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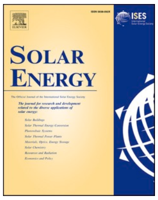

A comparative survey of investment conditions for solar facades and rooftop PV in building applications

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ABSTRACT

Photovoltaics (PV) are a key technology for low-carbon power generation, especially in cities where rooftop systems are widely adopted. Despite the larger surface area and solar irradiation potential, building facades remain vastly underutilized compared to rooftops. Yet using them for solar electricity could substantially boost cities' decarbonization efforts. Here, we analyze why solar facades lag behind rooftop PV, focusing on the financial and investment perspective in Switzerland, a country with among Europe's largest solar facade deployment rates. Through interviews with 26 solar planners and architects, we analyze investment conditions – investment costs, operational costs, capacity factors, payback periods, and development timelines – for two facade types (facade-integrated and facade-mounted) and compare them to rooftop PV. Our findings reveal that compared to rooftop PV, solar facades feature three to five times higher investment costs, four times longer development, and 30 % less electricity per kWh output due to the vertical orientation and shading. These conditions result in mean 25 to 27-year payback periods for integrated facades versus 14 to 19 years for facade-mounted ones, depending on the size. We argue that future policies must simultaneously foster economic and aesthetic incentives to boost the adoption of solar facades, advancing sustainable urban decarbonization.

1. Introduction

Urban areas generate 70 % of energy-related CO_2 emissions and will, until 2050, house 68 % of the global population [1,2], making their decarbonization critical. Consequently, numerous cities have adopted decarbonization plans [3] through joining networks such as the Global Covenant of Mayors [4], where photovoltaic (PV) projects feature prominently [5]. PV panels have low design complexity [6] and low costs [7,8], making them an attractive decarbonization technology. However, urban PV remains confined mainly to rooftops [9,10] despite facades having greater building surface area and substantial solar irradiation potential [11–14]. Solar facades include a series of technologies that integrate PV into buildings, while having functions besides electricity generation. Foremost, this includes aesthetics such as colored PV modules that integrate into the building design [15]. However, an increasing number of solar facade technologies has a thermal role, in addition to aesthetics, including PV double-skin facades [16–18], PV/thermal curtain walls [19,20], adaptive PV louvers and shading devices [21,22] and semi-transparent PV glazing and PV windows [23,24]. In contrast, rooftop PV systems have uniform designs, and their primary function is electricity generation.

A key prerequisite for the widespread application of PV is the willingness of investors to finance the systems [25,26], mainly driven by risk-return considerations [27–31]. The cost of financing varies between technologies and investor types [32]. Because of this, governments enact policies to reduce investment risks, such as fixed electricity offtake prices and guaranteed sales [33,34]. These measures have driven rapid rooftop PV growth over the past two decades, reducing module and equipment costs [35]. In the building sector, rooftop PV with standardized modules and a high degree of replicability were the main contributors to this growth, leaving the solar potential of the existing building envelopes underutilized. Despite applying similar policy instruments for solar facades [36], their uptake lags significantly behind rooftop PV [37].

The lack of investments underscores the need to examine solar facades from an investor perspective. To address this gap, we interviewed

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26 PV experts, discussing differences in investment conditions and financing between rooftop PV and solar facades. This included their perceptions of risks and profitability drivers between the two PV applications, reported investment costs, cost structures, and profitability metrics for 47 solar facades and 31 rooftop PV projects. To control for various country-specific cost and risk drivers – such as country risk [38] – we focus on one representative case [39] – Switzerland, with one of the highest Building Integrated PV (BIPV) installation rates in Europe [36], and 277 projects developed in 2023 alone [40].

We contribute to the literature on solar facades in several ways. First, existing research on solar facades (and, more broadly, BIPV) focuses on examining drivers and barriers. For instance, several studies suggest that the main implementation obstacles include high initial costs, greater technical complexity, lower production per kW, lack of public support policies, and the reluctance of architects to adopt solar facades [41–47]. This research stream omits finance and investment-related issues, and any quantitative analysis. Our study is the first to focus exclusively on the solar facade investors' standpoint and collect precise cost data to compare actual facade and rooftop projects. Second, while the literature discusses BIPV risks, it neglects the relative importance of financial risk and profitability drivers [41,43,45], or it focuses on merely technical risks [42,46]. We rank the relevance of investment risks and profitability drivers for facade PV, enabling policymakers to formulate de-risking policies [26].

Third, the literature on BIPV feasibility primarily focuses on the economic performance of case studies [48–54] or simulating investment conditions across countries [55–58]. Among this research, several studies provide detailed solar facade cost breakdowns, comparing them to conventional facades [48,49,57–60]. These studies usually cover investment costs (CAPEX) in monetary units (such as EUR) per meter squared, a metric commonly used when designing buildings. However, research on energy systems usually expresses CAPEX as costs per kWp. While CAPEX values and component breakdowns are readily available for rooftop PV (for instance, see NREL (2022) [61]), data is lacking for solar facades, limiting more accurate forecasting of urban energy transitions [62–64]. We provide CAPEX values for facade PV projects in Switzerland by components and further metrics relevant to energy system models, such as operational expenditures and expected production.

2. Research design

2.1. Research case

Our research centers on Switzerland, a representative case study with abundant experience in integrating PV into urban settings [39]. Switzerland is a forerunner in decarbonization, with plans to become carbon neutral until 2050 [65]. Solar energy is a cornerstone of this strategy, with a foreseen tenfold increase in solar electricity production, from 3.9 TWh in 2022 to 34 TWh in 2050 [66]. The addition of PV is meant to replace the existing nuclear power plant fleet, which covered 36 % of domestic electricity consumption in 2022 and will be shut down. Consequently, PV is already a fast-growing market, with 8150 MW installed until 2024, which accounted for about 11 % of Swiss electricity consumption [67]. Because of legal limits to developing PV on the ground, most of the new capacity will be installed on existing infrastructure, highlighting the importance of PV integration into the built environment. Besides the nuclear energy phase-out, another challenge is closing the winter electricity import gap, equaling one fifth of Switzerland's consumption in 2020 [66]. The import of electricity is a security concern and has gained relevance following the Ukraine war outbreak in 2022. The resulting price increases triggered a shift in public opinion towards more self-reliance, as opposed to increasing electricity interconnection to enhance trade [68]. Moreover, in a recent referendum, the Swiss confirmed with a 68 % majority vote the adoption of an Electricity Law [69], which intends to increase electricity production from renewables.

Existing regulations and support policies – including the newly accepted Electricity Law – greatly impact PV investment risks, profitability, and the overall financial attractiveness of rooftop PV and solar facades, which we study in our analysis. The new law mainly impacts federal regulations, although cantons and municipalities also apply their individual rules, leading to considerable fragmentation in support policies [70]. On the federal level, Swiss rooftop PV projects are eligible for an investment subsidy that covers 380 CHF/kW (as of 2025) for conventional rooftop PV systems smaller than 100 kW. Solar facades benefit from this framework and receive additional support because of their steeper panel angles, varying between 580 CHF/kW and 820 CHF/kW depending on the level of aesthetic integration of the panels into the building design [71,72]. Furthermore, there are no long-term electricity offtake and price guarantees. Instead, there are more than 600 utility companies, each with its own PV and electricity tariff, which vary yearly based on their electricity production and procurement costs [73], leading to inconsistent returns during the plant's lifetime and across Switzerland. The Electricity Law aims to harmonize these offtake prices by implementing, as of 2026, a minimum price and a harmonized quarterly market price. Utility companies will have to remunerate solar electricity at least the quarterly market price, while systems smaller than 150 kW will benefit from a minimum price triggered when the quarterly price drops below the minimum [74].

Apart from electricity market regulations, building-related laws also impact solar facades and rooftop PV in Switzerland. As of November 2023, a federal regulation obliges buildings with an applicable area larger than 300 m^2 to install PV systems, whose exact size depends on individual cantonal provisions, ranging from 10 % of the applicable area in the small canton of Zug in central Switzerland to 40 % in Valais in the Southwest [75]. Some cantons like Zurich are considering an even stricter mandate, requiring new and existing buildings to implement a PV plant during the first major roof renovation or until 2040 at the latest [76]. Specific fire hazard regulations have an additional impact on solar facade development. The Canton of Zurich Building Insurance Company started requiring, as of 2023, proof that solar facades taller than 11 m can withstand the spreading of fires [77], resulting in regulatory uncertainty. These region-specific regulations impact risk and profitability and are mirrored by our results.

