 gCO_2/kWh in Australia (U.S. Energy Information Administration (2023); Energy Institute - Statistical Review of World Energy (2023)).

Reduction in terms of fine particles (***PM 2.5***) is also a widespread indicator and offers complementary information to CO_2 emissions. Additionally, more ambitious indicators, which attempt to provide a 'real-life' order of magnitude, are sometimes used, such as the ***number of hours of AC usage***, ***driving distance***, or the ***number of hours a 60 W lightbulb*** is in operation.

Table 6: Summary of Environmental Indicators

Environmental	Unit	Occurrence
CO_2 savings (tons/year)	tons or kg /year	17
CO_2 savings over T years	tons or kg	5
PM 2,5 (kg)		22
Grown trees		6
Passenger cars		2
60-W lightbulb		1
Air Conditioning (h)		1
Driving Distance (km)		1
Home Powered		1

4.3.5 Other indicators

The installation of a PV system is affected by various constraints, with some of them having a significant impact on the feasibility of the project. In certain cadasters, specific constraints are outlined. For instance, in Europe, numerous buildings or districts are designated as heritage areas, encompassing old buildings, churches, historic structures, or protected zones for biodiversity preservation. In these areas, installing PV systems on roofs can be challenging or, in some cases, impossible. However, it is important to note that these constraints vary considerably between countries, and some cadasters explicitly mention the presence of ***heritage constraints***.

Some cadasters also propose a “***Suitability***” indicator but without definition. It is therefore difficult to assess the meaning of this indicator, especially given that ‘Suitability’ can have several aspects, from technical suitability to economic or environmental suitability (Florio et al., 2018; Marja Lundgren & Johan Dahlberg, 2018).

Table 7: Summary of other indicators

Other	Occurrence
Heritage constraints	5
Suitability	4
Greening potential	1
Proximity of airport	1
Delivery Time	1
Construction period	1

4.4 Installed capacity

Solar cadasters display the potential for installing active solar energy systems on roofs (and sometimes façades). Some solar maps, however, show the actual installed solar energy systems, either as a stand-alone map or combined with the theoretical potential as those maps described in the previous section.

One example is the map by the Australian PV Institute (APVI), mapping Australian Photovoltaic installations with the aim to see how active solar energy system contribute to a Renewable Energy Target. For each postcode, local government area, and electorate, the map shows the estimated percentage of dwellings that have a PV system and the total photovoltaic capacity installed. This is also available at a local government area level and for electorate regions that can offer useful insights during political election cycles.

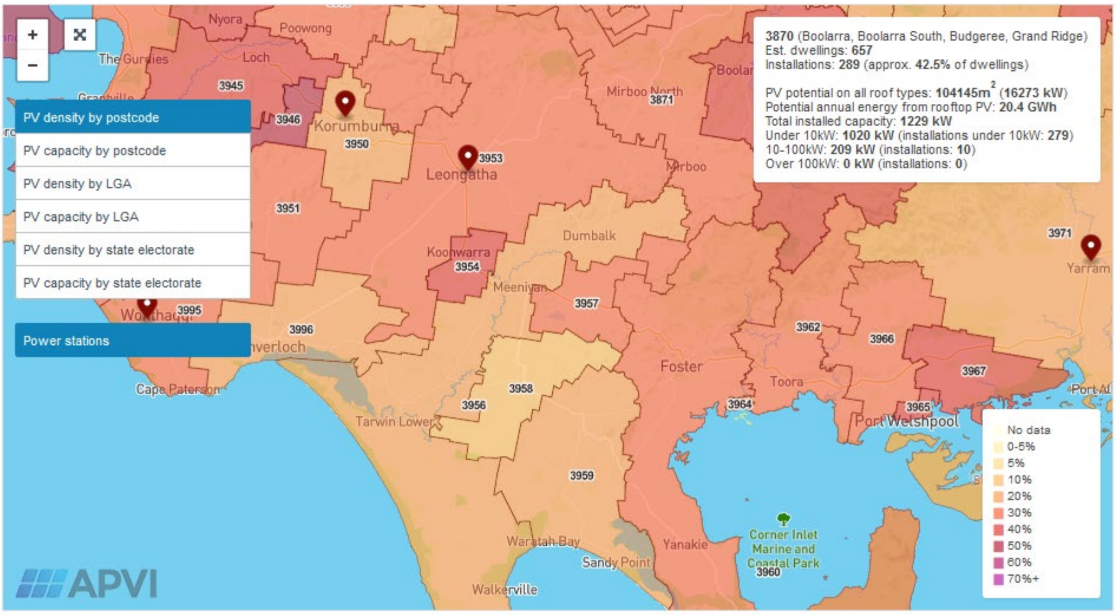

Figure 3: Installed capacity as displayed by the Australian PV Institute

The APVI has also calibrated a solar decision-making tool called SunSPOT (Australian PV Institute, 2024) (Figure 4) that intuitively guides the user through building energy usage data and a PV mapping tool to generate detailed performance estimates related to energy usage. Consideration is also given to inclusion of battery storage, calculated outputs by season and return on investment. The tool can be scaled to capture citywide data as provided below for the Australian Capital Territory government covering PV installations for the Australian capital city, Canberra in line with its accomplishment, since 2020, to source 100% of electricity from renewables.

