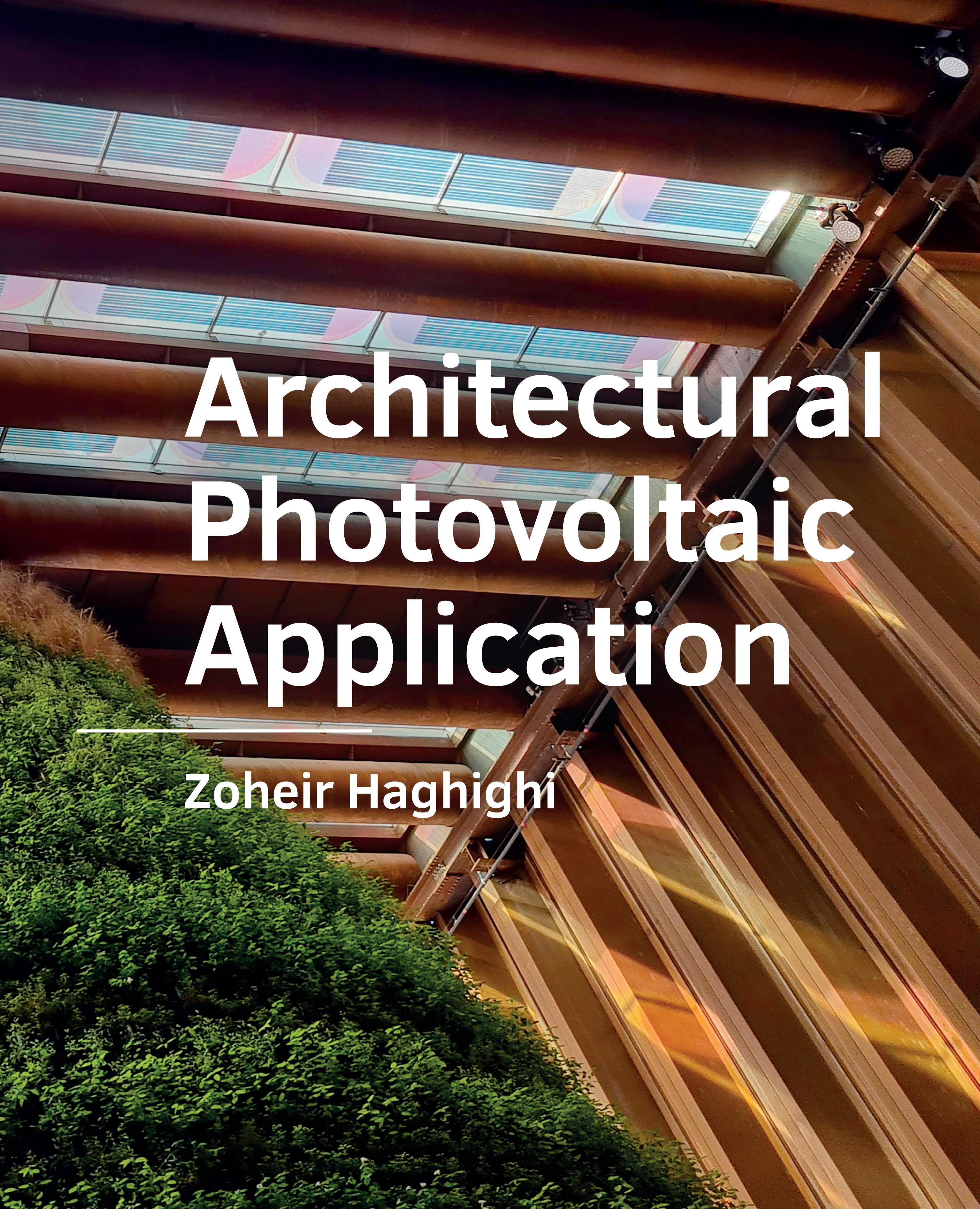

Architectural Photovoltaic Application

Zoheir Haghighi

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Architectural Photovoltaic Application

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by

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… dedicated to my mother, my wife, my sisters
and all women of my country.

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This Research project started in March 2017 and ended in July 2022. In the first 4 years and three months, I worked as a full-time PhD candidate in the chair of climate design and sustainability of the TUDelft faculty of Architecture and built environment. Since June 2021, I have continued as a part-time researcher while working for Sustainalytics-Morningstar as a senior associate on the development of a taxonomy of sustainable activities. Next to that, I supported the development of Photoaire (the spin-off company based on the PV Chimney) in collaboration with Delft Enterprise.

Within the span of his project, I went through several events. Most importantly the covid-19 pandemic started exactly at the beginning of my research internship at Arup, Berlin. Nevertheless, thanks to the quick adaptation and support in adjusting to working online, my research received little impact. However, I lost the opportunity to physically interact with colleagues. And afterwards, until today, it was indeed very unfortunate that the last 2.5 years of my time at TUDelft has been spent behind the screen, isolated from the office environment, socialising after work, and all other benefits we could enjoy pre-covid. However, I am so glad that during the first 3 years before the pandemic, I was able to join several conferences, conduct 28 interviews in person, make several physical models in our labs, and carry out on-site measurements and data collection. If it were not for this, the post-covid situation would have had a much stronger impact on my research and a longer delay would have been expected.

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Zoheir Haghighi
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Summary

Today, photovoltaic technology is one of the fastest-growing fields of technology and is becoming the lowest-cost option for electricity generation in the greatest part of the world. Based on IEA projection, the number of households relying on solar PV grows from today's 25 million to more than 100 million by 2030. Based on this projection, we must use all surfaces on and around buildings of an entire city to absorb solar radiation and transform it into usable electricity (or useful heat). However, current attempts to harness these potentials within the built environment leaves much to be desired. It is readily apparent that the current roof-top installation approach is neither aesthetically appealing nor technically efficient and consequently not sustainable, long-term, and reliable. Back in the 1990s, the Integration approach was introduced to address these issues. However, the introduction of this solution has neither increased popularity nor helped with untapping the solar energy potentials within the built environment.

The fundamental problem addressed in this dissertation is the lack of appropriate guidance and well-structured knowledge about the approaches and considerations which should be deliberated in the design and decision-making process for deploying PV technology in architecture. The overarching goal of this research is to promote the use of PV technology in the built environment while being thoughtful of the symbiotic and functional relationship between the technology and the urban fabric. Specifically, it aims to support the decision-making process required for the adoption and development of photovoltaic products in the built environment.

This thesis builds upon the interrelations between the concept of Integration, design decisions, and technological decisions. As the starting point, we looked into 'integration' as an alternative approach to the existing addition or attachment of PV into buildings. To do so, we explored given definitions and requirements outlined for the concept of Integration within the context of the application of PV in building architecture. In existing literature, integration is described as the solution for wider adoption and acceptability of PV in the built environment and defined as situation where PV module replaces a building material in a building. However, our findings show that integration does not presume photovoltaic products to be used as part of the construction material and serve a secondary or tertiary function. Furthermore, it highlights under the definition of Integration, the PV system can still be part of the architecture and remain a building service and perform a singular function as a renewable energy generator.

In the next step, we looked into how architects have used PV technologies in buildings. We shortlisted 30 projects and categorised them based on those design decisions that made them different from one another. We highlighted that these projects could be categorised based on decisions made on (i) visibility of PV system in the building architecture, (ii) mounting strategy and structural connection of PV panels and building, (iii) the customisation level of PV module, (iv) the building fabric used, and (v) the role of PV in the building system.

Subsequently, 30 architects were interviewed to study their experiences and perceptions about the architectural application of photovoltaic. In this study, we approached two groups of architects: one with experience of using PV technologies and the other with no relevant experience. Based on the input received, we witnessed three types of motivations for using PV technologies in architecture projects: the first type was related to external incentives that drive the project (e.g., NZEB), the second type was rooted in the architect's interest in environmental-friendly and climate-responsive technologies in buildings, and the final one is a communicative gesture in which PV technologies was used as a symbol of sustainability mandated by the project owner. The findings also shed light on the differences in opinions between architects who had already applied PV technology and those who had not. Unlike those with experience working with PV technology in their previous projects, who believed that working with this technology is not complex and problematic, the group with no experience believed that working with PV technology is challenging. Furthermore, a common opinion between the two groups was the need for more versatility in colour, transparency, size, and reflectivity of module products.

In the following step, we looked into the existing PV technologies and explored their its various features and potential in architectural application. The findings highlight that the first-generation technologies (c-Si) are the most advanced and can perform better for building applications. However, the physical flexibility of this technology for customisation on the cell level remains limited. In the second-generation technologies, higher temperature tolerance is an advantage for them to be compatible in situations where double-sided ventilation is not possible. Even though most of the second-generation technologies are already lightweight and flexible, and although it they have some level of transparency in contrast to the first generation, their automated production lines make customisation of size and shape fairly difficult. The third-generation technologies received more attention because they offer lower production costs, reduced environmental impact, and a relatively higher efficiency compared to the first and second generations. This makes them an interesting option for architectural application, even though their limited service life expectancy remains an important disadvantage. Aside from the criteria mentioned for comparing these alternatives, many other factors are involved in finding the most suitable PV technology for a certain application. The architects interviewed highlighted these criteria. So, we looked into advanced decision-making methods to see if such methods can be applied in the selection process of PV technology. Through the development of a pilot tool on multi-criteria decision making method, analytic hierarchy process, and test within a concept development project, we concluded that such a method can be very helpful in finding the most suitable technology for a certain application.

In the final stage, we worked on development of new concepts for the application of PV technology in buildings as based on several reports reviewed and on results of interviews, it became apparent that existing PV products cannot fulfil current market demands and consequently the sustainability targets. We then examined the R&D processes of these projects, which showed that despite the differences in scope, objective, and nature of the concepts, several similarities could be articulated into a generalised concept development process. According to this analysis, the R&D process before the commercialisation phase can be divided into 7 steps, namely (i) scoping and definition (ii) exploration (iii) concept development (iv) proof of concept (v) optimisation (vi) application design development (vii) prototyping.

Overall, the findings of this research can be summarized in three recommendations: first, integration in this context as perceived and defined in the standards and manuals cannot be seen as a comprehensive approach to include all the architectural styles and approaches to use PV technologies in buildings. Therefore, rethinking its definition and requirements is essential. Secondly, suppose we want PV technology to become a default building service, we need to leave it to architects to accommodate it within the design concept as they wish, and the PV industry should not try to impose this technology on architecture. And lastly, we need to develop a new discipline around the design and engineering of energy-producing buildings. We need to train and equip future practitioners with insight, know-hows, and tools to use the ultimate solar energy potentials to produce energy, store, and utilize the generated energy on-site.

Samenvatting

Tegenwoordig is fotovoltaïsche (PV) technologie een van de snelst groeiende technologiegebieden en wordt het de goedkoopste optie voor elektriciteitsopwekking in het grootste deel van de wereld. Op basis van de IEA-prognoses groeit het aantal huishoudens dat afhankelijk is van zonne-PV van de huidige 25 miljoen tot meer dan 100 miljoen in 2030. Op basis van deze voorspelling moeten we alle oppervlakken op en rond gebouwen van een hele stad gaan gebruiken om zonnestraling te absorberen en om te zetten in bruikbare elektriciteit (of bruikbare warmte). De huidige inspanningen om deze mogelijkheden binnen de gebouwde omgeving te benutten, laten echter veel ruimte voor verbetering. Het is duidelijk dat de huidige aanpak van installatie op het dak noch esthetisch aantrekkelijk, noch technisch efficiënt is en als gevolg hiervan niet duurzaam, houdbaar en betrouwbaar. In de jaren negentig werd de integratiebenadering geïntroduceerd om deze problemen aan te pakken. De introductie van deze oplossing heeft de populariteit echter niet vergroot en heeft evenmin geholpen bij het volledig ontsluiten van het zonne-energiepotentieel in de gebouwde omgeving.

Het fundamentele probleem dat in dit proefschrift wordt behandeld, is het gebrek aan geschikte begeleiding en goed gestructureerde kennis over de benaderingen en overwegingen bij het ontwerp- en besluitvormingsproces voor het inzetten van PV-technologie in architectuur. Het overkoepelende doel van dit onderzoek is om het gebruik van PV-technologie in de gebouwde omgeving te bevorderen en tegelijkertijd rekening te houden met de symbiotische en functionele relatie tussen de technologie en het stedelijk weefsel. Specifiek heeft dit proefschrift als doel het besluitvormingsproces te ondersteunen dat nodig is voor de adoptie en ontwikkeling van fotovoltaïsche producten en oplossingen in de gebouwde omgeving.

Dit proefschrift bouwt voort op de onderlinge relaties tussen het concept van integratie, ontwerpbeslissingen en technologische beslissingen. Als uitgangspunt hebben we gekeken naar ‘integratie’ als alternatieve benadering van de bestaande toevoeging of bevestiging van PV aan gebouwen. In de bestaande literatuur wordt integratie inderdaad de oplossing genoemd voor bredere acceptatie van PV in de gebouwde omgeving. Om dit te doen, hebben we de gegeven definities en eisen onderzocht voor het concept van integratie van PV in de bouwarchitectuur. De bevindingen tonen aan dat integratie niet veronderstelt dat fotovoltaïsche producten worden gebruikt als onderdeel van het constructieve materiaal en dat zij eerder een secundaire of tertiaire functie vervullen. Volgens de definitie van integratie kan het PV-systeem nog steeds deel uitmaken van de architectuur en een gebouwdienst blijven en een specifieke functie vervullen als opwekker van hernieuwbare energie.

In de volgende stap hebben we onderzocht hoe architecten PV-technologie in gebouwen hebben gebruikt. We hebben 30 projecten gecategoriseerd op basis van de ontwerpbeslissingen waardoor ze van elkaar verschillen. We hebben getoond dat deze projecten kunnen worden gecategoriseerd op basis van beslissingen die zijn genomen over (i) de zichtbaarheid van het PV-systeem in de architectuur van het gebouw, (ii) de montagestrategie en de constructieve verbinding tussen PV-panelen en het gebouw, (iii) de aanpasbaarheid van de PV-module, (iv) het gebruikte bouwmateriaal, en (v) de rol van PV in het bouwproces.

Vervolgens zijn 30 architecten geïnterviewd om hun ervaringen met en percepties over de architecturale toepassing van fotovoltaïsche energie te analyseren. In dit onderzoek hebben we twee groepen architecten benaderd: de ene met ervaring met het gebruik van PV-technologie en de andere zonder relevante ervaring hiermee. Op basis van de ontvangen input konden we drie soorten motivaties voor het gebruik van PV-technologieën in architectuurprojecten onderscheiden: de eerste type was gerelateerd aan externe incentives die het project aandrijven (bijv. BENG), het tweede type was geworteld in de intrinsieke interesse van de architect in milieuvriendelijke en klimaatbestendige technologieën in gebouwen, en de laatste groep is de groep waarin PV-technologie werd gebruikt als een symbool van duurzaamheid in opdracht van de opdrachtgever. De bevindingen werpen ook licht op de verschillen in inzicht tussen architecten die al ervaring hadden in het toepassen van PV-technologie en degenen die dat nog niet eerder hadden gedaan. In tegenstelling tot degenen met ervaring in het werken met PV-technologie in eerdere projecten, die geloofden dat het werken met deze technologie niet per se complex en problematisch hoeft te zijn, geloofde de groep zonder ervaring dat het werken met PV-technologie een grote uitdaging is. Een conclusie die beide groepen met elkaar deelden is de behoefte aan meer veelzijdigheid in kleur, transparantie, grootte en reflectiviteit van producten.

In de volgende stap hebben we gekeken naar de bestaande PV-technologie en hun verschillende functies en gebruikspotentieel in architecturale toepassingen onderzocht. De bevindingen benadrukken dat de technologie van de eerste generatie (c-Si) het meest geavanceerd is en geschikt is voor toepassing in gebouwen. De flexibiliteit en de mogelijkheid tot maatwerk op celniveau blijft echter beperkt voor deze technologie. De technologie van de tweede generatie heeft als voordeel dat de hogere temperatuurtolerantie het mogelijk maakt om compatibel te zijn in situaties waar dubbelzijdige ventilatie niet mogelijk is. Hoewel de meeste technieken van de tweede generatie al licht in gewicht en flexibel zijn, en ze een zekere mate van transparantie hebben in tegenstelling tot de eerste generatie, maken hun geautomatiseerde productielijnen het aanpassen van grootte en vorm relatief moeilijk. De technologie van de derde generatie kreeg meer belangstelling omdat ze lagere productiekosten, een lagere impact op het milieu en een relatief hoge efficiëntie biedt in vergelijking met technologie van de eerste en tweede generatie. Dit maakt deze een interessante optie voor architecturale toepassing, al blijft de beperkte levensduur een belangrijk nadeel. Naast de bovengenoemde criteria om deze alternatieven met elkaar te vergelijken, spelen nog vele andere factoren een rol bij het vinden van de meest geschikte PV-technologie voor een specifieke toepassing. De geïnterviewde architecten benadrukten deze criteria. We hebben daarom gekeken naar geavanceerde besluitvormingsmethoden om te zien of dergelijke methoden kunnen worden toegepast in het selectie- en besluitvormingsproces van PV-technologie. Door de ontwikkeling van een pilottool voor besluitvormingsmethodes die is gebaseerd op het meewegen van meerdere criteria, een analytisch hiërarchieproces dat is getest binnen een conceptontwikkelingsproject, hebben we geconcludeerd dat een dergelijke methode zeer nuttig kan zijn bij het vinden van de meest geschikte technologie voor specifieke toepassingen.

In de laatste fase hebben we gewerkt aan de ontwikkeling van nieuwe concepten voor de toepassing van PV-technologie in gebouwen. Op basis van verschillende beoordeelde rapporten en uit de interviews konden we concluderen dat bestaande PV-producten niet volledig kunnen voldoen aan de huidige markteisen en daarmee aan de duurzaamheidsdoelstellingen. Vervolgens hebben we de R&D-processen van deze projecten onderzocht, waaruit bleek dat ondanks de verschillen in reikwijdte, doelstelling en aard van de concepten, duidelijke overeenkomsten konden worden vertaald in een algemeen conceptontwikkelingsproces. Volgens deze analyse kan het R&D-proces voorafgaand aan de commercialiseringsfase worden onderverdeeld in zeven stappen, namelijk (i) definitie en afbakening, (ii) verkenning, (iii) conceptontwikkeling, (iv) proof of concept, (v) optimalisatie (vi) ontwikkeling van applicatieontwerp (vii) prototyping.

Concluderend kunnen de bevindingen van dit onderzoek worden samengevat in drie aanbevelingen: ten eerste kan de integratie in deze context, zoals waargenomen en gedefinieerd in normen en handleidingen, niet worden gezien als een alomvattende benadering om alle architecturale stijlen en benaderingen voor het gebruik van PV in gebouwen op te nemen. Daarom is het heroverwegen van de definitie en vereisten nodig. Ten tweede, ervan uitgaande dat we willen dat PV een standaard installatie wordt, is het belangrijk dat we architecten de vrijheid geven over de wijze waarop ze dit willen accommoderen binnen hun ontwerp. De PV-industrie moet deze technologie niet proberen op te leggen aan de architectuur. En tot slot moeten we een nieuwe discipline ontwikkelen rond het ontwerp en de engineering van energieproducerende gebouwen. We moeten toekomstige specialisten opleiden en uitrusten met het inzicht, de kennis en de middelen om het zonne-energievermogen van gebouwen om energie te produceren en de opgewekte energie ter plaatse op te slaan en te benutten.

Buildings in our urban ecosystems
must carry out a similar function as trees in the woods.
This way, buildings would collect energy in its outer surface,
and be able to conveniently transform and accumulate it
to be used for its own needs. This way of approaching the issue
would reduce dependence on external energies:
the urban grids would be minor, functioning
more like a balance of energy than a supplier

Markvart & Castañer, 2003

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Lison, Portugal, Author's personal collection

1 Introduction

1.1 Background

Starting with relevant background, it is essential to thoroughly study the keywords that shape this dissertation. There are sides to the triangular concept of 'integration of innovation' (Aksamija, 2017). First is the technology itself, referring to photovoltaic (PV) technology. Second comes the urban environment and buildings defined as the grounds for deployment, and third is the relationship between the two which we hope to develop. This is where integration is perceived to be the key approach. The research presented in this dissertation will be constructed upon the crossroads between PV technology and the built environment: the potential of how (the latest development in) PV technology can be used in the buildings, and – vice versa – the possibilities that exist in such an environment to incorporate PV technology.

This first section presents a background on the urgency regarding the urban energy transition, summarises the main drivers stimulating this transition, and addresses distributed energy systems and the advantages they offer to the urban environment. It ends by highlighting the potential that exists within the urban environment for the deployment of solar energy and tackles the question **why on-site renewable energy technologies are essential**.

Subsequently, an introduction to solar energy and photovoltaic technology is made. It follows with some insights on the latest developments of this technology, key drivers in the reduction of its price and the increase to ease of installation and argues for the relevance of photovoltaic technology as the primary technology to be utilised in the urban energy transition. The last section provides a background on the approach of integration. It outlines the existing rationale and motivations for integration and justifies the search for alternative approaches to existing applications of PV technology in buildings.

1.1.1 Renewable Energy and the Urban Energy Transition

Over the last few decades, the world encountered urbanisation at an unprecedented rate. Today, more than half of the world population lives in cities, and this figure is estimated to grow to 60% by 2030 (UNGA, 2016). This means an ever more increasing number of people will be based in cities, with an increasing demand for energy, resources, and infrastructure needed to respond to such a trend. According to the UN, between 60-70% of the world's total energy consumption occurs in urban areas. The energy demand in an urban environment is mainly limited to transportation (goods and people), lighting, heating or cooling indoor spaces, and appliances running on electricity or gas. Presently, this demand is almost entirely supplied by fossil fuels, which are responsible for almost 75% of CO_2 emissions into the atmosphere (Madlener et al., 2011). Because of demographic growth and a trend towards higher energy consumption per capita, it is projected that the world energy demand will increase by 28% between 2015 and 2040 (IEA, 2017). In order to meet such a demand, the global community is facing two interrelated problems. First, the instability and unreliability of existing energy resources (fossil fuels) from an economic and geopolitical point of view, and second, the environmental issues, the most challenging one, climate change, the direct result of CO_2 emissions from the combustion of fossil fuels (Gaiddon, Kaan, & Munro, 2009; Sijmons, Hugtenburg, Hoorn, & Feddes, 2014).

In 2015, as part of the measures from governments needed to address climate change, the Climate Agreement of Paris was signed, which calls for stabilising temperature change to two degrees Celsius compared to pre-industrial levels, and if possible, significantly less (Dhakal et al. 2017). However, although countries are the formal signatories of UN agreements, city leaders, as representatives of the civilians who are mainly responsible for climate change, have also been taking centre stage at the Paris Agreement (Acuto, Parnell, & Seto, 2018). This presence was also followed by the 2030 United Nations Sustainable Development Agenda, adopted by 193 member states in 2015, which includes a sustainable development goal (SDG) that focuses explicitly on urban areas (SDG 11) (UNGA, 2016).
Later, 170 countries agreed to a new urban agenda that highlights the importance of including an urban perspective in both national and international agreements and development implementation.

In the European context, member states agreed to implement energy-saving strategies to reduce at least 27% of the energy consumption by the year 2020 and also try to increase the share of renewable energy by at least 27%, and cut CO_2 emissions by 40%, compared to 1990 levels (European Commission, 2020). Therefore, member states and covenant signatories should develop a Sustainable

Energy Action Plan (SEAP), which is the key document outlining how they intend to reach the CO_2 reduction targets. At the building scale, the European Parliament and Council implemented the Energy Performance of Building Directive (EPBD, 2010/31/EU), which is also known as nearly Zero-Energy Building (nZEB). It required member states to ensure that, by the end of 2018, buildings owned and occupied by public authorities meet the nZEB requirements and that by the end of 2020, all new buildings also meet these requirements. This directive also defines a nearly zero-energy building as “a building that has a very high energy performance and the nearly zero, or very low amount of, energy required should be covered to a very significant extent by energy from renewable resources, including energy from renewable resources produced on-site or nearby” (EU, 2010).

Derived from European directives and EPBD, national regulations have been introduced to meet the mentioned goals. In the Netherlands, for example, the national policy on nearly zero-energy building came into effect on 1 January 2021 (van Veen, 2020). According to Bijna EnergieNeutrale Gebouwen (BENG), which translates to ‘Nearly Zero-Energy Buildings’, all newly built buildings in the Netherlands must meet the requirements of BENG. This policy mandates reduction of CO_2 emissions from new buildings through: (i) Reduction of the building primary energy demand, (ii) Limiting the use of fossil energy sources and (iii) Increase in the share of renewable energy technologies on-site. In particular, this policy enforces using renewable energy technologies to supply a minimum of 30% of the total energy consumption of the building. In addition, it specified that all generation of renewable electrical energy must happen on-site (van Veen, 2020).

From another angle, in addition to the urgency to move towards renewable energy sources and emissions of less Greenhouse Gas (GHG), a transition towards Distributed Energy Resources (DER) is also essential. One reason is that energy distribution is much cheaper and more efficient the closer it is to the end-user. while there is other cost-saving potential from the infrastructure and land. Furthermore, history shows us that in centralised energy systems, many security concerns exist. It has been argued that diversity with respect to energy sources and increased spatial distribution leads to better protection of the energy system from human (e.g. wars) or natural (e.g. earthquakes, floods) disruptions (Lovins et al., 1982). In other words, in the future landscape of cities, at least 50% of the city’s energy demands should be supplied from small-scale interconnected nodes of energy sources within the city proper instead of full reliance on a few large-scale energy production plants outside of the city (Butera, 2008; Sijmons et al., 2014).

1.1.2 Solar Energy (photovoltaics) and the Urban Environment

If we regard the 19th century to be the era of coal and the 20th as the age of mineral oil and natural gas, the 21st century is to be the time for gradual obsolescence of fossil fuels and the shift towards renewable energy technologies and in particular, an era of solar energy (Anderson 1977; Kurtz et al. 2017; Randal et al. 2001). Among all renewables, solar energy is the most abundant, inexhaustible, and clean source of energy (Parida et al., 2011). Moreover, Kennedy et al. (2006) argued that different renewable energy sources such as solar, wind, biomass, and hydro-electric, are all directly or indirectly based on solar energy. It is estimated that the amount of solar energy that reaches our planet in less than one hour can be enough to supply one year of the world’s energy budget (Lewis, 2007). Ironically, however, it should be noted that the most important threat to our planet in this century – climate change and global warming – are directly associated with the sun and its irrepressible radiation.

During the time mankind has lived on the earth, people have adapted their lives in such a way as to get the most out of solar energy. For example, ancient peoples constructed their houses of materials as stone and clay, which absorbed the sun’s heat during the day and provided heat throughout the night (known as the decrement delay factor in present-day passive building design). Our use and development of sunspaces, solaria, atria, and conservatories in buildings, as spaces dedicated to maximising the solar heat gained (through the greenhouse effect), is another example of that.

From the architectural engineering perspective, there are two approaches in using solar energy in buildings: firstly, passive techniques, which are the strategy for reducing the energy demand by adjusting the solar heat gain in buildings without the use of electrical or mechanical equipment. Secondly, active techniques, the approach in which technologies that directly convert solar radiation to either heat (with solar thermal collectors), electrical energy (with photovoltaic cells), or a combination of both (PV-thermal: PVT) are used in buildings to supply a part or all of the building energy demand.

The term photovoltaic is coined from the Greek word for light (phos) and the unit of electric voltage (volt). It describes the principle of the photovoltaic effect, which concerns converting radiated short-wavelength radiation (from the sun or other sources) into direct current (DC) electricity (Gaiddon et al., 2009).

The photovoltaic effect was first discovered by A.E. Becquerel in 1839 (Labouret et al., 2010), and 115 years later, in 1954, scientists at the Bell Laboratories unveiled the first photovoltaic cell capable of generating a measurable electric current, using a silicon semiconductor (Richter, Lincot, & Gueymard, 2013).

In the early 1970s, technological developments on the photovoltaic cell brought the price down from $100 to $20 per watt. This reduction allowed the development of different applications, ranging from outputs of milliwatts for clocks, toys, and radios, to megawatts for power plants (Weller, 2010). The first energy crisis in 1973, including a massive increase in the oil price, greatly stimulated research into the development of PV. In the same year, the University of Delaware constructed the first PV-powered house in the United States, named “SolarOne House” (Böer, 1978). The system on the SolarOne house was the first combination of PV and thermal collectors being installed on the building.

FIG. 1.1 Solar One House in Newark, Delaware, completed in March 1973 and built by the team of Karl W. Böer. Photo credit: University of Delaware (Böer, 1974)

Energy yielded from photovoltaic technology is converted to electricity, which is the most versatile form of energy. Nowadays, with the development of electric mobility and energy storage systems, all of the energy demands of a population living in a city can be supplied via electrical energy (Hegedus & Luque, 2005; Kurtz et al., 2017). There are other advantages of PV: Steven Hegedus (2005) refers to the fact that solar PV runs with no emissions, pollution, combustion, waste, and no operational sound. He also argues that, given the low operation and maintenance costs due to no involved moving parts and an infinite fuel source, results in a long service life expectancy and the reliability of PV technology.

Throughout the past five decades, photovoltaics have experienced significant growth in technological development, installation capacity, and cost reduction. In terms of PV technology today, almost 20 different PV cell techniques are available and under laboratory circumstances, cell efficiency has reached around 26.7% with mono-crystalline silicon cells (M. A. Green et al., 2021). After all these mentioned developments, patented innovation in PV technology holds the greatest share (26%) compared to other renewable technologies (IRENA, 2021). In terms of installed capacity, by the end of 2016, the total amount of solar PV installed across the globe was equivalent to 320 GW; this is growth by a factor of 40 in only 10 years (Kurtz et al., 2017). The power output of these systems is more than 1.3% of the electricity used globally in 2016 (Fraunhofer ISE, 2017). In terms of economics, since 1980, the price of photovoltaics has been reduced by a factor of 50 (Polman, Knight, Garnett, Ehrler, & Sinke, 2016). This significant reduction is due to several reasons, mainly the economics of scale, in addition to technological progress in solar cell efficiency, standardisation of technology (conventional PV modules), improved module manufacturing techniques, and lower cost of production of feedstock materials (Reinders, Sark, & Verlinden, 2018). Today, the final solar PV electricity cost can compete with conventional electricity prices in many countries. However, in many other places across the globe, this is still dependent on governmental incentives. With all these improvements in such a span of times, we are not far from the point where PV technology becomes fully affordable and accessible to a majority of consumers, as a self-sustaining, alternative energy technology independent from subsidies (Prieto, Klein, Knaack, & Auer, 2017).

Today, its application varies from the megawatt-scale utility-scale power sector to usage in agriculture, construction, telecommunication, aerospace, transportation, security, military, and many other industries. With such a vast array of applications, the demand for photovoltaics is increasing every year (Parida et al., 2011).

Among existing renewable energy technologies, PV is the most widely applicable energy solution for the production of distributed electricity in an urban environment (Gaiddon et al., 2009). Certain features of PV technology make it suitable for application in an urban environment, i.e., technical potential, integration possibility, scalability, and silent operation (Reinders et al., 2018; Weller, 2010). In addition, physical properties of the PV cell allows design flexibility for development of different modules in varied form, shape, colour and translucency (Markvart et al., 2013).

During the last decades, several studies have aimed to quantify the urban environment's technical potential for PV application. These studies mostly measured the horizontal surfaces available in different countries that can be covered with PV modules. A few worthy of mention are: "Technical potential for photovoltaics on

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buildings in the EU-27" (Defaix, van Sark, Worrell, & de Visser, 2012), "Potential for Building Integrated Photovoltaics, report IEA-PVPS T7-4" (Nowak, Gutschner, Ruoss, Togweiler, & Schoen, 2002), "Roof-top solar photovoltaic technical potential in the united states, a detailed assessment" (Gagnon, Margolis, Melius, Phillips, & Elmore, 2016) and "Potential of solar electricity generation in the European Union member states and candidate countries" (Súri, Huld, Dunlop, & Ossenbrink, 2007). Among these studies, the study of Sijmons et al. (2017), "Energy and Space: A national perspective", looking into energy transition in the Dutch context, shows that in the Netherlands, due to a relatively low number of solar hours, proper utilisation of surface in the urban environment is essential for meeting sustainability targets. The study of Sijmons et al. investigated whether the Netherlands target of 800 PJ of renewable energy by 2050 and a share of 200 PJ for solar PV energy, can be met by placing PV on different surfaces. The study shows that only 1111 km^2 of land (3% of the Dutch land surface) is sufficient. But evidently, 3% of the Netherlands cannot be purely dedicated to the production of solar electrical energy, as some of these lands are privately owned, have high agricultural production value, or are ecologically protected. The conclusion indicated that in the Netherlands the usable area of roofs (30% of the total roof surface) can supply 121.5 PJ of this target, around 55% of the energy needed (Ibid).

Considering that cities only occupy 3% of the earth's land (Butera, 2008), that surfaces are scarcely available for the production of solar energy with the ground-based (utility-scale) system, and that the same unused potential is present in the urban environment, an increasing number of applications should be developed for harvesting solar PV energy in the urban environment.

