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Assessment of the Building-Integrated Photovoltaic Potential in Urban Renewal Processes in the Swiss Context:

Complementarity of urban- and architectural-scale analyses

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ABSTRACT: This paper presents two different approaches to deal with the assessment of the BIPV potential in building renovation projects in urban areas, taking Neuchâtel as a representative middle-size city of the Swiss plateau. 1) A building-scale analysis aiming to show to stakeholders involved in the renovation process that it is important to consider BIPV strategies to achieve the 2050 targets and that it is possible to produce quality architecture using BIPV products already available. For this, five real case studies of residential building archetypes are used. 2) An urban-scale analysis aiming at identifying the priorities of the interventions by comparing the potential of buildings from a large building stock. In each approach, we estimate the total on-site electricity production and the financial incomes provided by the BIPV installation taking into account the electricity self-consumed on-site and the injection of the overproduction into the grid, considering the building energy production and demand at an hourly resolution. Comparing the two approaches allowed us to show that the ranking of the buildings using the two methods remained consistent, despite the – expected – discrepancies in absolute results, and to discuss their complementarity in different stages of the planning and design process.

KEYWORDS: Integrated design, Building renovation, Building-Integrated Photovoltaics

1. INTRODUCTION

In view of the importance of urban renewal processes to reduce the impact on the global warming effect and climate change, building-integrated photovoltaics (BIPV) systems can provide a valid response to the challenges of the energy turnaround and help achieve long-term carbon targets. Functioning as both envelope material and on-site electricity generator, they can reduce the use of both fossil fuels and greenhouse gas (GHG) emissions [1].

This work is part of on-going research focussing on the renovation strategies for the Swiss residential building stock including BIPV to achieve 2050 targets for the energy turnaround fixed by the “2000 Watt Society” concept [2].

The paper presents two different approaches to deal with the assessment of the BIPV potential in renovation projects: 1) a building-scale analysis and renovation of five residential building archetypes (mainly defined by the construction period, from 1909 to 1990), already presented in [1] and illustrated in Figs. 1 through 5; 2) an urban-scale analysis that aims at identifying the priorities for building energy renovation and solar energy installation by comparing the potential of buildings from a large building stock.

The study uses five real residential buildings in Neuchâtel (Switzerland) as case studies; figures 1 to 5 show the current status and the characteristics of each residential archetype.

The emphasis of the study is placed on checking whether the ranking of buildings is consistent between the two analysis scales. We also highlight the complementarity of the two analysis scales and discuss their use as subsequent steps in the planning and design process of building energy renovation.

788 m^2 of floor area, 8 apartments.

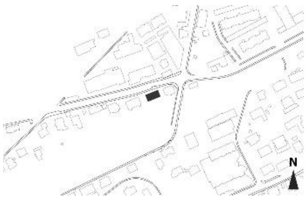

Figure 1: Archetype 1, built in 1909.

847 m² of floor area, 10 apartments.

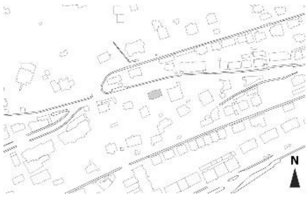

Figure 2: Archetype 2, built in 1938.

4’415 m² of floor area, 48 apartments.

Figure 3: Archetype 3, built in 1968.

5’263 m² of floor area, 52 apartments.

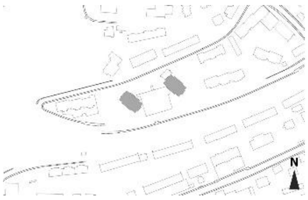

Figure 4: Archetype 4, built in 1972.

4’417 m² of floor area, 30 apartments.

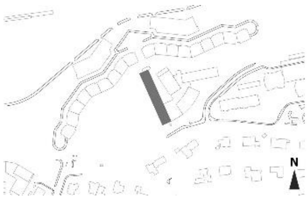

Figure 5: Archetype 5, built in 1990.

2. METHODOLOGY

This work was conducted using a simulation-based approach adapted to each analysis scale. Figure 6 shows an example of the 3D model of the same building at urban- and building-scales, with different levels of detail (LODs). The level of detail (LoD) of the 3D model is crucial to estimate the accuracy of the assessment. The CityGML standard defines five levels of details from LoD0 to LoD4, depending on the amount of information available about the building [3]. For the needs of PV calculation at the building scale, a LoD3 model is the best option, as it provides all the details about the external aspect of the building. However, at the urban scale, available datasets are often at a lower LoD. In this case, a LoD2 model including dormers and roof overhang is used (Fig 6).