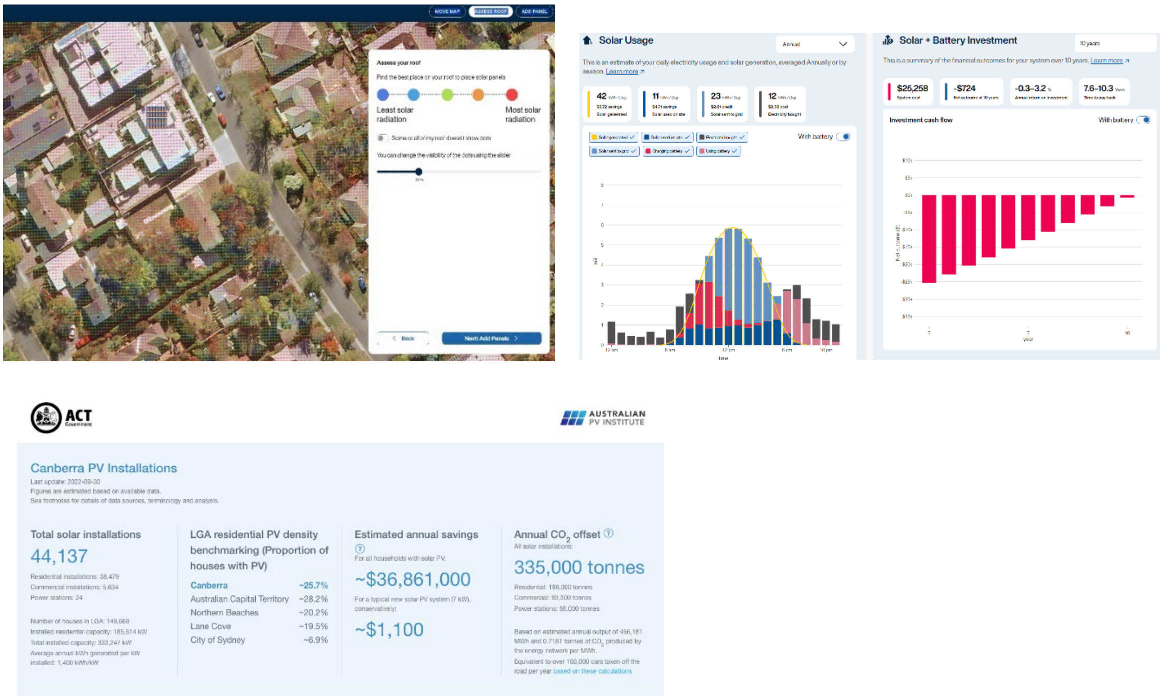

Figure 4: SunSpot tool and Canberra PV installations

An example that combines both the theoretical potential as well as the actual installed capacity are the maps developed by Mapdwell.

Figure 5: Installed capacity and theoretical PV potential as displayed by Mapdwell

4.5 Interface and visualization of solar cadaster

Advanced computer graphics and calculation algorithms can be used to estimate complex phenomena such as reflections from other buildings and shadow casting. These tools provide access to various GIS layers relevant to the solar cadaster, including solar irradiance, energy generation, visual aspects, and environmental factors.

Integrating renewable energy sources into urban environments requires different stakeholders to collaborate, including policymakers, urban planners, and technology developers. Interoperability between different software enables platforms and systems to communicate and exchange data seamlessly, facilitating collaboration amongst stakeholders.

Through the integration of meteorological data, geographical information and 3D city models, interoperable platforms enable private and public stakeholders and citizens to visualize the more suitable and usable locations and urban surfaces for the installation of active solar systems and to assess the feasibility of projects with optimal exploitation of solar energy resource. By leveraging web-based technologies, urban energy planning platforms, such as a solar cadaster, can facilitate stakeholders' engagement and public outreach through intuitive and user-friendly interfaces by interacting with complex data and simulation results to explore energy data and project results. These platforms enable real-time access to updated information, allowing stakeholders to monitor energy trends and project outcomes dynamically. Moreover, web-based visualization tools can support spatial analysis and scenario planning by overlaying energy data onto interactive maps and 3D cityscape models. This spatial context enhances stakeholder understanding of the distribution of RES, such as solar energy, and its impact on the urban environment. As a result, both technical and public communities can participate in the decision-making process and advocate for sustainable energy solutions that meet their needs and priorities.

The Auckland Rooftop Solar Energy Potential web platform (Solar Cadaster Auckland - University of Auckland, 2024) Figure 6, represents an example of how interoperable software solutions can enhance visualization capabilities for urban energy planning. By integrating solar cadaster data with energy and economic indicators, this web platform provides a comprehensive overview of solar energy potential at the municipal level. Through interactive maps and visualizations, users can explore the distribution of solar irradiation across urban roofs and identify the quantity for solar panel installations. Additionally, the platform offers tools for analyzing the economic feasibility of renewable energy projects and assessing their impact on local energy systems. By providing stakeholders and citizen with actionable insights and engaging visualizations, such platforms empower communities to transition towards more sustainable and resilient energy systems.

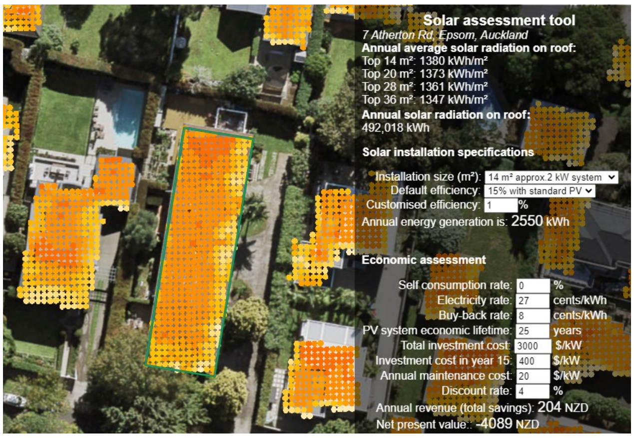

Figure 6: Auckland Rooftop Solar Energy Potential web platform

Analysing existing web platforms from a visualization point of view, three different levels can be found. The first two are represented by 2D data visualization: the first is very simplified and associates a single solar potential value with a single roof slope, while the second shows the solar distribution with a color gradient due to a higher level of roof modelling and shadow cast from architectural (e.g., overhanging parts) and services (e.g., plants, chimney) elements. This helps to visualize those parts of the roof that are most exposed and irradiated and therefore most suitable for the installation of active solar systems. The other type of platform that can be found represents more advanced geometric data dealing with 3D models. However, this type of platform is still at a very early stage of development. In fact, typically the functionality to track the façade elements and modelling, as well as the economic data of the investment, has not yet been implemented.

An example (Figure 7) is the solar map developed for the whole country of Norway. In this case, unique data is graphically visualized for each roof slope, indicating the suitability of the surface according to the amount of solar energy, on a scale from unsuitable to very suitable.

Figure 7: Solkart – Norway [4]

The case shown in Figure 8 is the solar cadaster for the city of Oslo. It can be seen that not all roof slopes are considered in the same way, as there are differences due to the presence of shading, chimneys or other objects that obstruct the solar irradiation. The data are given here using a numerical scale, considering the value of the annual solar irradiation obtained. An area with an irradiation of less than 650 kWh/m^2 is characterized as suboptimal, while an area with an irradiation of more than 900 kWh/m^2 is considered to be very good.

Figure 8: Oslo solkart[5]

In the solar map for the city of Helsinki[6] there is an additional level of development, as the façades of the buildings are analyzed in addition to the roofs. In this case shown in Figure 9, it is possible to evaluate the global, direct, and diffuse solar irradiation of each surface on an annual scale, but it is not possible to make economic evaluations of possible projects or to evaluate the productivity of the applied photovoltaic systems.