2.2. Method

To understand the differences between facade PV and rooftop PV investments, we interviewed experts active in both rooftop PV and facade PV in Switzerland. Applying interviews enables collecting in-depth replies where the participants provide project context; however, they limit the study reach considering the larger effort to organize and undertake them [78]. We consider three types of PV projects (see Fig. 1), including i) facade-integrated solar facades – colored PV modules are encapsulated into the building design ii) facade-mounted solar facades – conventional PV modules are mounted onto building surfaces, and – as a reference point – iii) rooftop PV plants on flat rooftops. We categorize the projects as small (below 100 kW) and large (above 100 kW), following the Swiss federal subsidy scheme's definition of project sizes [72]. We omit analyzing the various solar facade technologies with a thermal function to simplify the comparison with rooftop PV, which only generates electricity.

We contacted 94 individuals from 77 organizations and interviewed 26 (28 % response rate). The sample includes 54 % solar planners, 35 % architects, and 12 % academics (Table 1). The diverse respondent sample enabled the collection of varying perspectives. Architects and solar planners typically work together on building PV systems, but their focus is different. The solar planners in our sample usually develop the PV plant and understand the technical details and cost components. Architects, on the other hand, deal predominantly with the PV plants visual integration, especially for integrated plants. Hence, while the solar planners provided most of the cost data, the architects helped

Fig. 1. Exemplary solar facades. A. small facade-mounted (<100 kW) [79] B. small integrated (<100 kW) [80] C. large facade-mounted (>100 kW) [81] D. large integrated (>100 kW) [82].

Table 1
List of interviewees by organization type and role.

Code	Organization type	Title
INT 1	Solar planer	Head of Commercial Energy
INT 2	Energy company	Head of Asset Management
INT 3	Solar planer	CEO
INT 4	Energy company	Head of Photovoltaics
INT 5	Solar planer	Senior Technical Consultant
INT 6	Solar planer	Head of Solar team
INT 7	Solar planer	CEO
INT 8	University	Professor
INT 9	Solar planer	Head of Planning
INT 10	Solar planer	CEO
INT 11	Architectural office	Partner
INT 12	Architectural office	Partner
INT 13	Architectural office	CEO
INT 14	Solar planer	CEO
INT 15	Solar planer	CEO
INT 16	Architectural office	Partner
INT 17	Architectural office	Partner
INT 18	Solar planer	Partner
INT 19	Solar planer	CEO
INT 20	Solar planer	Head of Photovoltaics
INT 21	Solar planer	Partner
INT 22	University	Professor
INT 23	Architectural office	Partner
INT 24	Energy company	Head of Solar Technologies
INT 25	University	Senior researcher
INT 26	Solar planer	CEO

elaborate on the visual perspectives of integrating PV into buildings and additional insights on design tradeoffs and investor risk perceptions. Further, both expert groups work with the building investors and understand their risk drivers. Overall, we have collected specific cost data for 47 solar facades and 31 rooftop PV projects undertaken between 2018 and 2025 (five of which are still in the planning process) ranging in sizes from 10 kW to 2500 kW. Interviewee acquisition consisted of contacting personal networks, leading to snowball sampling where an interviewee recommends further individuals [83] and reviewing the winners of the Swiss Solar Prize between the years 2017 and 2024 [84]. The interviews lasted between 30 and 60 min and were recorded and transcribed.

Our interview process consisted of semi-structured and structured questions [85] (see Table 2 in Supplementary Information (SI)). In the semi-structured section, we asked the interviewees to provide insights on the slower uptake of solar facades versus rooftop PV. We then proceeded with the structured questions, asking them to identify specific projects they worked on (along categories *i* to *iii*), including the project size and commissioning year. Following this, they provided information on the projects' investment conditions, including the additional costs of the solar facade, the overall costs of the rooftop PV project, and a cost breakdown (see Table 3 in the SI for the cost categories).

The feasibility of solar facades is typically evaluated against the most likely alternative – a facade without PV components. The so-called extra cost approach assumes the CAPEX equals the difference between the two options [49]. Instead of this, we report on the full costs as defined by NREL or:

$$CAPEX_{PV} = \sum_{i=1}^{n} C_i \tag{1}$$

where C_i represents the individual cost components including modules, inverters, structural balance of system (BOS), electrical balance of system (EBOS), fieldwork, office work and other investment costs [61] – where we also include scaffolding – and n is the total number of considered components. The full list of components is given in Table 3 in the Supplementary Information. We selected this CAPEX approach for several reasons. First, using the full costs instead of extra costs makes the analysis between rooftop PV and facade PV directly comparable. Second, the full cost approach is directly observable and based on actual project costs, whereas the extra cost approach relies on a hypothetical alternative. For our analysis, using the full cost approach is more robust. Third, in energy economics and energy system modeling, it is conventional to use full costs. As such, the values for facade PV are directly applicable in studies that model urban decarbonization.

Further, our analysis collects OPEX estimates defined as:

$$OPEX_{PV} = \sum_{i=1}^{m} O_j \tag{2}$$

where O_j represents the different cost components and m is the total number of considered costs. For a full list of OPEX components, see Table 3 in the Supplementary Information.

Since the projects differ in their commissioning years, we aligned the CAPEX and OPEX data into 2024 real values using an inflation index for Switzerland [86]. The values exclude Value Added Tax. Besides investment costs, we also asked the interviewees to provide estimated payback periods, which reflect the payback for installing solar components on the facade.

Further, the interviewees ranked profitability and risk drivers, comparing rooftop PV and solar facades. We include general profitability drivers like CAPEX, OPEX, and solar irradiation and drivers specific to Switzerland, including the investment subsidy for small-scale installations (KLEIV) [72] and specific municipal and cantonal subsidies [87]. Regarding the risk drivers, we included risk categories following existing literature [88]. These include *i)* price risk: changes in the municipal PV and electricity tariffs *ii)* technology risks: equipment failure *iii)* political risks: changes in the support system, for instance, the KLEIV *iv)* regulatory risks: project approval and permitting processes *v)* resource risks: solar irradiation variability. Considering our focus on PV technologies in buildings, we add *vi)* liability risk, representing the risk of damage to the property and its surroundings. We aggregate the rankings for each technology type using the Borda count method[89].[1]

3. Results

3.1. Capital expenditures, cost structure, and project timelines

Fig. 2A shows the CAPEX distribution of the projects along the three types. The first main observation is that smaller facade-integrated projects are the most expensive, with a median CAPEX of 6.000 CHF/kWp, the lowest and highest values ranging between 3.500 CHF/kWp and 12.700 CHF/kWp. This is more than six times the median value of large rooftop PV, which are the least expensive, with 850 CHF/kWp. The large gap results from the higher complexity of integrated solar facades and their high customization requirements to align aesthetically with the building. Interviewee (INT 23) provides an analogy to picture this: “*I have a roof, and I hire a solar specialist to install a solar system. It's similar to buying a refrigerator or a car. But you can't buy a solar facade the same way […] A solar facade can only be developed if you also engage thoroughly with the entire architectural integration.*” Unlike rooftop PV that are replicable, “*buildings are always prototypes and […] standardization is very difficult*” *(INT 21)*. Second, facade-mounted projects have much smaller costs than facade-integrated projects, with median values of 1450 CHF/kWp and 2500 CHF/kWp for large and small projects, respectively. Facade-mounted projects are usually composed of regular solar modules, and since they are primarily installed on commercial or industrial buildings, there are fewer aesthetics requirements, leading to lower costs and smaller cost variances.

We next delve into the detailed CAPEX drivers. As shown in Fig. 2B, solar modules drive integrated solar facade costs, composing a mean of 45 % of overall CAPEX for small projects. In comparison, facade-mounted solar facades have cost structures where modules comprise 27 % and 24 % of CAPEX, similar to small and large rooftop PV with 22 % and 25 % of CAPEX, respectively. Facade-mounted projects and rooftop PV typically employ standardized modules, while facade-integrated projects apply customized modules with specific colors to fit the building's aesthetic design. Moreover, they come in various sizes to fit between the building elements, like windows, when the solar facade completely envelopes the building, as in Fig. 1B. To illustrate this point, INT 15 comments on having planned 40 kWp and 300 kWp integrated solar facade projects, consisting of 80 and 35 different module sizes, respectively, as opposed to one standardized module for rooftop PV or facade-mounted projects, as illustrated in Fig. 1C. Moreover, only a few companies supply customized PV modules, which are primarily located in Switzerland, as in the case of our interviewee sample. Hence, unlike rooftop PV, where cheap modules from Chinese manufacturers contribute to low project costs, this is not the same for solar facades.