PV can be installed on building envelopes and along roads, railways, or canals, and in pavement, allowing the possibility to combine energy production with other functions of the building or non-building structure (Prasad et al., 2002). The potential of combining solar energy with buildings and infrastructure is apparent because there is a lot of unused area where solar PV systems could be installed (Sijmons, 2017)

Deployment of solar energy in the cities in a distributed way can extensively contribute to the issues related to peak shaving in different locations and seasons (Rüther, Knob, da Silva Jardim, & Rebechi, 2008). PV operation is limited to daytime, but also the peak hours on the electrical energy grid start with the day. The study of Erban (2011) indicates how the deployment of PV on vertical surfaces and on different orientations (not only on south facing but also on east and west elevations., can be used for peak shaving, spreading the production of solar power over the day and seasons

1.1.3 Integration as an Alternative Approach

In the context of the application of PV technology on buildings and in the urban environment, frequent use of the words “integration” and “integrated” is noticeable in literature. These words have been used in relation to the concept of building-integrated photovoltaics (BIPV).

Since 1990, when research and development of different PV-integrated applications for buildings started, many groups and individuals have tried to define the BIPV approach (Scognamiglio et al., 2013).

The integration approach has been used in contrast to the concept of the addition of conventional solar panels on the roofs of the building, which has been referred to as roof-top application or building-added photovoltaics (BAPV). Although, based on the definitions given in literature, the line between BIPV and BAPV is not always very clear (Biyik et al., 2017; Ritzen, Vroon, & Geurts, 2013): there are several shortcomings in the BAPV approach which can be seen as adding value to the integrated approach.

Unlike the addition approach, where PV is applied regardless of the design of its hosting structure, integration may offer architectural value to the building in various dimensions (I. Hagemann, 2004; T. Reijenga, 2000; Ritzen et al., 2013). It means that instead of having an element added to the architecture of the building, it can be a homogeneous element dissolved in the architecture of the building.

In terms of safety, some risks are associated with BAPV. As external components, BAPV modules are not attached to the structure of the building and are less protected against severe weather conditions. In some cases, the installation of the PV support structure on the roof may also lead to leakage and increase the costs to repair the water-tightness of the building envelope (Roecker, 2011). Moreover, BAPV impose extra unforeseen weight on the roof structure and are subject to any of the consequences related to building instability.

In terms of potential, several researchers also argued that solar potential on horizontal surfaces are solely insufficient to achieve the nearly zero-energy target within cities and that the potential on vertical surfaces also needs to be considered (Farkas et al., 2013; Scognamiglio et al., 2014). These studies concluded that in the aim to reach nZEB for buildings higher than 3 stories, it is not feasible to rely on the roof area to install PV modules. In the same vein, the International Energy Agency (IEA) indicates that application of PV on building façades may only increase PV-suitable surfaces in buildings by about 35% (Nowak et al., 2002). It alludes to the fact that PV needs to be used on the façade and other surfaces in buildings, and but it cannot be done without taking into account the architectural considerations of buildings (Farkas, 2011) .

The integration approach may result in a decrease in the initial investment necessary for construction as the product may serve a dual function: an energy-producing function and construction material. It can also lead to the reduction of material needed for installation where the mounting system of the façade or roof element can be used for holding the module instead of requiring additional mounting, such as brackets or rails. It also may considerably increase the capital saved in terms of installation costs (Jelle et al., 2012; Roecker et al., 1995).

In terms of aesthetics, many researchers expressed their concerns about the use of PV in buildings as an add-on element to the architecture of the building and an unpleasant symbiosis of the PV and building anatomy (I. Hagemann, 1996; A. Scognamiglio, 2008).

1.2 Problem statement

When we look into the share of different types of applications of photovoltaic technology globally, we see the so-called roof-top PV (or BAPV) accounts for half of the global installed capacity versus 1-3% share of Integrated applications (Castellanos et al., 2017; OECD/IEA, 2017; R2M et al., 2016). Furthermore, in recent years, many photovoltaic applications have been developed to be suitable for integrated approaches; however, the annual report of SEAC-SUPSI (2017) indicates that 35% of the products that were available in their previous issue ceased their production, because they either had a very small market share, remained a niche technology, or failed completely to scale up from their concept status. These findings highlight a problem in the acceptability of the so-called integrated applications of PV technology by architects and users which later referred as BIPV. According to the survey concerning the integration of solar energy systems and architecture, conducted during IEA Task 41, after socio-economic aspects, which were perceived as a significant hurdle, a lack of sufficient architecturally oriented literature on different aspects of photovoltaic technology was found as the second most important barrier (Farkas, Probst, & Horvat, 2010). On the other hand, even though the roof-top application or BAPV approach is still rapidly expanding across the globe, due to limitations of using existing products on different surfaces, a great potential of utilising PV on buildings is still unexplored (Ritzen, 2017). Therefore, an approach that enables uses of other surfaces of urban fabric is essential. Focus on an alternative approach, may lead to other benefits outside of energy production too, allowing up to 5000 km^2 of land aimed for solar power plants in the EU to be saved for other purposes such as farming or housing (Defaix et al., 2012).

Based on the background provided in the previous section and problems highlighted above, the key problem that this research is addressing is:

In order to successfully go through the urban energy transition, deployment on-site PV technology is essential. At present, however, attempts to harness the untapped potential of PV technology in the urban environment leaves much to be desired. Existing approaches (roof-top/BAPV) are not suitable to fully realise this potential. In addition, the future regarding the development of alternative approaches to PV in buildings is not clear, with key steps needing to be taken within the design and decision-making process in order to ensure proper articulation of goals and challenges towards designers and other concerned parties.

1.3 Research objectives and questions

The high-level goal of this research is to promote the use of PV technology in the urban environment while being thoughtful of the symbiotic and functional relationship of the technology with the urban fabric. This goal can be achieved once architects find PV technology as a feasible, reliable, and cost-effective technology in their toolbox when designing an energy-producing building and hopefully later as a business-as-usual approach in renovation and newly built constructions.

To accomplish this goal, this research tries to pave this road by introducing the field of architectural photovoltaic application (APA) and providing sets of information and guidelines for architects and product developers on key decisions, challenges, and considerations in the application of PV technology in the built environment. In this respect, we hope to be able to clearly define APA in this dissertation.

This research looks into the application of PV technology in buildings and their surroundings, from the perspective of architects as the key stakeholder in the development and adoption process of PV in buildings.

In order address the problem highlighted above and to achieve the goals, the main question that this study tries to answer is:

What are the considerations in the development and adoption process of architectural photovoltaic applications (APA) that can be used to support design and decision-making in a wider utilisation of the solar energy potential in the urban environment?

To be able to answer this question, several sub-questions first need to be answered. Below are these sub-questions:

- According to different definitions, what does 'integration' imply in the context of photovoltaics (PV) and architecture?
- What are the design decisions in realisation of APA?
- Based on realised projects and according to architects, what are the motivations, lessons learned, and personal perceptions regarding the adoption of APA?
- What are the commercially available PV technologies, and how can we find the best-suited technology for APA?
- What are the steps and processes in new product development of APA?

1.4 Research method and thesis outline

In this dissertation an explorative research approach is adopted to answer the questions presented previously and to investigate different aspects in developing new applications of PV in the built environment. The methodology used to develop the research scheme includes collecting and synthesising various sources from primary and secondary data, which eventually feed into sets of recommendations for new concept development and adoption guidelines for APA. Thus, it consists of different steps, as explained below. Figure 1.2 shows a schematic overview of those steps and collated them to the thesis chapters. The boundaries of this dissertation were defined by the goal and objective planned to achieve. Therefore, in this research, we did not go into the electrical engineering aspects of PV technology, but instead we focused on the design and integration possibilities of this technology into different surfaces in the built environment.

From another perspective, we also do not include any information about the economy of this technology and its applications, nor the life cycle costs and environmental impact associated with the production or use of PV technology. This research also tries to stay on the production side of the energy cycle. It means it will not go into the subject of conversion, storage, transmission, nor energy saving potentials and energy efficiency topics in the buildings. Furthermore, this research tries not to limit the scope of results based on particular geographical conditions, instead, having a global perspective on the subject.

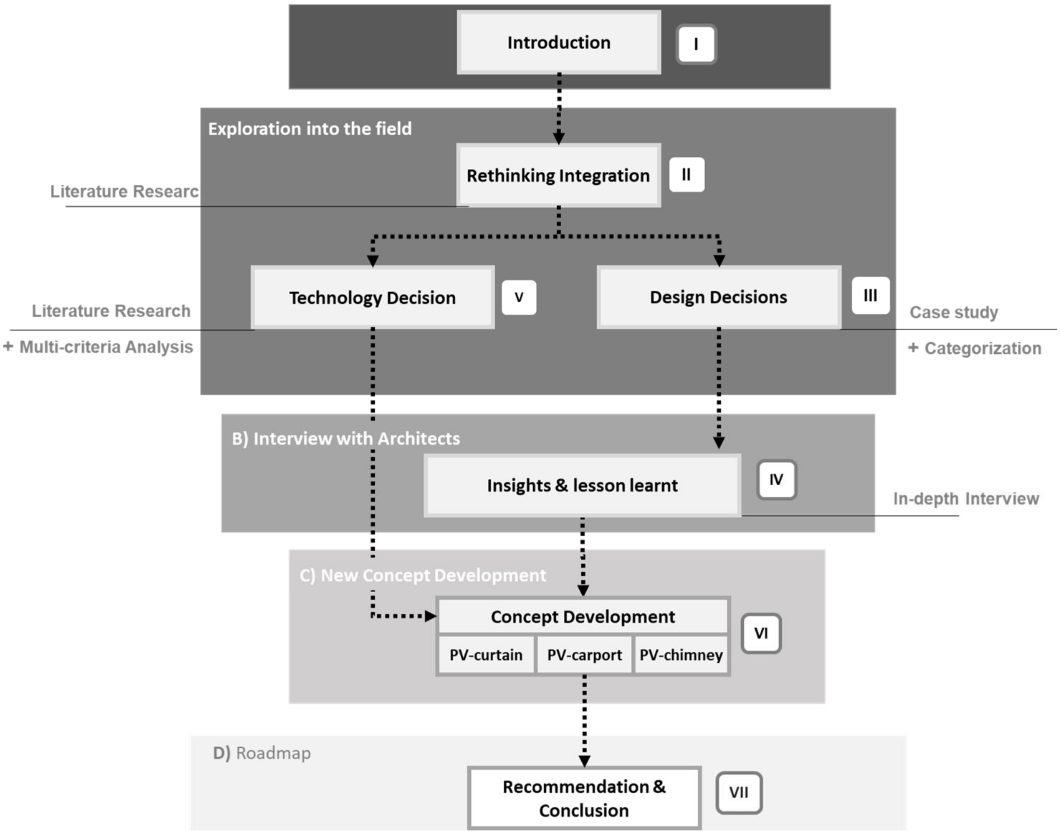

FIG. 1.2 Research Scheme

1.4.1 Exploration into the field

The first part includes 3 chapters that provide the overall foundation of the study and an expansion of the background. First, Chapter 2 looks into understanding the meaning of integration. It entails a literature study into the existing definitions in norms, scientific papers, and commercial reports to retrieve the use and application of the concept of integration in this context. The chapter concludes with several discussions and questions on the relevance and inclusiveness of the definitions given to achieve the sustainability targets in the urban environment. Subsequently, Chapter 3 maps the approaches in the use of PV in buildings (excluding the rooftop BAPV) through a case study of 30 selected projects. These projects are also used to identify the design decisions that resulted in their different uses of PV. These design decisions are presented in a scheme to demonstrate that an architect can use PV by means of different approaches and that these decisions are interrelated.

After this, Chapter 5 looks into the existing PV technology and explores different options from the technological perspective. The results of this chapter highlight the techniques that can result in higher PV performance on building applications. In addition, this chapter looks into the decision-making method that can assist in finding suitable technology for a particular application. A multi-criteria analysis (MCA) decision-making method is considered and evaluated as a potential approach for easier decision making on finding the best-suited technology.

The findings of the first part shape the body of this research and pave the way for the following parts of the dissertation.

1.4.2 Interview with architects

In the second part, Chapter 4, we conduct 30 in-depth interviews with 2 groups of architects: one group with experience of using PV and one without any project realised with PV. We needed to understand the motivations to use PV and bottlenecks that prevent its utilisation. To this end, we used the case studies from Chapter 3 and invited the architects of those projects to join the study, outlining their experiences. In addition, we asked them about their understanding of integration in the practice of applying PV and their criteria for selecting PV technology. Understanding the background of each project through qualitative research methods helped us to see how architects perceive PV technology and its associated challenges in the adoption process. The findings highlight that the main motivations to use PV can be classified into 3 groups that influence the way a project is carried out in addition to influencing the architects' position regarding integration. In addition, the interviewed architects reflect on their understanding of the concept of integration. The majority considers integration as a concept to see PV as part of the artistic design process and not necessarily as functional integration.

1.4.3 Concept development

The previous part investigates the application of existing products in realised projects and highlights the challenges that result in the unpopularity of integrated approaches and the untapped potential in using PV in architecture. As part of this study and in collaboration with a team of students, we worked on different projects to develop new applications for PV for building use. In this part, Chapter 6, 3 of these projects are presented. In these projects, we mainly adopted the research-by-design approach and tried to map the process of concept development. We started with the technical research on the development of a new curtain system with PV. The scope of this research remained limited to the technical potential and exploration into the technologies that can be used to fit the concept. The second concept was to develop a PV system that can be used in building façades, through combination with a double skin façade system and building HVAC system, which has greater architectural integration potential and system performance. This project started from technical proof of concept and reached product definition. The last concept was a PV Carport. This project was initiated with external stakeholders to develop a multi-functional structure with PV for carports. The scope of this project is defined by looking into different alternatives optimised by different objectives. These projects depicted different approaches and processes with concept development, further highlighting the significance of the project goal and motivation in the process.

1.4.4 Roadmap

In the final part of the study, based on the findings in the previous sections, we presented a series of recommendations on the integration, design, technological considerations, and the process for the adoption of APA.

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Paris Courthouse – Renzo Piano Building Workshop, Author’s personal collection.

2 Rethinking Integration

Since the 1980s, a new trend has appeared in the research and development of photovoltaic applications and that places emphasis on the concept of 'integration' regarding PV in the built environment. It has been mentioned as the optimal goal for these applications, and various benefits have been highlighted by different actors. At this moment, there are several definitions that present different approaches toward integration and its outlined requirements; however, a unified understanding among these different actors has not yet been achieved.

This chapter intends to review the origin and significance of the concept of 'integration' in the context of PV and architecture, ascertaining whether the current insights and beliefs of this key concept result in higher utilisation of solar energy potential in the urban environment.

In the following chapter, a comprehensive literature review has been conducted to catalogue definitions, theories, norms, and standards developed around the integration of PV in buildings. In addition, several questions are raised regarding the applicability of existing definitions of integration.

2.1 Introduction

Among early examples of the application of PV technology in buildings in 1974, the easiest and probably the most reasonable application was a simple bolting or attaching of the PV modules onto the roofs of existing buildings or structures. For years, such an application was considered promising and held as a symbol of green and sustainable practice. However, soon after the first projects were realised, many concerns were raised regarding the symbiotic relationship between PV and architecture. The first conference on *Solar Collectors in Architecture: integration of photovoltaic and thermal collectors in new and old building structures*, held in 1983, is one of the first conferences that addressed the integration of solar collectors in architecture. At this conference, several architects and researchers argued that PV should not be utilized as an add-on to buildings with some referring to contemporary uses of PV on buildings as “ugly and eyesores” (Palz, Vianello, & Bonalberti, 1984). These arguments were not only limited to aesthetic aspects, but also addressed economic, environmental, and social aspects (Ellis, 1983; Schmid, 1983; Stammers, 1983). Very soon, the concept of ‘integrating PV onto buildings’ was developed, with many scholars referring to it. In its usage, ‘integration’ as a concept was used in different forms, as a noun, adjective, or verb and often in combination with other terms. The most known and frequently used combination is Building-Integrated Photovoltaics (BIPV). This phrase first appeared in literature from the early 1990s, and today it is commonly used in academia and industry, as well as in marketing PV technology. Throughout the years, several theories have been proposed attempting to define concrete requirements for integration; however, a univocal consensus among the different stakeholders has yet to be achieved (Ballif et al., 2018; Pelle et al., 2020; Scognamiglio & Ossenbrink, 2014). Some of the research presented visual examples of successful integration (Ballif et al., 2018; Kaan & Reijenga, 2004; Deo K. Prasad & Snow, 2004), while others defined requirements and conditions for integration (Frontini et al., 2013; Hagemann, 1996; Sick & Erge, 1996).

The issue that arises is that these definitions are not exhaustive and vague(IEA, 2002a). This led to a lack of clarity in the requirements of recognising integrated PV in architecture. For example, across different countries, different requirements for integration are considered in national funding programmes and feed-in tariffs (Maturi & Adami, 2018).

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This chapter aims to answer the following questions:

- According to different definitions, what does ‘integration’ imply in the context of photovoltaics (PV) and architecture?

We explored this topic through a systematic literature review to catalogue definitions, theories, norms, and standards developed around the concept of PV integration in buildings. And based on our findings, several topics were discussed regarding the relevance and applicability of given definitions to the current practice of PV application in the built environment.

2.2 Method

To understand “integration in the context of PV and the built environment, the meaning of the term was first looked up in various dictionaries, followed by exploring the use of the term in the broader context of buildings and architecture. In the next step, a comprehensive literature review was conducted of reports, books, and scientific documents, including peer-reviewed journal articles and conference proceedings in various databases, as shown in Table 2.1.

TABLE 2.1 Overview of parameters for the finding phrases containing integration

Sources	Books
	Scientific publications (articles, conference proceedings)
	Reports (European research projects, IEA tasks)
Keyword family	(building OR architecture OR architectural OR structure OR mounting) AND (photovoltaic OR PV OR solar OR active OR collector) AND (integration OR integrate OR integrated OR integral)
Web Search database	Google Scholar
	Science direct
	Scopus
	books.google.com
	tudelft.nl/library
Publication date	Between 1979 to 2019

It was essential to find the phrases containing ‘integration’. Therefore, three strings of keywords were selected as inputs for the search. Table 2.1 summarises these search filters and keywords.

Based on the preliminary results, phrases(concepts) coined during the period from 1979 to 2019 were identified. In the final round, the parameters of Table 2.2 were used as input for the search with the concepts found as keywords instead of initial keyword families.

TABLE 2.2 Overview of parameters for the finding definitions for PV integration concepts

Sources	Books
	Scientific publications (articles, conference proceedings)
	Reports (European research projects, IEA tasks)
	International Standards
Integration Concepts	1. (integral-mounting OR integral) AND photovoltaic
	2. (building-integrated-photovoltaic) OR bipv
	3. architectural AND integration AND photovoltaic
Web Search database	Google Scholar
	Science direct
	Scopus
	books.google.com
	tudelft.nl/library
Publication date	Between 1979 to 2019

In the filtered instances, in order to find the definitions given to the concepts, the table of content, abstract/executive-summary, or the introduction section were first scanned to see whether the authors defined the concept or referenced previous definitions. Subsequently, the entire text of the instance was searched with the document search feature for the terms ‘definition’ and ‘define’. In the next step, all definitions and specifications found were clustered and analysed in a spreadsheet.

2.3 **Results**

This section presents the results from the investigation of the term ‘integration’, looking at the meaning of the term, followed by the first case of its occurrence, and finally, the concepts developed around ‘integration’ in the field of PV application in buildings. Figure 2.1 shows the three steps with a presentation of the findings.

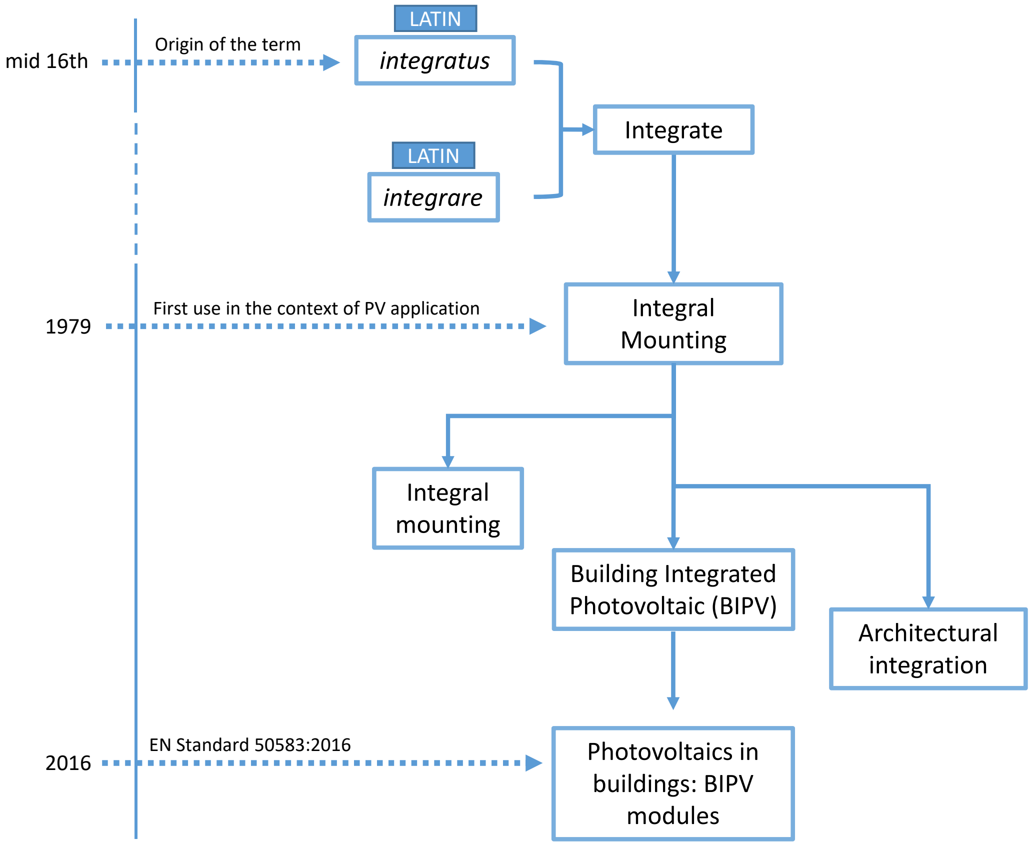

FIG. 2.1 Steps with research of the term ‘integration’ and its evolution in the context of PV and buildings

2.3.1 Origin, meanings in different contexts

To find commonly accepted meanings of the term ‘integration’, Oxford, Cambridge, and Merriam Webster’s dictionaries were consulted. According to Merriam Webster’s dictionary (Merriam-Webster)the origin of the term ‘integrate’ dates back to the mid-16th century and originates from the Latin term *integratus*, ‘made whole’, from the verb *integrare*. As a verb, the term ‘to integrate’ can mean:

- “To form, coordinate or blend into a functioning or unified whole” (Merriam-Webster)
- “To incorporate into a larger unit” (Merriam-Webster)
- “To combine two or more things in order to become more effective.” (*Cambridge English Dictionary*)

This term has been used in different fields and disciplines based on the topic and context. It may refer either to different processes or to a particular practice or paradigm. In the scientific area of architecture and the built environment, it has been used in various forms. According to (Bachman, 2004), the idea of integration as an independent topic came into practice in 1986 in the Building Systems Integration Handbook written by Reijenga and Kaan (2011). Some examples of these theories are: integral vs modular product architecture, integrated design or integrated building systems. Some of these theories address physical entities, and some refer to operations or processes. Bachman (2004) argues that the idea of integration in buildings can be seen through 3 lenses: A) hardware: integration among building systems, B) software: integration in the design process and C) philosophical digression: integration and the progress of technology.

Concerning the integration in hardware components of building systems, which is more relevant to the topic of this research, Bachman indicates that it can be approached with three distinct goals: these components should coexist in the same space; their arrangement has to be aesthetically resolved; they should function together and at least not defeat each other (ibid).

2.3.2 The earliest occurrence of the term in the context of PV technology application on buildings

In the first phase of the literature review, an extensive investigation was conducted to find the first instance of a form for the term 'integration' in the context of PV application in the built environment. Preliminary findings from the review identified proceedings from a conference held in 1983 on "*Solar Collectors in Architecture*" (Palz et al., 1984) as the oldest reference including the mentioned keywords. The conference proceedings include several papers that address problems with conventional application of PV technology in buildings, but without directly addressing the concept of 'integration' or suggesting integration as an approach. However, in some of these papers, a document was cited that did not appear in the literature search engines, i.e. a report from the U.S. Department of Energy, by J.R. Oster et al., entitled 'Residential Photovoltaic Array Requirement', published in June 1979 (Oster, 1979). In this document, some categorisation was made for PV application in residential buildings, and one of the typologies is 'Integral Mounting'. Our findings conclude this document was the earliest case when a form of the term 'integration' was used in this context. In the document mentioned, four generic mounting configurations for residential photovoltaic arrays were presented, and each one was given a description. According to Oster (1979) , these 4 types are:

- Rackmount, suitable for flat or low sloped roofs, or ground-mounted
- Stand-off, elevated structured away from the roof
- Direct mount, mounted on the top of the roofing
- Integral mounting, replacing the roofing material

Oster (1979) used the term '*integral*' for situations in which the PV module replaces the roofing product. In other words, the concept of 'integration', in the form of the adjective 'integral', was used to refer to the replacement of a primary element of a building with the photovoltaic module.

2.3.3 PV integration concepts

For the following part of this study, the phrases that were coined between 1979 until 2020 in the context of PV applications were identified in the literature. In general, the term 'integration' was used to address the unfavourable aspects of the retrofitting approach of adding or attaching the PV to the existing building fabric (known as building-added PV, BAPV). Each of these phrases tried to support, complement and promote the concept of integration. However, building-integrated photovoltaics (BIPV) remained most frequently used, presented and known in literature and industry.

In the following parts, literature that included a definition for found concepts are reviewed and presented. After each section, the findings on the definitions of each concept are summarised. These concepts are as follows:

A Integral mounting
B Building-integrated photovoltaics (BIPV – opposed to Building Added/Applied PV)
C Architectural integration of photovoltaics

A Integral mounting

As mentioned earlier, Oster (1979) defined integral mounting as a PV module that replaces roofing materials. He believed that from an aesthetic standpoint, integration was the preferred option and argued that aesthetic considerations played a prominent role in the development of new products for the housing industry. Ellis (1983) also outlined that integral mounts offer the highest potential for architectural flexibility with PV application. In addition, Oster (1979) and Strong (1983)highlighted the economic advantages of integral mounting compared to the other 3 typologies. Schmid (1983) also mentioned that in the 1970s, one of the main motivations for introducing PV technology in the built environment was a cost reduction with PV manufacturers. According to him, it was perceived that the penetration of PV technology in the construction industry might lead to a high demand for the technology and through the economy of scale, PV would become cheaper and result in the development of more terrestrial applications; therefore, an integrated approach was introduced to justify the financial benefits of a PV system (ibid).

Later, Barkaszi and Dunlop (2001) referenced the four categories of Oster and associated integral mounting and direct mounting to the building-integrated PV (BIPV) and stand-off and rank mounting to the building-attached PV (BAPV) categories. Table 2.3 presents the given definitions of integral mounting and specifications.

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TABLE 2.3 Definitions and requirements for Integral mounting

Integral mounting		
Given definitions/specifications		Authors
I	Integral mounting as a PV module as a replacement of roofing materials. Benefits/ challenges of Integral mounting: + Cost-saving potential due to the replacement of the conventional roofing product + Wiring is simplified as in this configuration; the back of the module is accessible and allows easier maintenance. + Double-sided ventilation to the module, which increases the electrical yield of the system. + offers the highest potential for architectural flexibility – Issues on water tightness, air tightness and condensation – PV collector is a strange device, being exactly halfway between a building component and installation component; it is not a complete product such as a window or household appliances.	Oster et al. 1979 Strong et al. 1983 Schmid et al. 1983 Ellis et al. 1983 Herzog et al. 1983)
II	Integral mounting is favoured for new buildings and especially for the sloped roof when an array of roof PV becomes a dominant architectural feature of the project	Strong et al. 1983
III	With the integration approach, the solar systems become part of the general building design (possibly regular building element). They must substitute other building elements, thereby serving dual functions and reducing total costs. The PV elements cannot be separate elements that are added after the building, or at least the architectural design of it, is completed.	Hestnes et al. 1999 Roecker et al. 1995
IV	Criteria for successful PV integration were identified. These criteria are listed below: • The natural Integration of the PV system, to form a logical part of the structure, • The PV system is architecturally pleasing, within the context of the building, • Good composition of colours and construction materials, • The PV system fits the fabric, is in harmony with the building and, forms a good composition together with it, • The PV system respect the context of the building (contextuality), • The system, and its integration, are well-engineered, • The application of PV has led to innovative design.	IEA PVPS task 7 Photovoltaic Power System Programme (PVPS) 2002
V	PV systems can be incorporated into buildings by either superimposition - where the system is attached over the existing building envelope, or integration - where the system forms a part of the building envelope	Fuentes 2007

B Building-integrated PV (BIPV)

One of the earliest definitions given of building-integrated PV is by Frantzis et al. (1994). They believe two approaches of PV application can be considered as integrated: first, the situation where PV functions as the exterior weathering skin, and second, where the PV modules are mounted on the existing building envelope. Other scholars defined BIPV systems as integrated modules replacing the traditional building materials to become a part of building envelope (Henemann, 2008; Peng et al., 2011; Strong, 1996). In the specifications given by the mentioned authors, there is consensus on what is not integrated, and that refers to the situation when PV is being installed as an add-on to the building as a separate system. In 2016, the EN code introduced a standard definition to building-integrated photovoltaic (BIPV). The definition given also underlies the replacement approach of integration. The main advantage outlined of these definitions is also the economic benefits of replacement coming from saving in initial investment costs, material costs, and labour expenses.

In the framework of IEA Task 15, ‘Enabling Framework for the Development of BIPV’, there was a subtask dedicated to reviewing different national and international BIPV definitions and specifications (Wilson, 2018). In this report, authors reviewed national codes from France, Spain, Italy, Switzerland, and China. In the codes and standards reviewed, the ‘dual functionality’ of generating electricity and serving a specific and integral purpose as a building component is common.

Nonetheless, from the early 1990s onwards, lack of consideration on architectural aspects in the given definition has directed more attention to the aesthetic and formal aspects of integration. This concept is separately defined and presented in the next section.

In recent years, scholars such as Frontini et al. (2015), Maturi and Adami (2018b) and Pelle et al. (2020) provided a broader definition and distinguished the different aspects of integration for BIPV. Frontini et al. (2015) initially made a separation between functional vs aesthetic integration. Maturi and Adami (2018) added aesthetic and energy integration in addition to functional/technological integration. They believe, despite the existing ‘BIPV’ definitions, in order to succeed in the BIPV system design, all three aspects must be considered.

In accordance with the earlier international standard (*EN 50583:2016*), a Delft working group elaborated a new standard that was published in September 2020. In this report, the approach with integration is still the same, and the focus remains on the roles PV can overtake in a building system, and integration has been used under the meaning of replacement.

Today, Building-integrated Photovoltaic (BIPV) has remained the most used and accepted concept for referring to the application of PV technologies in buildings. Table 2.4 presents definitions of Building Integrated Photovoltaic (BIPV).