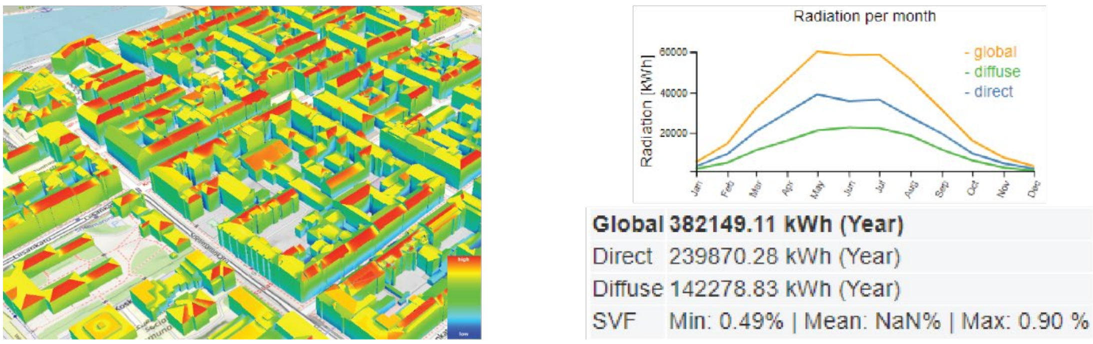

Figure 9: Solar Energy Potential map of Helsinki

[4] https://solkart.no/search

[5] https://od2.pbe.oslo.kommune.no/solkart/

[6] https://kartta.hel.fi/3d/solar/#/

The examples provided are highly representative of the current state of existing web cadasters. Numerous research groups are working on the topic of solar cadasters, as there are currently some visual limitations. Often the cadasters do not take into account the visual representation of façades, and if they do, they do not take into account the presence of overhangs, balconies, windows or doors. Differences in composition, in terms of materials that compose the buildings are also typically excluded. Also conspicuous is mention of future scenarios and use of, for example, ersatz future climate data for 2030 and 2050 horizons to simulate and assess climate change impacts.

4.6 Ownership

In the reviewed cadasters, two main types of ownership prevail. Most of the solar cadasters under review have been commissioned by a territorial governmental entity, which can include municipalities, metropolitan area administrations, department/region/county, or even the state. However, in some cases, the available cadaster may be developed by a research institute for the entire country, as seen in the Australian case (Australian PV Institute, 2024), or by a private company, such as the Google SunRoof (Google Project Sunroof, 2024) project in the USA.

For several of the reviewed cadasters, the commissioner does not personally develop the cadaster but entrusts the task to a specialized company. For example, tetraeder (tetraeder, 2024), Cythelia (Cythelia energy, 2024) which developed many solar cadasters such as the one for Amsterdam in the Netherlands (zonatlas, 2024) or Nantes in France (Nantes Métropoles, 2024). Nevertheless, some cadasters are developed by local academic or institutional actors, such as the solar cadaster of Geneva (*Cadastre Solaire Du Grand Genève*, 2024) mostly developed by academics from hesso-hepia, or the solar cadaster of London, developed by the University College of London (Greater London Authority, 2024).

In most cases, the solar cadaster, including both data and interface, is typically hosted on a governmental platform, allowing accessibility for public use.

4.7 Uses of solar cadaster by local actors

4.7.1 Solar Maps and stakeholders

Stakeholder engagement is important in urban solar mapping to enable the inclusion of institutions, industry players, financiers, and consumers/prosumers for their expertise and insights (Nicolas Caballero et al., 2024). This collaborative approach facilitates accurate data collection, policy development, and conflict resolution, thereby enhancing project outcomes. Moreover, transparent communication among the actors involved in the urban planning/project process fosters the integration of solar infrastructure, informs zoning regulations, and secures community support, underpinning the project's success (Chen & Musango, 2022).

The concept of integrating solar mapping with stakeholder engagement aims to enhance solar energy technologies. By involving a diverse range of public and private stakeholders in the process, it promotes the development, implementation, and acceptance of solar solutions. The process benefits can be presented as shown in Figure 10.

Figure 10: Key benefits of solar mapping and stakeholder engagement.

- **Informed decision-making stakeholders**: can make informed decisions about where to invest in solar systems in built environments by using solar maps methods as they provide detailed information about the solar potential of different urban surfaces (i.e., roofs, façades and ground) and city's zones which can enhance energy planning in urban areas and optimize solar systems installation.
- **Increased investment opportunities:** solar maps can support and inform investors and financial institutions in assessing the viability and profitability of solar energy projects and systems at various spatial domains, ranging from building to neighborhood and city scale, through the identification of the most irradiated urban surfaces and available urban locations and infrastructures (e.g., parking lots, bus and train stations), by reducing risks of investment and maximizing financial returns and ROI of the projects.
- **Community engagement**: solar maps can serve as educational tools for the community, raising awareness about the benefits of solar energy and its feasibility. In this approach through visual communication of solar potential, people can better understand how their neighborhood can exploit the full potential of solar energy and harness the deployment of solar systems.
- **Streamlining regulatory approval:** for projects requiring regulatory approval and permission such as for a historical area, solar maps can provide the necessary data and visualization to demonstrate compliance with local zoning laws and environmental regulations. This can speed up the approval process for solar system integration into urban surfaces by presenting clear, evidence-based arguments for the proposed solar installations in both existing, historical, and new urban areas.

Following this approach, the Helios research project (*Solar | Helios | Norway*, 2024) aims to emphasize the importance of transparent and informative dissemination activity to build trust between technology providers and communities on solar energy systems adoption and integration into building façades and roofs. Achieving this objective, requires overcoming common challenges of local resistance, despite general support for renewable energy sources. In that regard, the case study of Møllenberg in Trondheim (Norway) represents a valuable example of the application of such an approach. The Møllenberg neighborhood in the heart of Trondheim in Norway is characterized by architectural heritage value and a vibrant community. In the current era of sustainable low-energy transition, this area is at risk of being abandoned due to the high energy demand of two storey wooden buildings built 150 years ago. The Møllenberg district project aims to i) integrate PVs by preserving the area's historical heritage value; ii) enhance social acceptance of PVs through community engagement and iii) integrate different software for accurate solar mapping analyses and advanced visualization techniques to show the effects of PV system integration into roofs and/or into façades of refurbished buildings.

The Helios research project has developed two digital platforms aimed at promoting social acceptance by engaging stakeholders: the Helios Website and the Helios Application.

The Helios Website (Figure 11) serves as an engaging platform, offering immersive visualizations similar to Google Earth videos, drone videos, 3D models, and a 360° virtual tour to showcase solar technology within Møllenberg's landscape. This website combines aesthetic solar panel integrations with practical information on costs, energy generation, and technical details. Interactive features, such as virtual 'street views', enable users to explore their neighborhood post-PV installation. It can enhance stakeholder engagement through an interactive informative interface which can be helpful in making informed decision with practical information and speed up approval process by considering the limitations in historical areas (*Solar | Helios | Norway*, 2024).