Furthermore, a primary CAPEX driver in all project categories is the structural (SBOS) and electrical balance of systems cost (EBOS), along with field work. While these cost categories comprise 38 % of overall CAPEX for small integrated projects, they comprise 52 % and 55 % for small and large rooftop PV. Unlike PV modules, the products and services underlying these cost categories are less scalable, especially field work. The manual labor involved in module installation and overall project construction increases costs one to one, irrespective of the project size.

Finally, in Fig. 2C, we show the estimated project timelines for solar facades and rooftop PV. Solar facades require four times longer conceptualization and feasibility than rooftop PV, as they are integrated into building designs. Permitting alone takes four times longer, largely because of fire hazard requirements, leading to additional project costs. To illustrate this point, INT 11 comments on conducting a successful fire test [91], contributing to a state-of-the-art document for planning solar facades [92]. However, the exercise cost over 100.000 CHF, leading to uncertainty in the sector. Interestingly, financing timelines are almost identical between the two project types, primarily because Swiss investors typically invest through their balance sheets, requiring less time to arrange than project financing [32]. Finally, solar facades have longer installation times. Besides working on vertical surfaces, the extended installation stems from more prolonged waiting times to deliver customized modules (INT 26).

3.2. Operational costs and expected electricity production

The longer development timelines and higher costs compose some of the main reasons why solar facades are a slower developing market than rooftop PV. In addition to these factors, solar facades have higher expected OPEX than rooftop PV plants, although the difference is smaller than in the case of CAPEX. Fig. 3A shows that small integrated solar facades have an expected median OPEX of 33 CHF/kWp. In comparison, rooftop PV projects have a median OPEX between 21 CHF/kWp and 31 CHF/kWp for large and small projects, respectively. According to our interviewees, integrated solar facades have the highest OPEX because reaching and exchanging parts on a facade is more complex than on a rooftop, involving lifting equipment. These situations include exchanging standard parts like modules and inverters, but also optimizers for minimizing shading losses, which are more frequent with solar facades. However, some interviewees assign lower OPEX values to solar facades. For instance, INT 4 argues that these have to be cleaned less often and are easier to inspect, for example, when performing a thermography check. Unlike rooftop projects, they are not subject to

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[1] The Borda Count [82] is a ranking-based voting method that assigns points to candidates based on their position in each voter's preference list. The total points are then summed to determine the winner. For instance, we asked the interviewees to rank eight profitability drivers. The driver with the most importance are ranked fist, receiving eight points, while the one ranked last only one point. The total points are then summed to determine the most important profitability driver. We chose the method because it accounts for the full preference order, and not just top choices.

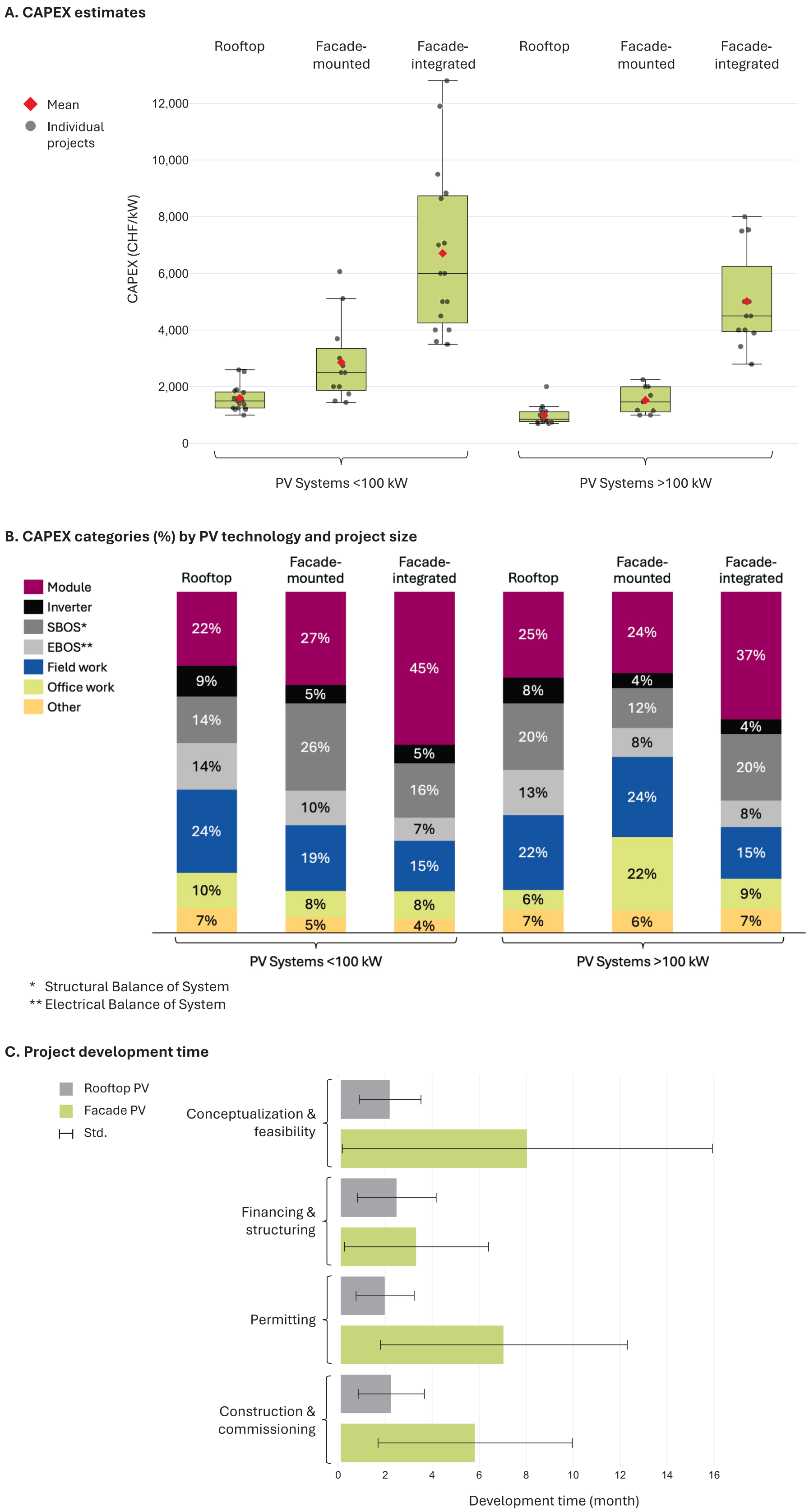
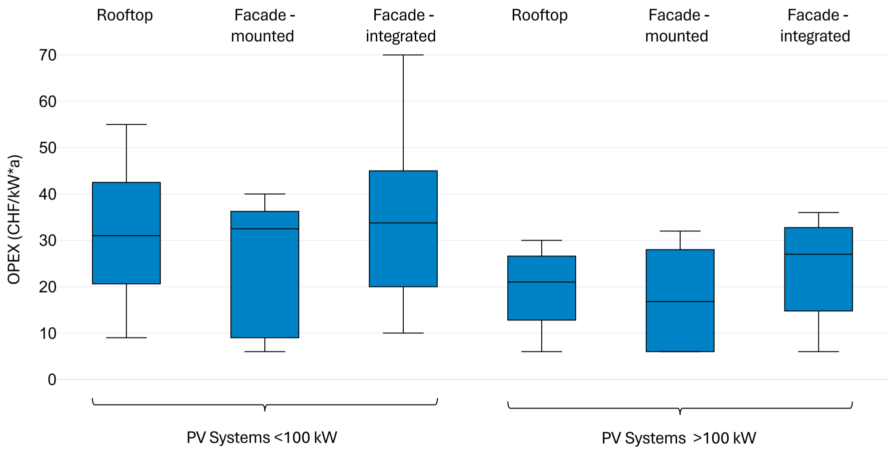


Fig. 2. A. Capital expenditures (CAPEX) estimates for small and large projects without Value Added Tax. The dots represent values for the individual projects. The box plots shows the range between the first and third quartiles, while the error bars are outliers within an interquartile range of 1.5. B. CAPEX structure along the main categories, following NREL (2022) [61]. Estimated mean project development timelines between rooftop PV and solar facades. The error bars represent one standard deviation from the mean. Timeline categorization according to Gumber et al. (2024) [90].