TABLE 2.4 Definitions of and requirements to Building Integrated Photovoltaic (BIPV)

Building-integrated Photovoltaic (BIPV)		
Given definitions/specifications		Authors
I	BIPV are two types of applications: 1) where the PV modules are an integral part of the building, often serving as the exterior weathering skin, and 2) the PV modules are mounted on the existing building exterior. When BIPV system is an integral part of the building, BIPV components displace conventional building materials and labour, potentially reducing the installed system cost of the PV system.	Frantzis et al. 1994
II	In BIPV systems integrated modules replacing the traditional building materials to become a structure's finished weathering skin	Strong et al. 1996
III	Building-integrated PV systems have an economical advantage over conventional PV generator systems: The PV modules serve multiple purposes. They are part of the building envelope, ideally replacing conventional facade or roof material.	Sick and Erge 1996 (IEA task 16)
IV	Building-integrated photovoltaic modules either displace conventional roofing materials or require no structural attachment hardware that would be required to install the roofing material. BIPV products can be indistinguishable from their non-PV counterparts. Aesthetically this can be attractive if there is a desire to maintain architectural continuity and not to attract attention to the array.	Barkaszi and Dunlop 2001
V	A BIPV system will be integrated successfully if it is incorporated into the building fabric with good design and structure and with a sensible energy concept.	Hagemann 2009
VI	The terms component-integrated and building-integrated photovoltaics (BIPV) refers to the concept of integrating photovoltaic elements into the building envelope, establishing a symbiotic relationship between the architectural design, functional properties and economic regenerative energy conversion.	Van der Zeeuw 2011
VII + • •	BIPV refers to systems and concepts in which the building element has an additional function, namely producing electricity. This dual functionality has the promise of reducing the initial investment costs material costs and labour expenses in comparison to traditional PV solutions. Two main types of integration can be identified: Functional integration refers to the role of the PV modules in the building. For this reason, we can speak about multi-functionality or double function criteria. Thus the building performance of the BIPV module is required for the integrity of the building's functionality. The aesthetical integration is the capability of the PV solution to define the linguistic/morphological rules governing the design, the structure and the composition of the building's architectural language	Frontini et al. 2015
VII	Photovoltaic modules are considered to be building-integrated if the PV modules form a construction product; thus, the BIPV module is a prerequisite for the integrity of the building's functionality. If the integrated PV module is dismounted (in the case of structurally bonded modules, dismounting includes the adjacent construction product), the PV module would have to be replaced by an appropriate construction product	(*EN 50583:2016, Photovoltaics in buildings BIPV modules*, 2016))

TABLE 2.4 Definitions of and requirements to Building Integrated Photovoltaic (BIPV)

Building-integrated Photovoltaic (BIPV)		
Given definitions/specifications		Authors
IX	A BIPV module is a PV module and a construction product together, designed to be a component of the building. A BIPV product is the smallest (electrically and mechanically) non-divisible photovoltaic unit in a BIPV system which retains building-related functionality. If the BIPV product is dismounted, it would have to be replaced by an appropriate construction product. A BIPV system is a photovoltaic system in which the PV modules satisfy the definition above for BIPV products. It includes the electrical components needed to connect the PV modules to external AC or DC circuits and the mechanical mounting systems needed to integrate the BIPV products into the building.	IEA Task 15-04: 2018
X • • •	The 'I' of the acronym 'BIPV' should stand for 'integration' considering its triple meaning: Technology (function), aesthetic (architectural) and energy integration, Technological (functional) integration: referring to the replacement of construction materials with PV Aesthetical integration: capability of the PV solution to define the linguistic/ morphological rules governing the design, the structure and the composition of the building's architectural language Energy integration: capability of a PV system to interact with the building and district energy system	Maturi and Adami 2018 Frontini et al. 2015 Pelle et al. 2020 Maturi & Adami, 2018
XI • • • • • • • • • •–	BIPV modules relate to photovoltaic modules providing one or more functions of the building envelope. Moreover, the BIPV functions should be electricity generation and, depending on the application, one or more of the following: mechanical rigidity structural integrity primary weather impact protection: rain, snow, wind, hail shading, daylighting, thermal insulation, fire protection noise protection, separation between indoor and outdoor environments security shelter safety	(IEC 63092-1: 2020* Photovoltaics in buildings - Part 1: Requirements for building-integrated photovoltaic modules) *based on the draft from 2018

C Architectural Integration

Even as early as the 1990s, aesthetic issues associated with PV application in buildings have always been one of the main drivers behind the idea of integration; these have been raised mainly by architects and researchers focussing on the built environment (Reijenga, 2000). Therefore, parallel to the definitions advocating for functional integration, they tried to come up with definitions that included aesthetic considerations. The term architectural integration was introduced, addressing the fact that PV modules should be integrated into the architecture and functional integration alone is not favourable (Reijenga, 2000). Although some researchers such as Kaan (2004)and Reijenga (2011) argued that it is hard to formulate a definition of architectural integration, as the definition refers to the physical symbiosis of a photovoltaic unit into the overall design, researchers such as Bahaj et al. (2007), Hagemann (1996, 2004) and Roecker (2011) specified architectural integration. According to Hagemann (1996), a PV system will be architecturally integrated successfully if it is incorporated into the building fabric with good design and structure and with a sensible energy concept. He explains that architecture is more than the fulfilment of functional, rational, and economic needs and in order to achieve a successful integration of photovoltaic technology, it is essential to consider both technical aspects as well as aesthetic and architectural design aspects. Later, in 2004, he came up with a more elaborate definition of architectural integration: In this definition, he argues that for architectural integration of PV into the building fabric it is essential to consider a) Construction issues (the functional concept), b) Electrical issues (the energy concept), and c) aesthetic issues (the design concept). These are shown in Figure 2.2.

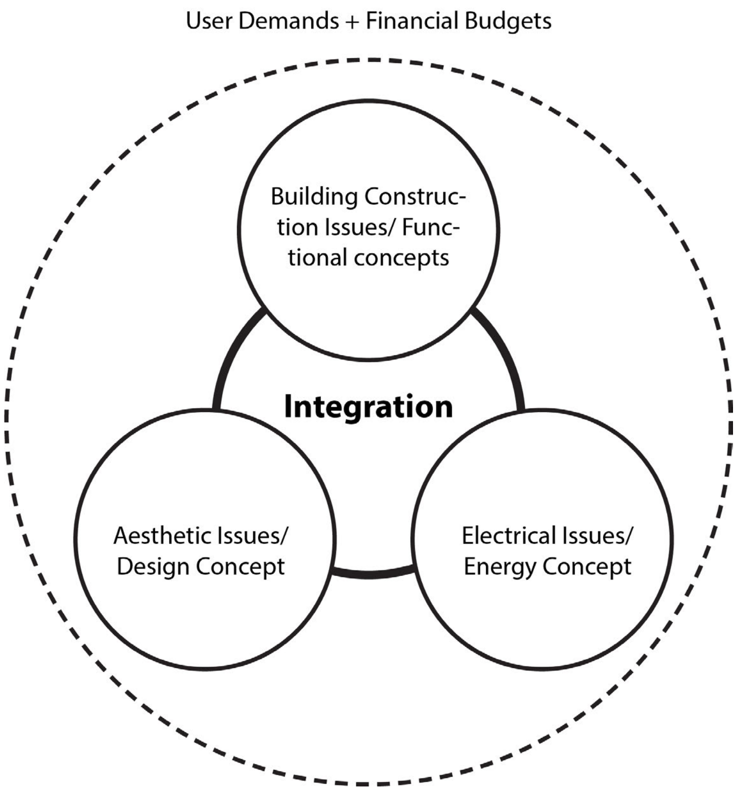

FIG. 2.2 Architectural integration of BIPV adopted from Hagemann 2004

Within IEA task 41, a subtask provides criteria for architectural integration of PV systems in buildings. In the final report published in 2013, it was argued that the architectural 'integrity' of solar modules could be considered from all three points of architecture: functional, constructive, and formal (aesthetic). Table 2.5 presents the overview of the definitions of architectural integration.

TABLE 2.5 Definitions for Architectural integration

Architectural integration		
Given definitions/specifications		Authors
I	for achieving technically and architecturally integrated, attractive and high-value PV applications on buildings, it is necessary that the PV system becomes, on all levels of design and construction, an integral part of an overall concept of a building.	Hagemann 1994
II	It will be necessary to integrate PV architecturally into the building fabric with regard to structural issues, electrical issues and esthetical design issues	Hagemann 2001
III	Defining architectural integration is hard to formulate, as it concerns the physical integration of a PV system into a building. For the architect, the aesthetic aspect, rather than the physical integration, is the main reason for talking about building integration. The optimal situation is a physically and aesthetically well-integrated BIPV system.	Reijenga and Kaan 2011
IV	For the successful architectural integration, size and position of collector field, collector material and surface texture, absorber colour, shape and size of the modules, type of jointing have all to be coherent with the overall building design logic.	Probst (2011)
V	The architectural integration quality of a solar energy system (either photovoltaic or solar thermal) is defined as the result of a controlled and coherent integration of the solar collectors simultaneously from all points of view. In particular, the integration has to consider three aspects: 1. Functional integration 2. Constructive integration 3. Formal (aesthetic) integration. The first two sets of criteria refer to the multi-functionality of the solar system taking over one or more envelope functions, The third criterion (formal) refers to all the system characteristics affecting building appearance (i.e. system formal characteristics) that should be coherent with the overall building design: • Size and position of module field • Module material and surface texture • Absorber colour • Module size and shape • Type of jointing	International Energy Agency 2012 IEA SHC Task 41, 2014 "Solar Energy and Architecture"

The concept that Hagemann (2004) explained is very similar to the concept of Maturi and Adami (2018). Both consider three layers of integration. However, in each of these layers, integration has different meanings. In functional integration, the replacement meaning is intended; in architectural or aesthetical integration, a greater unity between the product and design is assumed, and in energy integration, connection to a bigger energy grid system is considered.

2.4 Discussions

In this section, the results presented are analysed, and discussion is raised questioning the applicability of existing definitions for the vast adoption of PV in buildings.

2.4.1 Integration as a replacement

In most of the literature presented, integration was used in the meaning of '*replacement of the primary part of a unified system*'. That is closest to the first meaning found for integration in dictionaries.

Nonetheless, it raises a question: Why we are not using integration in the context of "*combining two or more things in order to become more effective*" (The 2nd and 3rd meanings based on dictionaries), or why by 'integration' are we not thinking about the process of adding a new feature to the building system to increase the system's performance?

Considering that, integration can be perceived as an approach to increase the system's efficiency, while, with the current perception of integration (BIPV system), the loss of system efficiency is always anticipated by an integrated application due to compromises between customisation and unoptimised configuration of PC modules.

2.4.2 Integration and dual functionality

Another discussion is related to the definitions given for integration and the additional functions of PV in the build environment. In the instances presented, the general idea is nearly the same in regard to functionality, with integration almost all refer to PV modules as a replacement of building material or product. It is boldly mentioned in the EN standard definition: it is a prerequisite that photovoltaic products should function as a construction material; otherwise, they are not considered integrated.

However, a question can be raised: how should we classify a situation where PV modules are accommodated in the design concept without replacing a pre-existing building material, only serving as an energy production device? Does it fall under BAPV and not BIPV? Indeed, it has been proven that integration with the meaning of replacement has financial benefits (to be discussed in section 3.4); however, the requirements in the EN code and other precedents seem to be a wrong starting-point for the promotion of PV in the build environment. It is not broad enough to capture the full potential of PV in buildings. Even when design aspects are considered in the definition of Frontini et al. (2015), Hagemann (2001) and Maturi and Adami (2018), the functional or technological integration (double functionality of PV module) has to be fulfilled, which is not always the case. Reijenga and Kaan (2011)discussed a visual analysis of realised projects, which showed many projects where PV is architecturally integrated into the building but not technically or functionally. An example is the Paris Courthouse designed by Renzo Piano (2019), where PV modules on the façade have no constructive or structural role. It is also difficult to say if the PV is contributing to light management in the building and/or if they are a shading device. However, from an architectural viewpoint, the PV elements on the façade are part of the design concept as imagined by the architect.

Therefore, a more comprehensive approach should give more attention to the symbiotic relationship of the components and building fabric rather than the multi-functionality of the module.

2.4.3 PV as a building service or building construction product

Today, considering the environmental challenges and regulations introduced in different regions, it is compulsory to produce a part of the energy demand of the building onsite (van Veen, 2020). Therefore, a key question now is how to accommodate these new renewable energy technologies into the building fabric to comply with sustainability targets enforced by legislative bodies. It appears to be more a question of design rather than a technological challenge. The primary role of PV, as a renewable energy technology, is producing on-site renewable energy and acting as a new component next to other building services dealing with day-to-day operations and tenant comfort, not as a constructive element. Therefore, if we shift the perspective of PV as a construction material to a building service, defining 'integration' can be approached differently. Thus, it will depend on the conceptual design of the project whether to utilise them as an expressive and exposed element or to conceal and hide them. In the example of the Paris Courthouse, the architects recognised the photovoltaic modules as a building service element, just like other services (e.g. the HVAC system), and tried to accommodate them in the architectural form.

Looking back in history, we can find several examples of technologies that were introduced as building service components and that were gradually accommodated within the architecture of a building. These components do not necessarily serve as a construction product or offer additional functionality in order to be accepted or economically viable. Thermal radiators in buildings are one example. If we look at the earliest examples of radiators, they were purely technical, and the fins were designed for maximum performance. Today, we see radiators merged into flooring materials, ceiling panels, or by having their panels hang from walls in different designs and colours. These radiators are not serving a constructive role in order to be considered acceptable or integrated, but as a building service, they have been accepted and accommodated in the building's anatomy.

We also are not referring to these building services as building-integrated in order to consider them a part of the building. We see products evolving by considering aesthetic, financial, environmental, and multi-functional considerations. In the case of PV technology, it may as well be concluded that, just as any other building service with a particular title (based on their function, such as a radiator), standard PV products for building and architectural application will get a title over time, enabling the suffix of 'building-integrated' to be discarded.

2.4.4 Economic advantages behind substitution meaning

Many of the results presented address the economic advantages of ‘integration’ as seen through the lense of ‘replacement’. As shown, the economic side of PV technology has been a powerful motivator in bringing up ‘integration’ in this context. Indeed, it was perceived that the Integration of PV in buildings could expand the PV technology market, and that may lead to the mass production and cost reduction of PV technology. However, in reality, this is not what occurred. Instead, what led to a massive decrease in the price of PV products was the technological advancement and mass production of standard PV modules in the Far East (Heinstein et al. 2013; Schmid 1983). In this regard, the PV industry tried to standardise different aspects of PV modules (e.g. size, shape, number of PV cells) for deployment in large-scale solar farms to maintain the trend of cost reduction. These standardised and high-performance modules developed for maximum energy yield ended up on the roofs of many houses and created a huge market, developing the industry around itself. Today, the share of so-called rooftop PV (BAPV) installed in the world is somehow equal to the PV modules installed in solar farms (IEA, 2017), whereas the share of so-called integrated applications (BIPV) is between 1-3% of the total capacity installed (Zanetti et al. 2017). From another perspective, the results of a survey conducted by Prieto et al. (2017) show that the high costs of integrated solar applications are perceived to be the main barrier for faster adoption in the built environment. This also explains why the competition is far more aggressive for so-called integrated products in the market due to the low price of industry-standard PV modules. This competitive market caused the economic failure of several BIPV manufacturers in a short period of time, even with high-tech, innovative products and clear technical advantages (Heinstein, Christophe, et al., 2013). To recall the first point, it seems that stakeholders in the PV industry had an unrealistic expectation of the benefit that ‘integration’ can offer to the development of the PV industry. Moreover, perhaps the requirements in the definition of ‘integration’ that are advocating for economic benefits are no longer essential, and those standards need to be reconsidered.

Nowadays, PV products are regarded as a symbol of a future-oriented, environmentally conscious attitude among individuals and corporate entities (Hagemann, 2004). Therefore, we may also include decorative, ornamental and advertisement purposes as a part of the functionalities that PV can have in the overall building operation. In this regard, we can see PV has been used in some projects for decoration purposes or to provide a green and sustainable image. Such an approach is an innovative approach and business case for an organisation to offset their expenses used for improving their image regarding corporate and social responsibilities. In this case, the specified functionalities in the given definition shall also be reconsidered.

2.5 Conclusion

The research presented reviewed the origins and derived concepts from the idea of ‘integration’ in the context of photovoltaic application in buildings. In addition, the results from the analysis on the given definitions raised many questions regarding the applicability and comprehensiveness of existing definitions; bringing into question whether current definitions and beliefs are still relevant for optimal utilization of PV’s full potential in the built environment.

The review and analysis of the definitions presented and requirements highlighted the following: scholars with different agendas, intentions, and motivations have different preferences in defining ‘integration’. This can be traced in the requirements as seen in the definitions. However, all of them in some way agree that the current retrofit practice of bolting PV modules onto the building roof or façade (the BAPV approach) is undesirable for a variety of reasons. Following this, ‘integration’ in the context of ‘replacement’ has been dominant in the literature reviewed. The key issue is the focus on functional integration, whereas the concept of architectural integration has remained underdiscussed. In addition, through the lens of current understanding of integration, direct integration limits the ways we can approach the adoption of PV in buildings.

From the discussions, one conclusion is that integration does not presume photovoltaic products to be used as part of the construction material and serve a secondary or tertiary function. The PV modules can still be part of the architecture and remain a building service and perform a singular function as generators of renewable energy. This research also argues that there were unrealistic expectations placed on PV technology regarding the economic advantages of ‘replacement’, which further led to current definitions. Today we no longer need integration in the context of replacement to incentivise maximum adoption of PV technology. Nevertheless, it is still relevant and important to address the downsides of bolting or attaching industry-standard PV modules onto different surfaces of buildings without considering the technical and design aspects of the building fabric.

This research advocates remembering the role of PV technology in buildings and suggests repurposing PV’s role as a building service (i.e. boilers, radiators, HVAC units) and for integration, to be left to the jobs of architects and designers to accommodate PV systems within the anatomy of the building’s architecture: either exposed and as a part of the architectural language or concealed and hidden somewhere out of sight.

Furthermore, the findings of this research on the understanding of ‘integration’ raise a question whether redefinition of this term can be helpful in the long-term or if this concept is inevitably going to be discarded with further progress in the adoption and product development of PV technology. In the next chapters, we investigate the approaches adopted by architects without considering the requirements discussed for integration. Later in Chapter 4, we also ask architects to outline their personal understanding in regard to ‘Integration’.

Copenhagen International School Nordhavn design by C.F. Møller, Author’s personal collection.

3 Design Decisions

Chapter 2 provided a background on the definitions and requirements of the integration approach for architectural PV applications (APA). The findings showed diverse perspectives into the concept of integration and its requirements outlined by different parties.

Chapter 3 aims to provide an all-encompassing view on the approaches adopted in the deployment of PV technology by architects and to categorise them based on the decisions made in the design process. In this chapter, we surveyed built projects using PV technology and analysed these cases based on the parameters (design decisions) involved in the decision-making process. Therefore, this chapter presents a thorough case study of these approaches and develops a baseline categorisation for a further analysis of APA. For this section, thirty projects were selected for an objective and visual analysis. In chapter 4, we interviewed the architects of some of these projects to dive further into the actual experiences gained in practice.

3.1 Introduction

In recent years, the push to use on-site renewable energy technologies in urban environments requires the development of new design approaches for accommodating PV technology into building architecture. Considering the SolarOne project as the first example of the use of PV technology in the built environment, it has been over 45 years since PV technology was introduced to the construction sector, and since then, PV has been used in a wide range of applications and approaches.

Looking into realised projects utilising PV, architects and designers have taken various approaches to accommodate PV within their designs. In literature, some researchers investigated the adopted approaches and addressed them by categorising them, based on the type of PV technology or building fabric used to apply the PV system (Ballif et al., 2018; Hagemann 2010; Heinstein et al. 2013; Scognamiglio 2008). Among these works, some of these built projects with PV as depicted, however the focus remained on the technological aspects and possibilities that the modules can offer. As an example, the SUPSI centre for BIPV research classified these projects according to their functional typology (e.g. residential, commercial, etc.) and also classified the approaches by the building surface used to accommodate the PV (Zanetti et al., 2017).

As discussed in Chapter 2, architectural and design-related factors are key determinators in the widespread adoption of PV in the built environment. With regard to this, contemporary analyses on existing build projects lack insight into the design aspects and decisions that designers needed to take in regard to accommodating the technology into their design concept.

In this chapter, we investigated how the architects adopted this technology over the last years to better understand not only the different approaches but also design decisions involved with adopting APA,

Therefore, this chapter aims to answer the following questions:

- What are the design decision in realisation of APA?

In the following section, the process undertaken with this research is explained. Then, we will illustrate the cases studied, followed by different parameters we used to categorise these projects. At the end, we developed a matrix to show how the design decisions are interrelated and how their synthesis can result in a new approach.

3.2 Method

As mentioned earlier, the primary goal of this chapter is to identify key design decisions in the adoption of PV in architecture. We tried to achieve this goal by mapping different design approaches and analysing them based on the variations resulted from different design decision.

For cases in this study, we refer to realised buildings in which PV has been utilised. It is to be noted that we excluded approaches in which PV has been installed to the building as what is known as BAPV approach. In order to select cases for this study, we first conducted a thorough internet-based survey to find realised projects with different PV technology. In this phase, special attention was given to include as many varieties as possible in terms of location, building functionality, date of realisation, architectural style, and the type of PV products used, exposure of PV to the general public, and the structural system of the PV. To select these cases, online databases such as the website PVdatabase (PVdatabas.com) and SUPSI BIPV research centre (BIPV.ch) were consulted. To acquire detailed information about the cases, architectural websites, such as ArchDaily (ArchDaily.com) and project architect websites, were accessed. A long list of projects was gathered, which were later filtered to produce a shortened list of 30 projects. In the process of filtering the sample cases, we tried to exclude those that were identical in regard to the condition of the PV and the building. However, it is worthy of mention that the list is not exhaustive, although we aimed at representing a diverse set of design approaches.

Secondly, we aimed to find the parameters that influence the different design approaches. So, we visually analysed the symbiotic relation of PV and design concepts In choosing these parameters, the focus lay on decisions that the architect and design team had to make as part of the design concept, for example how identifiable the PV integration is, and not parameters related to the context of the project or external conditions, such as location, weather data, and functionality of the project. In addition, the relationship between these parameters and how they are interrelated were the primary factors for selection. Subsequently, a scheme was developed to map the network of these parameters and the approaches in the practice of using PV in the built environment.

3.3 Cases Selected

As discussed earlier, 30 projects were shortlisted to be analysed in the research. In these realised projects, PV technology has been used in different architectural approaches and on different building surfaces. The projects are shown in Table 3.1, where the projects are sorted in chronological order of realisation.

TABLE 3.1 Cases used for this study

	Project name	Year	Architect	Picture	Reference
1	Public Utilities Building	1991	Georg Feinhals		(Heinstein et al., 2013)
2	Solar Cultural Centre	1997	Thomas Spiegelhalter		(Scognamiglio, 2008)
3	Langedijk Solar Home	1999	Tjerk Reijenga		(Bear-ID Architects)

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TABLE 3.1 Cases used for this study

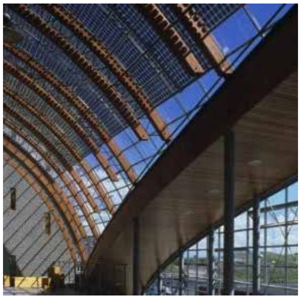
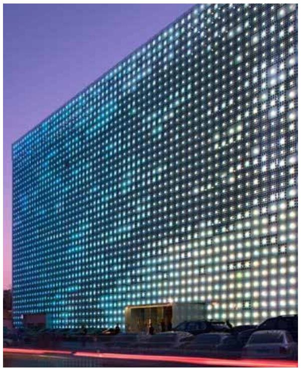
	Project name	Year	Architect	Picture	Reference
4	Centre Mont-Cenis	2000	Hegger Hegger Schleiff		(Kumar & Raheja, 2016)
5	ECN building	2002	Tjerk Reijenga		(Bear-ID Architects)
6	Sino-Italian	2006	Mario Cucinella		(Sino-Italian by daniele-domenicali)
7	Zero Energy Media Wall	2008	Simone Giostra		(GreenPix: Zero Energy Media Wall ArchDaily)

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TABLE 3.1 Cases used for this study

	Project name	Year	Architect	Picture	Reference
8	Monte Rosa Hut	2009	Bearth & Deplazes		("Monte Rosa Hut," 2009)
9	National Stadium	2009	Toyo Ito		(Solar Stadium in Taiwan, 2014)
10	Umwelt Arena	2012	Rene Schmid		(Zumbuehl, 2015)
11	Green Dot Animo	2013	Brooks + Scarpa		(Linden)
12	SwissTech Convention	2014	Richter Dahl Rocha		(Grätzel, Richter Dahl Rocha & Associés)

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TABLE 3.1 Cases used for this study

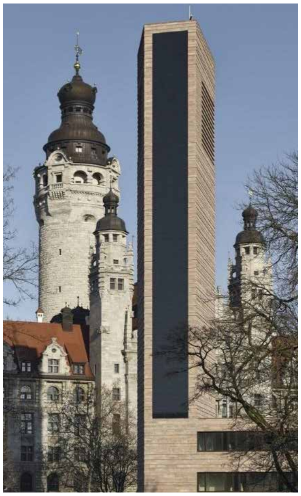
	Project name	Year	Architect	Picture	Reference
13	Nursery +E In Marburg	2014	Opus Architekten		(Marburg, 2014)
14	Tour Paradis	2014	Jaspers Eyers		(Janberg, 2018)
15	St. Trinitatis Catholic	2015	Schulz-und-Schulz		(Schulz und Schulz)

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TABLE 3.1 Cases used for this study

	Project name	Year	Architect	Picture	Reference
16	New-Blauhaus	2015	Kadawittfeld-architektur		(Horsky, 2017)
17	Toshima ward office	2015	Kengo Kuma		(Kenji Kobayashi)
18	Energy Academy Europe	2016	Broekbakema		(Zijlstra, 2016)
19	EWE & Bursagaz HQ	2016	Tago		(TAGO ARCHITECTS, 2012)

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TABLE 3.1 Cases used for this study

	Project name	Year	Architect	Picture	Reference
20	Stavros Niarchos	2016	Renzo Piano		(“RPBW,” 2016)
21	De spakler Amsterdam	2017	Mecanoo		(“De Spakler-Amsterdam Lingotto,”)
22	International School	2017	C.F.Moller		(C.F.Moller)
23	La Seine Musicale	2017	Shigeru Ban Architects		(“SBAE | Ile Seguin Musical City,” 2017)

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TABLE 3.1 Cases used for this study

	Project name	Year	Architect	Picture	Reference
24	EDGE	2017	PLP Architecture		("The Edge,")
25	Grosspeter Tower	2017	Burckhardt Partners		(Adriano Biondo, 2017)
26	European Patent Office	2018	Jean Nouvel & Dam		(Dam & Partners,)
27	Apple HQ	2018	Foster and Partners		("ABC News," 2018)

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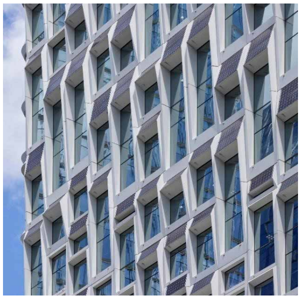
TABLE 3.1 Cases used for this study

	Project name	Year	Architect	Picture	Reference
28	Breez Hotel	2019	OZ Architects		
29	Hanwha Headquarters	2019	Unstudio		(“UNStudio)
30	Paris Courthouse	2019	Renzo Piano		(“RPBW,” n.d.)

3.4 Categorisation parameters

By analysing the way PV products are accommodated within the building's anatomy, the visibility of PV in the building is considered an informed decision by the design team. In some projects, PV is a prominent element in the building, while in some projects, it is fully dissolved into the building fabric. Moreover, there are different strategies in mounting the PV system. Having in mind the discussion in chapter 2 on the replacement approach, we can see in several projects that the PV is added on top of the final finish, sometimes replacing it entirely. In a few cases, an additional element is designed to carry the PV system.

Another aspect that differentiates the cases from each is PV product used. Indeed, regardless of the technology, sometimes standard PV modules are directly used in the project and sometimes their physical properties are customised and adapted to the design concept or even going so far as to develop a completely new product. This was a key decision for the design team, as it would directly influence other parameters. One other differentiating feature that can be seen is the fabric used to apply PV. We assume it is an important decision for the design team as they need to consider it during concept design development and deciding where to apply the PV is a critical decision which can be linked to the amount of energy the building aims to generate. Following the discussions raised in Chapter 2, we also assume that the multi-functionality of the PV can be seen as an important decision during the design process; whether to use PV as a mono-functional product or to rely to the product's physical or thermodynamic properties to take over other functionalities in the building. Table 3.2 summarised the parameters chosen to classify the cases selected and the following sections explain in more detail the parameters and their variations.

TABLE 3.2 parameters and developed typologies

Parameter	Description	Variations
Visibility of PV in design concept	Decision regarding the exposure of the PV in the design concept	• Hidden • Exposed
Mounting strategy	The strategy used to mount the PV product on the building fabric	• Additional element • Attachment • Substitution • Pixelation • Concealed
PV product type	The extent to which the PV product was customised (From standard to fully customised)	• Customised • Standard • Building material Replica
Fabric Used	The building structure that the PV system is applied or connected to	• Roof • Façade • Extensions
Functionality	Other than electrical energy generation (mono-functional), the additional role the PV product plays in the building system	• Electrical Energy (Mono-functional) • Constructive role (Multi-functional)

3.4.1 Visibility of the PV in the design concept

The first parameter identified that influences the design approach is the decision on whether the PV technology should remain visible or be hidden in the visual communication of the project. This decision can determine the possible mounting strategy, the specific type of PV technology or building fabric that is chosen.
The indicator used for this parameter is whether the perceived image of the PV technology (e.g. crystalline blue cells with silver-coloured stripes and a silver-coloured aluminium frame) is visible in the pictures publicly published of a project and whether PV is part of the visual message of the building.

For example, in the Green Dot project, PV is strongly present, displaying the technology to the public, whereas in the Grosspeter tower case, PV is ‘silent’ and dissolved into the façade and kept hidden in the building. These two projects are good examples indicating that architects have a clear choice whether to keep PV as an expressive element in the design concept or hide and dissolve the modules in the design concept. The decision of visibility is one of the main decisions the design team and project stakeholders made, because it would influence other choices further into the design process. Therefore, in that respect, the cases studied can be divided into two categories, *exposed* versus *hidden,* as shown in Figure 3.1.

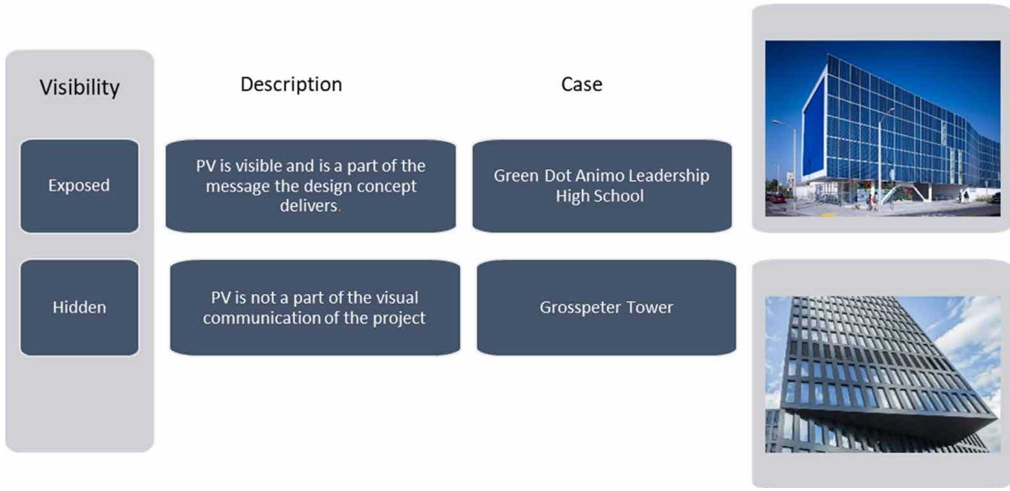


FIG. 3.1 Visibility of PV in overall building design

3.4.2 Mounting strategy

Depending on the decision regarding the visibility of the PV in the project, but also independently, there are different strategies in mounting the PV product to the building fabric. We have differentiated the mounting strategies based on PV visibility. Figure 3.2 and Figure 3.3 present the mounting strategies related to the exposed and hidden concepts.

For the exposed PV concept, in the examples of *additional elements*, the architect designed an additional element connected with the building fabric to hold the PV technology. In this example, PV technology was treated as a purely technical element and is placed at the optimal tilt and angle for maximal energy production. In the a*ttachment* type, PV is mounted on the building fabric's final finishing, as shown in the De Spakler case. In such a project, less focus is paid to the orientation or tilt of the module and instead, the design team tries to fill the maximum amount of available surface on the building with PV modules. In the *Substitution* type, the Monte-rose Hut, PV was used to replace the final finishing of the fabric. Therefore, in this case, some degree of adaptation in the PV modules had taken place, but PV remained an expressive element within the design concept. Figure 3.3 shows the mounting strategy in the case that PV technology is hidden or hard to spot.

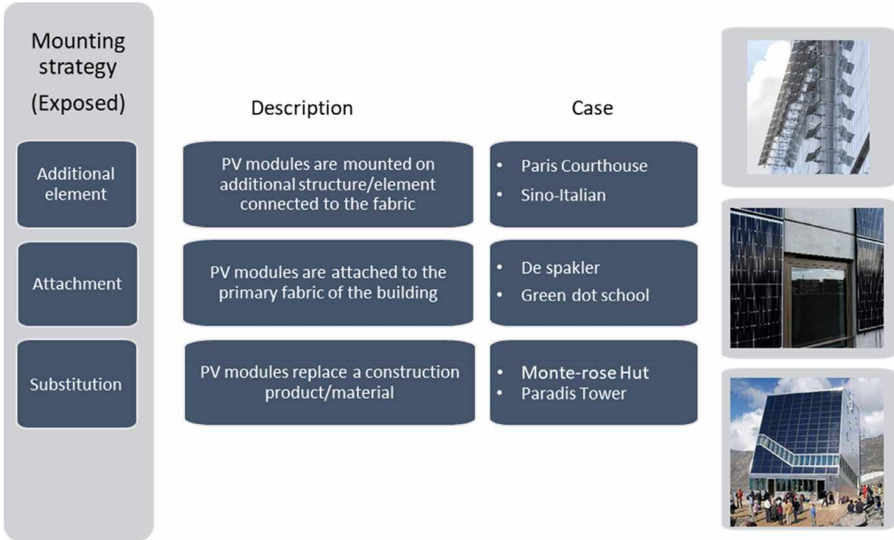


FIG. 3.2 Mounting strategies for exposed PV

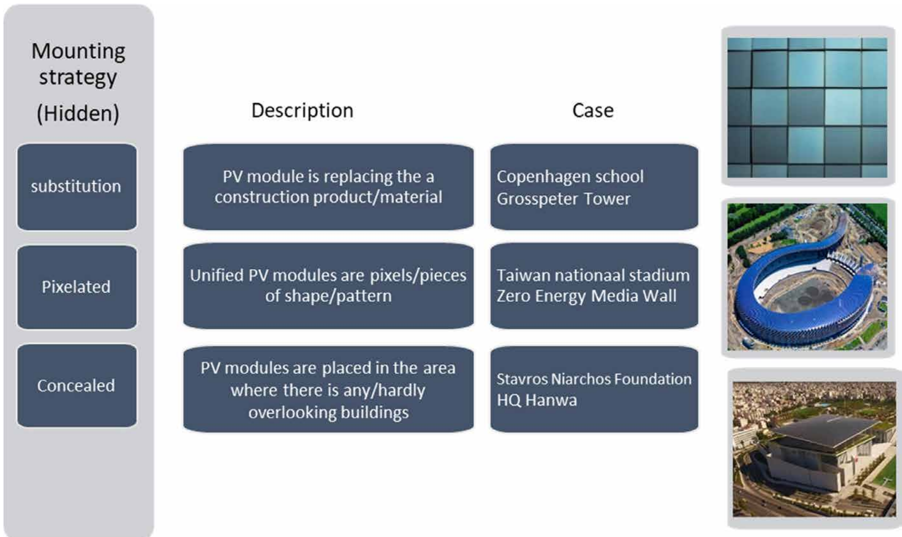


FIG. 3.3 Mounting strategies for hidden PV

For the hidden PV system, there is also a *Substitution* strategy but with a different type of PV product. A PV customisation to a greater extent was needed for these cases, with the PV modules being used in different colours, shapes, and sizes.