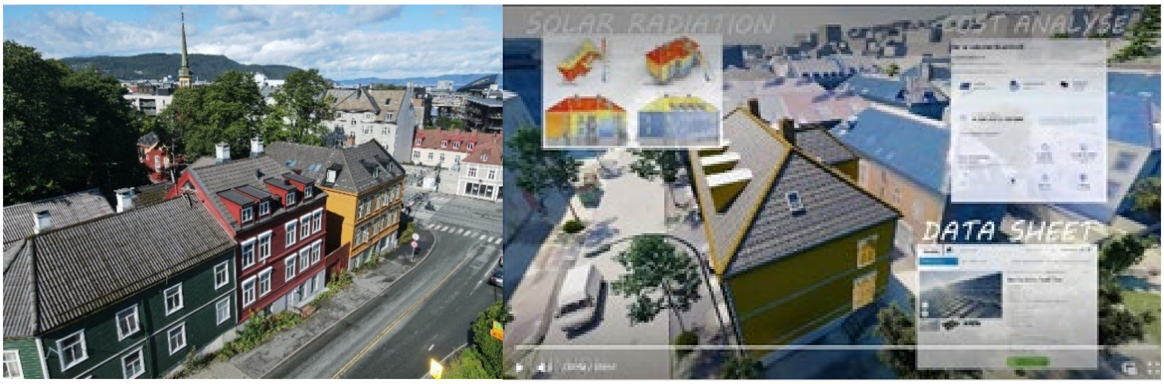

Figure 11: Møllenberg neighborhood, Trondheim, Norway and Helios website containing a virtual tour in Møllenberg and pilot project with possibility to source required information: solar radiation, technical aspect, cost analysis.

The Helios Application (Figure 12) proposes a user friendly application by Extended Reality (XR) to simplify and enhance the solar technology adoption process. It allows users to visualize potential solar installations through QR code scans in their neighborhood which provides interactive access to product information and energy savings. Key to the app is its creation of a "Solar Community," encouraging discussions on solar benefits and sharing real-time data on energy production and savings. This fosters a transparent, engaging environment that boosts community involvement and increases the opportunity for investment by social acceptance of solar energy, facilitating a progressive step forward in Møllenberg's journey towards urban sustainability (*Educational Outcomes - Helios - NTNU*, 2024).

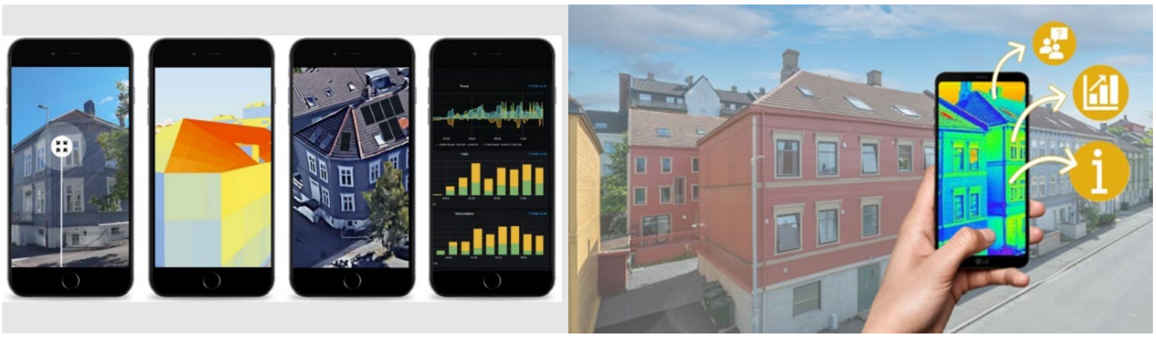

Figure 12: Helios App and Idea of using Extended reality (XR) to simplify the solar technology adoption with providing technical and financial information in user friendly app.

4.7.2 Solar cadaster of Geneva and solar governance

The canton of Geneva was one of the first regions in Switzerland to develop a solar cadaster back in 2011. The solar cadaster of Geneva relies on a very rich and comprehensive database provided by the SITG (SITG, 2024), which includes accurate Digital Surface Models, building and roof cadaster, land cover data, and more. The solar cadaster offers detailed information on the photovoltaic and thermal solar potential of roofs and buildings (Desthieux et al., 2018). All of the SITG's data, including the outputs from the solar cadaster, can be freely downloaded by any user (open data). Thanks to the richness of the SITG database and its public accessibility, the solar cadaster of Geneva has been utilized for over a decade by the academic community for teaching and research activities and serves as a valuable resource for developing and testing urban solar models. In a sense, Geneva has become a living laboratory for urban solar studies. The open data approach of the SITG contributes to a better appropriation of the solar cadaster and the other valuable attribute data provided by the information system. On this basis, the solar cadaster required further development in two significant ways.

Firstly, solar access should not be confined solely to the Canton of Geneva but should be extended to the Greater Geneva region, presented in Figure 13, which is a cross-border agglomeration spanning both France and Switzerland, made up of three main entities: the Canton of Geneva, the Region of (which is the Vaud region included in the Greater Geneva area), and the French Genevan Metropolitan Area (PMFG). This covers a total of 209 municipalities, an area of 2’000 km^2 and a population of 1 million inhabitants. The region is dedicated to achieving carbon neutrality by 2050 in response to the climate emergency. This underscores the significance of solar energy in facilitating this transition and highlights the role of the solar cadaster at an agglomeration level in supporting the development of solar projects.

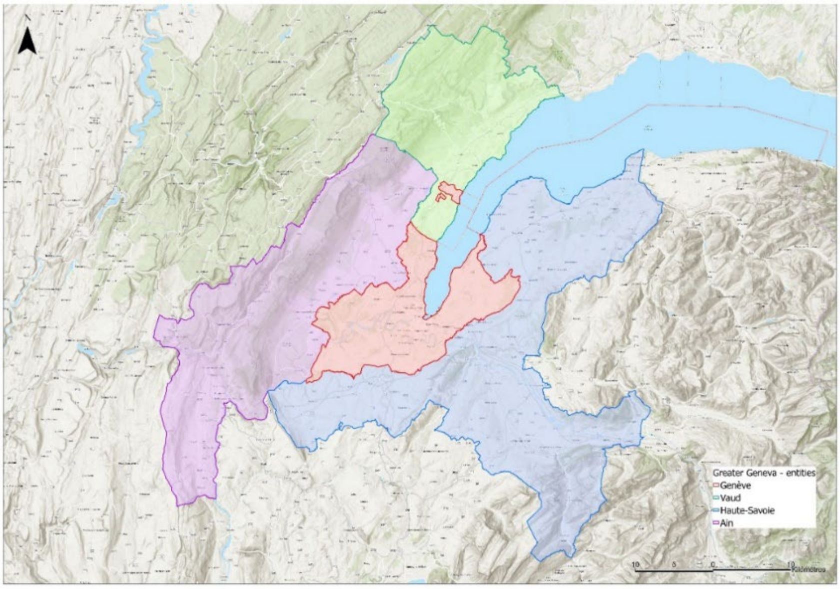

Figure 13: The Greater Geneva with its three entities: Canton of Geneva (red), Region of Nyon (green), French municipalities located in two departments (Haute-Savoie in blue, Ain in purple)

Secondly, since the end of the last decade, the business model for solar PV installations on building roofs was based on selling the entire solar power generated back to the grid. Subsidies were provided to the owner based on the amount of energy sold. With the introduction of the new energy law in Switzerland in 2018, however, subsidies have shifted to supporting the initial investment in solar installations, while also promoting self-consumption of the solar power. French regulation is following the same trend. As a result, the solar cadaster needs further development to model the potential for self-consumption of the solar energy generated in buildings, considering their electricity load.