The comparison of the two approaches is based on the same renovation scenario, proposing an envelope transformation that meets the minimum legal requirements according to SIA norm (Swiss Society of Engineers and Architects) 380/1:2016 [4], while maximising the electricity production using both roofs and façades as active surfaces.

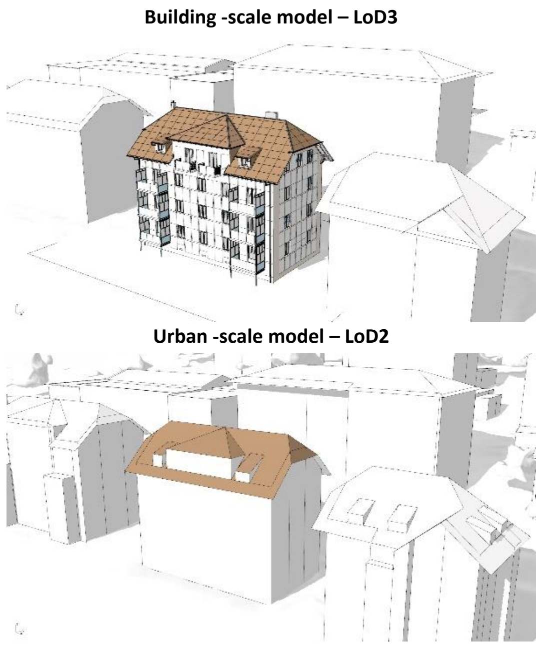

Figure 6: 3D models for the archetype 1, built in 1909.

For both scales, a building energy renovation scenario is proposed, which includes an insulation improvement of the building envelope (insulation of opaque elements and replacement of existing windows) in order to reduce heating energy needs according to the current legal requirements defined by SIA 380/1:2016 [4]. Moreover, in terms of active strategies, we propose an improvement of the heating system through a replacement of the existing oil or gas boiler by an air-water heat pump (AWHP). The latter has a coefficient of performance (COP) of 2.8 and is used for both heating and domestic hot water (DHW) needs.

In order to present the climate conditions of Neuchâtel (Switzerland), Figure 7 shows the monthly diurnal average data from the hourly-step weather file used to conduct the calculations.

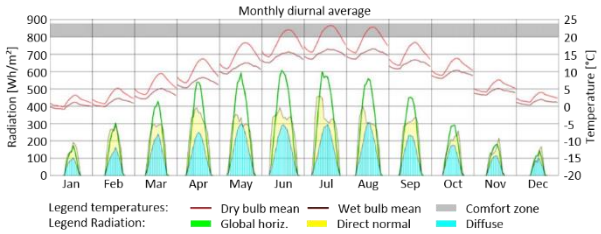

Figure 7: Climate conditions of Neuchâtel, monthly diurnal average

2.1 Building-scale analysis

Thermal simulations are conducted in EnergyPlus (DesignBuilder interface) [5] using a detailed 3D model (LOD3) reconstructed using the original plans of the building for the base-case, and a building-specific design proposal for the renovation scenario. From this simulation phase, hourly-step consumption is obtained for lighting, appliances, heating and domestic hot water (DHW).

We use Daysim [6] to simulate the plane-of-array hourly irradiances, which are then processed in PVLIB [7] to calculate the direct current (DC) power output of the photovoltaic (PV) modules. The arrangement of BIPV modules is defined from an architectural design phase, defining the potential active surfaces by composing the façade and the roof using standard-sized BIPV elements.

The objective of this design phase consists in identifying the maximum area that could suit PV modules. This approach and the final selection of the active surfaces are described in [8]. In the context of this study, we only consider the approach maximising the number of modules fitting on the building surfaces.

2.2 Urban-scale analysis

Simulations are conducted on a 3D city model, including buildings at LoD2, obtained from a 3D cadastre, and terrain and far-field obstructions obtained from Digital Terrain Models at 1-m and 25-m resolution respectively.