In the next category, *Pixelated*, the designer tried to benefit from the project scale to make a pattern using the PV modules. Therefore, in zoom-out images, it is very difficult to spot the modules, whereas, with a closer look, PV cells in modules are noticeable. In these examples, the architect has made a pattern with PV modules.

In the *Concealed* category, the designer accommodated PV on the building surface, which is out of public sight. Therefore, they had more freedom in choosing PV technology and products. In the examples given, the Stavros Niarchos Foundation in Athens had an overarching layer designed on the building roof and PV modules fully covered this layer. In the other example, HQ Hanwa, the PV modules are hardly noticeable from pedestrians' viewpoint, with the help of parametric design and a tilt of the modules.

3.4.3 PV Product type

As mentioned previously, the PV technology used in projects had been a parameter for categorisation in earlier studies. However, we used the extent of adaptation of a PV module from a standard module to a fully customised module to categorise these cases. The evolution of technological development in PV manufacturing allows for increased architectural customisation of PV products in the form of dimension, shape, colour, and surface properties. Therefore, existing PV products can be categorised into three types: Industry standard, semi-custom, and building material replica. Figure 3.4 shows the example and description for the three types that have been developed.

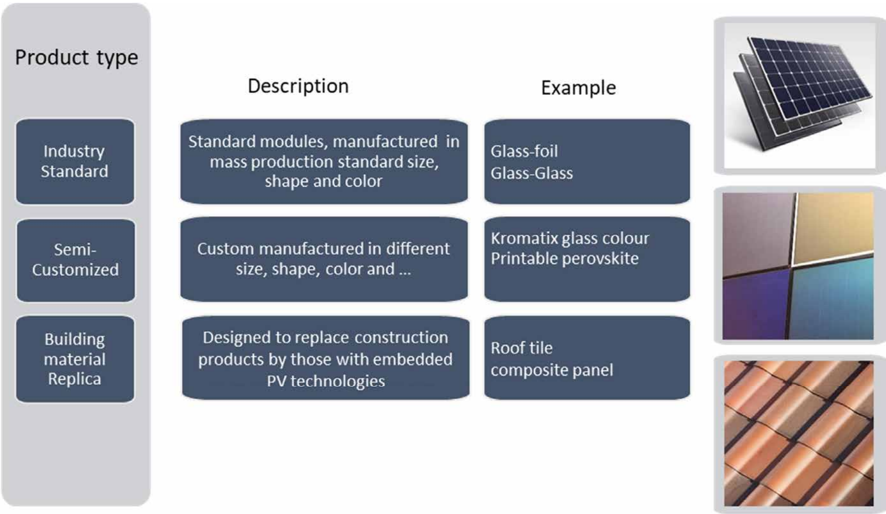


FIG. 3.4 PV product typologies

3.4.4 Building Fabric used

For the division of approaches adopted, another distinguishing factor is the building fabric considered for the application of the PV system. In this respect, the roof structure as a horizontal surface and façade as a vertical surface are the main hosting surfaces. The third type is the extension structure designed and added to the building to hold the PV system.

Traditionally and in most cases, to maximise the yield, we see PV modules either installed on flat surfaces with racks and inclination systems to place PV at an optimal angle or mounted on sloped surfaces facing the sun. In the cases studied, it was observed that sometimes, the architect had adopted the PV system to be installed in parallel to the surface and sometimes in the tilted position. In Figure 3.5 , different types of PV application on various building fabrics are presented.

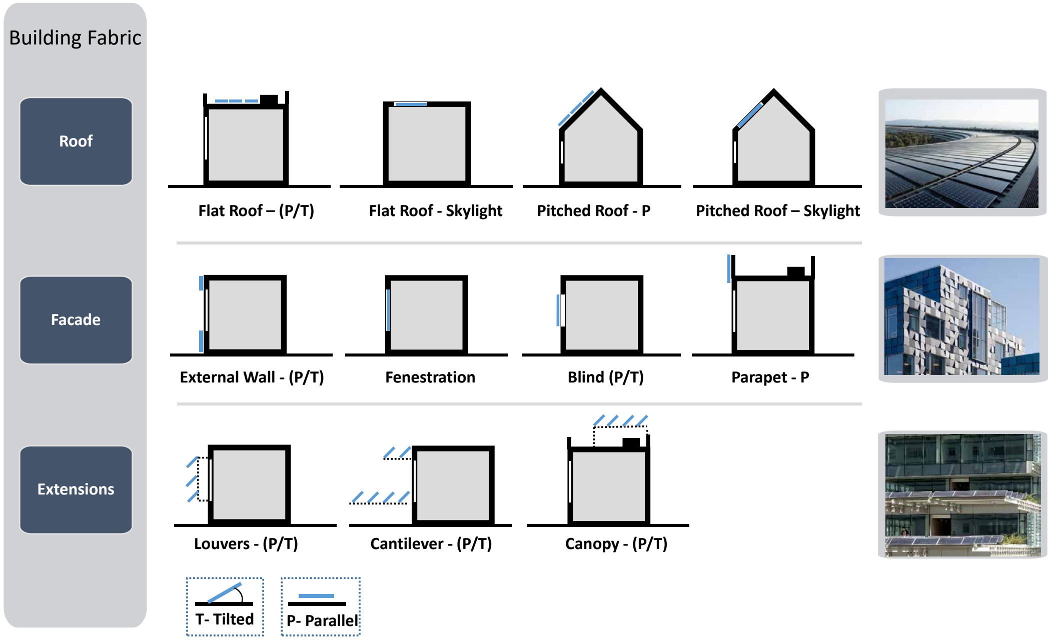


FIG. 3.5 Building Fabrics Used

One important consideration in planning and designing with photovoltaics is the inclination of the modules. The modules' inclination directly influences the final installed capacity and energy yield of the system. For example, having tilted modules on the flat surface dictates less installed PV capacity as the modules have to be distanced in order to avoid overshadowing each other, whereas, in the parallel installation, more modules can be installed as modules can be placed next to each other. This can be a significant advantage in favour of pitched roof application compared to the ground-mounted PV system.

With parallel application, PV modules can be mounted on a simpler structure as the wind load is reduced compared to the tilted system.

Roofs

In buildings, roofs are responsible for covering the top of the structure and protecting it against rain, snow, sunlight, wind, and temperature extremes. Traditionally, the roof surface is perceived as a suitable place to install PV systems (known as rooftop application). Looking into the cases studied in this research, only in a few cases did the design team use the roof surface to accommodate the PV system. In the **Apple Campus,** PV systems are installed on the flat roof and modules are positioned all around the cylindrical shape of the building, following the design concept. In this type, the modules are mounted in a parallel position to the roof surface and installed in an edge-to-edge layout, the usable area is greater compared to the tilted system as the modules do not cast shadows on each other.

Furthermore, the system looks relatively seamless and homogeneous from the design perspective compared to the tilted configuration. Nevertheless, in the flat roof application, the aesthetic and design integrity of the PV system with the building is less of a concern as the modules are placed in an area which seldom receives visitors and is mostly invisible from a street view. Moreover, architects are less involved in the design and engineering of the PV system when it is placed on a flat roof, as the system is perceived as a pure technical unit like other HVAC systems accommodated on the roof.

Depending on the PV technology and design concept used, as seen in the ECN building and Centre Mont-Cenis, the glazing material can be equipped with PV cells and used as a skylight or atrium glazing. In these applications, the ratio factor of PV cell and transparent area can be adjusted based on the expected energy yield and the amount of daylight needed inside the building.

Installation of a PV system on a sloped roof is one of the most popular PV applications in the residential sector. Installation of PV modules on a sloped surface and in a parallel configuration is ideal for PV yield and space efficiency. In Tour Paradis, a PV system was used on the sloped roof of the tower. In this project, the façade design followed the sloped roof, and a combination of semi-transparent and opaque PV cladding modules was applied. In another example, the Energy Academy, the south-facing sloped roof area was dedicated to the PV system.

Due to the potential and popularity of this application in the residential sector, the PV industry invested heavily in developing PV products replicating generic roofing materials for pitched roof application.

Façades

According to Herzog (2012), “The façade is a separating and filtering layer between outside and inside, between nature and interior spaces occupied by people”. From a design standpoint, the façade could be considered the most important element in the architecture of the buildings as it has the most visual interaction with the surroundings (Ibid).

Regarding APA and this study, projects that deployed PV on the façade are the majority in the selected cases. As the example project, De Spakler, the PV modules are mounted over the external walls and parallel to the building façade. Such an approach can be an independent installation, with minimal construction work and little obstruction of the ongoing operations of a building and is suitable for renovation projects. In the Nursing School case or Copenhagen School, PV was also used on the external walls, but with a different type of PV product, which led to a less expressive PV system. In the case of the Swiss convention, the curtain wall was used to apply the PV technology. The curtain wall system and all other types of transparent elements on façades are categorised under fenestrations in the categorisation. Other applications of PV on façades are seen in the shading components, blinds, and parapets. Depending on how they are designed and the complexity of the design components, the project may also fall under other categories. For example, in the La Seine Musicale case, an extension system was designed on the core dome to cast a shadow on the transparent central dome to avoid overheating. Therefore, the concept may be categorised under both façade shading system and extension system.

Extensions

Surface limitations on the roof and façade sometimes resulted in the design of an auxiliary structure to enable the application of PV technology. As shown in a few examples, the design team extended the surface area in parallel to the roof or façade to accommodate the PV system. The Sino-Italian case applies PV modules on the overhanging structure (cantilever), extending the horizontal surfaces of the building. In such a project, the architects designed rack systems to keep the PV modules in a tilted position. In other examples, i.e. the roof area of the EPO and Paris Courthouse and the façade of the ECN Building, an auxiliary structure was created to hold PV modules like louvres.

3.4.5 Additional function of PV product

Another important perspective to consider with the selected cases is the additional functionality that PV products may serve in the building system. Chapter 2 discussed that functional integration is the dominant perspective within the given definition to integration. These cases were analysed to see whether the architect used the PV module as a mono-functional product delivering on-site renewable energy to the building or as a multi-functional one, also playing a constructive role. As discussed, the physical characteristics and technological development in module manufacturing allow PV products to be suited and capable of performing more functionalities other than power generation. In Figure 3.6, two types with these parameters are explained.

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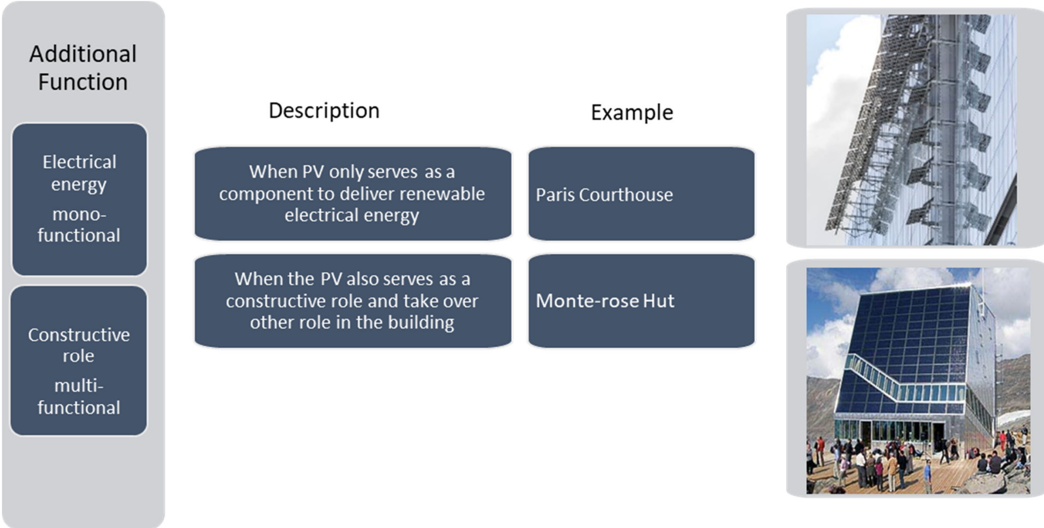


FIG. 3.6 Additional function of PV product

Besides the constructive and power generation role as outlined earlier, considering the physical characteristics of the PV module (e.g thermal conductivity) and without adjusting any part of a PV product, PV modules may indirectly influence the performance of the building envelope. Below, some of these contributions are summarised, however we didn't include them as intended additional functionality in the analysis of these approaches:

- Light management: Mounting PV in front of a transparent part of the fabric can control solar heat gain, prevent solar radiation from entering internal spaces, and the PV can function as a shading component. (Maurus et al. 2004)
- Thermal or acoustic insulation: Mounting on or as the final finishing of opaque parts of the fabric can lead to additional thermal or acoustic insulation. (Rüther et al. 1996)
- Heat source: A PV module may produce a significant amount of heat during operation. It may affect the HVAC system and transmit this heat into the building (Yang et al, 1999)

Moreover, considering the different functionalities in the overall building operation, we may also include decorative, ornamental, or promotional purposes. In this regard, we can see PV in some projects used for decoration purposes or even to provide a green and sustainable image to the building. However, as it is not possible to objectively judge whether the project owner has such an intention or not, it has not been considered in the analysis.

3.5 Analysis

Table 3.3 presents the cases used for this study and the parameters chosen; accordingly, in each column, we see how each project is categorised.

TABLE 3.3 Matrix cases studied and applied parameters

	Project name	A) PV Visibility	B) Mounting Strategy	C) PV product type	D) Building fabric	E) Functionality
1	Public Utilities Building	Exposed	substitution	Customised	Façade	Constructive
2	Solar Cultural Center	Exposed	Addit. Element	Standard	extensions	Electrical Energy
3	Langedijk Solar Home	Exposed	attachment	Customised	Roof	Electrical Energy
4	Centre Mont-Cenis	Hidden	Addit. Element	Customised	Extensions	Electrical Energy
5	ECN building	Hidden	substitution	Customised	Roof	Constructive role
6	Sino-Italian	Exposed	Addit. Element	Standard	Extensions	Electrical Energy
7	Zero Energy Media Wall	Hidden	Addit. Element	Customised	Façade	Electrical Energy
8	Monte Rosa Hut	Exposed	Substitution	Customised	Façade	Constructive
9	National Stadium	Hidden	Concealed	Customised	Roof	Constructive
10	Umwelt Arena	Hidden	Substitution	Customised	Roof +Façade	Constructive
11	Green Dot Animo	Hidden	Pixelated	Standard	Façade	Electrical Energy
12	SwissTech Convention	Hidden	Substitution	Replica	Façade	Constructive
13	Nursery +E In Marburg	Hidden	Substitution	Replica	Façade	Constructive
14	Tour Paradis	Hidden	Concealed	Customised	Façade	Constructive
15	St. Trinitatis Catholic	Hidden	Substitution	Replica	Façade	Constructive
16	New-Blauhaus	Hidden	Concealed	Customised	Façade	Constructive
17	Toshima ward office	Hidden	Pixelated	Replica	Façade	Electrical Energy
18	Energy Academy Europe	Exposed	Addit. Element	Standard	Roof	Electrical Energy
19	EWE & Bursagaz HQ	Hidden	Addit. Element	Replica	Façade	Electrical Energy
20	Stavros Niarchos	Hidden	Concealed	Customised	Roof	Electrical Energy
21	De spakler Amsterdam	Exposed	Attachment	Standard	Façade	Electrical Energy
22	International School	Hidden	Substitution	Replica	Façade	Constructive
23	La Seine Musicale	Exposed	Addit. Element	Customised	Façade	Electrical Energy
24	EDGE	Hidden	Concealed	Customised	Façade	Electrical Energy
25	Grosspeter Tower	Hidden	Substitution	Replica	Façade	Constructive
26	European patent office	Hidden	Concealed	Standard	extensions	Electrical Energy
27	Apple HQ	Exposed	Attachment	Standard	Roof	Electrical Energy
28	Breez Hotel	Hidden	Substitution	Replica	Façade	Constructive
29	Hanwha HQ	Hidden	Concealed	Standard	Façade	Constructive
30	Paris Courthouse	Exposed	Addit. Element	Customised	Façade	Electrical Energy

The design teams of the cases studied had several possibilities that enabled or limited the options of the following parameter. As an example, if the first decision is to keep PV exposed, the architect has three possible approaches to make the PV visible in his design. But based on the approach taken, he cannot freely choose between all PV types: a building material replica would not serve his purpose as the PV is not noticeable in the product. Subsequently, he cannot expect PV to be a multi-functional product. Moreover, he should use PV in a visible fabric (either from the street or from other buildings).

In Figure 3.7, we randomly selected 6 cases from the cases and illustrated their decision-making process on the dashboard.

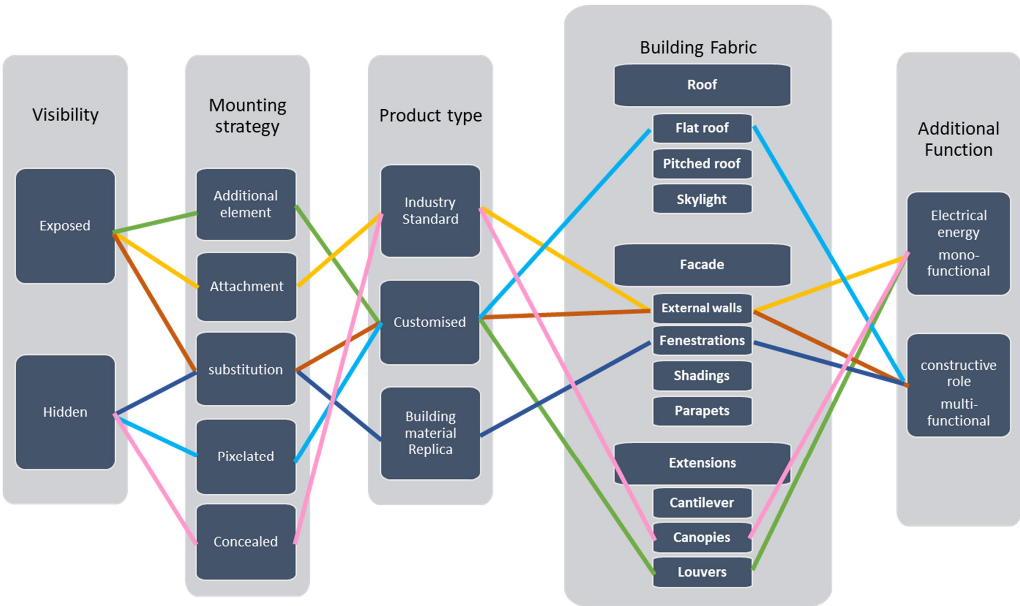


FIG. 3.7 Examples of mapped decision decisions

Analysis of the cases and what is shown in Figure 3.7 can be consulted for the development of a generalised dashboard interface, which can be used during the design process for the adoption of PV in an architectural project. An important point to mention is the approaches adopted in the selected cases helped us identify these parameters, but the combination of parameters next to each other may also result in the discovery of an approach that is not seen in our cases.

The current sequence shown in Figure 3.7 is not always pertinent to different projects. Only using visual analysis, it cannot be determined what sequence was used in each of the studied cases. It could be assumed that certain PV products were dictated from one of the project stakeholders, or that the pre-defined design concept does not allow the use of PV on the building façade and forces the design team to take a different path in the decision-making process. Therefore, the sequence and relationship can be defined differently based on the design concept and motivation for the use of PV in the project.

3.6 Conclusion

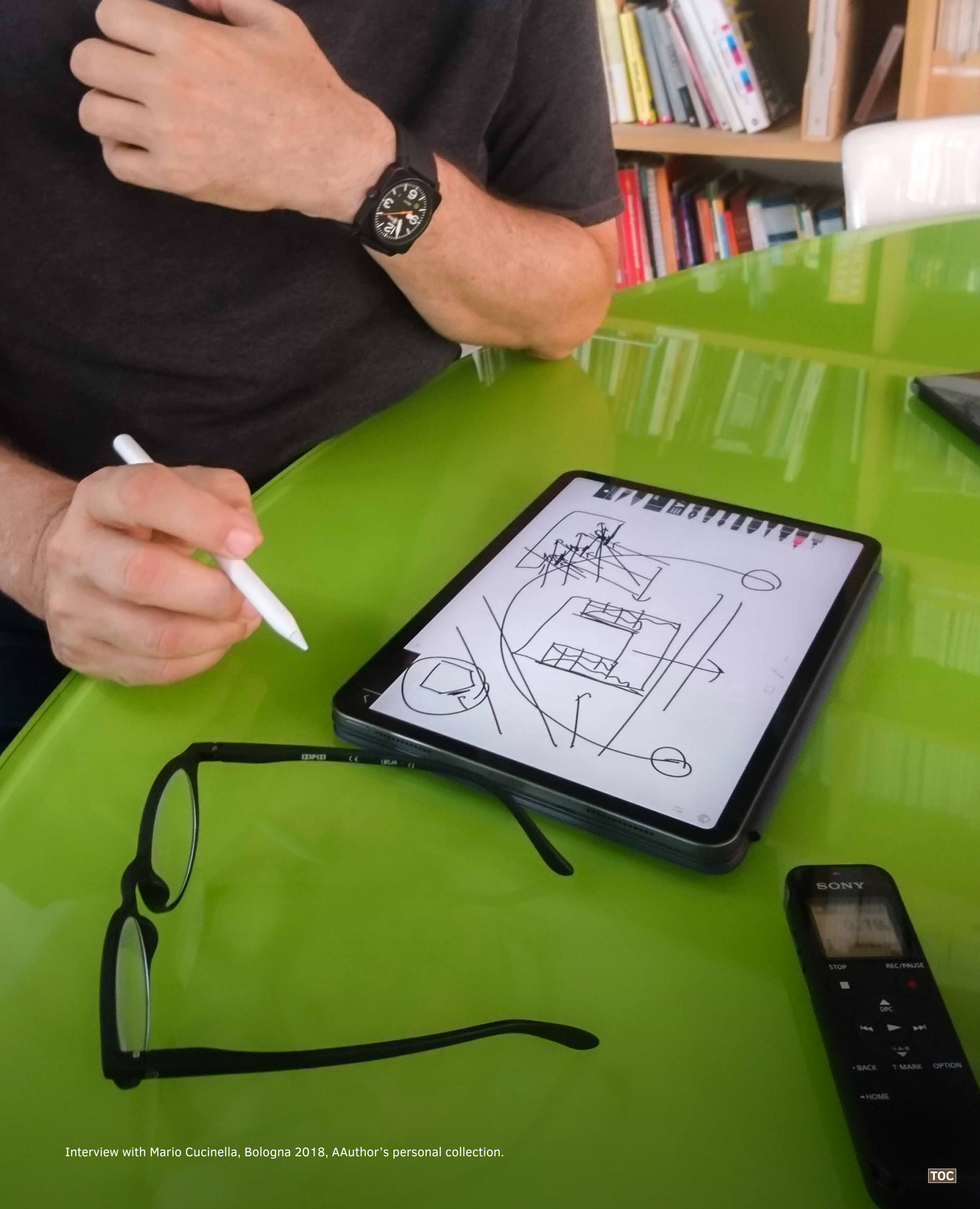
In this chapter, we tried to identify the decisions involved in the design process of using PV technology in architecture. In addition, the chapter presented the approaches adopted for the realisation of APA by studying 30 projects. Amongst the findings of this study, some of the design decisions were identified, and the interconnected relationship between these parameters, which leads to these different approaches, are presented.

The factors below are identified as design decisions that need to be made by the design team for the adoption of PV in architectural application:

- Visibility of the PV system
- Mounting strategy
- Physical customisation of PV modules
- Building fabric used for application
- Additional functionality considered for PV modules

Looking into these approaches allowed us to conclude that architectural approaches to deploying PV in buildings are not necessarily limited to what is known as integration as defined in chapter 2. This analysis showed the architects used PV through a wider range of approaches. PV as a building material, which is prescribed for BIPV application and is known as an integrated approach, is only a tiny portion of the possibilities.

The parameters used in this study to categorise these approaches help to further study the experiences of architects with realising those projects and to highlight the design process in the adoption of PV. This will be further elaborated in Chapter 4. In addition, the matrix can be used for the architects as a tool to use within the design process and exploration between different possible approaches to accommodate PV in the building's anatomy.



Interview with Mario Cucinella, Bologna 2018, AAuthor’s personal collection.

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4 Insights and Lessons learnt

This chapter is adapted version of the following publication:
Haghighi, Z.; Angali Dehnavi, M.; Konstantinou, T.; van den Dobbelsteen, A.; Klein, T. Architectural Photovoltaic Applications: Lessons Learnt and Perceptions from Architects. *Buildings* **2021**, *11*, 62. https://doi.org/10.3390/buildings11020062

As shown in the previous chapter, there are several examples of projects that have adopted APA across the globe. In Chapter 3, we explored these projects and categorised them based on the design decisions made during the realisation process. In this chapter, we take a deep dive into some of these cases to better understand the design process and experiences of architects in working with PV technology.

Chapter 4 presents the results of a series of in-depth interview with selected architects from selected studied cases in Chapter 3, along with some other architects who have yet to use PV in their projects. These results are classified based on different themes - for instance, lessons learned from realised projects or insights generated regarding certain issues that relate to APA. The results showed apparent differences between practical experiences and inexperienced perceptions. The analysis of the visual implication of PV integration shows that, to the eyes of architects, integration of PV into architecture does not depend on the PV product used, but instead, when PV is a part of the design concept and process, the outcome is seen as a meaningful integration.

4.1 Introduction

During the last several years, technological advancement in photovoltaic cells and module manufacturing techniques have allowed for the development of new PV products with various sizes and colours in order to increase the popularity of PV technology among architects architects (Bonomo et al., 2016) . However, despite the overall growth, cost reduction, market maturity, and commoditization of conventional PV modules for large-scale and rooftop applications, the integrated products (BIPV) account for only 2% of all PV installed worldwide (Bonomo et al., 2016; R2M, Onyx Solar, Flisom, BEAR-iD, 2016). The same report also indicates that 35% of these products, which were already available in their report published one year before, are no longer available, as the manufacturers failed to maintain their businesses.

In a survey conducted on the causes of the unpopularity of building-integrated photovoltaic products, issues regarding lack of knowledge and costs were dominant among the respondents (Prieto et al., 2017) In the framework of the International Energy Agency (IEA) Task 15, building owners were interviewed to explore suitable business plans applicable to PV technology in the built environment (Larsson et al., 2018). According to another survey conducted about IEA Task 41 (concerning the integration of solar energy systems and architecture), after the socioeconomic aspects, which were perceived as a major hurdle, lack of sufficient architecturally oriented literature on the different aspects of photovoltaic technology was found to be the second most important barrier (Farkas et al., 2010). In various research articles focusing on the integration of PV technologies into historical and monumental buildings, it has been highlighted that the legislative process for any changes in regard to aesthetic appearance and historical values is another hurdle in addition to economic issues for the adoption of PV technology to these buildings (López, n.d.; Pelle et al., 2020).

Throughout the years, there have been many instances of architects using PV technology in their projects. They used different types of PV products and implemented them using different approaches. In literature, despite the effort made in IEA tasks (Horvat et al., 2011), we have found no documents addressing the experiences of architects with a focus on using PV products in their designs (Farkas, 2011). Nonetheless, in order to meet sustainability targets within the built environment, we need to identify the bottlenecks and challenges in the decision-making process and to learn the expectations and considerations of architects as leading stakeholders in the design and decision-making processes.

Therefore, in order to bridge this gap in knowledge, we conducted an explorative study aiming to collect a mix of qualitative and quantitative data from architects and other designers.

The research question in this chapter is:

- Based on realised projects and according to architects, what are the motivations, lessons learnt, and personal perceptions regarding the adoption of APA?

In order to achieve this, we interviewed 30 architects with and without experience in using PV technology. The aim was to find information regarding the design process, challenges in the use of PV products, bottlenecks within decision-making, and the overall experience. In addition, we aimed to see if “integration” as a concept holds any visual implication in architecture and if a definition of “integration” could be made, including any design specifications.

In the following sections, the method to set up the interview and the recruitment of interviewees is explained. Subsequently, the findings from the interviews regarding the design and decision-making process and the aspects influencing the integration of PV in a project are presented and interpreted. Finally, we conclude with insights about the further implementation of the lessons learnt.

4.2 Method

The main objective of this study is to document the experiences and perceptions of architects and other designers regarding architectural photovoltaic applications (APA). The research team has opted to apply an in-depth interview method to collect and explore the architects’ perspectives on the topic and to acquire more in-depth insight compared to what is available in contemporary literature. This method has recently been used by several researchers and is shown to be a practical approach for collecting qualitative data, primarily when experts and experienced respondents are targeted. For a similar topic, the adaptive façade, Attia et al. (2018) used this approach and concluded that the in-depth interview method provided comprehensive information for understanding the experiences and expectations of the respondents. In addition to the in-depth interview, one segment of the study aimed to collect quantitative information when respondents were required to rank important factors in the decision-making process.

In accordance with Yin (2009), based on the three types of interviews, an open-ended nature was selected for the in-depth interview when regarding qualitative data. Since the respondents were asked about the objective facts of a subject as well as their opinion and were requested to propose their insight on certain occurrences. Such an approach allows the interviewer to use such propositions as the basis for further inquiry. In addition, in certain parts of the interview, some of the questions were designed to be responded to using a group of predefined answers. The quantitative data helped the research team in approaching a more straightforward conclusion regarding the effects of certain factors in the decision-making process. This approach allowed us to gain broader insight into the results by being able to extract two types of data from one source. It should be noted, however, that in this model, the two data types are not influenced and are not related to one another: they exist parallel to one another and have separate methods of interpretation.

As shown in Figure 4.1, the interview process is composed of three steps; in chronological order, these are: research design, data collection, and content analysis.

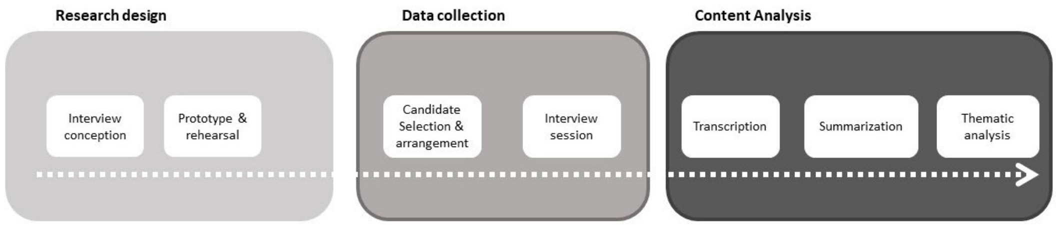

FIG. 4.1 Interview process by research design, data collection, and content analysis.

4.2.1 Research Design

In order to design the framework for the in-depth interview, the main areas and topics that had to be covered were drafted and, accordingly, a list of questions was formed. These questions were clustered together into four broader thematic sections:

1. Experiences and lessons learned,
2. Insights and perceptions,
3. Understanding integration,
4. Decision-making factors.

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At an early stage, the research team decided to divide the interviewees into two groups, A and B. Group A consisted of architects who have previously used PV technology in their designs. Group B consisted of architects that have not yet managed to use this technology in their design. This division was important because we could include both experiences that come out of a realised project and perceptions from the architects who have not yet used the technology. Therefore, a more comprehensive range of information could be collocated and comparison in the received responses could be made between the two groups. It is a common approach in interview methods and known as a control group approach (Lavrakas, 2012).

The interview was divided into three parts (Figure 4.2). The first two parts were aimed at collecting qualitative data, whereas the third part collected quantitative data. This approach is known as the mixed-method approach (Creswell, 2009) and proved to be useful and relevant to the study's nature, as we needed to collect qualitative data for objective thoughts including experiences, perceptions, and understandings in the first two parts. In the last part, we needed to be able to collect quantifiable information. This approach allows the researcher to gain broader insight into having two types of data instead of one. Although these data are not related to each other in this model, they stand side by side and have their method for interpretation (Creswell, 2009).