These two aspects—the expansion of the solar cadaster to cover Greater Geneva and the modeling of self-consumption—were developed within the framework of the European INTERREG G2 Solar project (2019-2022). This project entailed a complex partnership involving academics, energy utilities, and public institutions from both sides of the border, as well as the three representing entities (Cantons of Geneva and Vaud, and PMFG).

In this context, it is important to have a critical look at the extent to which the solar cadaster could serve as a support in uniting all stakeholders in the Greater Geneva area, foster a dialogue on solar energy and establish unified regional governance around solar energy through a complex agglomeration-wide partnership.

4.7.2.1 Governance structure of the platform

The project of the extension of the solar cadaster to the Greater Geneva was successfully completed thanks to a well-organized governance structure involving three types of Swiss-French partners: academics, public institutions and energy suppliers (DSO).

The project was led by **academics** who, in collaboration with the other partners, developed and implemented the methods and tools to carry out the solar cadaster and the various tasks, organized workshops with stakeholders and collected feedback and lessons learned from case studies. The project involved the **public institutions** representing the same three main geographical entities of the Greater Geneva area: the Canton of Geneva, the Canton of Vaud and the Region of Nyon, and the PMFG, which represents the French municipalities of the agglomeration. They were mainly involved in steering the project and facilitating access to the necessary data for the solar cadaster. Finally, **distribution system operators (DSOs)** are key partners in moving from potential analysis to implementation of solar projects. By testing the solar cadaster and web application on real cases, they helped to improve the tools. They also provided necessary data such as electricity consumption and load curves. ENEDIS is the main DSO in France.

The purpose of establishing a governance structure for the G2 Solar project is to ensure the continuous promotion and advancement of solar energy development in the Greater Geneva via the solar cadaster over the long term.

Towards an interactive web application of the solar cadaster for a wide audience

The solar cadaster project's primary assumption was that creating a dynamic, interactive, and accessible web application, commonly referred to as an app, would facilitate decision-making and governance in the implementation of local solar projects in the Greater Geneva area.

The first step was to extend the irradiation solar map, initially calculated for the Canton of Geneva only, to the Greater Geneva. Using the same solar modelling algorithms as for the Geneva solar cadaster, but improving the computation processing to pass from the Geneva canton area of 280 km^2 to the Greater Geneva area of 2'000 km^2, the raw irradiation on an hourly basis was processed for the whole area of Greater Geneva. Solar potential and energy production were calculated by building rooftop. Similarly, the app initially developed for the Canton of Geneva, was extended to cover Greater Geneva to showcase the results of the solar map at this scale. The initial version of the app was quite basic, as it only presented static yearly results. Users had no ability to interact with the application by modifying parameters. Also, it did not take into account the self-consumption potential based on hourly simulation.

To enhance and advance the app, it was necessary to initially identify the requirements and needs that the application should fulfill for stakeholders. To assess the level of satisfaction and identify potential areas for improvement, a survey (online questionnaire) and workshops were conducted with the app users. Workshops held in French communities with policymakers, municipal technicians, and representatives of solar communities proved to be particularly insightful. It became evident that the solar cadaster effectively supported the identification of potential areas for new solar project developments.

Another aspect was to provide feedback on pilot solar projects and case studies at a neighborhood level, taking into account different contexts: new neighborhood development, solar planning in villages with heritage issues, building retrofit, solar microgrid in industrial areas, grouping solar communities. The aim was to assess what kind of support was needed to bring these projects to completion, and whether tools such as the solar cadaster or other specific solar modeling tools could help in this respect.

The workshops, questionnaire, and case studies enabled a better understanding of opportunities and constraints in initiating local solar projects in various contexts, as well as expectations regarding the solar cadaster's app to support the design of such projects. The consortium of partners reached a consensus on which aspects the development of the new version of the app should focus on, with particular emphasis on self-consumption simulation. The new app works as represented in Figure 14.

Figure 14: Modules of the Web application APP. Reproduced from ©SITG—https://sitg-lab.ch/solaire.

4.7.2.2 Use of the solar cadaster Web application

The initial feedback from professionals has sparked a debate regarding the complexity of the app, its suitability for a broad audience, and the potential inclusion of additional functions outlined above. There is a consensus that the tool should not become more complex than its current state. The intention is not to replace existing simulation tools, such as PVSyst. To further refine the app's features and assess its complexity level, a new survey and workshops should be proposed, involving users to gather diverse experiences with the updated version. This survey would complement the monitoring system implemented since September 2023, which tracks metrics such as daily visitor count (both total and new), number of actions taken, and time spent on the tool. Initial findings for the first month indicate an average of 20 new daily visitors with an average total usage time of 23 minutes. Proactive advertising related to solar energy and energy transition initiatives is expected to enhance visibility and subsequently increase visitation numbers.

5 Opportunities and development needs in the use of solar planning tools

The use of advanced tools has enabled decision-makers to assess the added values of solar energy (both passive and active) in the urban design and building design process, also allowing experts to work together and communicate more effectively. The use of solar neighborhood tools presents numerous opportunities for advancing the utilization of solar energy.

One significant opportunity for the use of tools lies in their effective utilization for facilitating the deployment of solar energy systems. These tools enable the determination of the solar potential of a particular building, based on solar irradiation, shading, and obstructions. This information can then be used to identify suitable sites for solar installations, maximizing its energy generation and enhancing the overall feasibility of solar projects, e.g. the estimation of energy yield and the calculation of return on investment. Consequently, the use of solar planning tools can pave the way for increased investments in solar energy projects, promoting growth and expansion.

Analysing the added value of passive and active solar energy early in the urban planning process can promote the development of solar-powered cities and communities, reducing reliance on conventional energy sources and decreasing greenhouse gas emissions, encouraging the transition to a more sustainable and decentralized energy supply and ensuring good solar access to buildings, public and outdoor spaces.

While solar planning tools present numerous opportunities, there are also certain development needs that must be addressed. One crucial need is the continuous improvement and refinement of these tools. As technology advances, solar planning tools should keep pace with innovations, providing accurate and reliable information. Enhancements can include better algorithms, increased tool interoperability, and improved data integration to enhance the precision of solar potential assessments. Additionally, efforts should be made to make these tools accessible and user-friendly for a wide range of stakeholders, ensuring their widespread adoption and utilization.