A. OPEX estimates



B. Full load hours

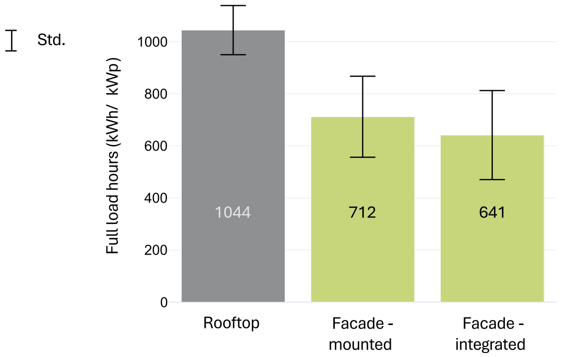


Fig. 3. A. Operational costs (OPEX) estimates for small and large project categories B. Estimates of full load hours according to category. The error bars represent one standard deviation from the mean.

yearly inspections of fall protection systems.

Another key factor in OPEX is annual electricity production, which is lower for solar facades than rooftop PV, as illustrated in Fig. 3B. This increases relative OPEX when expressed in monetary units per kilowatt-hour (kWh) (INT 15). For example, INT 15 notes that the cost of sending personnel to inspect a solar facade is higher relative to its output than for a rooftop PV system. Fig. 3B indicates that, on average, solar facades in our sample generate about 30 % less electricity than rooftop PV, although there are large differences depending on the single project. Several factors explain this reduced output. First, most solar facades feature vertically aligned modules, which are not optimized for peak summer solar irradiation. Instead, they produce relatively more electricity during winter compared to rooftop PV systems. Second, solar facades are more prone to shading from surrounding structures. Third, due to aesthetic integration, some facades include north-facing building surfaces, which receive the least solar irradiation and therefore reduce the overall mean production. Facade orientation has a strong impact on output; for instance, one interviewee reported a project with 700 kWh/kW on south-facing surfaces, 570 kWh/kW on east and west, and 300 kWh/kW due north (INT 9).This roughly corresponds to the variations documented in the literature (for example, see [93–95]).

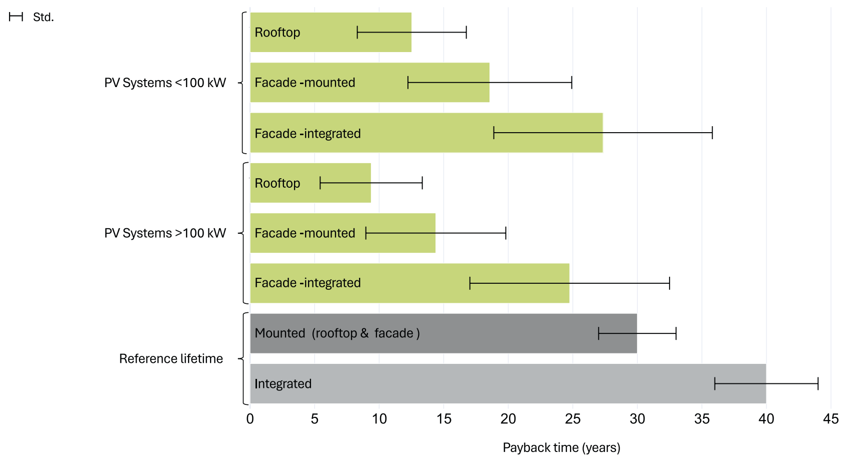
3.3. *Profitability and risk drivers*

The above-discussed investment conditions greatly impact the profitability of solar facades. As shown in Fig. 4A, the expected mean payback period for large and small integrated solar facades is 25 and 27 years, respectively, and 14 and 19 years for facade-mounted systems. In comparison, rooftop PV systems have mean payback periods of between 9 and 13 years. However, these results exhibit a large variation, indicating various possible outcomes depending on the assumed self-consumption rates and electricity and PV tariffs. These payback periods do not consider the marginal costs of the solar facade over an alternative facade. Instead, we consider the full solar facade costs.

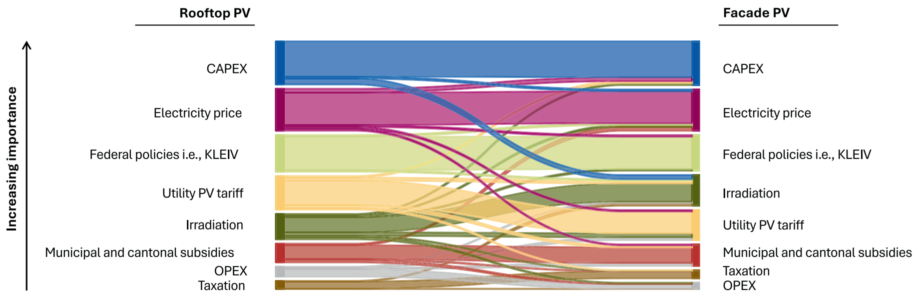
Fig. 4B further compares the most important profitability drivers between rooftop PV and solar facades. Most interviewees consistently ranked CAPEX as the most impactful profitability driver, followed by the electricity price and investment subsidies. OPEX ranked among the least impactful investment conditions for both technologies, corroborating the findings from Fig. 3A, showing the near equality in OPEX between the project types. The reason electricity price ranks second indicates the importance of self-consumption in PV project economics in Switzerland.

Moreover, the interviewees ranked solar irradiation as slightly more critical to the profitability of solar facades than rooftop PV. A facade's precise location and orientation play a more important role than they do for rooftops, as facades are particularly susceptible to shading from surrounding structures, an effect amplified in winter when the sun sits lower on the horizon. Unlike rooftop PV systems, solar facades encounter unique tradeoffs and limitations, as highlighted by our interviewees. For instance, north-facing facades, which generate the least electricity, are sometimes used. In contrast, south-facing facades often have more windows, reducing the surface area for panels and forcing a compromise between indoor sunlight and energy output – tradeoffs absent in rooftop setups (INT 8). Additionally, facades are fixed in a single direction, limiting adaptability, whereas rooftop systems offer greater flexibility in orientation (INT 13, INT 15). Finally, utility PV tariffs are less critical for facade PV projects, considering their primary business model relies on self-consumption, not electricity sales (INT 26).

A. Payback time



B. Profitability drivers ranking



C. Risk drivers ranking

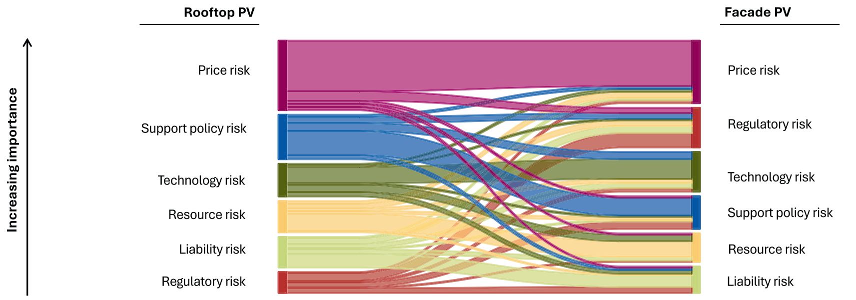


Fig. 4. A. Expected mean payback periods by project category and size. The payback periods are compared to typical rooftop PV [96] and solar facade project lifetimes. The mounted solar facade lifetime equals the lifetime of regular PV projects. We here assume this is limited by module durability. Integrated facade PV projects have longer lifetimes because of more durable modules, typically of 4 mm thick glass-glass type. Error bars represent one standard deviation from the mean B. Comparison of profitability drivers between rooftop PV and solar facades. A change in the Sankey diagram flow shows how individual respondents changed responses when comparing the two technology types C. Comparison of risk drivers between rooftop PV and solar facades. The diagrams in B and C show Borda counts of the responses.

Having explored the key profitability drivers, we now discuss investment risks, as shown in Fig. 4C. According to the majority of the replies, price risk is the most important risk driver in Switzerland, primarily because utilities change their PV and electricity tariffs yearly. The current support system does not guarantee long-term price stability, such as via feed-in-tariffs, but instead decreases investors' upfront investment costs via the investment subsidy [72]. However, this dynamic is set to evolve with recent regulatory changes. In the future, price changes will be more frequent, following the shift to quarterly tariff adjustments based on averaged market prices [74]. This shift aims to align remuneration more closely with market conditions, yet it amplifies price risk perception among some of our interviewees.