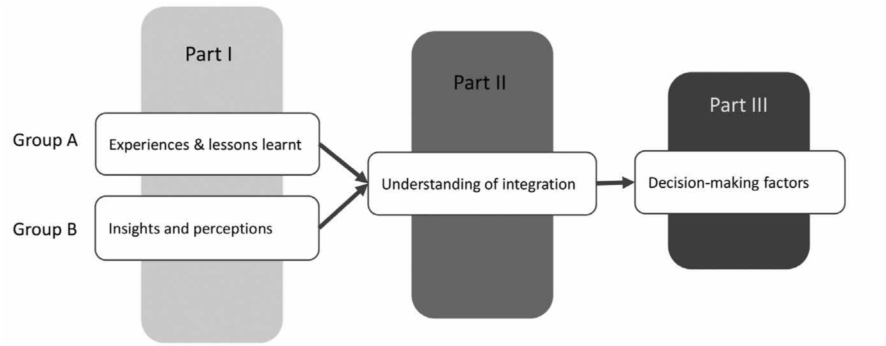

FIG. 4.2 Three parts of the questionnaires.

In Part I, each group was questioned differently.

For Group A, the questionnaire covered the following aspects:
- Project background, motivation, and key drivers
- Design process with PV
- Lessons learned and takeaways

For Group B, the questionnaire covered the following aspects:
- Motivators and barriers
- PV and architectural design
- Expectations of the PV product

Sometimes, similar questions were asked to both groups. However, it was essential to distinguish the data that were generated from the experience of an architect with specific cases, or the data that reflect the architect's insights and perceptions.

Part II was similar for both groups and revolved around "understanding of integration". In this part, it was requested that interviewees outline their verbal understanding of the implication of the term "integration". They were then presented with the images of six realised projects with different design approaches towards PV technology and configuration and were then asked whether they believe any of the projects were "integrated" or not and questioned about the reasoning for their answer. Finally, the architects were asked which one(s) among the projects best describes the example for the ideal definition of integration.

For Part III, also similar for both groups, a list of predefined influencing factors in decision-making was constructed. Interviewees were asked to indicate the relevance of these factors, based on a scale ranging from 0 to 9.

The questionnaires were tested in a series of pilot sessions conducted among peers and members of the research team, aiming to simulate an interview session, resolve any potential ambiguity in the questions, and refine the process based on received feedback. As the final stage, the research team assessed the relevance and clarity of the questions in an iterative process. Subsequently, a definitive list of questions with an ordered sequence was prepared. This list is available in Appendices A and B.

As per official data collection requirements at the Delft University of Technology (TU Delft, The Netherlands), the interview documents, including questionnaires and procedures of the interviews, were presented to TU Delft Human Research Ethics Committee (HREC) and received approval.

In order to recruit suitable interviewees, the research team took a purposive sampling approach (Lavrakas, 2012). Thus, candidates were consciously selected and invited. For Group A, the case study research in Chapter 3 was used as a baseline. In the study mentioned, some categorization was made by the design approaches to PV and each project was studied through the lens of five different parameters: 1. Visibility (of the PV module) in overall design, 2. Mounting strategy, 3. Level of adaptation, 4. Building fabric used, and 5. Additional functionality. Following this, one or two sample cases from each category was selected, and the architect behind the project was invited to participate in the interview. The research team also invited a few other architects/designers whose projects had been highlighted in professional networks due to the novelty of the PV products they used or because of new approaches they had implemented.

For Group B, architects who had no experience working with PV technology were targeted. For the selection of suitable candidates, the research team tried to include architects/designers from construction typologies differing in function and sector. The categorization of building typologies made by Euroconstruct reports was used (EUROCONSTRUCT - 2020), and according to each typology, different candidates were approached. For this group, a clear preference had been given to architects/designers who were available and accessible via the professional network of the research team, some of whom professionally linked to the Faculty of Architecture at TU Delft.

4.2.2 Data Collection

In this study, 30 interviews were conducted from October 2018 to June 2020 in five different countries in addition to national visits within the Netherlands. The interviews were recorded with a Sony PX470 digital voice-recording device with the consent of interviewees. The duration of the interviews ranged from 50 to 75 min. From the 30 interviewees, 15 were architects with one or more projects realised utilising PV and 15 were architects without such projects. In the following parts, the interviewees will be addressed by their number as seen in Table 4.1.

According to Attia et al. [16], transcription is an essential and inevitable step for any form of analysis on qualitative content [19]. In this study, manual transcription methods were used for most of the interviews, and some automated transcription software was tested. For this research, the “Google live transcription” mobile application (Google,) was used for some of the interviews. This Google app is able to transcribe with high accuracy; however, it has its shortcomings related to the exportation of transcribed texts. Therefore, a manual review on the automated transcription was also essential to prevent any errors or missing parts from compromising the interviews.

4.2.3 Content Analysis

The step after transcription consisted of summarising each interview and highlighting common areas, topics, and themes that were mentioned frequently. According to the research goals and questions, relevant themes were selected as the basis for the analysis. This is known as a deductive approach, in which the data are analysed based on predefined themes [19]. A spreadsheet was created containing keywords and a summary of the interviewees' answers. Afterward, the research team analysed the different viewpoints and experiences of the interviewees concerning each topic and produced an interpretation and overview, including some quotes from the interviewees. The findings were clustered into four themes as mentioned earlier; these are presented in the following section. The results have been summarised in tables in the beginning of each section. Each table includes the findings and remarks that were discussed, reference to the interviewees who made that point, the observation of the authors, and quotes that support and complement the arguments.

4.3 Results and Discussions

In this section, the findings and analysis of the findings are presented under the four thematic sections that the interview was based upon. Under each theme, there are subsections that focus on certain topics discussed with the interviewees. In addition to the results of the analysis and quotes from the interviews, each subsection presents the interpretation of the research team.

In Table 4.1 the list of interviewed candidates along with the projects discussed in the interview are presented. As mentioned, in the following sections, interviewees are referred to by the allocated number from this table.

TABLE 4.1 Interviewees

Group A: Architects with Realized PV Projects				Group B: Other Parties		
	Architecture Firm	Interviewee	Project		Architecture Firm	Interviewee
1	NBA Architect	Harold van de Ven	De Willem en de Zwijger	16	Dutch Government Architect	Floris Alkemade
2	Sunsoak	Jean-Didier Steenackers	Bota Solar	17	Architekturbüro Hagemann	Ingo Hagemann
3	Mario Cucinella Architects	Mario Cucinella	Sino-Italian	18	Van Schagen	Arjan Gooijer
4	Renzo Piano Building Workshop	Bernard Plattner	Paris Courthouse	19	Felixx Landscape Architect	Marnix Vink
5	Renzo Piano Building Workshop	Giorgio Bianchi	Stavros Niarchos Foundation	20	EOC Engineers	James O'Callaghan
6	Broekbakema	Steven Schulze	Energy Academy	21	Octatube	Mick Eekhout
7	SGP Architects	Simone Giostra	GREENPIX,	22	KAAN Architecten	Kees Kaan
8	Mecanoo	Dick van Gameren	De Spakler	23	Marjan van Aubel	Marjan van Aubel
9	OZ Architects	Wouter Zaaijer	Breeze Hotel	24	MVRDV	Nathalie de Vries
10	Dam Architect	Diederik Dam	European Patent Office (EPO)	25	Haskoning Architects	Sven Spierings
11	Kiss and Cathcart	Greg Kiss	APS Fairfield PV	26	Braaksma & Roos	Job Roos
12	Foster + Partner	Paul Kalkhoven	HQ in California	27	Solarix Studio	Marloes van Heteren
13	Van den Berg	Dick van de Merwe	Hoornbeeck College	28	Superuse Studios	Jos de Krieger
14	C.F. Moller	Mads Mandrup Hansen	Copenhagen School	29	Bear-id	Tjerk Reijenga
15	UNStudio	Ger Gijzen	Hanwa HQ	30	Arup Architecture	Nille Juul-Sorensen

4.3.1 Experiences and Lessons Learned

This section presents the findings and information collected from the first 15 interviewees, who had applied PV in their projects. In these 15 interviews, the respondents were asked to share their experiences in working with PV technology in their projects. The results, presented in Table 4.2, have been classified into three subsections: (1) Project backgrounds, motivations, and key drivers; (2) PV and architectural design; (c) Lessons learnt and takeaways.

TABLE 4.2 Experiences and lessons learned.

Topics	Findings	Interviewee	Observations/Interprets
Project Backgrounds, Motivations, and Key Drivers			
Motivations and key drivers	Complying with external incentives—Harvesting on-site renewable energy to address sustainable development goals	4, 6, 8, 12	Photovoltaics (PV) were found to be the best way to produce energy on-site and meet SD goals
	Green architecture—Concept and potentials for the use of technology	1, 3, 5, 7, 9	Considering PV from early stages of design is a challenging task—making a balance between form and function
	Marketing & demonstration—The building owner's image + education + testing and promotion of photovoltaic businesses	1, 2, 10, 11, 12, 13, 14, 15	PV is perceived as a sign of sustainability and, in the majority of cases, this aspect helped with its acceptability for investors
	Quotes: Architect 1: "We wanted to make people believe that PV panels are a material that has no problem being used in the façade, that they can look normal and working with them is quite easy." (referring to II and III) Architect 3: "The site allowed having plenty of south-facing surfaces and was ideal for capturing solar energy before they cause overheating in the building." (referring to II)		
Design process and PV			
PV in the design concept	There were intentions to show PV in the project, either by the architect or by the owner	1, 3, 4, 6, 7, 8, 12, 13	Condition of the visibility of the PV system in the design concept is linked to the original motivation of the project and also the general viewpoint of the architect in regard to the having exposed or hidden building services
	A specific PV product was chosen by the project owner, but the architect used creativity to blend the modules into their design concept	11, 15	
	Preferred to have PVs be invisible or not as a part of the design concept	5, , 9, 10, 14	
	Quotes: Architect 1: "PV is like a normal material, and it is not important to make it visible and expressive." (referring to I)		
Design process with PV	The PV product was considered from the early stages of the design process.	1, 2, 3, 4, 5, 7, 9, 15	It can be seen that applying PV in a building requires precautions that an architect must consider in the early stages of the design. When PV came late in the process, the possibilities and unification between the PV component and building design became limited and challenging
	Surface for applying PV allocated during early phases, but the modules are chosen later.	6, 8, 10, 12, 13	
	Quotes: Architect 9: "With the intention of working with holistic sustainability concepts, you can't develop a building without a well integrated design process, and you need to start from scratch with all the advisors." (referring to I)		

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TABLE 4.2 Experiences and lessons learned.

Topics	Findings	Interviewee	Observations/Interprets
Building surface to apply PV	Façade used when the roof space was not enough to supply the energy demand	1, 7, 8	Based on local conditions, the motivation, and initial design concept, the architect opted to use PV on different surfaces in the building. Such a decision heavily influences the design concept of the building and the outcome of the projects.
	Sloped roof or façade used in projects when visibility and external communication of the PV was important	3, 4, 6, 11, 13, 15	
	Roof space used for external communication in extra large scale projects	5, 12	
	The designer opted to use surrounding buildings or add additional structures to apply PV due to various reasons	2, 3, 4, 9, 12	
	Quotes: Architect 2: “A great solution for dense urban areas with limited surfaces and municipal restrictions for changing the building façade is to add additional floor levels with a PV system, which can increase the building service area and is a sweet incentive for investors.” (referring to IV) Architect 3: “The design concept allowed the building to receive light from three directions, and the use of a shading component to control the heat gain in the design was essential. The owner wanted to keep the façade opening as transparent as possible for outdoor vision, and therefore we designed an additional component with PV to act as shadin.”. (referring to IV)		
The PV product applied	Certain PV products were dictated by the project owner/developer or chosen by the contractor	3, 10, 11, 13, 15	In projects when architects had some freedom to choose the product or customise the existing products, they experienced many limitations, losses of efficiency, and a higher final cost.
	Architects were involved in the design and development of the PV product	4, 7, 9, 14	
	Some architects urged for custom sizes, colours, or transparency, which was either not possible or was too expensive.	5, 8, 13	
	In some locations, additional tests and certifications for safety issues were needed	9, 12	
	Quotes: Architect 13: “We spent a long time finding a supplier of nonstandard PV in our market, we found very few, and they mostly had products for roof application. During construction, we changed three times the supplies as the mounting system and modules were not reliable and safe for façade application” (referring to III)		

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TABLE 4.2 Experiences and lessons learned.

Topics	Findings	Interviewee	Observations/Interprets
Lessons Learned and Takeaways			
Experiences	Overall positive experience with working with PV, success for the firm	All except 4	Despite the challenges mentioned, the majority found it a great experience which made them recommend it to their peers and redo it on other projects
	They are already busy with more projects with PV and definitely would do it again.	1, 9	
	They would have done it differently or would not advise to do it again as it is	4, 8	When the driver of the project was the energy yield of the system, striking a balance between the design and energy yield was a challenge.
	Quotes: Architect 6: "We should use PV and other energy-producing technology on a larger scale; doing it in only a few buildings is not functioning well; we should see it in more buildings." (referring to II) Architect 7: "Working with PV has been easier than expected, more predictable, not very different than with a lot of more construction material". (referring to I and II) Architect 14: "We faced many problems during the process but after the inauguration of the building, we received huge interest and requests from visitors from all over the world to visit the project. Although the PV modules are not visible, many people want to know about it and see it. This is what we are proud of." (referring to I)		
Challenges, considerations, and takeaways	They faced design challenges working with standard modules which limited their design and possibilities	8, 12	These challenges and the final result of the projects show how sometimes a challenge can be turned into an opportunity; that's where an architect's role in this process became evident. How small considerations within the design of the system can highly influence the final performance, and indeed knowing them and considering them from an early stage of the design process is key to success.
	In façade application, making a balance between openings and PV–Window to wall ratio	6, 9, 14, 15	
	Accessibility of PV systems for maintenance, cleaning, and replacement	3, 4, 8	
	Safety considerations with PV modules and supporting structures	4, 9	
	Module tilt and angle—for optimal yield in summer and winter and prevent overshadowing of the modules	1, 3, 5, 9, 14	
	Required space for ventilation and cables of the modules while also being weather-tight	1, 5, 8, 11, 12, 14	
	Architect 14 :"Having the maximum number of PV on the façade and enough light during all seasons to have a good learning environment for the school was a challeng.". (referring to II) Architect 4: "Because of fire safety issues, we were forced to put frames all around the panels and two brackets to support the frames". (referring to IV)		

4.3.1.1 Project Backgrounds, Motivations, and Key Drivers

The overall result of interviewing the first group shows that each project had a different starting point, which eventually influenced the outcome of the project. The interviewees were asked to state the concept behind each project and outline the motivation and role of the stakeholders in the deployment of PV in the projects. Regarding initial motivations to use PV in the project, various responses were received.

The most common reason mentioned for using PV was producing on-site renewable energy to address sustainable development goals in the built environment and to comply with external incentives. They argued that even energy-efficient buildings require large amounts of energy to operate, and in order to meet these demands, photovoltaic technology was found to be the best solution.

Another motivation mentioned by two of the interviewees is the potential for harvesting energy in the design concept and the tendency of the design team to work with the principles of a green building.

Other motivations include marketing and demonstration, the building owner's image, and the testing and promotion of photovoltaic businesses. In these projects, the amount of energy that could be produced by the PV system was considered a 2^{nd} or 3^{rd} priority: external communication was the key driver. Looking at the stakeholders, in most cases, the project owners showed interest in using PV and requested its inclusion in the project. In others, the architect and design team convinced the client to utilise the technology.

To conclude, different motivations and starting points in using PV technology have directly influenced the design process, design concept, and decision-making process. As indicated, to use PV in the projects, building owners were the most influential stakeholders in the decision-making process, followed by the architects themselves.

4.3.1.2 Design Process and PV

PV in the design concept

The conventional photovoltaic panel is an element with a specific appearance, which often makes it difficult for architects to integrate into their designs. Nonetheless, there are also products in which PV cells are invisible, as defined by (Kuhn et al., 2020) . Some of these were used to realise some of the projects. During the design process, it is essential that the design team and project owner decide on the visibility of PV panels in the building to the eyes of visitors. The interviewees were asked whether having PV visible or concealed in their design was intentional and whether this was a part of the design concept or a product of circumstance due to limitations with PV products available at the time.

The majority of interviewees had chosen to have PV visible, but each had their reasoning and motivation. In some cases, such as with interviewees 15 and 11, specific PV products, conventional with visible cells, were chosen at the behest of the client, but the architect managed to implement them into the design concept through creative innovation. There were architects who preferred to have the PV cells invisible, or not to take PV as part of the design concept; they were not interested in showing or exposing PV in their design.

These experiences show that the visibility of a PV system in the design concept is linked to the original motivation of the project. It also highlights the numerous viewpoints of the architects regarding having exposed or hidden building services.

The design process with PV

The moment of introducing PV technology into the design process is an important factor and influential for the final design concept. In this part, interviewees were asked to mention when they introduced PV during the design process.

According to the interviewees, despite diverse outcomes and a symbiotic relationship of PV with the design, the idea of using PV came into the design process at an early stage of the concept development. The interviewees believe that it is necessary to think about PV from the beginning of the design process, as they want the PV to be felt as a part of the architecture and not merely as an add-on. In cases where PV took over some other functionalities in the building, it became even more vital to consider PV application from the beginning of the design process.

The significant difference was whether the team also decided at the early stage on the type of product they were interested in or planned to use. There were many projects in which the surfaces onto which the modules were to be installed had already been allocated in the design concept, but in which the electrical team or contactor later detailed it with conventional and cost-effective modules with optimal configurations. In these projects, the modules were relatively separated from the design concept.

To conclude, in most cases, PV was considered in the early decision-making process, which reflects its involvement in the overall building design. Applying PV in a building requires precautions that an architect must consider in the early stages of the design. Therefore, when it came late in the process, the possibilities and unification between the PV component and building design became limited.

Building surface to apply PV

In building applications, in order to capture energy from the sun using photovoltaic panels, these are commonly placed on the roof or façade. Embedding panels on the roof or façade is dependent on various factors. For many architects, the default place to put PV was the roof surface. One of the factors that led some of the architects to consider using the façade for PV application was the amount of energy that the building needed to produce.

Some architects used PV on a sloped roof and on the façade for external communication. According to interviewee 6, the project was big enough to allocate PV modules on the sloped roof, based on the function of the project: the design team placed the PV system in such a way that PV could be seen from the ground level to demonstrate the application of sustainable energy in their building. In large-scale projects, with formal design concepts, PV installation was also done on the roof area for external communication. Examples of these can be seen from the projects discussed with architects 5 and 12; in these projects, the roof area supplies only a portion of the energy demand, but the PV modules are not visible to pedestrians. In the project discussed with architect 10, the design team had also installed PV modules on the roof area, as the owner clearly urged the hiding of PV from visitor's view; therefore, small PV arrays had been placed on a canopy installation on the roof area, which was fully hidden and not accessible to visitors.

When the service area on the roof was insufficient, the building owner considered adding more space by renting the roof area of surrounding buildings and asked the design team to include an additional structure and space in the design concept. For the project discussed with architect 2, site restrictions led the design team to arrive at a unique approach. They designed a pavilion-like additional structure on the roof to hold the PV system. A similar approach had been used by architects 3 and 4 for newly built projects. In these two examples, an additional structure was designed on the façade to hold the modules. These architects ensured that the additional structures became a part of their design concept and were not just add-ons.

To conclude, based on local conditions, motivations, and design concepts, the architects opted to use PV on different surfaces of the buildings. Such a decision heavily influenced the design concept of the building and the outcome of the projects.

The PV product applied

The PV product selected had a strong influence on the outcome of the project. For this section, we asked the interviewees to outline what the decision-making process behind selecting the PV product was, how they found the product, and what their expectations were.

As discussed earlier, in some of the projects, the use of a certain PV product was dictated by the project owner/developer, so they played a key role in product selection. In other cases, the main contractors had already selected a product and provided it to the designer; the architects did not play a role in choosing the product.

For the projects where the architects had to select a product, they tried to find the product through various means—for example, by going to conferences related to solar power, searching the Internet, and inviting PV manufacturing companies to acquaint themselves with their products. Such close contacts allowed the design team's involvement in product development. For these projects, a certain degree of modification and customisation was possible, but for some, this only remained a wish. This was the case with interviewee 1, who asked for custom-sized modules and who preferred thin-film technology; the customization was not financially viable. In the cases of architects 4, 5, and 8, who wished for transparent glass-like PV panels, these were not available to them at the time. Architects 8 and 13 wished for a larger variety in colour; however, such a product would have less efficiency and, therefore, would be unfavourable to meet the project's energy target.

To conclude, there are many new possibilities with the customization of PV modules for fitting the design concept better; however, applying these changes to the product will increase the panel's price, sometimes influencing the accessibility of the modules for maintenance, and increase the operational costs of the building, which will, overall, make the owners and architect hesitant to opt for them.

4.3.1.3 Lessons Learned and Takeaways

Experiences

Overall, all architects interviewed, barring architects 4 and 8, were positive about their experiences and considered their working with PV to be a success. Some, i.e., architects 1 and 9, mentioned that the projects discussed were not their first and would not be their last. Some of them were involved in other projects utilising PV during the period of the interview.

In contrast to the positive stories, architect 4 was doubtful about the effectiveness of the technology in Central and Northern Europe because of lower solar radiation. Architect 8 had utilised a PV system in their project but received negative feedback from news and the media, as they found the design of the PV system ugly. He explained that because of energy efficiency ambitions of the building, they needed to produce the entire energy demand of the building on-site; as it was a social housing project, they were forced to keep the price as low as possible and work with the highest efficiency and cheapest PV module. This resulted in a building that appeared to be fully covered in PV cells. He mentioned this was a challenging project as they were limited in terms of design.

To summarise, the architects' experiences show that decision-making included many important issues and some points of interest that had to be considered. Most of them believe their experience to be positive: a successful project within their portfolio, which they are proud of.

Challenges, considerations, and takeaways

In this part, we asked the interviewees to share their experiences, lessons learnt, challenges they faced, and considerations for applying PV in their projects.

Projects in which a certain amount of energy production was targeted suffered from changes to the PV module. Striking a balance between the aesthetics of the system and energy yield was mentioned as one of the most challenging parts of using PV in the building. Another challenge lies in the design of openings in combination with PV modules on the façade. Some architects took measures to solve this problem; for example, architect 4 stated that "The building was designed with the idea of leaving the façade free to allow daylight and look better, so the PV was installed with a space of 1.2 m in front of the façade."

One other important issue mentioned was accessibility for maintenance; all interviewees stated this as a factor that needs to be considered in the design process. The panels must be designed and installed on the building in such a way that they can be easily replaced when necessary.

The next consideration is regarding the structure that is supposed to hold the panels. In addition to having sufficient strength to hold the panels, the structure must also be completely safe and comply with fire safety codes.

Another important point is a gap for cabling and for ventilating the modules. Without proper ventilation, the panel's temperature will rise, affecting the energy yield and also transmitting the heat into the building. In addition, weather robustness and rainwater tightness of the system was a challenge that needed detailed engineering.

In order to maximise the energy yield, the PV panels need to be at a certain angle, so architects must consider this when placing panels on roofs or the façades while avoiding overshadowing of the PV modules. Some architects, such as 14 and 9, played with this feature in their façade application and designed a vibrant 3D façade system.

In summary, working with PV, as with other technologies and materials, requires consideration with regards to design, technical aspects, safety, and operation. Many of these considerations were mentioned by the interviewees. These can be valuable takeaways for the targeted audience of this study.

4.3.2 Insights and Perceptions

In this part, sets of general insights provided by the interviewees, independent from any specific project, are presented. Due to the nature of the questions, said insights are mainly from Group 2; however, general input from Group A is also considered. The findings have been analysed and clustered in Table 4.3 as follows: Drivers and barriers, PV and architectural design, and Expectations of the PV products.

TABLE 4.3 Insights and perceptions.

Topics	Description	Interviewee	Observations/Interprets
Insights and Perceptions			
Drivers and barriers	External incentives and regulatory frameworks were perceived to play a crucial role	8, 28	By nature, architects with no experience working with PV have more doubts in using the products, and external pressures can be a good instrument to make them try this technology
	Investment needed for the PV system and higher operational costs of the building	22, 25, 28	From the architects who have not used PV in their projects, more questions, doubts, and considerations were raised. The majority of these concerns are valid and showed the complexity of applying PV technology in a building, but it seems that some of them can be handled easier than perceived by some architects
	Short-term interest in the buildings makes investment for PV difficult for developers	12	
	Doubts and unclear guidelines during the use phase of the building and PV system—who is responsible for maintenance and cleaning—renter, owner, owner's association, etc.?	14, 17, 18	
	Lack of diverse products with reasonable prices and reliable after-sale services	12, 15, 24	There are some variants of PV products with competitive prices in the market, but they are struggling to find their route-to-market.
	Lack of knowledge and experience among architects and designers	24	A guideline for the architects, including all the steps needed for the use of PV in a building, can help to address this issue.
	Shorter service life of PV modules compared to the buildings themselves	6, 12	Considering the 50–75-year lifespan of the average building in Europe, and the 25–30 year for a PV module, the product will, on average, need to be replaced at least once
	Quotes Architect 18: "In the dwelling, logically, the housing associations would be responsible for PV maintenance; maintenance is one of the reasons why architects often put PV separately on the roof." (referring to) Architect 24: "PV was not really made for façade application; it is tough to find the right product to make a façade. With PV, the building would look black or blue, and people would not like it." (referring to V) Architect 16: "Designers may work with this material in order to see what specific qualities it holds or what potential it has. Photovoltaic technology is quite advanced, yet architecturally, PV products are a bit clumsy, and more experimental product development is needed." (referring to VI)		

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TABLE 4.3 Insights and perceptions.

Topics	Description	Interviewee	Observations/Interprets
PV and Architectural Design			
Design process	The earlier PV comes into the design process, the better it would fit into the design concept.	16, 22, 25, 26	A conclusion can be derived that the question of where to apply PV is relative to the question of when to think about using it and which product to use.
	PV could always be considered even after finishing construction, such as roof application, or when you want to use it as an external shading component	14, 24, 28	
	Quotes Architect 21: “Instead of putting a solar panel on a sloped roof, which is not nice, or printing it as a pattern on the façade, the designer should start working with it during the design process and consider its size and texture when designing the façad.”. (referring to I) Architect 28: “In some buildings, PV comes last in the building process; so, it can be added on. Moreover, if the PV modules were not integrated into the building, such as by placing it on the roof, it’s easily able to be replaced or upgraded.” (referring to II)		
Building surface to apply PV onto	Application of PV on the roof is more practical and easier with installation, maintenance, cleaning, and replacement	5, 12, 25, 28	It is perceived that the easiest option for PV is using it on the roof space, and the demand for higher yield seems to be the main driver for thinking about other surfaces. The designer can be pragmatic about using a standard low-cost, high-performance product. There is minimal complaint regarding the ugliness of the standard panels, as they are only seen from a top-down view.
	When applying PV on a façade, it is more important to be careful with design and aesthetics; in an urban area, it is difficult to integrate it as part of the architecture	10, 29	
	In buildings that the PV is not a part of the main concept, it comes last in the design and then it is placed on the roof	26	
	Quotes Architect 25: “Based on calculations when there is enough space on the roof, the designer puts the PV there. This is the best solution if the client thinks that the PV panel is ugly.” (referring to I) Architect 27: “We believe that the façade should not only be utilised as thermal insulation for the building but also to generate energy and communicate and interact with the city and environment.” (referring to II) Architect 28: “When displaying a building’s ability to produce energy is important, a transition occurs in the design where PV is slowly removed from the roof and comes to façades.” (referring to II)		
Energy yield vs design	Making compromises and adaptation is a part of the responsibilities of the architect and, as they were used to it, found it easy to do so	14, 16	Creating a balance between the energy yield and aesthetic values is directly linked to the overall cost of the system, which is one of the bottlenecks with the use of PV technology in architecture.
	If PV is considered from an early staged, an adaptation of design would be needed	23	
	Quotes Architect 16: “Architects modify materials in order to make it fit in with the design; adapting a design depends on what kind of limitations the architect is confronted with”. Architect 23: “Architects have to be creative when selecting a technology and adapt it from the beginning and make it simple in order to encourage others to use it”.		

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TABLE 4.3 Insights and perceptions.

Topics	Description	Interviewee	Observations/Interprets
Visibility of PV in design	It depends on the design concept and it is the architects choice to hide or expose the PV	15	Architects' opinion on the visibility of PV is diverse, and it is difficult to make a clear statement on their preferences. However, it can be concluded that if the PV product is entangled as part of the design concept, there are fewer concerns with the visibility of the system.
	When the design is strong enough, and panels are a part of the design, it is fine to have the PV visible as a seamless building service.	18, 28, 30	
	Visibility of the PV system is important because it is a new technology and that the building should achieve a unique look using it	7	
	It is up to the client or project owner to decide on the visibility or when the project's concept centres within the use of green energy and sustainability	20, 24	
	Within intercity refurbishment projects with municipal restrictions, we need to hide PV in the design concept	24, 26	
	Quotes Architect 16 mentioned "Of course people often try to say that if I invest in it, I want to show the world that I am doing the right thing. That is good for the first phase when people want to demonstrate that they are responsible citizens of this planet, but that's not the end goal. The end goal should be that PV becomes an evident element in a building and that, for me, it is not necessary to expose the fact that it's a PV panel." (referring to IV) Architect 14: "The solar cell should be considered as part of a family. Designers must view it as a group of words that must be assembled into a sentence by the architect. It must fit into the systematic process of the project, and the system's productivity has to be in balance with its beauty. It is an interesting challenge."		

4.3.2.1 Drivers and Barriers

In the first step, interviewees were asked what factors could drive them to utilise PV in their projects. The respondents outlined their perceived obstacles and bottlenecks in their decision-making.

External incentives and regulatory frameworks were perceived to play a crucial role in most cases of adoption of PV in buildings. Architect 28 believes that government incentives and legal frameworks for promoting PV in buildings are the only way to convince investors to use PV.

From another perspective, the majority of architects mentioned that the investment needed to use PV had been the most significant consideration. Not only the cost of the PV panels themselves but also the cost of the labour required to install and maintain them will increase total building costs. This is especially true when an architect suggests involving nonstandard PV in their designs; decision-making for the investor becomes much more difficult as the payback period is extended.

Architect 14 also mentioned hindrance factors for architects surrounding legal issues in terms of responsibilities and guarantees regarding the PV product. Some doubt was raised several times by the architects about the responsibility for cleaning and maintenance of the modules: the building owner, building operator, or tenant. This issue influenced the building design; sometimes, the architect preferred to install PV on the roof to solve these problems.

The lack of diverse products with reasonable prices was also mentioned as a hindrance. The image of the current average PV is the industry-standard module that is used in large-scale solar parks, which also find popularity with single-family houses with pitched roofs. Considering this perception, several architects indicated that the issue lies with the lack of products. The research team reflected that various products are available, but due to a lack of knowledge, these technologies are perceived as expensive and not commercially available. This perception includes lack of trust and credibility regarding the quality assurance of PV products.

Lack of knowledge and experience among architects and designers is mentioned as another limiting issue. Even though the electrical and technical design of the system would be handled by an engineering team, similar to other areas of building design (e.g., structural, mechanical), architects need to understand and be familiar with the basics of the system in order to have a leading role in the design and decision-making process. A guideline for architects, including all the steps required for the application of PV in a building, can help to solve this issue.

To summarise, from the architects who have not used PV in their projects, more questions, doubts, and considerations were raised. Most of these concerns are valid and show the complexity of applying PV technology in a building. However, the architects who already had adopted this technology raised fewer of these challenges. This would indicate that some of the challenges can be handled easier than perceived by some architects. On the other hand, the complexity of implementing PV technology in the building is still evident. This will be especially true if it is to be a part of the building system itself. This influences architects to keep PV as an independent system, treating it as an add-on to the building, in order to ease the difficulties.

4.3.2.2 PV and Architectural Design

Design Process

While there was no mutual consensus among the respondents, there was an apparent belief that PV should be introduced as early as possible in the architectural design process. Such an approach matches the responses received from Group A.

There were, however, those who were opposed to this. They argued that they could always consider using PV even after finishing construction, such as a roof application or an external shading component.

Such polarised opinions on this issue show the interrelation and complexity of decision-making, such as some architects linking the question on where to apply PV to when to consider using it. These findings verify that there is a direct link between the moment when PV is introduced to the concept and design process, the suitable PV product, and the surface used for the application of PV.

Building Surface to Apply PV

On the question of where PV should be installed, many interesting ideas were proposed. As mentioned previously, some architects insisted on utilising the practicality and ease of installation when the PV module is mounted on the roof. Based on the responses received, in situations where PV is placed on the roof, the designer can be pragmatic about using a standard low-cost, high-performance PV product. There is minimal complaint regarding the ugliness of the standard panels as they are only seen from a top-down view.

In contrast, concerns arise when the PV modules are placed on the façade, as these are difficult to blend as a part of the architecture. However, when the space on the roof is limited, the architect is forced to give it a chance. Architect 27 brought up another reason for mounting the PV on the façade: “We believe that the façade should not only be utilised as thermal insulation for the building, but also to generate energy and communicate and interact with the city and environmen.”. In addition, the client’s desire to advertise a sustainable building was also noted.

In conclusion, the choice to install PV on the roof, hidden from the visitors’ views, seems to be a popular response among architects without experience. It gives less responsibility to the designer and allows the system to be independent and separable.