The arrangement of BIPV modules is determined on each surface by an automated algorithm, maximizing the number of modules on each surface. As for the building scale, we use Daysim [6] to simulate plane-of-array hourly irradiances, which are then processed in PVLIB [7] to calculate the DC power of the PV modules. Since the DC production is calculated on the plane of the building surface, we decided to apply a reduction factor of 0.5 for flat roofs (archetype 3 and 4). We assume in fact the use of tilted arrays, which have a lower total production because of the smaller number of modules fitting the roof surface. Similarly, the production for vertical surfaces is corrected by a reduction factor (= 1-window-to-wall ratio) in order to exclude the installation of BIPV modules on windows.

Thermal simulations for the base-case scenario are conducted in CitySim [9], using fixed assumptions for thermal parameters (e.g. U-value, window-to-wall ratio) depending on the year of construction, adapted from [10]. The heating needs for the considered renovation scenario were estimated scaling down the heating energy needs for the base-case scenario so as to reach the current annual requirements defined by SIA 380/1:2016 [4]. The final energy for heating is estimated using a fixed COP of 2.8. The electricity demand for domestic hot water, lighting, appliances and ventilation is estimated using annual values per floor area as calculated in the building-scale simulations, using the reference values and schedules defined by SIA 2024:2015 [11].

2.3 Financial calculations

Considering that both presented methods include on-site electricity production and energy demand estimation on hourly resolution, it is also interesting to compare the self-consumption (SC) and self-sufficiency (SS) potential, as defined in [8]. In particular, the self-consumption ratio represents the quantity of on-site electricity that is consumed directly by the building, i.e. avoiding the necessity of purchasing electricity.

We argue in fact that, in BIPV-driven building energy renovations, the size of the solar installation should be adapted to the real energy demand of the building to avoid too much overproduction and reduce the initial investment costs. In this study, we considered a cost of 0.22 CHF/kWh for purchased electricity and a rate of 0.087 CHF/kWh for injected electricity representing the current prices in the canton of Neuchâtel [12].

Since PV panels produce direct current (DC) electricity, we consider a Performance Ratio of 90% as recommended in [13] to obtain alternating current (AC) that is consumed by the building.

Through the self-consumption ratio, we estimate for each archetype the economic income potential expressed in CHF/m^2.year obtained after the renovation (building envelope with BIPV installation and HVAC system) [14].

The income is calculated on an hourly resolution using the following equation:

$$\text{Income} = \sum_{1}^{8760} PV \cdot [PE \cdot SC + IN \cdot (1 - SC)]$$

where *PV* - AC electricity production from PV (kWh);
PE - purchased electricity cost (CHF/kWh);
IN - injected electricity rate (CHF/kWh);
SC - self-consumption ratio (%).

3. RESULTS

Table 1 shows the results of the two analyses on the same case studies. It should be noticed that these results are extracted respectively from an urban-scale analysis including thousands of buildings, and a building-scale analysis including other renovation design scenarios. The comparison is here conducted only on the buildings that are comparable across the two analyses.

The total on-site electricity production is a good indicator to prioritise the buildings that could produce the larger amount of electricity per year. Similarly, it is possible to highlight the buildings with worst energy performance to classify them as a priority in urban renovation plans.

The ranking of the absolute production is consistent for both absolute and normalised production, with only a small change in archetype 4 and 5 regarding the absolute production. However, as expected, we can notice large discrepancies in the absolute results, especially for façades.

Table 1: Ranking results for each building archetype using the two analyses scales according to the total on-site DC electricity production.

Archetype	1	2	3	4	5
DC electricity production			**Urban-scale analysis**		
Roof [MWh/year]	27	10	60	35	161
Façades [MWh/year]	40	49	119	148	104
Total [MWh/year]	67	59	179	183	265
Ranking [-]	**4**	**5**	**3**	**2**	**1**
Total [kWh/m^{2}year]	91	77	55	42	67
Ranking [-]	**1**	**2**	**4**	**5**	**3**
DC electricity production			**Building-scale analysis**		
Roof [MWh/year]	29	21	73	23	173
Façades [MWh/year]	47	44	160	107	156
Total [MWh/year]	76	65	233	130	329
Ranking [-]	**4**	**5**	**2**	**3**	**1**
Total [kWh/m^{2}year]	97	77	53	25	74
Ranking [-]	**1**	**2**	**4**	**5**	**3**

This is because the urban-scale model considers a fixed window-to-wall ratio to consider the non-available façade surfaces, which cannot represent the variability of the façade configurations, and it does not include balconies. For instance, in terms of absolute results, especially for façade in archetype 4, the values differ mainly because of the characteristics of the façades, presenting a complex geometry typical of concrete prefabricate façade elements from the 70s not represented in the urban-scale model.