Regulatory risks are another major risk driver for solar facades, ranked second compared to sixth for rooftop PV. Inconsistent and fast-changing fire safety regulations across Switzerland are the main reason for high regulatory risks for solar facades, as explained in Section 3.1. In contrast, rooftop PV systems face minimal regulatory risks, as Switzerland requires only notification to authorities rather than a formal construction permit. Technology risks rank equally, although some interviewees rank these higher for solar facades due to their relative novelty. Investors often discuss equipment failures and the difficulties of replacing components within a facade structure, unlike rooftop PV systems, where abundant technical experience reduces such concerns. Additionally, the absence of long-term operational data for solar facades creates greater uncertainty about their durability [97,98], unlike rooftop PV, where performance degradation is well-understood and predictable (INT 16). Finally, our interviewees perceive policy risks lower for solar facades than rooftop PV. Solar facades, especially smaller ones, prioritize aesthetics over profitability, while rooftop PV systems focus on profitability, making them more sensitive to changes in PV tariffs.

4. Discussion

Several findings stand out from our study. First, our results underline that the aesthetic integration of solar modules into building design is costly. Nevertheless, it's interesting to observe that despite the higher costs, such projects are continually being developed, albeit in much smaller numbers than conventional rooftop PV. The interviewees highlight three main arguments when asked about the motivations for engaging in such projects: *i)* building investors turn to facades when rooftops alone are insufficient to meet stringent sustainability standards, such as Minergie – a Swiss certification system that mandates buildings generate more electricity than they consume [99] *ii)* when an expensive alternative facade – such as one made of glass – is already planned, upgrading to a solar facade does not significantly increase the overall facade investment costs, as suggested by earlier research [49,60] *iii)* installing a solar facade is a visual statement. In the words of INT 22: "*Why do people drive a Porsche when a Volkswagen can also get you from A to B?*". Integrated solar facades invoke values other than strict economic considerations. This corroborates earlier research that sustainable energy investments involve emotions and not primarily cost-effectiveness [100–102] as conventional energy economics literature suggests by assuming investors are rational decision-makers [103,104]. Buildings are not subject to entirely rational investment decisions (INT 22), and investors are willing to pay extra if sustainability standards or visual preferences are satisfied [105]. The finding aligns with earlier research on PV adopters in Germany, who in part, invest for non-economic reasons [30], such as environmentalism.

These findings might suggest that only affluent investors can afford solar facades, leading us to our second point: the role of support policies and the types of solar facades they should prioritize. The current Swiss investment subsidies would cover between 14 % and 23 % of investment costs based on our median CAPEX results of 6.000 CHF/kW and 2.500 CHF/kW for small integrated and facade-mounted solar facades, respectively. In comparison, small rooftop PV would receive 25 % investment costs, given a median CAPEX of 1.500 CHF/kW, similar to facade-mounted facades. However, the latter has about 30 % more production potential (see Fig. 3B), meaning the remaining investment would be repaid faster than with solar facades. While in comparison to other profitability drivers like operational expenditures, taxation, and even irradiation (see Fig. 4B), investment subsidies play a more critical role, it is uncertain how much they increase the likelihood of investors opting for solar facades. The availability of capital is not a chokepoint for Swiss building investors. Instead, our interviewees highlight that electricity prices play a more critical role in shaping investment choices (see Fig. 4C). This supports the argument that hedging long-term revenues via electricity offtake agreements could be more effective than investment subsidies in mobilizing solar facade investments [16].

Finally, our findings on the higher complexity and customization needs of solar facades vis-à-vis rooftop PV projects highlight that – according to theory [6] – we should expect lower learning rates, slowing down their roll-out in addition to the higher CAPEX. Conventional rooftop PV systems are primarily composed of standardized components. In contrast, solar facades have high design complexity because a single project is composed of tens of individually sized modules, and each project can differ in module color, depending on the building design [15]. This high degree of customization increases project costs. Moreover, longer project timelines mean slower project turnover and less learning, i.e., a smaller scope for cost reductions. It is important to note that we observe a similar cost dynamic with other subvariants of PV technology, which hold large potential but currently have high costs. Examples include mountain PV systems and floating PV [106], which will take time to acquire experience and induce learning to decrease costs. Hence, as we decarbonize with PV, it will take continued policy support to roll out these PV niches and achieve scale.

5. Conclusions

Our results indicate that integrated solar facades cost three to five times more than rooftop PV. Because of their vertical angle and non-optimal orientation dictated by the building design, solar facades have about 30 % lower electricity generation than rooftop PV systems. Taken together, integrated solar facades have estimated mean payback periods that are about 15 years longer than conventional rooftop PV systems, compared to only 6 years longer for facade-mounted systems. From a purely economic standpoint, these results imply that fostering solar facades on buildings where visual integration is less important is more cost-effective. However, in contradiction to this finding, our interviewees highlight that integrated solar facades undergo an investment decision dynamic where cost considerations play a lesser role. Instead, making an aesthetic statement is more relevant. Such investment dynamics question the rationale of conventional energy scenarios that assume rational and cost-optimizing decision-makers [103,104].

Despite the sizeable solar irradiation potential on building envelopes, solar facades rarely feature in cities' decarbonization plans [5,107,108]. Cities might be harvesting the low-hanging fruits first and prioritize rooftop PV over solar facades because the latter have lower CAPEX and fewer implementation challenges [109], leading to faster achievement of climate targets. However, despite this, two key arguments advocate implementing solar facades more proactively in decarbonization plans. First, solar facades are especially suitable for winter PV production because of their steep panel angles, especially in locations with little winter fog cover. Cities prioritizing only rooftop PV optimized for summer production will struggle with the seasonal balancing of their clean electricity generation, considering the decrease in winter irradiation in seasonal climates [110]. Moreover, in wintertime, electricity prices tend to increase the most [111], potentially leading to energy security concerns in countries that import electricity during winter.

Second, solar facades feature prominently on buildings. Supporting their development could benefit the symbolic value of the energy transition and increase the acceptance of renewable energy in urban environments. City governments could promote solar facades by raising PV tariffs in winter, which would also benefit other PV technologies or provide investment subsidies commensurate to their costs. Additional measures could include fostering building planning where fewer customized module sizes are needed to reduce solar facade costs.

Our study fills a critical research gap, integrating investment and finance considerations into the discussions on solar facades. Nevertheless, the analysis has several limitations. First, we do not apply the extra cost approach [49] – commonly applied in facade PV. Instead, we apply the full cost approach, which has some limitations. Our approach disregards the fact that facade PV primarily serves as facade cladding and has other purposes besides electricity generation, like thermal insulation and aesthetics, unlike rooftop PV whose primary purpose is electricity generation. Second, we omit analyzing rooftop-integrated PV systems, which besides electricity generation also have an aesthetic value. We consciously omitted analyzing this PV type because of the time and attention constraints in interviews. Apart from this, such systems are not installed as frequently as non-integrated rooftop PV. Third, we apply monetary units per kW instead of square meters, a more common metric in building design. Fourth, by focusing on one case study country only, we omit possible nuances in solar facade investments, which a comparative study between multiple countries could provide.

Further research could expand our findings by assuming the extra cost approach as the main metric and applying this to a larger number of buildings. Also, an analysis of other markets besides Switzerland would provide more context, since the framework conditions are very different, for instance, in neighboring Germany, Italy, France and Austria. Besides considering these countries, an analysis of the various types of solar PV technologies in the context of investment costs and risks – such as mountain PV, floating PV, and agricultural PV – would provide a deeper perspective on the role of PV in future decarbonization. Pursuing these research directions could shed light on how investment structures and risk perceptions can better align with solar facade deployment, ultimately bridging the gap between their potential and widespread adoption.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT and GROK 3 for text editing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Mak Đukan: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Tobias Schmidt:** Writing – review & editing, Visualization, Supervision, Funding acquisition, Conceptualization. **Bjarne Steffen:** Writing – review & editing, Visualization, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

[1] S. Lwasa, K.C. Seto, X. Bai, H. Blanco, K.R. Gurney, Ş. Kılkış, U. Systems, O. Settlements, C. Change, et al., Mitigation of climate Change: Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on climate Change, Cambridge University Press 2023 (2022) 861–952, https://doi.org/10.1017/9781009157926.010.

[2] Prospects (2018).

[3] S. Linton, A. Clarke, L. Tozer, Technical pathways to deep decarbonization in cities: eight best practice case studies of transformational climate mitigation, Energy Res. Soc. Sci. 86 (2022) 102422, https://doi.org/10.1016/j.erss.2021.102422.

[4] B. Steffen, T.S. Schmidt, P. Tautorat, Measuring whether municipal climate networks make a difference: the case of utility-scale solar PV investment in large global cities, Clim. Pol. 19 (2019) 908–922, https://doi.org/10.1080/14693062.2019.1599804.