Energy yield vs. design

As explained earlier, in order to use PV in a design, on several occasions, architects needed to make a compromise between the functional performance of the PV modules and their design concept. A few of them mentioned that making compromises and adapting are part of the responsibilities of the architect and, since they were used to it, found it easy to do so.

Others believed that if PV was considered from the beginning of the design process, there would be no need to adapt the design later.

It seems to be the case that striking a balance between the energy yield and aesthetic values in a project is directly linked to the investment and payback period of the system. Indeed, this issue seems to be one of the biggest bottlenecks in using PV technology in architecture.

Visibility of PV in the design

In another part, the respondents were asked about the visibility of PV in the design concept. Similar to the first group with experience, the second group gave a range of varying answers.

Some architects responded that it depended on the design concept itself, whether or not the photovoltaic cells were to be visible. They believed that when the design is strong enough, and panels are a part of the design, it is fine to have the PV visible as a seamless building service. Some of the architects believed that visibility of the PV system is important because it is a new technology and that the building should achieve a unique look using it. It could be the case that the client and project owners want the PV to be seen, as they have monetarily invested in it and wish to show it off and use it for external communication.

Some others were in favour of hiding PV in the design concept. They argued that, especially on listed buildings or in the intercity refurbishment projects where municipal restrictions apply, PV changes the appearance of the building, and so, it should not be visible. For these projects, there is an apparent demand for the development of PV products that resemble or replicate conventional building materials.

Indeed, the feedback received verified that the opinion of architects on the visibility of PV is diverse, and that it is difficult to make a clear statement on their preferences. However, it can be concluded that if the PV product is entangled as part of the design concept, there are fewer concerns with the visibility of the system.

4.3.2.3 Expectations of PV Products

In the following part, results regarding the interviewees’ expectations of PV products are presented. Most respondents spoke more on the physical characteristics of the modules and less so on the technical performance. Architect 16 mentioned that “Current PV is modern and developed from a technical perspective, but it would be good if developers take the product’s beauty into account”. The majority also mentioned that, in order to use PV in the building, customizability of the product is essential. Several architects complained about the physical limitations of current PV modules, considering it a challenge to include them in the design. However, most of these architects were not aware of new technological developments within PV manufacturing. This indicates a large gap between the science and market. Others who were aware of recent advancements mentioned that these developments increase the overall cost of the PV system and make it less appealing for investors.

To conclude, for projects where the architect is faced with a limited budget, a stock-standard PV product is required that can be ordered off-the-shelf. In projects where architects are less burdened with spending restrictions, however, they would enjoy the choice of being able to utilise custom-built modules, tailor-made to suit the project at hand. The industry should seek to develop and manufacture standard PV modules that come in a diverse range of sizes and colours that make it easier for architects to adapt them into their designs with limited budgets.

4.3.3 Understanding of Integration

In the context of using PV technology in buildings, there is an emphasis on the concept of the integration of PV technology. Following the discussions raised in Chapter 2 and the review conducted on the definitions outlined by researchers, in this part, we asked how our interviewees understand integration and how they verbally and visually explain their understanding. The results have been analysed and are presented in Table 4.4.

TABLE 4.4 Understanding of integration.

Topics	Description	Relevant Quotes
Understanding of Integration		
Verbal definition of Integration	The PV being a true element in the design concept in contrast to it being merely an add-on element	Architect 29: "PV is integrated when it looks like it belongs to the building and is designed in a way that is not just something that is added to the building design." Architect 14:"To integrate is an aesthetic acknowledgement. At the same time, the actual technical component (the PV), that is either hidden or exposed, is something that is brought into the traditional ways of architectural thinking. Once you accept this, you can't refer to it as integration; you could consider it a part of the overall possibilities of the materials you possess."
	The PV product should serve additional functions in the building, other than energy production, in order to be considered integrated	Architect 11: "PV has to serve some architectural function in addition to its energy generation function—a rain screen module, for example." Architect 16: "Why not have PV panels that are structurally sound enough that they become part of the structure itself? They should be incorporated in a way that the architecture itself is renewed by the new possibilities. It should be noted, however, that the architecture should not become a slave to these new possibilities (PV technology)."
	PV should be treated as another building material and should not be expected to take over other functions	Architect 20: "PV should be treated as just another building material, like a brick that is only a brick or a window that is only a window. PV can be part of the assembly of the building".
	Integration of photovoltaics could only be achieved if we implement an integrated design process and involve all the parties involved from the early stages	Architect 9: "Integrated design process and integrated product design and integrated manufacturing all addressing the fact that all parties should work together from scratch to reach an integrated outcome."
	Integration as a range of possibilities and diverse meanings depending on architectural style, project, local conditions, and design concept	Architect 30: "When we talk about bricks, we only talk about bricks. You may get some that are handmade and are so nice and fantastic, and then you can get ugly ones that come from factories, which are completely dead in the structure. That's the range of it, but we still call it a brick and I think that with photovoltaics, we should just call it photovoltaics, knowing that there is a range of products that you can use and like." Architect 4: "Integration is such a broad concept. It has many meanings and has to be defined by the architect in his own architecture; sometimes PV is more pronounced, sometimes less. Sometimes it's visible, and sometimes it's hidden. So, this is not a choice, it's about a response to an idea, the idea of a project, and it's always going to be different."
	Against integration in the meaning of unification of PV with design	Architect 6: "Having nice architecture is important, but PV should be made a separate element because PV has to be replaced in 15–20 years. If it serves other functions, it will cause many problems for the building."
Visual examples of integration	Case 1: where state-of-the-art coloured PV modules were used where the PV cells are nearly invisible and have been used as a cladding product. The architect had also tilted each of the coloured modules to create a pattern on the façade. Case 2: where standard PV modules are used but made a specific shape out of this module, akin to the scales of a fish	

For the majority (more than 70%) of the architects interviewed, the word “integration” can be defined as “PV being a true element in the design concept in contrast to it being merely an add-on element”.

In addition, roughly half (around 50%) of the interviewees stated that the PV product should serve additional functions in the building, other than energy production, in order to be considered integrated. Of those against multifunctionality, they suggested that PV be treated as a normal monofunctional element, like other building services or materials.

Another opinion received from two architects was the belief that the integration of photovoltaics could only be achieved if we implement an integrated design process and involve all the parties involved from the early stages of a project. A few other architects described integration as a range of possibilities, depending on the projects, local conditions, and design concept.

One architect, however, was against the idea of integration. He believed integration is not necessary because PV needs to be replaced and changed earlier than the end of life of a building and, therefore, should not be unified with it.

As presented, the ideas and opinions of what integration means to the architects were quite diverse and covered a wide range of stances. It can be said, however, that most architects, whether directly or indirectly, believe that PV should be a part of the design concept. In order to understand the visual implication of the given definitions and determine what can be considered “part of the design concept”, we showed pictures of realised projects to the interviewees. We believe the visual implication of integration is a quality that cannot be measured in an objective capacity, varying wildly from person to person and from project to project. Therefore, the research team reflects this by not presenting the result of the qualitative assessment: which of the presented projects had received the most votes in terms of integration by the interviewees. Instead, we asked them to explain why they consider it integrated or non-integrated.

In the responses received, despite subjective opinions on the projects, the majority of the interviewees referred to the same two cases as the example of integration.

One was a project where state-of-the-art coloured PV modules were used, where the PV cells were nearly invisible and had been used as a cladding product. The architect had also tilted each of the coloured modules to create a pattern on the façade.

The second project took a different approach. The architect had used standard PV modules but made a specific shape out of this module, akin to the scales of a fish. In contrast to the first project, the PV modules are visible, and the architects could easily spot the modules.

Considering the results presented, the following conclusion can be made: integrated usage of a PV product in a project does not necessarily require design flexibility in the product itself. In other words, integration considers the design concept as a whole: it is not necessarily dependent on aspects of the PV product itself, such as the range of customizability, but rather the creativity and innovativeness of an architect and their ability to implement PV products properly into a project.

4.3.4 Decision-Making Factors

This section presents the results from the quantitative assessment of the important factors in the decision-making process for utilising PV in buildings. The interviewees were asked to rank, on a scale ranging from 0 to 9, each of the factors listed based on their importance and on the impact of the decision in implementing PV in a given project. Figure 4.3 presents the average score among all 30 interviewees, ordered from most to least significant:

The figure illustrates that several factors strongly influence the decision-making process when working with PV. Although most of the scores are relatively close to each other, the design and aesthetic aspects of the product and customizability regarding different physical aspects (e.g., shape, colour, size,) scoring higher than other factors. In terms of significance, the technical performance of the product and financial investment needed are next. Interestingly, marketing and branding of the PV module was scored as the least important aspect by the architects interviewed. It is important to note, however, that a few of the architects consider the branching of companies, such as Tesla, into the photovoltaic market has had a noticeable impact on the acceptability of the technology.

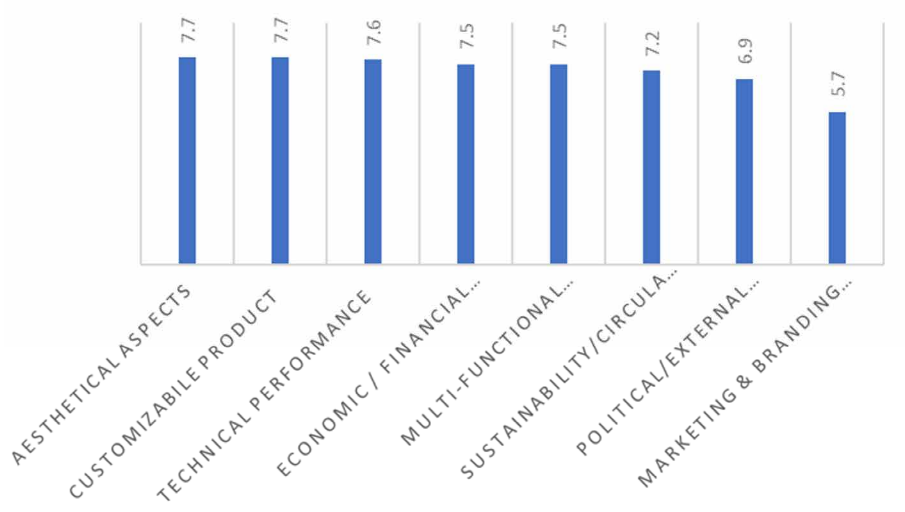


FIG. 4.3 Decision-making factors

4.4 Conclusions

The study presented in this paper investigated the inputs from architects in regard to various aspects of architectural photovoltaic applications (APA). Some of these inputs come from the architects' experiences with realised projects while some concern their opinions, perceptions, and other experiences. We utilised a mixed method in this study, which showed to be a useful approach in collecting input in the form of both qualitative and quantitative data.

The main results can be summarised by the following points:

- In regard to PV and architectural design, there is a direct link between the time when PV is introduced to the design concept, the suitable PV product, and the surface used for the application of PV.
- Comparing the experiences of Group A (architects that had applied PV already) and the insight and perceptions of Group B (architects and other designers that had not) showed that working with PV technology in practice was not as difficult and complicated as Group B had expressed. It should be noted, however, that most of

these realised projects are larger-scale projects and had the background context and budget necessary for the experimentation with PV. Therefore, Group B's insights are still of value and relevant to architects who have yet to utilise this technology in their architectural designs.

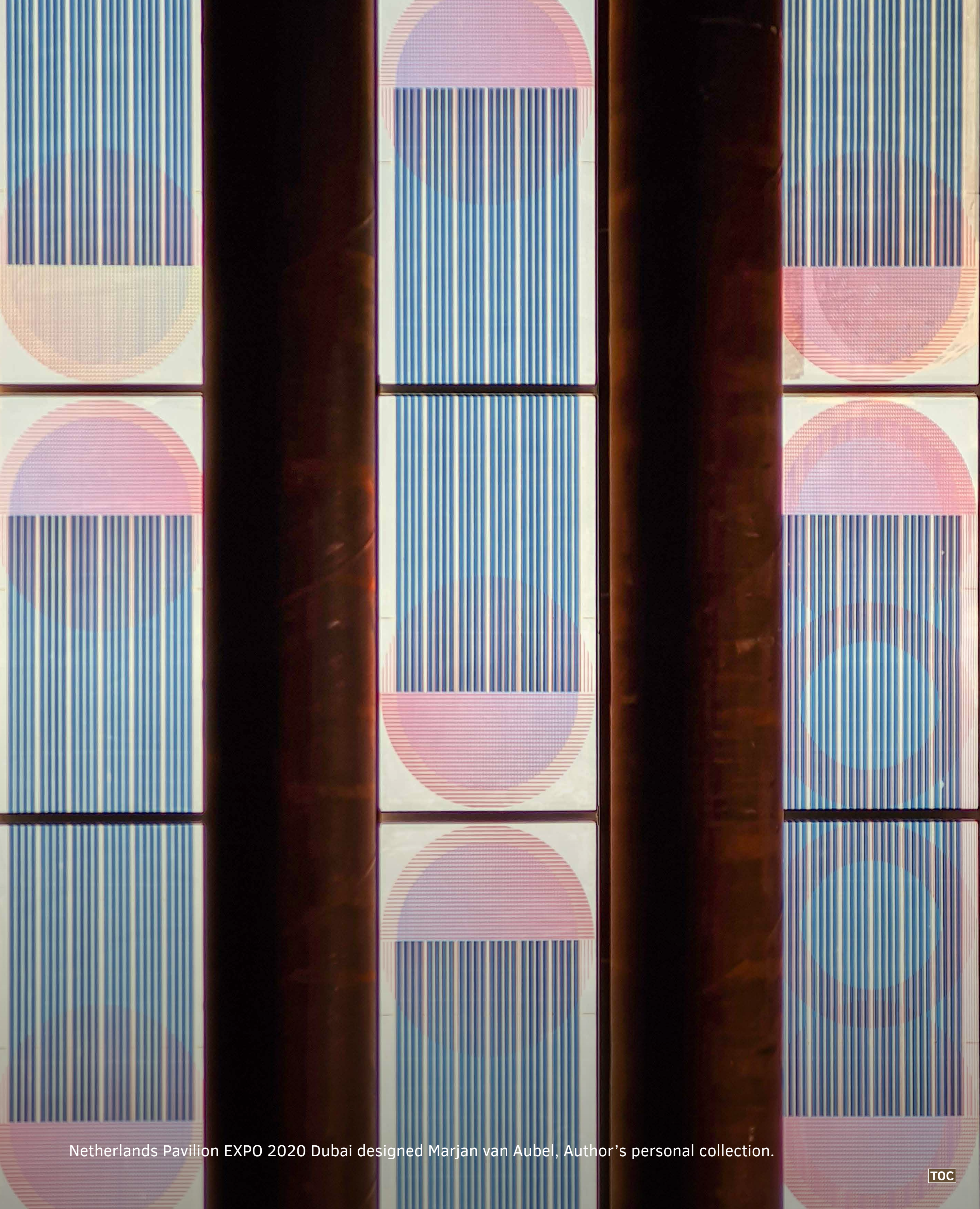
The findings highlighted several practical considerations for APA that need to be considered within the design concept:

- Space required for ventilation and cables of modules
- Overshadowing of the modules
- Window-to-wall ratio, size of building openings
- Accessibility of the system for maintenance and cleaning of modules
- Safety considerations with PV modules and the supporting structure
- Weather resistance and tightness of the PV system

This research concludes that versatility in colour, transparency, size, and reflectivity of module products are the most requested options by architects. The industry should seek to develop and manufacture standard PV modules that come in a diverse range of sizes and colours, which make it easier for architects to utilise them in their designs.

Regarding the understanding of architects of the concept of "integration", we learned that architects are interested in seeing PV as part of the design concept itself. This is treated as the most important concern. Assessing this quality, however, is mainly subjective and left to the discretion of the architect. It can be concluded that beside functional integration, having PV serves secondary functions in the building, and architectural integration, assimilating PV into the design concept, are aspects that can be important in determining the scope of integration.

As a reflection, it should be noted that the method applied in this research entails a time-consuming process, from the design and validation of the questionnaire, via the selection of architects and arrangement of interviews, to the transcription and analysis of data. Nevertheless, it remains the best suited approach, which can provide a comprehensive view of the topic for different stakeholders of the subject area.



Netherlands Pavilion EXPO 2020 Dubai designed Marjan van Aubel, Author’s personal collection.

TOC

5 Technology Decision

This chapter is an adapted version of the following publication
Haghighi, Z., Ortiz Lizcano, J. C. O., van den Dobbelsteen, A., Isabella, O., Konstantinou, T., & Zeman, M. (2018). Assessment of the suitability of photovoltaic cell technologies for product development of building integrated solutions using the analytical hierarchy process (ahp). EuroSun 2018 Conference Proceedings doi:10.18086/eurosun2018.02.17

Currently, more than twenty types of photovoltaic (PV) cell technology exist, all delivering electrical energy but made from different semiconductor materials with various physical features. Speaking of design considerations, it is important to know how to find the technology suitable for a certain application and design concept. In regard to this, considering the multiple parameters and criteria that are outlined in Chapter 4 by the architects throughout the decision-making process, it is a complex task to find the best-suited technology.

Chapter 5 aims to present the state-of-art PV technologies and then to see how a multi-criteria analysis method (MCA) can be used in this context to make the most optimal decision on technology selection.

In the following chapter, we first present commercialised PV cell technologies and their features for architectural application, and in the second part, we assess the possibility of using an Analytic Hierarchy Process (AHP) method to support the decision-making process.

5.1 Introduction

In recent years, the photovoltaic industry has been one of the fastest-growing fields of technology (IRENA, 2019). During the past 5 decades, photovoltaics have experienced significant progress in technological development, utility scale, roof-top installed capacity, and cost reduction. Today, almost 20 different PV cell technologies are available (Green, 2021) . According to the latest photovoltaic (PV) global report from Fraunhofer ISE (2020) , the compound annual growth rate of PV installations was 35% from 2010 to 2019. Globally, the cumulative PV installations were close to 584 GWp by the end of 2019; this represents a growth by a factor of 40 in only 10 years with China, Europe, North America, and Japan acting as the leading countries in its adoption (Frahnhofer ISE 2020, Kurtz et al., 2017). Currently, most of the PV modules are produced in China, with an annual output of nearly 100 GWp in 2019. In terms of economy, since 1980, the price of photovoltaics has reduced by a factor of 50 (Fraunhofer ISE, 2020). This significant reduction is due to several reasons, mainly the economies of scale; in addition, technological progress in solar cell efficiencies, standardisation of the technology (conventional PV modules), improved module manufacturing techniques, and lower costs of production of feedstock materials, mainly thanks to Chinese manufactures (Reinders et al., 2018)

All the above-mentioned facts and figures specify, that thanks to the efforts of different stakeholders in the PV industry, from high-level research organisations working on the multi-junction PV cell technology to the producers of PV modules in far east asia, that PV technology is on way to become the mainstream in the energy sector (Energy Agency, 2021; Kurtz et al., 2017). Beside the mentioned growth, innovation and new technologies allowed the development of more diverse applications and products incorporating PV technology. Today, its application varies from residential to utility-scale, and it is used in agriculture, construction, telecommunications, aerospace, transport, security, military, and many other fields. With such a vast array of applications, the demand for photovoltaics is increasing every year (Fraunhofer ISE, 2020).

The physical properties of PV cell technology allow for design flexibility during the development of different modules in various forms, shapes, colours, and degrees of translucency (Markvart & Castañer, 2003). However, such variety makes selecting the most suitable technology for a specific application a complex decision (Farkas, et al, 2010; Van De Kaa et al. 2014). In the previous chapters, the relevance of the integration approach, the importance of design aspects, and considerations for the use of PV in buildings are highlighted. Since there will always exist a trade-off between the aesthetic aspects of PV and its functional performance, meaning customisation offers energy production (Ritzen et al., 2013; Urbanetz, Zomer, & Rüther, 2011), it is crucial to minimise this loss through a more thoughtful selection of technology. Therefore, to find an optimal configuration and to choose the best-suited technology, designers and product developers should be able to apply their priorities to different aspects and subsequently be presented with a technology that meets these priorities. These aspects are not limited to the function and form of the product but also to the economic and environmental aspects that play an important role in the decision-making process (Troldborg, et al., 2014)

The objective of this chapter is to first provide a background information on the different PV technologies that can be used for architectural application and secondly to look into the advanced decision-making methods and see if such methods can be applied in the selection process of PV technology.

This chapter aims to answer the following questions:

- What are the commercially available PV technologies, and how can we find the best-suited technology for APA?

In the following section, the methods applied and process in this chapter outlined and in the following we first provided an overview on the commercially available PV technologies and then presented the result from application of multi-criteria analysis method into one of the product development projects to find the best suited PV technology.

5.2 Method

In order to make an inventory of the commercially available PV technologies, the main method applied in this chapter was literature research. As part of this process, we first identified the different generations of technologies from the literature. We then looked for the trends and latest developments for each branch of technology. The resources we accessed included websites of high-ranking PV manufacturers, the annual reports from the international research institutes like Fraunhofer institute for Solar Energy Systems and other scientific papers. Our findings in the literature and information provided by the architects interviewed outlined the importance of the physical characteristics of the PV modules in the decision-making process (Farkas, 2011). So, we expanded our research on the technologies to understand their performance in regard to the following aspects:

- Rigidity (Flexibility)
- Transparency
- Size
- Colour

In the second part, we conducted literature research on the application of MCA methods in a wide range of topics to understand the MCA mechanisms and how it could be applied to complex decision-making. Our research showed Analytic Hierarchy Process (AHP) is used in all similar situations as it translates to qualitative information- in this case, priorities of a particular criterion over another one- into quantitative data that can be used to rank alternatives.

As part of the interviews conducted in Chapter 4, we asked the architects to mention important factors in the decision-making process for utilising PV in buildings. Below are the factors mentioned and ranked by the interviewees.

- Aesthetical aspects
- Customizability
- Technical performance
- Economic factors
- Multi-functionality
- Sustainability/circularity aspects
- External incentives
- Marketing and branding aspects

These factors were used as an input criterion and the types of PV technology reviewed were used as alternatives for the AHP method. In the last step, to understand the method's applicability, we applied the method to find the best-suited technology for one of the product development projects as described in the following section.

5.3 Result

5.3.1 Overview of PV Technology

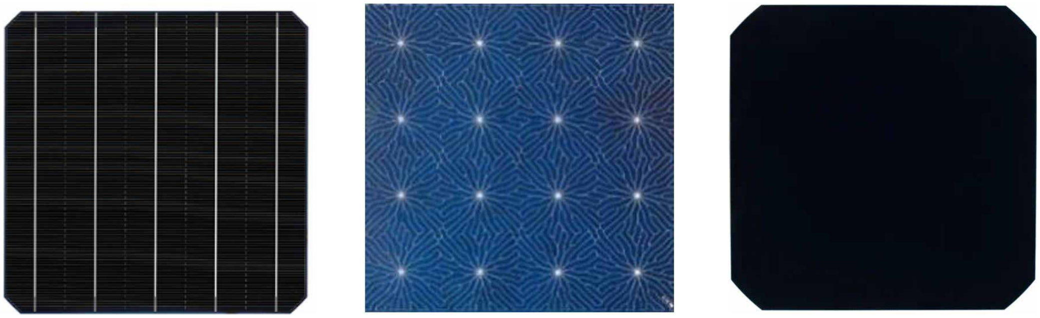
In this part, existing technologies in the market are presented and organised based on the industry classification of the generation of the technology.

5.3.1.1 First-generation PV Technologies: c-Si Solar Cell

Crystalline silicon solar cells are by far the most popular technology currently available on the market. In 2019, silicon-based PV cells represented close to 95% of the entire production (Fraunhofer ISE, 2020). Crystalline solar cells (c-Si) are made from silica (SiO_2), which is mined as quartz sand (Alsema, 2012). Crystalline silicon cells are available either as single or polycrystalline wafers, which result in two types of cells: mono-crystalline silicon (m-Si) and multi/polycrystalline silicon (p-Si) (Tripathy, et al., 2016). Their main difference lies in the manufacturing process. Generally, p-Si solar cells are cast based on multi-crystalline line material, whereas m-Si cells are obtained via the Czochralski process (Ferrazza, 2018) . By 2018, the market distribution of p-Si and m-Si solar cells was 55% and 45%, respectively; by the end of 2019, m-Si solar cells became the dominant technology holding 65% of the market share (Fraunhofer ISE, 2020).

The energy efficiency of crystalline silicon solar cells depends on several factors. In the last decades, different cell architectures have found their way from the laboratory to commercial modules; these variants are described fully by Nayak (2019). Their implementation has boosted the efficiency of commercial modules in a way that cells with 20% efficiency are currently not uncommon. Laboratory efficiencies are getting closer to the theoretical maximum of 29.4% (Green, 2018). For c-Si solar cells, the current laboratory records are 23.3% for p-Si and 27.6% for m-Si, respectively (NREL, 2021).

In Figure 5.1 , the most common types of c-Si solar cells are presented.



(a) Monocrystalline Silicon (m-Si) solar cell

(b) Poly-crystalline Silicon (p-Si) solar cell with metal wrap-through technology

(c) Monocrystalline Silicon (m-Si) with both contacts on the backside, commonly known as Interdigitated back-contacted (IBC) solar cell

FIG. 5.1 Types of c-Si solar cells.

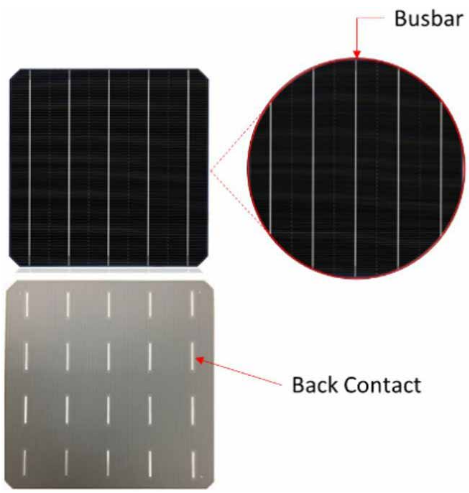


FIG. 5.2 Front and back contacts of a standard m-Si solar cell.

FIG. 5.3 Front and rear representation of an Interdigitated back-contact cell

As shown in Figure 5.1, on commercially available PV modules, front and back contact cells are most commonly used. In the case of front and back contact solar cells, interconnection is done via soldering metallic ribbons from the backside of a solar cell with the front side of the next. These contacts are known as busbars (Figure 5.2). Since they cover a part of the front side of the cell, they represent a loss as the light that reaches them is reflected instead of being absorbed by the cell.

Recently, commercial implementation of back-contacted solar cells is gaining more attention. These cells have no metallic front grid, thus eliminating light reflection losses. In addition, their metallic free appearance provides better aesthetic appeal. Their connection is relatively simple and is achieved by bridging the two extremes of a cell with opposite polarity.

As stated before, light intensity greatly affects electrical current generation in solar cells. If cells are connected in a series, the array efficiency is limited to the worst performing cell. Imagine a one-lane road filled with constantly moving cars. The maximum speed on that road is limited to the slowest car. If a shadow is cast on just one cell within a 60-cell module, the remaining 59 will see their current limited to the value produced by the shaded cell. This not only results in a lower energy yield but can severely damage the module. To overcome this issue, micro-electronics are developed as bypass diodes to reduce both the effect on energy production and potential damages.

Photovoltaic modules are being integrated into urban environments at an ever-increasing rate. Contrary to PV farms-utility scale PV power plants - which are located in specifically selected areas, standard modules, placed on rooftops and façades can have a great extent of their energy lost due to shading from surrounding buildings or obstacles. The industry has developed new approaches to tackle such challenges. The half-cell c-Si (shown in Figure 5.4) module is an example of a new development. It consists of laser-cut solar cells arranged in two groups. Each group usually has 72 series-connected half cells. Both groups are then connected in parallel. Given their lower surface area, half cells produce less current, but since both groups are connected in parallel, the overall current of the module is almost identical to that of one with full area cells. This is advantageous for two reasons. Firstly, a lower cell area reduces current-related losses and secondly, it makes the module more shade resilient (Hanifi, et al, 2015).

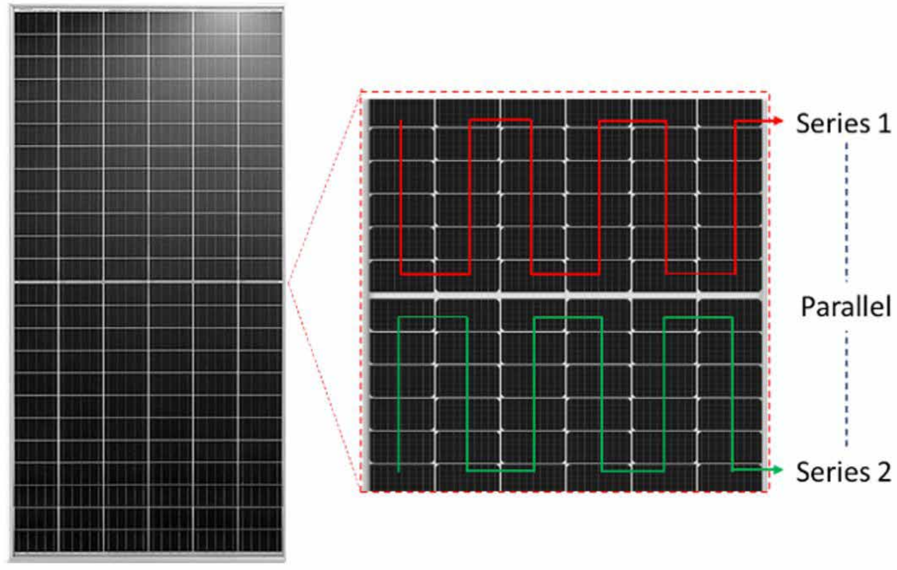


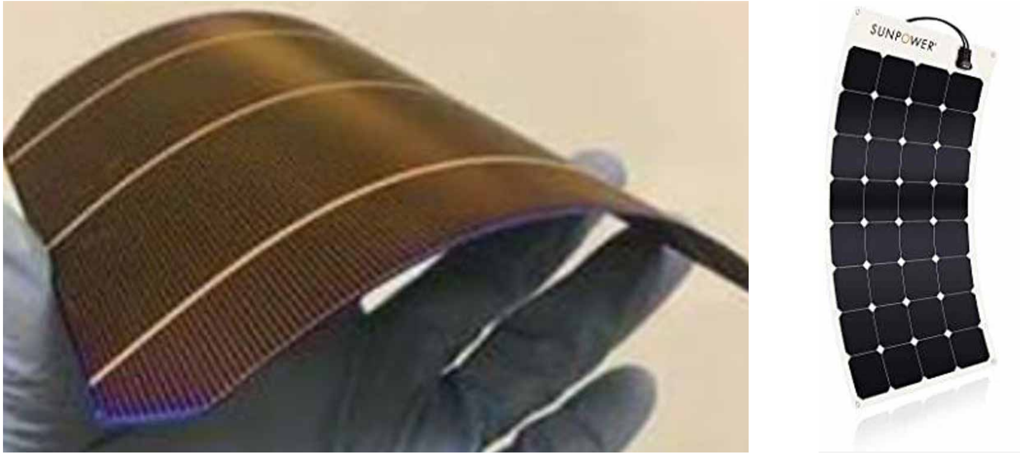
FIG. 5.4 Example of a half-cell module consisting of two groups of solar cells connected in parallel

Physical consideration for architectural application

Crystalline silicon-based PV modules have the highest market share, lower cost, and, most notably, the best efficiencies among single-junction technologies currently available (Kuhn et al., 2020). On the standard modules, the shape, size, cell arrangement, and numbers are meant to produce as much electrical energy as possible without much consideration to their appearance when applied in building. Nonetheless, customised c-Si based PV modules are emerging in the market, and several physical modifications can be made to the modules to better fit the demands for architectural application (Pelle et al., 2020).

Rigidity (Flexibility)

Due to their structure, c-Si based solar modules are mostly limited in their flexibility. The crystalline structure of standard cells cannot withstand numerous bending cycles without resulting in direct damage to the cells. However, research was carried out to produce thinner designs with greater flexibility for vehicle applications (Ohshita et al., 2019). Some modules are currently available in the market with some degree of flexibility. SunPower's flexible panels are an example, being made from highly efficient IBC solar cells which are able to bend up to 30° (Sunpower, 2020). Overall, for applications that require substantial flexibility, c-Si based technologies are currently not suitable options.



(a) A flexible PERT solar cell developed by (Ohshita et al. 2019)

(b) A commercially available flexible module by SunPower, based on c-Si IBC solar cells (Sunpower 2020)

FIG. 5.5 Examples of crystalline silicon cells and modules with mechanical flexibility

Transparency

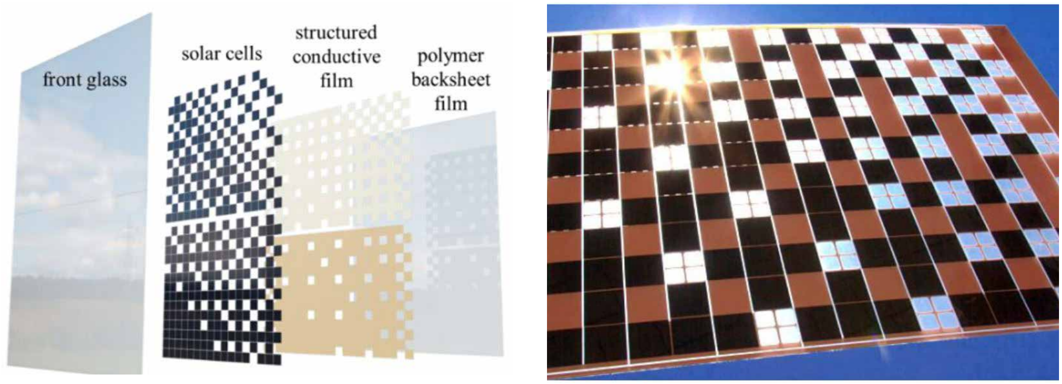
Up until recently, c-Si modules achieved limited levels of transparency by using a glass-glass configuration. This entails the standard white back sheet being replaced by another glass laminate to let light pass through the spaces between the cells. These modules have been used regularly in skylights and atriums. To achieve higher levels of transparency in the c-Si modules, methods include increasing the spacing between the cells as shown in Figure 5.6. However, the greater the distance between the solar cells, the lower the energy produced per unit of area, although such an application also benefits from double-sided exposure to air circulation, which prevents power losses due to increased temperature.