To encourage the use of solar planning tools and ensure their effectiveness, it is imperative to see them in the context of legislation, standards and daily practices of urban planners, architects, engineers and real estate developers. The European Standard EN 17037 *Daylight of Buildings* is an example of a standard that had to aim of harmonizing different ways of measuring day- and sunlight in buildings. In some European Member States, this standard is referred to in the national building regulations and could have an impact on which metrics are being used and how they should be calculated or simulated.

In the following sections, we highlight several opportunities for the increased use of advanced tools for solar neighborhood planning; (section 5.1) the added value of using tools, 5.2 The influence of tools on the design process, 5.3 simplification of methods, tools, and metrics, 5.4 better tool interoperability and interscalability, and 5.5 solar readiness and solar rights.

5.1 The added value of using tools for solar neighborhood planning

Good decision-making in the planning process of solar neighborhoods can be supported by a smart use of (advanced) tools. The quantification of the potential amount of produced solar energy can be used as an input for the calculations by main stakeholders like real estate developers. Without good data, those key players rely normally on their Business-as-Usual approach concerning renewable energy production. Since every project has specific framework conditions, it should be clear for clients to assess the added value of performing advanced simulations.

Using one (geometrical) model to analyze different parameters in parallel can reduce time spent on projects, which is for example beneficial for consultants. Also, being able to take a more holistic approach analyzing several parameters simultaneously will likely benefit the outcome for the consultants, architects and engineers involved in the process.

5.2 The influence of tools on the design process: an example from White Arkitekter

How tools are used within a project is an important input for designing the workflow while adding value to its use. One key question is how the results will be used to inform the project's stakeholders in an efficient way underlying the importance of how results are presented. Tools are often not used to generate or optimize a building by itself, but rather to combine the competences of the team members and their experience with digital workflows to perform more in-depth and multifactorial studies with the results of achieving a more sustainable project.

Another key question is to understand which information is known at which stage and which tool is needed to provide the right information/output needed to take decisions in achieving a certain goal. Depending on the competences within the design teams, the process of using tools might be different. To gain the most out of advanced digital tools and workflows, as well as project output, an interdisciplinary team is desirable.

People with different competencies can lift each other and discuss results from simulations and calculations to achieve better outcomes. Efficient workflows together with an interdisciplinary team can create new neighborhoods with (among other things):

- Low energy use
- High daylight levels indoors
- Good indoor thermal comfort
- Good outdoor microclimate
- Solar energy production
- Low climate impact

During this R&D-project at White Arkitekter, two case studies have been conducted to investigate how different workflows inform the projects and how the team dealt with more information in early stages, as well as how this has affected the design.

In both of the case studies, knowledge from other R&D-projects provided good know-how and could provide "injections" to the project workflows. These tools provided detailed information and knowledge in a stage in the ordinary process where usually there is less information available but important decisions determining the future "frames for solutions" are taken. These decisions will determine the shape of a building and can hinder good solutions if they are introduced too late after decisions have been fixed.

5.2.1 Veddesta – Case study description and lessons learned

Figure 15: Veddesta case study © White Arkitekter

The case study of Veddesta is a noise-exposed residential project that includes two blocks located next to and on top of a new bus terminal and a new commuter train station (Figure 15). Noise also comes from a closely located highway. Challenges in this highly dense project included daylight provision, access to direct sunlight, energy use, thermal comfort and green areas. Within the case study, a conventional workflow process has been investigated with new interactions of a more interdisciplinary process. Below is a short description of the process and the lessons learned of the case study.

5.2.1.1 Process

In typical Swedish building projects, daylight analyses in the early design stage (structure plan phase) consist of a VSC (Vertical Sky Component) analysis ensuring that in later stages, the daylight requirements in the building code can be met and daylight provision can be optimized during the project. These early-stage analyses are, however, limited in their use and are normally fast and agile. Challenges can occur when the design and project demands are more complex. The project in this case study identified that design support between the structure plan and the building permit is very much needed.

A more in-depth analysis using VSC, as well as other design parameters such as story height, rooms depth and window sizes was performed to understand the daylight levels. This detailed analysis was called ‘project injection’. This provided more data input to the design team and functioned as a guide while designing the floorplans, floor heights, location and sizes of the balconies and the windows. Due to the complexity of the project, the output of the analysis in this stage was needed to create a good dialogue and a valuable exchange of information between the sustainability specialists and the architects to steer the project in the right direction.

Energy performance simulations are often carried out at a late design stage when a large amount of information is known about the project. Often, energy performance simulations are only performed for the first time to obtain a building permit. In the case of Veddesta, an early energy analysis was performed to roughly understand the potential future energy consumption due to the form factor of the building and the average U-value. In order to comply with the Swedish building regulations, there was a need to decrease the energy consumption and balance it with PV. Therefore, a solar potential analysis was conducted to provide feedback on which surfaces would be suitable for PV and how much energy the neighborhood could harvest.

5.2.1.2 **Lessons learned**

The enhanced process with the injections (the early analysis) guided the design team in the complex design of the building. It is important that the analysis is at the right level and provides the information that is important at a given stage.

Pedagogic communication: designers, project management and the customer need to understand the analysis undertaken and associated findings so they can make informed decisions.

5.2.2 Stadsljus – Case study description and lessons learned

Figure 16: Veddesta case study © White Arkitekter

The case study of Stadsljus is a high-rise residential building proposal located in Stockholm Royal Seaport. The area is known for its sustainability focus and high goals regarding energy efficiency and greenery. In this specific project and case study, which was a competition, the focus was on how the design process and the analysis were carried out iteratively for energy, daylight and microclimate.

5.2.2.1 **Process**

The Stadsljus project followed quite an unconventional process. The competition was carried out in three separate phases with high deliverable requirements that led to an iterative interdisciplinary process. The design methodology was based on both qualitative and quantitative sustainability analyses:

1. From early stages (indicators and rough analysis)
2. Detailed analysis when needed
3. Proof of compliance (final analysis)

The challenge was the round shape of the building, as well as the large footprint resulting in a core of the building where daylight levels were low. This led to multiple iterative design decisions that also affected the structural system of the building, as well as its climate impact.

To ensure that apartments were well lit, some window solutions resulted in a focus on avoiding thermal bridges. The “hash-tag”-shaped footprint of the building in the final stage was analysed with the help of wind simulations and proved to provide good sheltered small pockets around the façade at ground level.

5.2.2.2 **Lessons learned**

The importance of all the important sustainability aspects in the project and tough goals connecting to the design in early phases led to a very complex process with the need for quick team decisions and agile ways of working. In particular, thermal bridges became more and more important when buildings are increasingly insulated, placing focus on construction details in earlier phases.