[5] G. Ulpiani, N. Vetters, D. Shtjefni, G. Kakoulaki, N. Taylor, Let's hear it from the cities: on the role of renewable energy in reaching climate neutrality in urban Europe, Renew. Sustain. Energy Rev. 183 (2023) 113444, https://doi.org/10.1016/j.rser.2023.113444.

[6] A. Malhotra, T.S. Schmidt, Accelerating Low-Carbon Innovation. Joule 4 (2020) 2259–2267, https://doi.org/10.1016/j.joule.2020.09.004.

[7] C. Wilson, A. Grubler, N. Bento, S. Healey, S. De Stercke, C. Zimm, Granular technologies to accelerate decarbonization, Science 368 (2020) 36–39, https://doi.org/10.1126/science.aaz8060.

[8] F. Creutzig, P. Agoston, J.C. Goldschmidt, G. Luderer, G. Nemet, R.C. Pietzcker, The underestimated potential of solar energy to mitigate climate change, Nat. Energy 2 (2017), https://doi.org/10.1038/nenergy.2017.140.

[9] SolarPower Europe. EU Market Outlook for Solar Power 2024-2028. 2024.

[10] IEA. Approximately 100 million households rely on rooftop solar PV by 2030 2022. https://www.iea.org/reports/approximately-100-million-households-rely-on-rooftop-solar-pv-by-2030 (accessed February 24, 2025).

[11] R. Zhu, M.S. Wong, L. You, P. Santi, J. Nichol, H.C. Ho, et al., The effect of urban morphology on the solar capacity of three-dimensional cities, Renew. Energy 153 (2020) 1111–1126, https://doi.org/10.1016/j.renene.2020.02.050.

[12] K. Shono, Y. Yamaguchi, U. Perwez, T. Ma, Y. Dai, Y. Shimoda, Large-scale building-integrated photovoltaics installation on building façades: Hourly resolution analysis using commercial building stock in Tokyo, Japan. Solar Energy 253 (2023) 137–153, https://doi.org/10.1016/j.solener.2023.02.025.

[13] M. Panagiotidou, M.C. Brito, K. Hamza, J.J. Jasieniak, J. Zhou, Prospects of photovoltaic rooftops, walls and windows at a city to building scale, Sol. Energy 230 (2021) 675–687, https://doi.org/10.1016/j.solener.2021.10.060.

[14] P. Redweik, C. Catita, M. Brito, Solar energy potential on roofs and facades in an urban landscape, Sol. Energy 97 (2013) 332–341, https://doi.org/10.1016/j.solener.2013.08.036.

[15] A. Borja Block, J. Escarre Palou, M. Courtant, A. Virtuani, G. Cattaneo, M. Roten, et al., Colouring solutions for building integrated photovoltaic modules: a review, Energ. Buildings 314 (2024) 114253, https://doi.org/10.1016/j.enbuild.2024.114253.

[16] X. Liu, C. Shen, J. Wang, C. Zhang, Y. Shuai, Static and dynamic regulations of photovoltaic double skin facades towards building sustainability: a review, Renew. Sustain. Energy Rev. 183 (2023) 113458, https://doi.org/10.1016/j.rser.2023.113458.

[17] X. Liu, Y. Huang, C. Shen, L. Lu, Quantitative assessment on the visual effects of photovoltaic double skin façade: Towards a sustainable building prospect, Energy 317 (2025) 134642, https://doi.org/10.1016/j.energy.2025.134642.

[18] X. Liu, H. Yang, C. Shen, L. Lu, J. Wang, Quantifying the parameter interaction of photovoltaic double skin façade: a sensitivity analysis based on second-order Morris method, Appl. Energy 386 (2025) 125579, https://doi.org/10.1016/j.apenergy.2025.125579.

[19] E.D. Rounis, A.K. Athienitis, T. Stathopoulos, BIPV/T curtain wall systems: Design, development and testing, Journal of Building Engineering 42 (2021) 103019, https://doi.org/10.1016/j.jobe.2021.103019.

[20] Y. Tang, J. Ji, C. Wang, H. Xie, W. Ke, Performance prediction of a novel double-glazing PV curtain wall system combined with an air handling unit using exhaust cooling and heat recovery technology, Energ. Conver. Manage. 265 (2022) 115774, https://doi.org/10.1016/j.enconman.2022.115774.

[21] G. Yu, H. Yang, D. Luo, X. Cheng, M.K. Ansah, A review on developments and researches of building integrated photovoltaic (BIPV) windows and shading blinds, Renew. Sustain. Energy Rev. 149 (2021) 111355, https://doi.org/10.1016/j.rser.2021.111355.

[22] R. Ito, S. Lee, Development of adjustable solar photovoltaic system for integration with solar shading louvers on building façades, Appl. Energy 359 (2024) 122711, https://doi.org/10.1016/j.apenergy.2024.122711.

[23] W. Ke, J. Ji, C. Wang, C. Zhang, H. Xie, Y. Tang, et al., Comparative analysis on the electrical and thermal performance of two CdTe multi-layer ventilated windows with and without a middle PCM layer: a preliminary numerical study, Renew. Energy 189 (2022) 1306–1323, https://doi.org/10.1016/j.renene.2022.03.090.

[24] Y. Sun, K. Shanks, H. Baig, W. Zhang, X. Hao, Y. Li, et al., Integrated semi-transparent cadmium telluride photovoltaic glazing into windows: Energy and daylight performance for different architecture designs, Appl. Energy 231 (2018) 972–984, https://doi.org/10.1016/j.apenergy.2018.09.133.

[25] F. Polzin, M. Sanders, How to finance the transition to low-carbon energy in Europe? Energy Policy 147 (2020) https://doi.org/10.1016/j.enpol.2020.111863.

[26] F. Polzin, F. Egli, B. Steffen, T.S. Schmidt, How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective, Appl. Energy (2019), https://doi.org/10.1016/j.apenergy.2018.11.098.

[27] Y. Karneyeva, R. Wüstenhagen, Solar feed-in tariffs in a post-grid parity world: the role of risk, investor diversity and business models, Energy Policy 106 (2017) 445–456, https://doi.org/10.1016/j.enpol.2017.04.005.

[28] S. Lüthi, R. Wüstenhagen, The price of policy risk - Empirical insights from choice experiments with European photovoltaic project developers, Energy Econ. 34 (2012) 1001–1011, https://doi.org/10.1016/j.eneco.2011.08.007.

[29] B. Petrovich, S. Carattini, R. Wüstenhagen, The price of risk in residential solar investments, Ecol. Econ. 180 (2021) 106856, https://doi.org/10.1016/j.ecolecon.2020.106856.

[30] S. Salm, S.L. Hille, R. Wüstenhagen, What are retail investors' risk-return preferences towards renewable energy projects? a choice experiment in Germany, Energy Policy 97 (2016) 310–320, https://doi.org/10.1016/j.enpol.2016.07.042.

[31] S. Rodrigues, R. Torabikalaki, F. Faria, N. Cafôfo, X. Chen, A.R. Ivaki, et al., Economic feasibility analysis of small scale PV systems in different countries, Sol. Energy 131 (2016) 81–95, https://doi.org/10.1016/j.solener.2016.02.019.

[32] M. Đukan, B. Steffen, Cost of capital for renewables and enabling technologies: measuring the multidimensional heterogeneity in Switzerland, Appl. Energy 390 (2025) 125822, https://doi.org/10.1016/j.apenergy.2025.125822.

[33] L. Kitzing, C. Mitchell, P.E. Morthorst, Renewable energy policies in Europe: Converging or diverging? Energy Policy 51 (2012) 192–201, https://doi.org/10.1016/j.enpol.2012.08.064.

[34] T. Couture, Y. Gagnon, An analysis of feed-in tariff remuneration models: Implications for renewable energy investment, Energy Policy 38 (2010) 955–965, https://doi.org/10.1016/j.enpol.2009.10.047.

[35] J.P. Helveston, G. He, M.R. Davidson, Quantifying the cost savings of global solar photovoltaic supply chains, Nature 612 (2022) 83–87, https://doi.org/10.1038/s41586-022-05316-6.

[36] Corti P, Bonomo P, Frontini F, Van Overstraeten J, Macé P, Van Rechem A, et al. Building Integrated Photovoltaics: A practical handbook for solar buildings' stakeholders. 2024.

[37] P. Bonomo, F. Frontini, Building Integrated Photovoltaics (BIPV): Analysis of the Technological transfer Process and Innovation Dynamics in the Swiss Building Sector, Buildings 14 (2024), https://doi.org/10.3390/buildings14061510.