Another example of module technology that changes the standard cell interconnection patterns and results in transparency to some extent is the mosaic method, developed by Fraunhofer ISE (Mittag, et al., 2018). The concept consists of metal wrap through (MWT) cells that can be distributed across the module area in any given pattern. A structured conductive film is then carefully designed to match the cell distribution. The structure of this module can be seen in Figure 5.7.

(a,b) Examples of two applications with c-Si solar modules (Building Constructions 2020)

(c) A recent development in semi-transparent c-Si PV windows by (Peng et al., 2019)

FIG. 5.6 Examples of transparent c-Si applications



(a) The mosaic module concept developed by Fraunhofer ISE

(b) Schematic of how the module is manufactured (Mittag, et al, 2018)

FIG. 5.7 Mosaic module technology

Size

C-Si solar cells are usually available in two sizes, 5 and 6 inches. Commonly used commercial modules consist of 60, 72, or even 96 solar cells connected in a series, resulting in voltages of around 40 V to 63 V per module. Cutting techniques have also helped to create c-Si based modules with different shapes and sizes. This is important because integration into built environments is no longer constrained by a standard module size. Fraunhofer ISE developed the Design2PV method as an algorithm that allows users to cluster different cell sizes and shapes into a variety of different module layouts (Fraunhofer ISE, 2020). Since cells can vary in shape and size, it is important to connect them carefully. As stated before, in a series connection, the cell generating the lowest current limits the entire array; therefore, connecting a high area cell in series with a very small one hinders the ability of the larger cell to produce more power. The algorithm prevents such a problem (Kuhn et al. 2019).

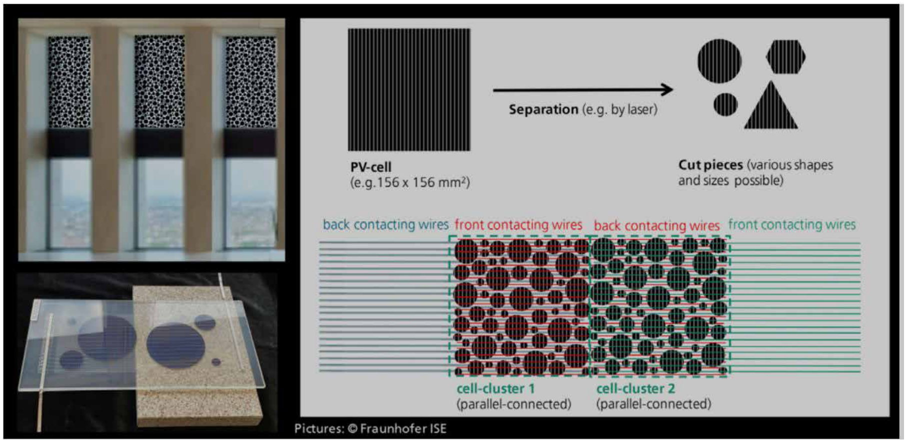


FIG. 5.8 The Design2PV concept by Fraunhofer adopted from (Kuhn et al. 2020)

Colour

In response to growing demands for architectural applications of PV technologies, many new techniques have been developed to introduce a large variety of colours into c-Si based PV modules. However, some of these technologies can also apply to some of the second-generation PV technologies (thin-film technologies). Some of the common ways to develop a PV product with a different colour (besides the standard dark blue or black colour) are the following:

(a) Dutch design solar brick pattern printed module (Slooff, et al., 2017)

(b) The Colorblast® concept by Kameleon Solar (Kameleonsolar 2020)

FIG. 5.9 Ceramic pigment on c-Si based PV modules.

(a) MorphoColor module by Fraunhofer ISE (Kuhn et al. 2020)

(b) The Kromatix™ concept developed by Swissinso (Kameleon solar 2020)

(c) optic filter approach developed by TU Delft

FIG. 5.10 Optic systems deployed on c-Si solar modules.

A - Ceramic pigments

Ceramic pigments can be fused into a glass matrix during tempering. The pattern selected can be applied either via rolling, screen printing, or digital printing (Kuhn et asl. 2019). This technique offers incredible versatility of design, such as mimicking standard building materials such as bricks (Slooff, van Roosmalen, L.A.G. Okel 2017), to even reproducing works of art such as the concept presented by Kameleon Solar (Kameleonsolar, 2020).

The coverage factor plays an important role in effectively hiding the solar cells beneath the patterned glass, the greater the coverage factor, the greater the energy losses produced by the technique. Careful steps are taken to properly hide the solar cells whilst keeping energy losses as low as possible (Slooff et al., 2017).

B – Coloured coatings

Selective reflection of light within the visible spectrum via photonic structures is another way to change the colour of a PV module. This technique requires careful design of filters that only reflect the light of a given wavelength range whilst improving transmittance in the remaining. In this way, losses are kept relatively low. One advantage of the technique is that highly saturated colours can be produced, but compared to ceramic inks, its versatility is limited to monochromatic tones (Kuhn et al., 2020).

As is the case of ceramic inks, energy loss is highly dependent on the colour produced, the use of textured surfaces, and other parameters (Røyset, et al., 2020).

5.3.1.2 Second-generation PV Technologies: Thin-Film Solar Cells

Another family of PV technology are thin films which are thinner than c-Si technologies by a factor of 100, which allows for the development of lightweight and flexible modules. These technologies are also known as thin-film photovoltaic technology. Thin-film technology is much better at light absorption than c-Si technology, however, these technologies suffer from other drawbacks when it comes to power generation that limits their efficiency to a maximum of around 17-18% (Rezaei, et al., 2018). Currently, c-Si remains the leading technology in terms of efficiency and durability; therefore, the market share of thin-film technologies is quite low, at 5% (Fraunhofer ISE, 2020)

Three commercially available thin-film technologies are presented below:

I - Amorphous silicon solar cells (a-Si:H)

Amorphous silicon (a-Si) is the oldest thin-film solar cell technology available. It has been heavily used in small electronic devices such as calculators, watches, etc. Compared to mono-Si solar cells, a-Si has nearly 40 times better light absorption (Mesquita, et al., 2019); however, the presence of tail states in its structure produces a significant reduction in the voltage the cells can produce (Nayak et al., 2019), hence making it one of the least efficient technologies available, alongside the Staebler-Wronski effect (Staebler & Wronski, 1977), resulting in stagnation in efficiency improvements. Nayak et al. (2019) argue that no significant breakthrough has been achieved for this technology in the last ten years, with most of the current research focussing on its use in Silicon Heterojunction (SHJ) solar cells. Current laboratory efficiency records remain close to 14%, whereas in commercial modules, it is closer to 10% (Mesquita et al., 2019).

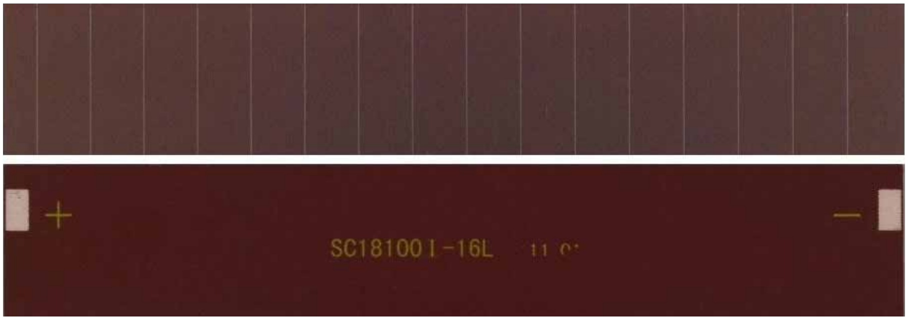


FIG. 5.11 a-Si solar cell from WSL solar (WSPSolar, 2020)

II- Cadmium-Telluride technology (CdTe)

Among the thin-film technologies, CdTe solar cells constitute the greatest share of production worldwide, with North American companies being the main producers (NREL, 2020). In Figure 5.12, the layers of stacked elements on a CdTe cell are shown.

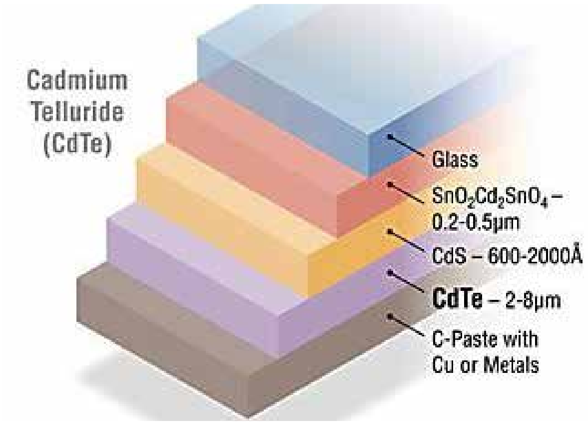


FIG. 5.12 Schematic of a CdTe solar cell. (NREL, 2020)

Recent breakthroughs have led to an increase of the power conversion efficiency of CdTe solar cells, close to 21% (Nayak et al., 2019), making them compete with multi-crystalline silicon solar cells but at a lower manufacturing cost (NREL, 2020). Another advantage of this technology is excellent thermodynamic stability, which means that under high temperatures, its efficiency losses are significantly lower than c-Si technologies (Mesquita et al., 2019). The main drawbacks of CdTe cells are concerns about environmental and health hazards, as cadmium is considered a toxic material. Additionally, telluride is a rare element, raising concerns about scarcity if it receives high demand (Ghosh, 2020).

III- Copper Indium Gallium Selenium (CIGS)

CIGS solar cells are among the most versatile technologies that have reached industrial maturity (NREL, 2020b). The technology also has a gallium-free variant, usually refer to as CIS. Because of this, many literature sources use the general abbreviation of CI(G)S (Ghosh, 2020). Their versatility relies on the fact that these cells can be deposited on metallic, plastic or glass substrates in any form factor. The schematic of the cell is very similar to that of CdTe, as shown in Figure 5.13.

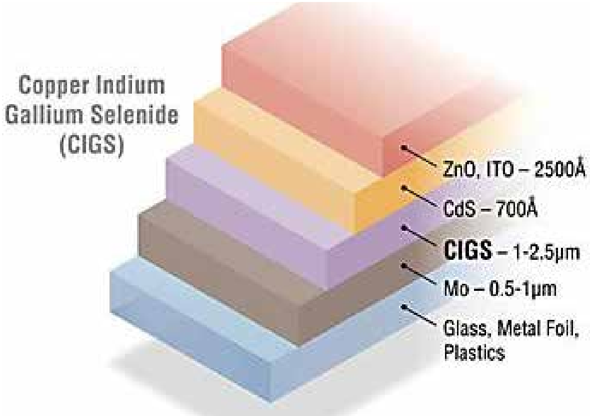


FIG. 5.13 Schematic of a CIGS solar cell. (NREL, 2020)

In terms of power conversion efficiency, laboratory cells have reached 22.9% and laboratory modules 19.2% (Mesquita et al., 2019). However, commercial module-level efficiencies are still around 15%, with degradation rates being their most significant challenge to overcome (Ghosh, 2020).

Cell interconnection of thin-film solar cells is a process performed during manufacturing. In contrast to c-Si technologies, thin-film cells are created via scribing techniques that differentiate one cell from another. Given that in thin-film modules, solar cells usually have relatively small surface areas compared to c-Si cells, commercial thin-film modules have low current and very high voltage values. A c-Si module with a rated power of 400 Wp has a maximum voltage of around 40 V and 10 A of current generation. A thin film module with a similar power value has 2.3 A of current, and around 175 V of voltage. However, smaller cell layouts have proven to be very effective in shading tolerance (Ziar et al., 2017).

Physical consideration for architectural application

One of the key benefits of thin-film technology for architectural application is that it is more versatile in physical customizability. In terms of flexibility and weight, these technologies offer much more than c-Si technology. Thin-film technology has been used to create semi-transparent windows with a vast array of sizes, colours, and transmittance levels.

Flexibility

Currently, there is a great variety of products based on thin-film technology, which are lightweight and have great flexibility. One such example is eFlex from Flisom (2020), whose CIGS panels are constructed on a Polyamide substrate to achieve weight densities of less than 2 kg/m^2 for a power production of 215 W on a 2.24 m^2 area.

FIG. 5.14 Flexible CIGS solar panel from Flisom (2020) With an efficiency of 9.59%

Another advantage of flexible thin-film solar products is their relative ease of manufacturing via roll-to-roll (R2R) techniques; this, alongside the low use of substrate materials and cheaper substrates, can result in economically attractive products with the highest power per kg of any other cell technology (Ramanujam et al., 2020). However, their power conversion efficiency on commercial products is still behind that of standard c-Si panels, with commercial modules from companies such as MiaSole reporting cell efficiencies of 17.5% (Miasole, 2020). While lab research has shown improvement with reported efficiencies of around 20.4% (Ramanujam & Singh, 2017).

In thin-film technology, as with other families, physical customisation introduces losses. As an example, FirstSolar's rigid modules have an efficiency of 22.1%, while on flexible willow glass substrates, efficiencies reach 16.4% (Ramanujam et al., 2020).

Customised shapes can be produced by separating production into three processes. Firstly, an endless thin-film solar cell is produced via an R2R technique. Secondly, laser cutting is performed in the required size and shape. Finally, cell interconnection is done via lasers and printing (Adamovic, et al., 2017). This provides a level of customizability that c-Si technologies do not have. Some new concepts are being developed based on this approach. SIARQ (2020) has showcased concepts based on CIGS that combine both flexibility and a custom shape. A pentagonal shape concept, and a solar urban HUB, both of which can be seen below.

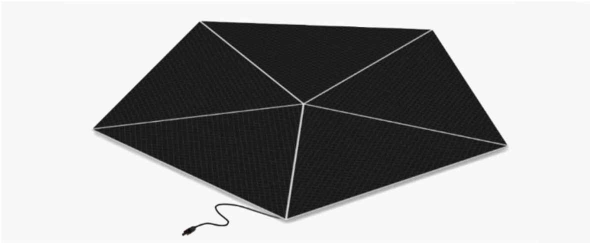


FIG. 5.15 Examples of CIGS modules with a custom shape, size, and flexibility (SIARQ, 2020).

Transparency

Thin-film technology is also highly versatile with regards to transparency. In this aspect, thin-film technology offers the following advantages: (a) The ease in which transmissivity can be achieved, as the level of transparency can be tuned with high versatility, (b) given that they have low temperature coefficients, the cells can be incorporated in window layouts without negative performance effect due to high operational temperature (Yeop Myong et al. 2015).

One company with substantial experience in semi-transparent solar glass is Onyx Solar(2018). The company offers products with several levels of transparency with power densities ranging from 28 Wp/m^2 for the most transparent to 57.6 Wp/m^2 for the products that have almost no transparency at all. The maximum transmittance of visible light on their products is around 28.4% (Onyx Solar, 2018).

FIG. 5.16 Semi-transparent a-Si skylight system from Onyx Solar. (Onyx Solar 2018)

Colour

Most colour techniques used are applied on the encapsulated glass of the PV modules. Most of the examples presented for the first-generation PV technologies are suitable for thin-film technology as well. For this family, customisation of colour and transparency can also be achieved via modifying the absorbers' thickness (Tsai, 2020).

FIG. 5.17 Transparent and coloured PV modules via modification of the Cell thickness (Tsai, 2020).

5.3.1.3 Third-generation PV Technology: Novel Concepts

It was a commonly held belief that the first generation of PV technology (c-Si) was due to be replaced by the second-generation (thin film) because of the ease of fabrication and lower costs (Ramanujam & Singh, 2017). However, a third generation was envisioned back in 2002 (Green 2002) to tackle the performance problems of single-junction technologies, such as the ones discussed above. The third generation is currently a compromise between a wide variety of solutions that seek to overcome material scarcity, flexibility, and costs. The number of PV technologies that can be considered as belonging in this category is vast. However, very few of them are currently in or close to commercial status for regular terrestrial applications. In this section, two technologies that could potentially find use in architectural applications are briefly discussed: Perovskite solar cells and organic solar cells.

I - Perovskite solar cells

In recent years, Perovskite solar cells (PSC) have rapidly become one of the most researched technologies in the PV sector (Roy et al., 2020). The interest lies in that this technology combines the high performance of the c-Si cell with comparatively lower production costs. In terms of efficiency, this technology had a jump from 3% (Kojima, Teshima, Shirai, & Miyasaka, 2009) to 25.2% (NREL, 2021) in just 10 years. Such an improvement took several decades for other technologies.

Despite the evident advantages, PSC must overcome a series of obstacles to reach commercial status. Degradation is a major concern: while c-Si solar cells can have a lifespan of up to 25 years, so far, PSCs have only reached a maximum of one year of use. The factors that most contribute to this degradation are moisture, oxygen, temperature, and illumination-induced degradation (Roy et al., 2020).

II - Organic solar cells

Organic solar cells (OSC) can be manufactured with similar techniques as those of PSCs. This technology is one of the most suitable in terms of flexibility (Ajayan et al., 2020) and customizability (Gevaerts 2017). Unlike PSCs, OSCs have reached a relatively mature industrial status, with commercial products already available to the public. The main drawbacks of this technology are low electron mobility, sub-optimal light absorption (Ajayan et al., 2020), and degradation (Gevaerts, 2017). The power conversion efficiency of the OSC is rather limited. Although laboratory concepts have reached 18% (NREL, 2021), most of these products have values below 10% (Ajayan et al., 2020), making it the least efficient PV technology among those presented here.

Physical consideration for architectural application

Since one of the main appeals of the technologies discussed is their flexibility, good encapsulation techniques are required to reduce the danger of early degradation due to moisture. Flexible foils have been developed to overcome this issue and companies such as ASCA claim that, with proper care, the lifetime of a module can reach 20 years (ASCA, 2020).

Some examples of the versatility of the technology are shown below. The Infinity PV solar tape showcases the high flexibility achieved by OSC. The product has an efficiency of 1-6% depending on the product. The width of the tape ranges from 152 – 305 mm, with lengths up to 100m (InifinityPV, 2020).

One example of an operational project is the Smart Design Bench by ASCA. Installed in the King Abdullah University of Science and Technology, users can recharge their mobile devices via USB ports. A battery is installed and based on the luminosity of the environment, lights inside the furniture turn on and off automatically (ASCA, 2019).

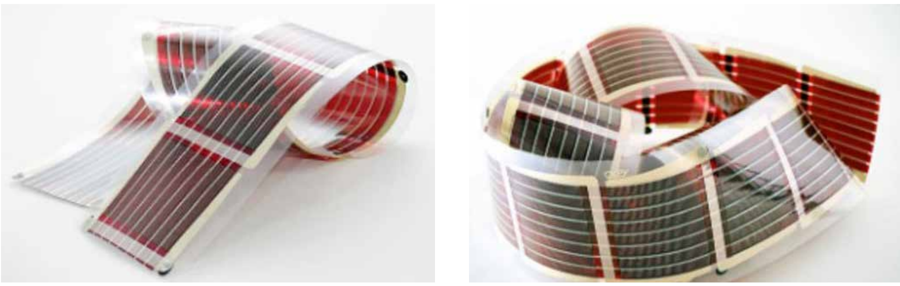


FIG. 5.18 The infinity PV tape based on OSCs with power production of 1-6 W/m2. Can be attached to a variety of surfaces using an adhesive.

FIG. 5.19 PV module based on OSC integrated into street furniture (ASCA, 2019)

5.3.2 Overview of the technologies presented and their features

In the last section, we reviewed different generations of PV technology and explored new possibilities which allow their architectural application. In Table 5.1 , this information is summarised.

TABLE 5.1 Overview on the PV cell technologies

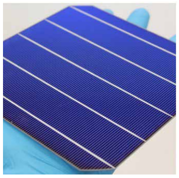
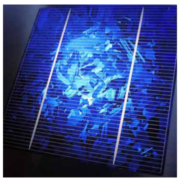
			Technical properties			Physical properties						
									Customisation			
			Cell Level (%) (M. Green et al., 2021)	Module level (%) (M. Green et al., 2021)	Power loss (%) per °C of temperature above 25°C	Colour	Shape	Size	Flexible	Translucency	colourisation	Resize
1st Generation Silicon based	**Mono TOPcon (m-Si)**		**24.6** (Chen et al., 2020)	**23.0** (Jinko-Solar, 2021)	**0.32** (Wu et al., 2019)	Blue/ black	**Sq**	**6’**	✗ ***	✗	✓	**
	Poly (P-Si)		**21.3**	**20.4**	**0.45** (Adeeb, Farhan, & Al-Sa-laymeh, 2019)	Blue/ black	**Sq**	**6’**	✗ ***	✗	✓	✓ **
	Mono IBC		**26.6**	**24.4**	**0.29** (SunPow-er, 2010)	Blue/ black	**Sq**	**5’**	✗ ***	✗	✓	✓ **

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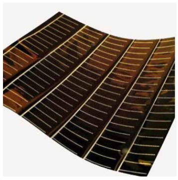
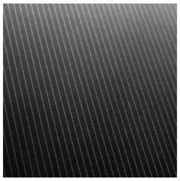
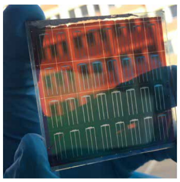
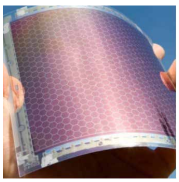
TABLE 5.1 Overview on the PV cell technologies

			Technical properties			Physical properties						
									Customisation			
			Cell Level (%) (M. Green et al., 2021)	Module level (%) (M. Green et al., 2021)	Power loss (%) per °C of temperature above 25°C	Colour	Shape	Size	Flexible	Translucency	colourisation	Resize
2st Generation Thin Film	CdTe		22.5	19.0	0.15 (Singh & Ravindra, 2012)	Black	V	V	✓	✓	✓	✓
2st Generation Thin Film	CI(G)S		23.3	19.2	0.36 (Virtuani, Pavanello, & Friesen, 2010)	Black	V	V	✓	✓	✓	✓
2st Generation Thin Film	Amorphous silicon (a-Si:H)		10.2	12.3	0.13 (Virtuani et al., 2010)	Brown	V	V	✓	✓	✓	✓
3rd Generation	Perovskite		25.5	17.9	0.17 (Jošt et al., 2020)	varies	V	V	✓	✓	NA	NA
3rd Generation	Organic		18.2	8.7	+0.007 (Bristow & Kettle, 2015)	varies	V	V	✓	✓	✓	Y

*** Size can be changed to a limited degree*

**** Flexibility at the module level is possible, but not of the cell itself .*

V – Varies

Sq – Squared shaped

Sizes are given in inches (Commercial cells)

Table 5.1 shows the characteristics of the discussed photovoltaic cell technology generations. These characteristics can be analysed to assess the suitability of the technology for specific APA. In general, due to the maturity of the c-Si technology market, customisation on both the cell and module level is possible, and its higher technical performance in terms of conversion efficiency leads it to being the dominant technology for architectural applications (Farkas, et al., 2013; Kuhn et al., 2020). Although these technologies have a longer service life and higher performance, their manufacturing processes include higher energy consumption, labour costs, and degrading faster with increased temperature (T. Zhang, Wang, & Yang, 2018). Moreover, some other technical and physical properties of thin-film technology make them more suitable for specific locations and certain applications, especially considering their shade-tolerance in urban applications and flexibility for use on curved surfaces. Regarding 3rd generation technologies currently, their low conversation efficiency and stability remain the biggest drawback for their use in APA. However, these issues are being steadily solved via research projects, and soon will be able to compete with 1st and 2nd generation technologies. In addition, extensive research and development is also dedicated to combining these technologies as an additional layer (known as multi-junction/tandem) to 1st and 2nd generation cells in order to increase conversion efficiency.

5.3.3 Method for finding a suitable technology

In the following section, we explored the possibility of using one of the multi-criteria analysis methods – Analytical Hierarchy Process (AHP) – to find a suitable PV technology in the context of the architectural application.

In the science of management, there are methods to overcome complex decision-making processes. Multi-criteria analysis (MCA) is an operational assessment method for decision support that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multiple interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems (Wang et al., 2009). It has been widely applied in social, economic, agricultural, industrial, ecological, and biological decision-making processes, specifically applied in many projects related to sustainable development and environmental impact analysis (ibid).

Analytical Hierarchy Process (AHP) is one method for MCA and most preferred for tangible and intangible factors (Odemir and Sahin 2018). As the AHP method uses simple ranking questions and a schematic overview of the criteria, it is suitable for situations with stakeholders who are not familiar with the underlying theoretical concepts of the decision-making situation (Wang et al., 2009). The AHP method consists of dividing a given problem into different components and establishing a hierarchy shown in Figure 5.20. The hierarchy is constructed starting from the main goal of a given project. At a second level, the main criteria are selected based on inputs from experts on the main factors involved in the decision-making process, which can vary, depending on the project goal. In addition, sub-criteria can be introduced to consider further aspects and to enrich the model's level of detail. The structure then is analysed by the selected hierarchy; this means that alternatives are studied according to each sub-criterion and weighed according to the main goal of the project.

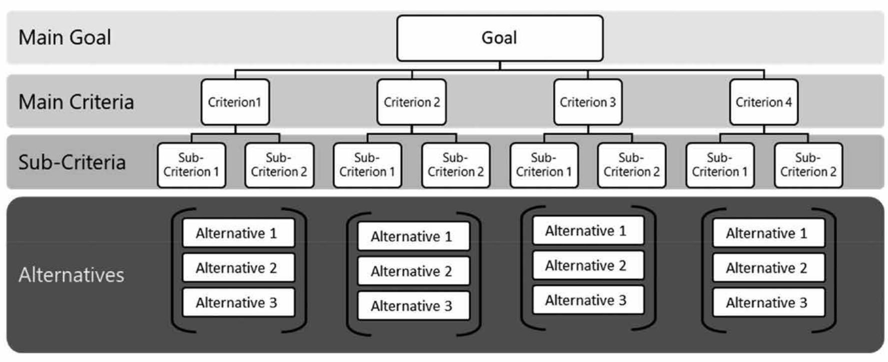


FIG. 5.20 Multi-level AHP Structure

As shown in Figure 5.20, the model has four attributes that need to be defined based on the context and goal of the project:

A Project goal
B Criteria and sub-criteria (defined by experts of the field)
C Alternatives (options on which we need to select)
D Weights (specified by the user of the and problem-owner)

Next to the project goal, which varies depending on the project, criteria on which decision making should happen needs to be selected by experts of the field or the user. Then a sub-criterion is chosen as an indicator for the main criterion. In the next step, based on the sub-criterion, each alternative is compared with another and is given a ranking. It is important to have secondary data of all the alternatives in regard to each of the sub-criterion selected. In the final stage, in order to have prioritisation over the main criteria, the user weighs the level of importance of each criterion over one another, dependent on the goal of the project and his personal preferences in a so-called pairwise comparison (Figure 5.21).

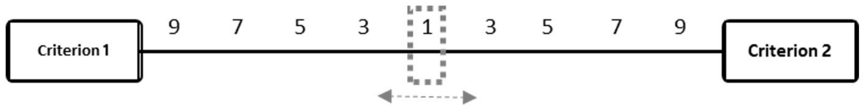


FIG. 5.21 Pairwise comparison

In the pairwise comparison, each number has been assigned to a degree of preference and shown in the table below:

TABLE 5.2 Numbers assigned to the level of importance

Intensity of importance	Definition
1	Equal Importance
3	Moderate/weak importance
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance

The result for each process is a matrix that will be used to calculate ratios and quantify preferences over all the alternatives. More detail on the processes in the AHP method and complete mathematical calculations can be found by Saaty (1980)

As part of this study, we experimented on whether the AHP method can be applied to the challenge of comparing and selecting different PV products or cell technology. We first reviewed the method and applied it to the graduation project of Jari Dijkema on Product Development for Modular PV (Dijkema, 2019).

To reflect on important factors in the decision-making process with applying PV into architecture, and as part of the interviews with architects conducted in chapter 4, we asked the architects about the decisive factors involved in their decision-making process. They ranked the importance of these factors by providing us with a score ranging from 1-9. In Table 5.3 these factors are presented. Some of these factors are important when stakeholders choose a ready-made product/module while others find importance within the development process of cell technologies. Moreover, for each of these factors, we have suggested some indicators.

TABLE 5.3 Decision-making factors for APA

Average score (0-9)	Decision-making factor	Indicators linked to factor	Product or cell level
7.7	Aesthetical aspects	• Product Form • Homogeneity • Available colours • Reflectiveness • Pattern • Texture • Junction box position	Product/ level
7.7	Customizability	• Size • Shape • Transparency • Flexibility • Colour • Pattern	Cell level
7.6	Technical performance	• Efficiency • Shade resilience • Degradation rate • Temperature coefficient • Spectral response	Both
7.5	Economic	• Cost per Wp • Cost per m² • Service life (years)	Both
7.5	Multi-functionality	• Load-bearing • Water-tightness • Cleaning technology	Product level
7.2	Sustainability/circularity aspects	• End of life scenario • Recyclability • Energy pay-back period (EPBP) • LCA (Climate-change + resource depletion + toxicity	Both
6.9	External incentives	• Quality assurance • Safety certificates • Compliance with national codes of BIPV	Product level
5.7	Marketing and branding aspects	• Market share • Company history and portfolio	Product level

Stakeholders can select the suggested indicators to detail the preferences they have on specific factors and, accordingly, make a more informed decision. In the AHP method, these factors can be considered the 'main criteria', and our suggested indicators can be regarded as 'sub-criteria' with the PV technologies themselves acting as the 'alternatives' in the AHP method.

5.3.4 Benchmark Study: Application of AHP in Modular PV Carports

This study is part of the graduation project of Jari Dijkema (from now on referred to as the 'researcher'). In his study, he investigated the design and development of a solar carport structure. To apply the method, the researcher needed to assign the elements in the hierarchy to the context of the project. In this project, the goal is to find the PV technology best suited for Modular PV carports. Based on the input from project stakeholders, in Figure 5.22, the main criteria considered for this analysis are selected. Based on these selections, the researcher, along with project stakeholders, selected the sub-criteria. The project stakeholders are asked to give their preferences on each pair of main criteria as shown in Figure 5.23.

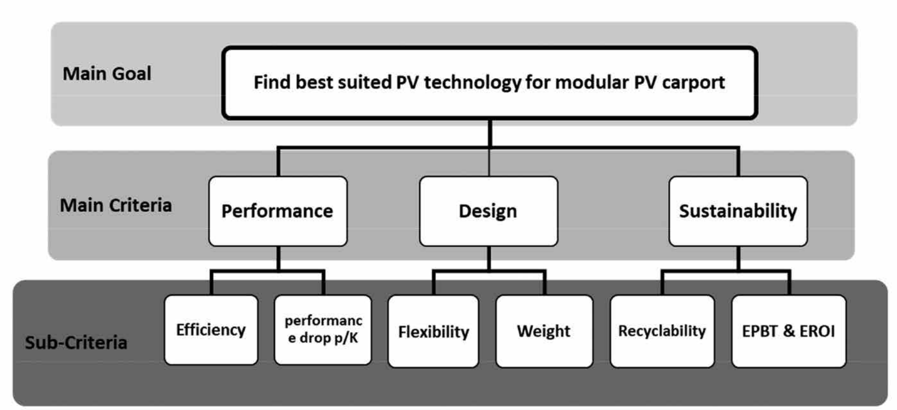


FIG. 5.22 Applied AHP hierarchy

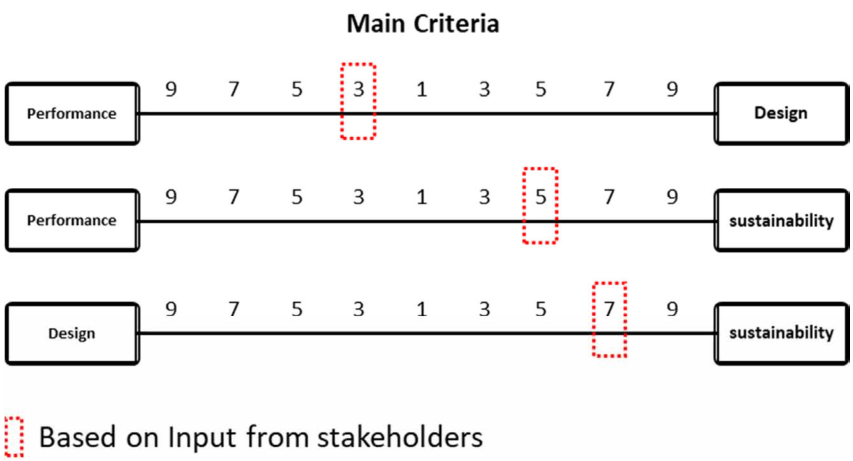


FIG. 5.23 Pairwise comparison

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During the next step, the PV cell technologies used for comparison were selected. For this project, 5 types of PV technology are considered as alternatives. The researcher made their selection based on the maturity and availability of the technology in the market. Based on the information in the literature and product specification, the pairwise comparison for each sub-criterion was developed. Two examples from the matrices developed based on the pairwise comparison of alternatives for *efficiency* and *recyclability* sub-criterion are shown in Figure 5.24.

sub-criterion: **Efficiency**

	mono c-Si	poly c-Si	CdTe	a-Si	CI(G)S
mono c-Si	1	3	7	9	7
poly c-Si	1/3	1	5	9	5
CdTe	1/7	1/5	1	5	1
a-Si	1/9	1/9	1/5	1	1/5
CI(G)S	1/7	1/5	5	5	1

Normalised and averaged →

	result
mono c-Si	0,51
poly c-Si	0,29
CdTe	0,09
a-Si	0,03
CI(G)S	0,09

sub-criterion: **Recyclability**

	mono c-Si	poly c-Si	CdTe	a-Si	CI(G)S
mono c-Si	1	1	9	3	7
poly c-Si	1	1	9	3	7
CdTe	1/9	1/9	1	1/5	1/3
a-Si	1/3	1/9	5	1	3
CI(G)S	1/7	1/5	3	1/3	1

Normalised and averaged →

	result
mono c-Si	0,38
poly c-Si	0,38
CdTe	0.03
a-Si	0.15
CI(G)S	0.06

FIG. 5.24 Pairwise comparison of alternatives for efficiency and recyclability sub-criterion

Final score	
mono c-Si	0,238
poly c-Si	0,247
CdTe	0,242
a-Si	0,116
CI(G)S	0,157

FIG. 5.25 Final Results

Regarding efficiency, as discussed in the previous section of this chapter, crystalline silicon technologies have the highest position compared to other alternatives. Mono and polycrystalline technologies also have better performance for recyclability, based on the recyclability scenarios mentioned by (Vellini et al. 2017; Xu et al. 2018).