5.3 Simplification of methods, tools, and metrics

When implementing solar planning tools, it is important to carefully consider the stage of design at which assessments are needed. Different design stages require different levels of detail and complexity in the assessment metrics or performance indicators utilized. However, there may be challenges in selecting appropriate metrics when the model is still in its early stages of development and does not have access to high-detail inputs.

During the early design stages, there is typically data with a limited level of detail available as many parameters of the project and associated models are yet to be determined. This limitation presents a challenge when choosing assessment metrics that require high-detail inputs. Complex metrics, which typically provide more accurate and detailed information, are better suited for late-stage designs where a higher level of detail in the models can be assured.

To address this challenge, simpler metrics are required for the early design stages, along with appropriate methods and tools (Czachura, Kanters, et al., 2022; Nault et al., 2015). It is important to align the complexity of the metrics and tools with the complexity of the model being utilized. Simple low-complexity metrics can offer valuable insights and guidance for decision-making at the early stages, even with limited available information. Nevertheless, to confidently implement simple metrics as performance indicators, there should be evidence to assure that they correlate well with more complex metrics and can reliably predict late-design performance (Czachura, Gentile, et al., 2022).

An example of such simplification efforts in tools and metrics is the early daylighting assessment of buildings. Typically, metrics that are required for daylight compliance are complex and require fully developed architectural models with interior details. For instance, metrics such as the Daylight Factor (DF) or Daylight Autonomy (DA) are calculated via simulations for a reference place inside a room, where high level of detail is at hand. A simplified assessment of daylight is possible by the VSC metric. It is a much simpler daylighting metric that can be applied in the early design stages with low level of detail (e.g. urban planning), because it is calculated at the façade level instead of inside a room. Its correlation to the complex *compliance metrics* has been recognized. (Czachura et al., 2023) demonstrated that VSC is a good predictor of daylighting and can be used as an early performance indicator as it correlates with compliance to daylighting regulations. Because of the simplicity of the VSC metric, simpler tools designated for early design stages have been adapting it into their interfaces for daylight assessments (Autodesk, 2024; White arkitekter, 2022).

5.4 Better tool interoperability and tool interscalability

Although current tools and tool workflows can assist key players when planning for solar neighborhoods, there is still a need for better tool interoperability (from tool to tool) and better tool interscalability (between scales). When it comes to interoperability, a distinction should be made between the building scale and the city scale.

At the building scale, the development of the Industry Foundation Classes (IFC) (an open standard file format and a digital description of the built environment, including buildings and civil infrastructure) has made interoperability more common, and sometimes key actors are legally obliged to model according to the IFC standard. Being able to use the same 3D model for different kinds of simulations will result in less time spent on data preparation and thus greater efficiency and reduction in overall project delivery costs.

The open format defines a wide range of objects, but it may not capture all the necessary semantic information needed for specific workflows, especially simulated data such as solar irradiation and daylight availability. This can result in data loss or misinterpretation when transferring information between different software applications. IFC files can become large and complex, making them challenging to manage and process efficiently. As building models become more detailed, the size of IFC files increases, leading to potential performance issues and difficulties in sharing and collaborating on large-scale projects.

When it comes to interoperability on the city scale, there are several standards that have the aim to make data modelling and exchange easier. City scales tools such as solar cadasters are generally based on GIS tools that process both raster and vector data. The latter, particularly related to buildings, should be converted into shape format (2D or 3D), regardless of the data sources. The CityGML exchange format is particularly well-suited as it enables the conversion of building footprints and roof areas into shape format.

Another aspect of interoperability is the combination of several tools for solar modeling. Solar modeling tools are rarely integrated into a single "press the button" tool, at least not in the development of in-house tools through academic and experimental studies. Therefore, various data formats, script languages, and tools should be considered. For instance, the set of tools used for the solar cadaster in Geneva, including the façade component, required the use of GIS for the pre-processing and post-processing stages, and scripts encoded in Java, C++ and Cuda for solar modeling and shadow casting. GIS scripts were encoded in Python and FME (Feature Manipulation Engine) to process the various steps of data preparation (pre-processing) and the calculation of Key Performance Indicators (KPIs) (post-processing). Data flow between all these steps and tools involved the use of .csv, .shp, and .tiff formats.

Interoperability between different scales is vital for the seamless exchange of geometry and data between tools used in the AEC industry. While IFC is designed for detailed representation of building information, GIS / CityGML is a more general-purpose technology for geographic data analysis. This difference in data structures and representations presents challenges when integrating IFC and GIS solutions.

To enable smooth geometry handling between the two, aligning schemas and developing mapping rules becomes essential. Defining Levels of Detail (LOD) and aggregating elements can create a generalized representation suitable for multi-scale models between IFC and GIS, ensuring reliable interoperability. Additionally, converting 3D coordinates used in IFC to the appropriate GIS coordinate system is necessary for proper georeferencing and alignment. For example, implementing a solar cadaster involves managing different scales. On one hand, the most accurate data in terms of Level of Detail (LOD) are needed at the building scale. The minimal requirement is to have building footprints that enable the extraction of solar radiation on buildings and related energy indicators. However, advanced LOD (>LOD2) is particularly useful for identifying suitable areas for solar installations on roofs (excluding technical installations, for instance) and façades (excluding windows, selecting balconies, etc.).

Similarly, the resolution of the Digital Surface Model (DSM) should be as fine as possible to represent the heterogeneity of roofs, obstacles, and simulate related shadow effects. The choice of resolution also balances computation time and data storage, which increases with resolution. For instance, in Geneva, if the latest version of the DSM (2023) is available at a resolution of 20 cm, 50 cm is a good balance between accuracy and computing solar modeling at the city scale. Of course, if the simulation is performed at the neighborhood scale, the highest resolution can be considered. This introduces the other aspect of interscalability, the spatial extension of solar modeling. While collecting as much data as possible to model solar accessibility for each building, the process is performed at the scale of large urban areas, such as Greater Geneva, which totals an area of 2,000 km^2.

Preserving metadata, attributes, and relationships between elements during the conversion process and different LODs are crucial to maintaining data integrity and enabling effective analysis. Embracing OpenBIM principles and standards, including IFC, enhances the exchange of geometry between BIM and GIS environments.

5.5 Solar readiness and solar rights

Implementation of stricter (building) legislations offers a range of opportunities for improved use of solar planning tools. These stricter regulations have led to a growing demand for incorporating solar energy systems in new constructions, and in turn the demand for efficient and effective solar planning tools. These tools can assist key players -such as real estate developers, engineers and architects- in seamlessly integrating solar energy into their designs, ensuring compliance with the regulations and maximizing the solar potential of each building.