[38] M. Đukan, L. Kitzing, A bigger bang for the buck: the impact of risk reduction on renewable energy support payments in Europe, Energy Policy 173 (2023) 113395, https://doi.org/10.1016/j.enpol.2022.113395.

[39] J. Seawnght, J. Gerring, Case selection techniques in case study research: a menu of qualitative and quantitative options, Polit. Res. Q. 61 (2008) 294–308, https://doi.org/10.1177/1065912907313077.

[40] BfE. Statistik Sonnenergie: Referenzjahr 2022. 2023.

[41] H.C. Curtius, The adoption of building-integrated photovoltaics: barriers and facilitators, Renew. Energy 126 (2018) 783–790, https://doi.org/10.1016/j.renene.2018.04.001.

[42] R.J. Yang, Overcoming technical barriers and risks in the application of building integrated photovoltaics (BIPV): hardware and software strategies, Autom. Constr. 51 (2015) 92–102, https://doi.org/10.1016/j.autcon.2014.12.005.

[43] Y. Lu, R. Chang, V. Shabunko, A.T. Lay Yee, The implementation of building-integrated photovoltaics in Singapore: drivers versus barriers, Energy 168 (2019) 400–408, https://doi.org/10.1016/j.energy.2018.11.099.

[44] T. Chen, H. Sun, K.F. Tai, C.K. Heng, Analysis of the barriers to implementing building integrated photovoltaics in Singapore using an interpretive structural modelling approach, J. Clean. Prod. 365 (2022) 132652, https://doi.org/10.1016/j.jclepro.2022.132652.

[45] R.J. Yang, P.X.W. Zou, Building integrated photovoltaics (BIPV): costs, benefits, risks, barriers and improvement strategy, Int. J. Constr. Manag. 16 (2016) 39–53, https://doi.org/10.1080/15623599.2015.1117709.

[46] R.A. Agathokleous, S.A. Kalogirou, Status, barriers and perspectives of building integrated photovoltaic systems, Energy 191 (2020) 116471, https://doi.org/10.1016/j.energy.2019.116471.

[47] M.A. Alim, Z. Tao, M.K. Hassan, A. Rahman, B. Wang, C. Zhang, et al., Is it time to embrace building integrated Photovoltaics? a review with particular focus on Australia, Sol. Energy 188 (2019) 1118–1133, https://doi.org/10.1016/j.solener.2019.07.002.

[48] R.P.N.P. Weerasinghe, R.J. Yang, R. Wakefield, E. Too, T. Le, R. Corkish, et al., Economic viability of building integrated photovoltaics: a review of forty-five (45) non-domestic buildings in twelve (12) western countries, Renew. Sustain. Energy Rev. 137 (2021) 110622, https://doi.org/10.1016/j.rser.2020.110622.

[49] P. Corti, A. Follo, P. Bonomo, Workflow to support cost-benefits comparison and sensitivity analysis of BIPV case studies: three examples of BIPV facades in the south of Switzerland, Energ. Buildings 322 (2024) 114732, https://doi.org/10.1016/j.enbuild.2024.114732.

[50] G. Evola, G. Margani, Renovation of apartment blocks with BIPV: Energy and economic evaluation in temperate climate, Energ. Buildings 130 (2016) 794–810, https://doi.org/10.1016/j.enbuild.2016.08.085.

[51] H. Gholami, H. Nils Røstvik, N. Manoj Kumar, S.S. Chopra, Lifecycle cost analysis (LCCA) of tailor-made building integrated photovoltaics (BIPV) façade: Solsmaragden case study in Norway, Sol. Energy 211 (2020) 488–502, https://doi.org/10.1016/j.solener.2020.09.087.

[52] W. Wang, Y. Liu, X. Wu, Y. Xu, W. Yu, C. Zhao, et al., Environmental assessments and economic performance of BAPV and BIPV systems in Shanghai, Energ. Buildings 130 (2016) 98–106, https://doi.org/10.1016/j.enbuild.2016.07.066.

[53] H. Gholami, H.N. Røstvik, D. Müller-Eie, Holistic economic analysis of building integrated photovoltaics (BIPV) system: Case studies evaluation, Energ. Buildings 203 (2019) 109461, https://doi.org/10.1016/j.enbuild.2019.109461.

[54] D.H.W. Li, S.K.H. Chow, E.W.M. Lee, An analysis of a medium size grid-connected building integrated photovoltaic (BIPV) system using measured data, Energ. Buildings 60 (2013) 383–387, https://doi.org/10.1016/j.enbuild.2013.02.007.

[55] A. Kylili, P.A. Fokaides, Investigation of building integrated photovoltaics potential in achieving the zero energy building target, Indoor Built Environ. 23 (2013) 92–106, https://doi.org/10.1177/1420326X13509392.

[56] G.P. Hammond, H.A. Harajli, C.I. Jones, A.B. Winnett, Whole systems appraisal of a UK Building Integrated Photovoltaic (BIPV) system: Energy, environmental, and economic evaluations, Energy Policy 40 (2012) 219–230, https://doi.org/10.1016/j.enpol.2011.09.048.

[57] H. Gholami, H.N. Røstvik, Economic analysis of BIPV systems as a building envelope material for building skins in Europe, Energy 204 (2020) 117931, https://doi.org/10.1016/j.energy.2020.117931.

[58] M.J. Sorgato, K. Schneider, R. Rüther, Technical and economic evaluation of thin-film CdTe building-integrated photovoltaics (BIPV) replacing façade and rooftop materials in office buildings in a warm and sunny climate, Renew. Energy 118 (2018) 84–98, https://doi.org/10.1016/j.renene.2017.10.091.

[59] C. Renken, P. Corti, P. Bonomo, F. Frontini, Andreas Hekler, Ruedi Meier, Handlungsanleitung zur energetischen und wirtschaftlichen Bewertung, Integrierte Solaranlagen, 2020.

[60] P. Bonomo, F. Frontini, R. Loonen, A.H.M.E. Reinders, Comprehensive review and state of play in the use of photovoltaics in buildings, Energ. Buildings 323 (2024) 114737, https://doi.org/10.1016/j.enbuild.2024.114737.

[61] NREL. U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks, With Minimum Sustainable Price Analysis: Q1 2022. 2022.

[62] J. Allegrini, K. Orehounig, G. Mavromatidis, F. Ruesch, V. Dorer, R. Evins, A review of modelling approaches and tools for the simulation of district-scale energy systems, Renew. Sustain. Energy Rev. 52 (2015) 1391–1404, https://doi.org/10.1016/j.rser.2015.07.123.

[63] C.F. Reinhart, D.C. Cerezo, Urban building energy modeling – a review of a nascent field, Build. Environ. 97 (2016) 196–202, https://doi.org/10.1016/j.buildenv.2015.12.001.

[64] J. Keirstead, M. Jennings, A. Sivakumar, A review of urban energy system models: Approaches, challenges and opportunities, Renew. Sustain. Energy Rev. 16 (2012) 3847–3866, https://doi.org/10.1016/j.rser.2012.02.047.

[65] BfE. ENERGIEPERSPEKTIVEN 2050 + ZUSAMMENFASSUNG DER WICHTIGSTEN ERGEBNISSE. 2021.

[66] BfE. Energieperspektiven 2050+: Technischer Bericht. 2021.

[67] Swissolar. Solarmonitor Schweiz 2024: Entwicklungen, Trends und Perspektiven im Photovoltaik-Markt Schweiz. 2024.

[68] B. Steffen, A. Patt, A historical turning point? Early evidence on how the Russia-Ukraine war changes public support for clean energy policies, Energy Res. Soc. Sci. 91 (2022), https://doi.org/10.1016/j.erss.2022.102758.

[69] UVEK. Vorlage für eine sichere Stromversorgung mit erneuerbaren Energien 2024. https://www.uvek.admin.ch/uvek/de/home/uvek/abstimmungen/vorlage-sichere-stromversorgung.html#1854410028 (accessed June 21, 2024).

[70] T. Schmidt, I. Stadelmann-Steffen, M. Đukan, D. Giger, N. Schmid, V. Schneuwly, Quantifying the Degree of Fragmentation of Policies Targeting Household Solar PV in Switzerland. (2023), https://doi.org/10.3929/ethz-b-000596612.

[71] BfE. Faktenblatt: Neuerungen im Energierecht ab 2025. Bundesgesetz über eine sichere Stromversorgung mit erneuerbaren Energien. 2024.

[72] Pronovo. Einmalvergütung (EIV) 2023. https://pronovo.ch/de/foerderung/einmalverguetung-eiv/ (accessed January 15, 2024).