Table 2: Ranking results in terms of financial income due to self-consumption ratio for each building archetype using the two analysis scales and implementing a renovation scenario achieving current regulation defined by SIA 380/1:2016 [4].

Archetype	1	2	3	4	5
			Urban-scale analysis		
Total electricity demand [MWh/year]	34	36	172	178	170
Self-sufficiency [%]	36	35	33	26	34
Self-consumption [%]	16	17	22	35	16
Income [CHF/m^2.year]	5.0	3.0	2.4	1.0	5.4
Ranking [-]	**1**	**3**	**4**	**5**	**2**
			Building-scale analysis		
Total electricity demand [MWh/year]	34	31	178	191	150
Self-sufficiency [%]	30	29	20	22	31
Self-consumption [%]	14	14	29	32	14
Income [CHF/m^2.year]	12.3	9.6	6.0	2.9	9.6
Ranking [-]	**1**	**3**	**4**	**5**	**2**

The ranking based on the annual income per m^2 of floor area is shown in Table 2. We can notice that the ranking remains consistent for both scales. Figure 8 shows that the building energy balance profiles are consistent as well.

These results also highlight the importance of façade – installed systems for archetypes with large and well-exposed façade (archetype 3 and 4) and with more apartments per building (more energy demand intensity), as these have a larger SC ratio (with similar SS) than archetypes 1, 2 and 5. This is because the consumption-production profiles match in a better way for archetypes using more intensively façades.

It is important to note that, in this study, we focussed on the impact of a BIPV installation using all available surfaces (roof and façade) and considering a minimum energy renovation to achieve the legal targets.

However, as recommended in [15], we encourage to implement a deeper energy renovation to achieve the 2050 targets, which include for example carbon reduction too.

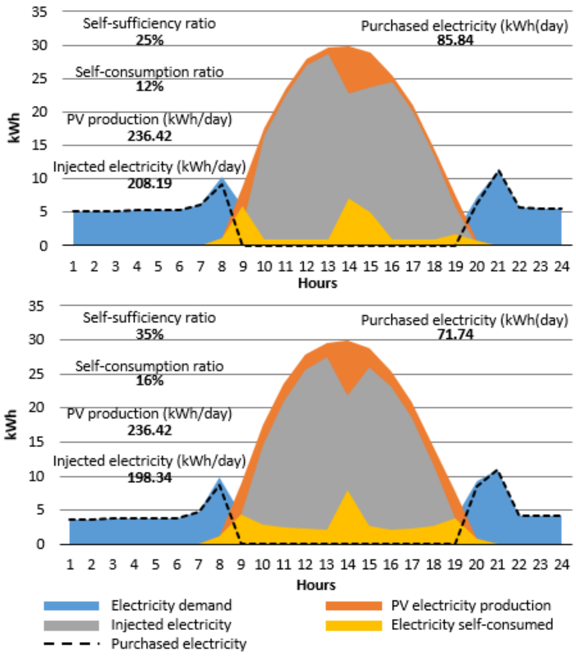

Figure 8: Example of energy balance of 21 march for both, building (top) an urban-scale (down).

4. DISCUSSION

Even if the city-scale 3D model provides a good level of detail, many hypotheses are required to estimate the PV production of façades (e.g. window-to-wall ratio), and of flat roofs (i.e. tilt and spacing), which cannot represent the variability of conditions of the building stock: urban-scale assessments cannot replace detailed assessments of single buildings. Both methods should be also further validated with real measurements. However, we argue that the two methods are rather complementary, as they refer to subsequent stages of the urban renewal process. In this sense, the first phase of this process is to identify the priority intervention areas, for which simplified methods can give enough information. The second phase is to identify possible intervention solutions, with reference to best-case renovation design strategies.

5. CONCLUSION

This article presented two different-scale analysis methods and showed their relevance for assessing the potential for building energy renovation.

We have shown that the ranking of the BIPV potential of the analysed buildings is consistent across the two methods, i.e. we can identify the priority level of the interventions in an urban area, despite the expected discrepancies in absolute results due to different levels of detail, available information, and architectural design specificities.

Urban-scale assessments can help decision-makers identify priority areas/buildings, while architectural-scale analyses offer designers and building owners valuable benchmarks and guidelines on possible renovation strategies to give a response to different archetypal situation taken into account the soundings of the building.

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