Legislation that protects solar access and daylight provision also presents an opportunity for solar planning tools to play a significant role. These tools can help urban planners and architects assess solar access and daylight availability of proposed buildings, ensuring that they do not obstruct sunlight in neighboring properties or public spaces. This data-driven approach can aid in creating more sustainable urban environments with optimized solar energy utilization and enhanced quality of living.

The enforcement of net-zero energy requirements for new developments further emphasizes the need for sophisticated solar planning tools. To meet these requirements, developers must design buildings that not only consume less energy but also generate a substantial amount of their energy needs through solar installations. Solar planning tools can assist in accurately estimating the energy production potential of solar systems, enabling developers to achieve net-zero energy goals effectively.

Requiring new buildings to be "solar-ready" opens opportunities for solar planning tools to provide standardized and easy-to-implement design guidelines. These tools can help architects and building owners incorporate the necessary provisions and infrastructure for future solar installations, simplifying the process of adopting solar energy systems at a later stage. Solar planning tools could also facilitate collaborative solar projects in communities. These tools can assist in assessing the feasibility of shared solar systems and determining the optimal locations for such installations. By involving multiple stakeholders and promoting shared clean energy initiatives, solar planning tools contribute to the development of more sustainable and resilient solar neighborhoods.

Finally, offering incentives or tax breaks for achieving green building certifications creates a favorable environment for the adoption of solar planning tools. These tools can help developers and architects showcase the potential energy savings and environmental benefits of integrating solar energy systems, making it easier to qualify for these incentives.

It should also be clearer how urban planners can use tools to evaluate and optimize their zoning plan for the full utilization of solar energy. Some larger cities might use such advanced tools, while others might not use them (Kanters et al., 2021). These routines are, however, not always used by all urban planners in those cities, nor is it a widespread routine followed by other smaller cities and municipalities, and it is very often limited to daylight compliance and not the active energy potential.

5.5.1 Solar rights and solar easements as long-term goals

Solar rights are rights to access and harness the rays of the sun for light, warmth or energy (Bronin, 2009). Such rights can not only have economic consequences, but also determine certain aspects of quality of life (Bradbrook, 2011). The increase in installed solar systems in cities have made it clear that solar rights need to be discussed to provide the possibility for everybody to produce energy themselves. In some countries and cities, solar rights are protected by means of solar easements. One example is the city of Boulder in the USA, where the solar easement states that there should be a 12 foot or 25 foot solar fence on property lines to protect solar access for 4 hours (from 10.00 – 14.00 on the 21st of December) (City of Boulder Planning and Development Services Center, 1981). A section explaining the solar fence can be seen in Figure 17.

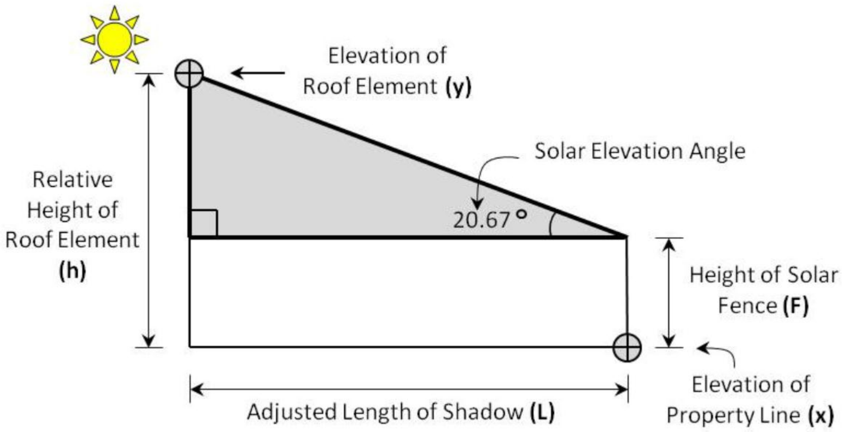

Figure 17: Section along Shadow Length at 10 AM

The idea of the solar easement is to enable all citizens to use this rather simple 2D approach. In the case of advanced plots and building shapes, this approach may become complicated. The solar easements in Utah (USA) has a provision whereby "land owner agrees to ensure adequate exposure of sunlight such that on any given clear day of the year, not more than 10 percent of the collectible solar power will be blocked" (Solar Easements, 1979). This could rather easily be checked by means of advanced tools and could therefore be taken into account when planning for densification.

A more advanced approach can be seen in Norway, where 3D regulations provide a standardized framework for managing geospatial data and incorporating three-dimensional information in planning and design processes. Norway is currently developing and testing 3D regulations with the Norwegian format SOSI version 5.0. By utilizing tools like SOSI and implementing 3D regulations, urban planners, architects, and policymakers can foster sustainable development practices that prioritize solar access and daylight exposure, contributing to energy efficiency, well-being, and overall environmental sustainability in urban areas. By utilizing SOSI and 3D regulations, urban planners can perform solar potential assessments for different areas.

These assessments involve analyzing the solar exposure of existing and proposed buildings, identifying areas with high solar potential, and avoiding or minimizing construction that might block sunlight on other properties. This can also help engage the public and stakeholders in the planning process. It allows for more informed discussions about potential impacts and benefits of proposed developments, facilitating better decision-making and community involvement. With standardized geospatial data and 3D regulations, local authorities can develop and implement solar-friendly policies and regulations. This may include solar easements or rights-of-way to protect specific areas from future development that could obstruct solar access for neighboring properties or virtual 3D building plot boundaries that limit building heights in respect to building heights.

6 Conclusions

The use of solar planning tools offers significant opportunities for the advancement of solar energy utilization, both passively and actively. These tools enable the efficient deployment of solar systems, estimation of financial viability, daylight provision, and integration of solar energy in urban planning. However, continuous development and improvement of these tools are essential to enhance their accuracy and user-friendliness. By leveraging solar planning tools effectively, stakeholders can contribute to the growth and development of sustainable solar energy solutions.

Interoperability and interscalability are points of improvement. The interoperability standard on the building level, IFC, has significantly contributed to improve interoperability in the construction industry. However, challenges remain that need to be addressed to achieve true and seamless data exchange between software tools. Complete implementation, file optimization, and semantic information enhancement are vital steps towards enhancing tool interoperability and realizing the full potential of IFC and BIM in the AEC industry. By overcoming these challenges, stakeholders can benefit from improved productivity, reduced data preparation time, and increased profitability in construction projects.

With interscalability it should be possible to change between different scale levels and the data. For instance, if data from a solar map could be transferred to a more detailed model, it could become easier to take the right decisions later in the building design process.

Solar planning tools play a crucial role in optimizing solar energy utilization, promoting energy-efficient design practices, and facilitating the development of solar neighborhoods and sustainable urban environments. As the demand for solar energy and daylight access continues to grow, innovative and user-friendly solar planning tools will be essential in realizing the full potential of solar power in our cities and communities.

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