[73] BfE. Der Schweizer Strommarkt. 2018.

[74] Swissolar. Neues Stromgesetz ab 2025: Grosse Chancen für Photovoltaik 2024. https://www.swissolar.ch/de/wissen/neues-stromgesetz (accessed February 21, 2025).

[75] Energieheld. Solarpflicht in der Schweiz - Hier ist Photovoltaik ein Muss 2023. https://www.energieheld.ch/solaranlagen/photovoltaik/solarpflicht.

[76] Kanton Zürich. Stromversorgung stärken mit Solardächern und Saisonspeichern 2024. https://www.zh.ch/de/news-uebersicht/medienmitteilungen/2024/08/stromversorgung-staerken-mit-solardaechern-und-saisonspeichern.html#:~:text=Geeignete%20D%C3%A4cher%2C%20die%20gr%C3%B6sser%20sind,bis%20sp%C3%A4testens%202040%20erstellt%20werden. (accessed March 4, 2025).

[77] Schneebeli D. Solaranlagen an Fassaden werden in Zürich nicht mehr toleriert 2023. https://www.tagesanzeiger.ch/solaranlagen-an-fassaden-werden-in-zuerich-nicht-mehr-toleriert-384843863739 (accessed February 20, 2025).

[78] M.Q. Patton, Qualitative research & evaluation methods: Integrating theory and practice, London (2015), https://doi.org/10.1016/S1098-2140(01)00162-X.

[79] U. J. Alexander iStock. Residential house with balcony power plant and facade collectors stock photo. 2025.

[80] Kämpfen Zinke + Partner. Plusenergie-Haus Zürich-Höngg, 2018.

[81] B.E. Netz, Photovoltaik Fassade Egli Mühlen (2023).

[82] Biondo A. Grosspeter Tower 2025.

[83] L.A. Goodman, Snowball sampling, Ann. Math. Stat. 32 (1961) 148–170, https://doi.org/10.1214/aoms/1177705148.

[84] Solaragentur Schweiz. Schweizer Solarpreis 2025. https://www.solaragentur.ch/de/solarpreis/schweizer-solarpreis (accessed September 18, 2025).

[85] E. Knott, A.H. Rao, K. Summers, C. Teeger, Interviews in the social sciences, Nat. Rev. Methods Primers 2 (2022) 73, https://doi.org/10.1038/s43586-022-00150-6.

[86] BfS. Harmonized Consumer Prices 2025. https://www.bfs.admin.ch/bfs/en/home/statistics/prices/harmonized-consumer-prices.html (accessed March 11, 2025).

[87] Energiefranken. Förderprogramme für Energie und Mobilität 2022. https://www.energiefranken.ch/de (accessed January 15, 2024).

[88] F. Egli, Renewable energy investment risk : an investigation of changes over time and the underlying drivers, Energy Policy 140 (2020) 111428, https://doi.org/10.1016/j.enpol.2020.111428.

[89] P. Emerson, The original Borda count and partial voting, Soc. Choice Welf. 40 (2013) 353–358, https://doi.org/10.1007/s00355-011-0603-9.

[90] A. Gumber, R. Zana, B. Steffen, A global analysis of renewable energy project commissioning timelines, Appl. Energy 358 (2024), https://doi.org/10.1016/j.apenergy.2023.122563.

[91] Energie 360. Grünes Licht für PV-Fassade 2023. https://www.energie360.ch/de/unternehmen/medieninformationen/gruenes-licht-fuer-pv-fassade/ (accessed February 20, 2025).

[92] Swissolar, Brandschutz für hinterlüftete Photo-voltaikanlagen an Fassaden, Übergangsdokument Für Planung Und Brandschutznachweis. (2024).

[93] J. Polo, N. Martín-Chivelet, M. Alonso-Abella, C. Alonso-García, Photovoltaic generation on vertical façades in urban context from open satellite-derived solar resource data, Sol. Energy 224 (2021) 1396–1405, https://doi.org/10.1016/j.solener.2021.07.011.

[94] W.L. Schram, E. Shirazi, PV on façades: a financial, technical and environmental assessment, Energ. Buildings 328 (2025) 115010, https://doi.org/10.1016/j.enbuild.2024.115010.

[95] M. Díez-Mediavilla, M.C. Rodríguez-Amigo, M.I. Dieste-Velasco, T. García-Calderón, C. Alonso-Tristán, The PV potential of vertical façades: a classic approach using experimental data from Burgos, Spain. Solar Energy 177 (2019) 192–199, https://doi.org/10.1016/j.solener.2018.11.021.

[96] Danish Energy Agency. Technology Data: Generation of Electricity and District Heating. 2022.

[97] N. Aste, C. Del Pero, F. Leonforte, The first Italian BIPV project: Case study and long-term performance analysis, Sol. Energy 134 (2016) 340–352, https://doi.org/10.1016/j.solener.2016.05.010.

[98] C. Del Pero, N. Aste, F. Leonforte, F. Sfolcini, Long-term reliability of photovoltaic c-Si modules – a detailed assessment based on the first Italian BIPV project, Sol. Energy 264 (2023) 112074, https://doi.org/10.1016/j.solener.2023.112074.

[99] Minergie. Was ist Minergie? 2025. https://www.minergie.ch/de/.

[100] M. Martiskainen, B.K. Sovacool, Mixed feelings: a review and research agenda for emotions in sustainability transitions, Environ. Innov. Soc. Trans. 40 (2021) 609–624, https://doi.org/10.1016/j.eist.2021.10.023.

[101] J. Corbett, B.T.R. Savarimuthu, From tweets to insights: a social media analysis of the emotion discourse of sustainable energy in the United States, Energy Res. Soc. Sci. 89 (2022) 102515, https://doi.org/10.1016/j.erss.2022.102515.

[102] J. Loder, The happy and proud serial adopter: Emotional influences on solar PV adoption in Germany, Sol. Energy 290 (2025) 113352, https://doi.org/10.1016/j.solener.2025.113352.

[103] S. Pfenninger, A. Hawkes, J. Keirstead, Energy systems modeling for twenty-first century energy challenges, Renew. Sustain. Energy Rev. 33 (2014) 74–86, https://doi.org/10.1016/j.rser.2014.02.003.

[104] H.-K. Ringkjøb, P.M. Haugan, I.M. Solbrekke, A review of modelling tools for energy and electricity systems with large shares of variable renewables, Renew. Sustain. Energy Rev. 96 (2018) 440–459, https://doi.org/10.1016/j.rser.2018.08.002.

[105] S.L. Hille, H.C. Curtius, R. Wüstenhagen, Red is the new blue – the role of color, building integration and country-of-origin in homeowners' preferences for residential photovoltaics, Energ. Buildings 162 (2018) 21–31, https://doi.org/10.1016/j.enbuild.2017.11.070.

[106] M. Đukan, D. Gut, A. Gumber, B. Steffen, Harnessing solar power in the Alps: a study on the financial viability of mountain PV systems, Appl. Energy 375 (2024) 124019, https://doi.org/10.1016/j.apenergy.2024.124019.

[107] M. Salvia, D. Reckien, F. Pietrapertosa, P. Eckersley, N.-A. Spyridaki, A. Krook-Riekkola, et al., Will climate mitigation ambitions lead to carbon neutrality? an analysis of the local-level plans of 327 cities in the EU, Renew. Sustain. Energy Rev. 135 (2021) 110253, https://doi.org/10.1016/j.rser.2020.110253.

[108] G. Ulpiani, E. Rebolledo, N. Vetters, P. Florio, P. Bertoldi, Funding and financing the zero emissions journey: urban visions from the 100 Climate-Neutral and Smart Cities Mission, Humanities and Social Sciences Communications 10 (2023) 647, https://doi.org/10.1057/s41599-023-02055-5.

[109] W. Broers, R. Kemp, V. Vasseur, M. Markantoni, N. Abujidi, Z. Vroon, Crossing multiple solar energy gaps: a dutch case study on intermediation for building-integrated photovoltaics, Energy Res. Soc. Sci. 102 (2023) 103149, https://doi.org/10.1016/j.erss.2023.103149.

[110] M. Đukan, D. Giger, N. Schmid, T. Schmidt, Incentivizing winter solar PV production in regions with seasonal weather patterns: case study of Switzerland, Environmental Research: Energy 2 (4) (2025) 045014, https://doi.org/10.1088/2753-3751/ae123d.

[111] EMBER. European Wholesale Electricity Price Data 2024. https://ember-energy.org/data/european-wholesale-electricity-price-data/ (accessed December 13, 2024). v.