In this project, the final synthesis of the different values resulted in the poly c-Si scoring higher than other alternatives and being deemed the best-suited technology for modular PV carports. For this project and based on the weights given, poly-c-Si technology showed to be recyclable with high efficiency whilst still having a relatively low energy pay-back time.

Although the results are very close in the first 3 technologies, analysis of the final scores show, surprisingly, that the CdTe technology comes seconds after poly c-Si. In fact, the weights received by the stakeholders on the sustainability aspects resulted in both CdTe and poly-c-Si scoring higher than mono-c-Si, which has the highest efficiency amongst the alternatives.

5.4 Discussion and Conclusion

This chapter explored different generations of PV technologies and provided an overview of their potential in architectural application. In the second part, we benchmarked the application of the AHP method as an approach to more precise decision making in selecting these technologies for specific applications/projects. Our overview of contemporary technology presents the following:

First-generation technologies (c-Si) have secured the greatest market share due to the advances in efficiency and technical performance. Such dominance has allowed the technology to benefit from the economy of scale, leading to extensive cost reduction and accessibility in the form of various module types. However, the physical flexibility of this technology for customisation on a cell level remains limited, therefore most of the development has focused on module manufacturing technologies. In regard to 2nd generation technologies, higher temperature tolerance can make them a more appropriate technology for applications that suffer from double side ventilations. However, automated production lines make it difficult for customisation in terms of size and shape but still allows them to be lightweight and flexible, with some level of transparency. Finally, 3rd generation technologies have received increased attention due to advances in the laboratory environment leading to them being better able to compete with 1st and 2nd generation, with lower production costs and reduced environmental impact. This makes them an interesting option for architectural application, although their limited service life expectancy still remains an imposing challenge.

As shown in the previous section, the AHP method can help to translate qualitative preferences of stakeholders into numerical values and to enable applying those preferences onto each of the factors in the decision-making process. Overall, the benchmark showed, despite the effort needed for the development of the mathematical calculation, that the results generated by the method are accurate and reliable.

The benchmark, on the suitability of the AHP method can be seen from two angles. For product development purposes, the benchmark showed that the AHP method can be helpful as there are several PV technologies available in the market to choose from. Furthermore, the method can be used throughout different stages of development. Firstly, when selecting the cell technologies themselves, mostly considering the technical, environmental, and economic aspects, and later when selecting module manufacturing technologies, it helps to see which allows more customisation of the appearance of the product. Therefore, if a tool includes different PV technologies (presented in the first section) and decision-making factors (as discussed in the second section) become available, the users can simply select their preferences regarding the technologies and important aspects of their project and then assign a weight to each factor, with the tool being able to present the best suited technology.

The AHP method can also be helpful for finding a suitable PV product. However, as there is a lack of alternatives when it comes to commercialised products with reliable and professional sale and after-sale services, and safety certification needed for architectural application, it is not clear whether the effort needed for the development method can be justified. Instead, as a recommendation, an independent web-based search database can be developed to allow the comparison of different PV products including detailed information from each supplier on the product and possibilities with regards to customization and architectural adaptation.

As a recommendation for future studies, we believe the AHP method has the potential to be developed for the decision-making process in this field, however, it requires extensive and impartial data collection of the PV technology or from module manufacturers who would like to be transparent about the specifications and performance of their products. Moreover, some aspects such as brand reputation and marketing, as discussed in Chapter 4, have been shown to have an impact on decision making that is hard to be quantified and considered in the AHP method. This research can be considered as a feasibility study for the development of the online tool for comparing and choosing a suitable PV technology for concept development and product selection on projects.

PV-Chimney Experimnetal protytype, 2018 PVMD. Author’s personal collection.

6 Concept Development

Part of this chapter is published as:
Ortiz Lizcano, J. C., Haghighi, Z., Wapperom, S., Infante Ferreira, C., Isabella, O., vd Dobbelsteen, A., & Zeman, M. (2020). Photovoltaic chimney: Thermal modelling and concept demonstration for integration in buildings. Progress in Photovoltaics: research and applications, 28(6), 465-482.

PV chimney concept has been filed as a patent:
Haghighi Zoheir, Camilo Ortiz Lizcano Juan, Isabella Olindo, Zeman Miroslav, Van Den Dobbelsteen Andy (2021), PV-chimney, WO2021006726A1, World Intellectual property organisation, https://bit.ly/2ODjs9d

In the previous chapters, we explored the different approaches to the usage of PV in architecture and provided an overview of the existing PV technologies and approaches in the adoption process, presenting it in the form of the design decisions matrix. Moreover, we discussed the symbiotic relationship that could be developed between PV and the building anatomy and highlighted the experiences and considerations architects have in mind for using PV in architecture.

In this chapter, we investigate new concept development with PV technology for architectural application and present three case studies on new concept development for different projects. Based on these cases, we tried to derive a general approach for concept development.

6.1 Introduction

In response to a fundamental question on why we require PV products/modules, it is important to keep in mind that PV technology, the technology in which semiconducting materials convert photons into electrons, cannot be deployed without the development of a product (or what is known as a module). The reason behind it roots in the technical and physical limitations of PV cells. From a technical angle, a single solar cell cannot produce sufficient power to be used in an electrical energy system and for that reason, they need to be connected in series to deliver a certain voltage (Zhang et al., 2018). On the other hand, the semiconductor material used in the PV technology is used in very thin wafers, which make them very fragile and vulnerable when exposed to extreme weather conditions (Farkas et al., 2009). Therefore, encapsulation materials such as ethylene-vinyl-acetate (EVA) are used to ensure the cell's consistent performance, reliability, and stability; this is also used to keep out moisture. In addition to EVA, connected cells are deposited between transparent or opaque covers using hardened or tempered glass and tedlar sheets for protection against the environment – humidity, dust, corrosion (Zhang, et al., 2018) – And to increase the mechanical strength; for fixation and mounting, aluminium frames are used around the PV module. Figure 6.1 shows one layout of a PV module, including PV cells, layers of EVA and the front and back glass.

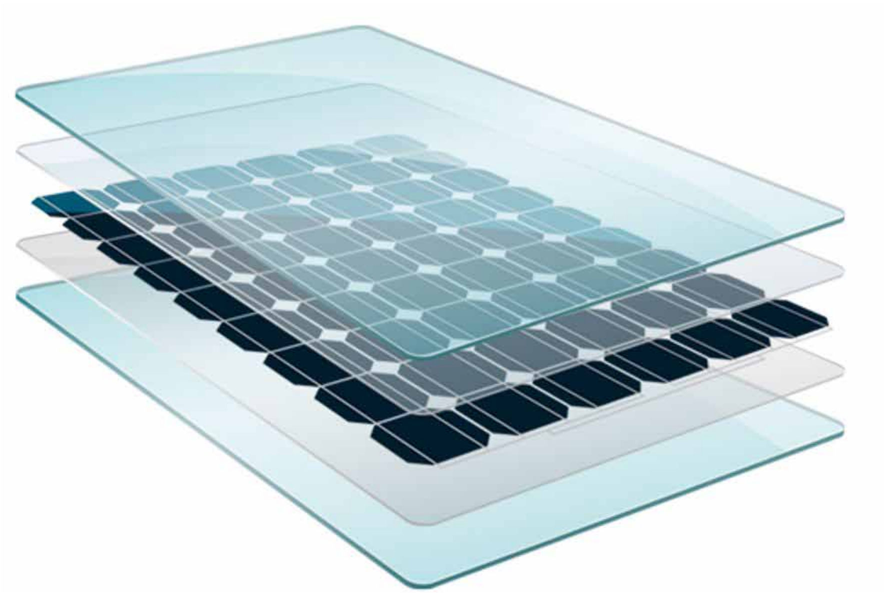


FIG. 6.1 Glass-Glass PV module (Swissinso, 2021)

Existing PV products that are known as standard modules and are mass-produced in the industry, are made of 2 protective layers (in front and back), encapsulation materials (EVA) and a frame. The size of these PV modules is somewhat standardised, which is directly linked to the power outputs of each PV cell. Overall, the arrangements of all of these additional layers root in the goal of optimising the energy yield of the PV system. However, for the architectural application of PV technology, such considerations are not the only ones a product is required to meet. Some of these considerations are mentioned by architects in Chapter 4. From the first instances in the adoption of technology PV in the built environment, these considerations have been undermined by the PV module manufacturer (Palz et al., 1984; Shukla et al., 2017). This is evident by the ever-rising trend of the use of industry-standard modules for rooftop applications.
Overall, an exploration of existing products shows an insignificant effort being put by the PV industry into the development of PV modules for architectural applications. This lack of consideration has existed from the early stages of research and development. At the same time, there is a long way to go to reach the development of products that are accessible for end-users.

In the previous chapters, we explored different PV technologies and the approaches that have been applied in the use of existing products in buildings. On the one hand, there has been a steep growth in the development of PV technology and addition of features and possibilities, and consequently, an expansion of the market demanding new applications of PV technology in the built environment, resulting in a growing interest to develop new products that fit better with market needs, offering better performance in terms of power generation (Jelle et al., 2012; Shukla et al., 2017). Furthermore, qualitative and quantitative research conducted on the unpopularity of PV technology amongst architects highlighted the lack of PV products for architectural application as one of the barriers for wider adoption of this technology (Farkas, et al., 2013; Larsson et al. 2018; Prieto et al. 2017).

The existing trend of new product developments can also be seen similarly to what is discussed in Chapter 3, on the degree of adaptation from a purely technical and industrial standardised modules toward full replication of generic building materials, as shown in Figure 6.2:

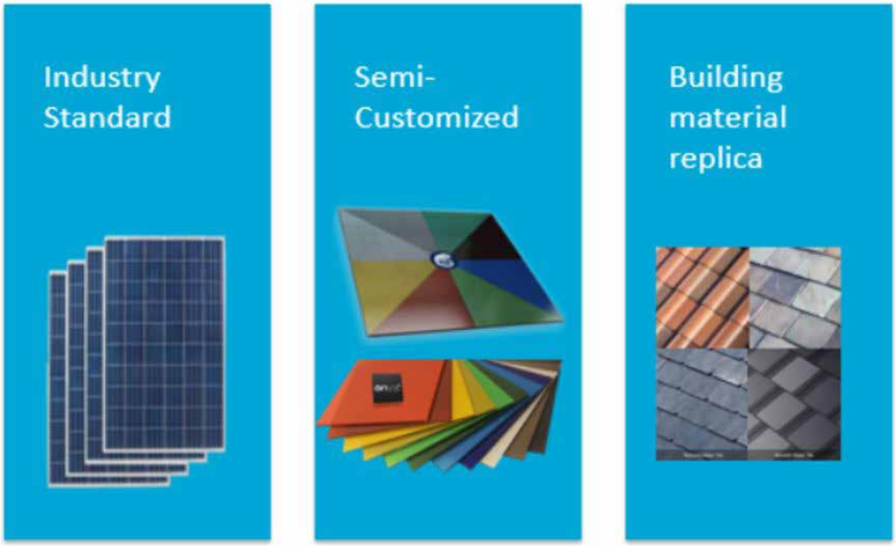


FIG. 6.2 Extent of adaptation of PV modules from industry standard to building material replica

As mentioned, industry-standard PV modules are still the PV products most used in building applications (IRENA, 2019). However, after the emergence of demand for building-integrated solutions, the manufacturers, without the introduction of a new line of PV products, tried to keep up with the trend by investing in R&D for the mounting system, which allowed for their standard modules to be used on the façade. In addition, they acquired certifications needed to comply with building regulations. Such a strategy can be seen in the product portfolio of many mass-producers of PV modules, where the R&D focus is primarily on the mounting system and the incremental improvement of products to meet building code requirements.

Several producers have realised the limitations of the first-generation products in architectural integration. Consequently, this has led to the emergence of two main trends in product development: Some research in recent years has identified the demand for customisation of standard PV products (Farkas, et al., 2013; Horvat et al. 2011; Kaan et al., 2004; Pelle et al. 2020; Reijenga et al., 2011).The physical properties that have been mentioned in almost all of this literature is, for instance, customisation in terms of size, shape, colour, and pattern (as discussed in Chapter 4 and 5). Based on the demand for modification and customisation of PV modules, a new approach emerged in the market that allows a limited degree of customisation to conventional PV modules, being aware of product cost increases and potential losses in energy yield, as a compromise to a higher acceptability and better aesthetic homogeneity to the hosting structure. These possibilities were discussed in Chapter 5 but mainly refer to using different colouring techniques, customisation of size and shape, and graphical patterns to further enhance design possibilities.

In a more extreme perspective, researchers are trying to develop PV products that are, to some degree, identical to conventional and generic building materials. Therefore, a 3rd R&D wave has emerged for products seeking to replicate generic building materials, mimicking their appearance. The best-known kind of these categories is the roof tile PV products that received a lot of attention after the introduction by Elon Musk of the development of Tesla roof tile products.

FIG. 6.3 PV tiles replicating generic roof tiles made (Solar Roof | Tesla 2016)

Although the Tesla roof tile products failed to enter and secure a share of the market several times, the trend inclined, and many other companies tried to come up with a product for the demand and expectations created for PV roof tiles (Ruposov & Belikov, 2021)

Several national and international organisations, such as SUPSI Swiss BIPV Competence Centre, EURAC Institute for Renewable Energy, SEAC and BIPVnederland, offer inventories of existing commercialised BIPV products for building applications. Although these databases are not always exhaustive, they provide a good overview of market trends and potentials in product development. In the status report from SUPSI, which gets published every 2-3 years, a market overview, perspective, and inventory of products are presented. In the report from 2020, despite a 14% reduction in the number of products represented in the database compared to the report from 2017, the share of products developed for roof applications was maintained at around 60% (Corti et al., 2020). In another research on existing BIPV products conducted by Abdelrazik (2018), the ratio of PV products suitable for roof vs façade is 80% vs 20%.

The points raised in this section, shows that despite the growing interest for PV products for use in buildings, existing companies struggle to fulfil market demands and consequently go bankrupt. This observation can be linked to some of the socio-economy reasons that are mentioned by architects in Chapter 4; It can also be linked to the fact that these new products are mostly designed for rooftop applications. As mentioned, rooftop applications are still very popular in the building sector, however, in the urban setting, the roof area is not enough to supply the energy needed to meet sustainability targets (Shirazi et al., 2019).

This chapter aims to understand the processes and different approaches in concept development and to document some of these experiences and identify the different steps and considerations in the development of new concepts with PV technology.

This chapter aims to answer the following question:

- What are the approaches, steps, and processes in the new product development of APA?

In the following section, we present our approach in the development of three concepts. Subsequently, the development of these concepts is explained and analysed, in order to identify the requirements and key considerations. Finally, the process map and discussions derived from these projects are presented, constituting a recommendation for a general process of product development with PV for architectural application.

6.2 Method

The study reviewed and analysed 3 concept-development projects. These projects were executed as part of the graduation projects for Masters' students at the Faculty of Architecture and Built Environment and at the Faculty of Electrical Engineering, Mathematics, and Computer Science of TU Delft, within the framework of the SolarUrban research programme. The selection of these projects is based on the concept novelty and research approach in the development process, but not through predefined categories. Figure 6.4 shows the projects that are studied in this chapter.

(a) PVCurtain (Prabhudesai, 2019) (b) PVcarport (Dijkema, 2019) C) PVchimney (Lysandrou, 2019)

FIG. 6.4 Overview of concept development projects

The discussion section analyses and compares the concepts based on their starting-points and on the research and development processes. The aim is to derive a general approach by mapping the processes and comparing the steps made by these case studies. The concept development is organised into 3 parts.

1. Project background, which includes the motivation for the initiation of the project, the requirements, and goals.
2. Research and development process, which presents the different steps in which the research finding or informed decisions by stakeholders directed the process.
3. Lessons learnt, which reflects on the project approach and steps undertaken in the process.

It is noteworthy to mention, considering the novelty and quality of these projects, that they could be seen from various perspectives, merely based on their technical and innovative findings. However, in line with the overall objective of this dissertation, we put an emphasis on the process and, in particular, on the starting-points, steps, and decisions in the research and development process. Furthermore, the findings of other chapters in this dissertation have not systematically been considered and applied Within the development cycle of these projects. The main reason is that these projects are developed in different timelines, and some results came in after the completion of these projects. However, based on the nature of these projects, we tried to apply some of the preliminary results and insights and use these projects to get feedback.

In the following section, each of the case studies are discussed and organised in accordance with the steps mentioned.

6.3 Concept development projects

6.3.1 PV curtain

6.3.1.1 Project Background

In recent years there has been growing attention to the research and development of bifacial solar cells (BSC) (Liang et al. 2019). A bifacial solar cell (BSC) is a photovoltaic solar cell that can produce electrical energy when illuminated on either of its surfaces, front or rear. The added value of the technology lies in the possibility to absorb reflected radiation that is not absorbed by the front surface. The application of bifacial modules is currently limited to applications such as pergolas or other ground-mounted or floating PV systems where the solar panels are elevated from the ground, and where a reflective surface exists beneath the module, which reflects a certain portion of light onto the backside of the bifacial module, thereby generating more electricity. Despite the trend in R&D and industrial bi-facial products, application of the technology within the built environment remains relatively unexplored. The above-mentioned facts were the key driver and starting-point to think about the development of the application for this technology for the built environment.

This project was carried out by Sukanya Prabhudesai as a master thesis graduation project of the Sustainable Energy Technology master track at the Faculty of Electrical Engineering, Mathematics, and Computer Science of TU Delft (Prabhudesai, 2019).

6.3.1.2 Process within the research and development

Step 1: Project Scoping and definition

To develop a building application with bifacial PV technology, it was necessary to investigate different surfaces in a building to see where such a technology can add value. In that respect, the team conducted a brainstorm and analysed surfaces that are exposed from two sides to direct or indirect solar radiation. As a result, few applications are found to be suitable to benefit from bifacial technology. These surfaces are:

- Parapets and roof barriers
- Roof canopy and skylights
- Transparent façade surfaces

Analysis of these applications showed that existing commercialised bifacial glass-glass PV modules could be applied to almost all the mentioned applications, without a necessity for deeper modification. A glass-glass module could not be used on all the elements of the facade, especially shading elements, therefore, we decided to explore the possibility of developing a shading component using bi-facial PV technology that not only faces external space and direct sunlight, but that also faces internal spaces of the building and may receive reflected light and artificial light during the night. This decision defined the scope of the project.

From the techno-economic perspective, important information needed for the development of this concept was proof of the hypothesis that bi-facial PV integrated into a shading element can result in higher energy yields compared to mono-facial PV technology. Therefore, the goal and approach of the project is defined based on the evaluation of the potential gain (energy) of the concept.

Step 2: Exploration – benchmarking existing concepts, prior-art concepts, and available technologies

After scoping and defining the project, the team proceeded with exploring existing solutions by exploring prior research on similar concepts and research on the tools and methods applied in similar situations to measure the technical potential of such a concept. Moreover, the different kinds of shading systems developed with PV technology are reviewed to narrow down the type of shading element that suits the project best.

The result showed that among existing concepts under shading components with integrated PV technology, none of them yet explored the possibility of deploying bi-facial PV cells configuration. The examples in Figure X depict some of these products/concepts.

Based on the analysis of these concepts and products, the application of PV on cloth-based curtains was found to be relatively unexplored. The few cases that attempted to develop a PV curtain not only remained on the conceptual level, but also only used a single-sided PV configuration. The failure to commercialise these concepts could be linked to the high costs of PV at the time of the project's conceptualization. We could not find any data about the performance of these products in terms of energy yield, nevertheless, it became clear that the potential for such a product is unexplored and bi-facial technology might be an interesting combination with cloth-based curtains and may result in higher energy yields and increase the commercial feasibility of the application.

Following the decision to use bifacial PV for a cloth-based curtain, the team needed to research the PV technology best suited for such an application. As discussed earlier in Chapter 5, different kinds of PV technology can accept some degree of flexibility but have other physical and technical properties that need to be considered beforehand. Therefore, the team researched different PV technology that could be placed in a bifacial configuration and that offer some degree of flexibility. In this part, instead of the multi-criteria analysis approach that we developed in Chapter 5, we used a comparative approach and tried to see which technology had been used by other projects. The findings showed that, in nearly all cases, crystalline silicon PV technology was mainly used because of its long service life, relatively high efficiency, and cheaper cost. However, crystalline silicon does not emerge as a popular choice on cloth application, with limited flexibility being the main problem. Most of the options explored in cloth-based solar curtains used organic PV or dye-printed PV (known as third-generation technology). Despite the attractiveness due to the ease of integration by printing, flexibility, and low environmental impact, most third-generation technology suffers heavily from low resistance to moisture and performance degradation induced by an increase in temperature. For this study, considering the easy accessibility of bi-facial crystalline silicon in the market for our research and the lamination facilities required to develop mini-modules in our laboratory, and in addition to the mentioned drawbacks of other technologies, we decided to use this technology for understanding the technical potential of the concept. In addition, a novel method of foil-foil encapsulation that imparts a limited degree of flexibility for c-Si wafer cells was considered for this application.

Step 3: Concept Development – schematic design of the concept

Based on the defined scope and the PV technology to be used, the team came up with the design for the potential product. Following discussions on the integration concept, at this stage of development, it was more important to see how the technology could function in this configuration. Therefore, integration remained on the technical side, with architectural and design concerns potentially being addressed within later steps of development.

In this design, the PV cells are vertically attached to the fabric, as shown in Figure 6.5.

TOC

FIG. 6.5 Schematic visualization of the concept bi-facial PV curtain (Prabhudesai, 2019)

Step 4: Proof of Concept – Simulation and validation of the model

A critical consideration in the design and development of such a concept is the added value of the new technology/configuration compared to conventional systems. Therefore, a quantitative assessment of the yield was essential. To measure the potential, the team simulated a three-dimensional model utilising raytracing. This method is found to be the most reliable way of answering this question. The team first developed the computer model and then validated the model with an experimental prototype in the lab and eventually used the model to predict the performance of the concept. In the first step, as a function of time, the irradiance incident on the PV system's Plane of Array (POA) had to be calculated. The POA irradiance is dependent on several factors, such as the sun's position, array orientation, irradiance components (direct and diffuse), ground surface reflectivity (albedo), and shading (near and far obstructions). The model allowed for simulation of the room environment on one of the sides the curtain was installed and to calculate the amount of radiation reaching the front and back sides of each cell attached to the curtain. In order to validate the model and simulated data, four different situations were simulated in the computer model and experimental setup and subsequently compared for validation. In Figure 6.6 situations are depicted.

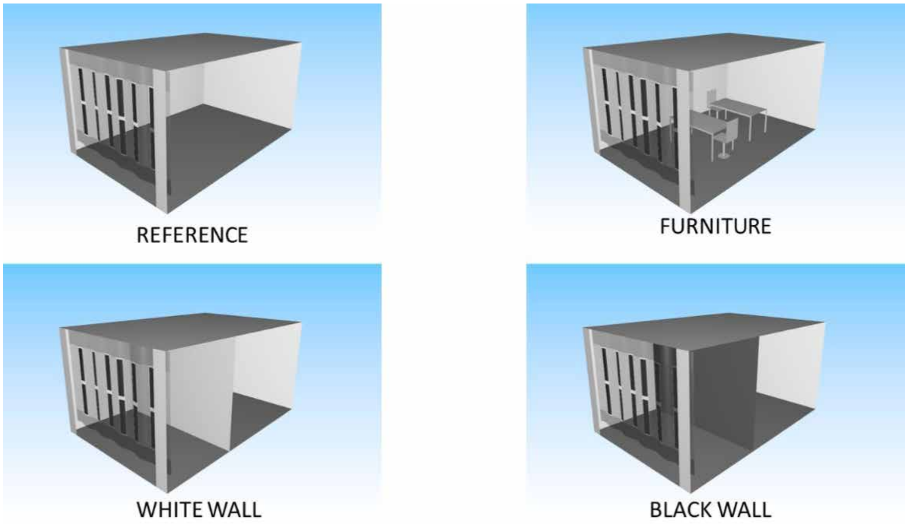


FIG. 6.6 Simulation configuration (Prabhudesai, 2019)

1. An empty room with the PV curtain (as a reference case)
2. A room with furniture with the PV curtain (to measure the reflections made by furniture)
3. A room with lower closer wall painted white (to measure the impact of room depth to reflection)
4. A room with lower closer wall painted black (to measure the impact of room depth to reflection and colour)

In the following step, we made a small-scale PV-curtain as designed in the concept. These cells have been laser-cut lengthwise into pieces, connected to the fabric curtain, and hung on the modelled room.

After completing the assembly of different components of the experimental model, we placed it in front of the solar simulator in our laboratory and collected several datasets of the performance. These data were compared to the information generated from the software simulation.

Compared to the base case, the trend showed a slightly higher power output for the case of furniture. The white-wall case performed best by reflecting a maximum of incoming radiation onto the cell (Prabhudesai, 2019). The black-wall case performed better experimentally than anticipated in the model, showing that the tiny reflection of incoming radiation from its surface onto the PV was still slightly more significant than the reflection from the distant rear wall.

These results showed that the difference between the two datasets had an error margin ranging from 3% to 11%, which was within the defined boundary, and the model was successfully validated.

In the following step, the model was used to measure the performance of the concept applied onto an actual case. Therefore, a random office room on TU Delft Campus was selected, and the room's dimensions and weather data from Delft were put into the model. A similar arrangement of PV cells (around 30% of PV to fabric) and 60% of fabric transparency was also applied to the model.

The annual yield showed to be 188 kWh, and the bifacial feature resulted in around +8.6% gain compared to the monofacial system.

Step 5: Optimisation – Fine-tuning the model

During the previous phase, it became evident that bifacial technology on the PV curtain can positively influence the energy yield. In the next step, the team tried to identify what parameters could help optimise this performance to develop the concept further.

With the change of some of the conditions in the models, the team could also find out the aspects that influence the system's performance. As an example, different room orientations were applied in the model, and it was found that the energy yield of the concept is highly sensitive to orientation. However, the rear cells exposed to the indoor environment were less sensitive and had a nearly constant yield. Also, the model's sensitivity to location showed that the bifacial feature is also not sensitive to changes of location as it remains somewhat similar in different cities.

On the variation of room's geometry, the depth of room was shown to play a significant role in PV power output, giving a nearly 2% improvement in both bifacial gain and annual PV power output for the same room of half the depth (Prabhudesai, 2019).

Moreover, the team changed the density of PV cells (ratio of PV cell to the fabric) in the model; It was found that while reducing the cells can result in better rear side yield at the cost of lower overall yield, increasing the PV can result in reduced rear side yield but higher net yield. It was also concluded, by process of varying the percentage of PV in the curtain, that although 60% of PV gives as much higher (nearly double) annual PV yield compared to the base case with 30% PV integration, it may not be the best option, considering that the curtain would not be classified as semi-transparent anymore due to most of the curtain being opaque.

6.3.1.3 Lessons learnt, reflection on the approach and recommendations

Figure 6.7 presents the process followed in the previous section. As discussed, the project was shaped around the main goal, and in this case, it was an exploration of the potential energy gain by using bi-facial cells on a cloth-base curtain.

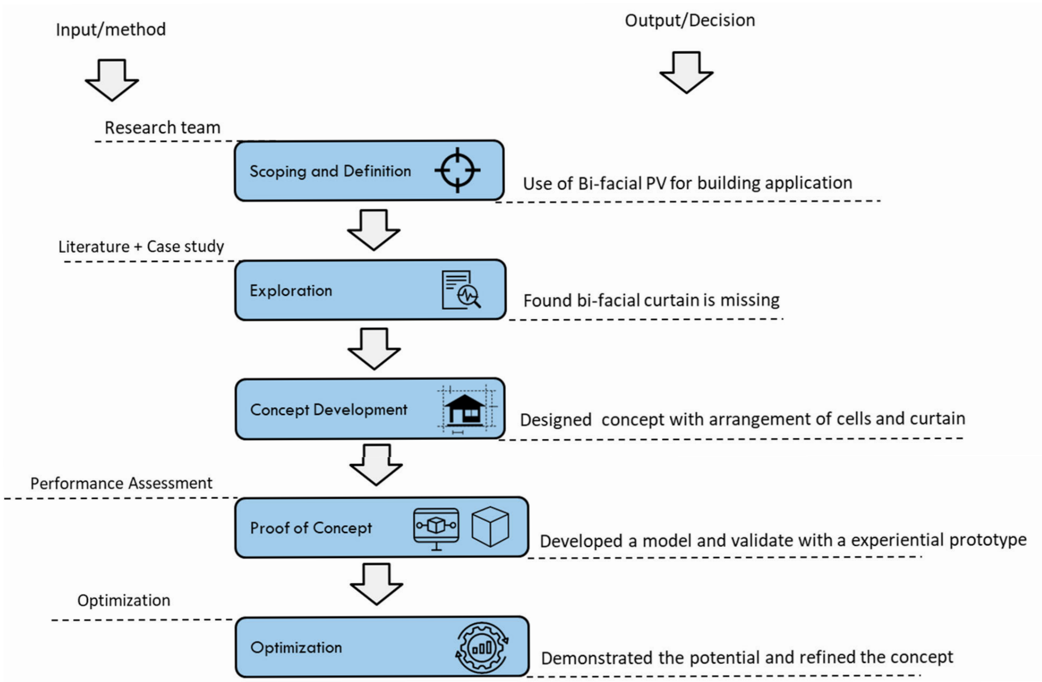


FIG. 6.7 PV curtain research and development process

The process undertaken shows that once there is a new technology or configuration, the first step in developing the application is to see whether that technology can offer a reasonable advantage compared to other proven approaches. Regarding the approach, since the key mandate in this project was to explore the opportunities of using this new technology in a situation where conventional technology yield is low, the focus remained on the evaluation of the functional performance of the concept and not on design aspects and fulfilment of the curtain functionality. Since it was concluded that this technology in this application can have added technical advantages, in the next steps of development, a prototype can be developed with a stronger focus on product design.

In this project, we not only explored a new configuration but also contributed to the development of applications designed to be used within the indoor space of a building. In this case, findings showed that beyond the layout and depth of the room, the colour of the walls and furniture in the room can impact the product's performance. Therefore, it is not so straightforward to draw general conclusions on the advantages offered by the product.

Despite the result of our research, showing the crystalline silicon might not be the best option in the long run, considering the physical limitations mentioned regarding PV technology selection, we decided to use that for our experiment as we could find a local supplier with reasonable costs. It reflects the discussion we had in Chapter 5 on the applicability of linear decision-making tools in finding the best-suited technology.

In regards to the integration and symbiotic relationship of the technology and the host, in this phase of development, we understood that it could not be the primary concern, whereas the energy performance of the full functionality of the application is of the highest priority. However, it should not undermine the importance of design aspects in the next steps of development.

6.3.2 PV carport

6.3.2.1 Project Background

In recent years, there has been growing social and political pressure on corporations to deploy sustainable development goals within their business. It includes taking some action in regard to reduction of their operational carbon emission and offsetting measures. As discussed in Chapter 4 on the motivations for many projects, the adoption and application of PV technology on the physical assets of companies has become one of the approaches to reflect a company's attention to green and sustainable business. In this project, the team joined forces with NS, the Dutch national railway operator, to explore the opportunity to develop a modular carport structure for application in their Park and Ride (P+R) locations. The main driver of the project route is the market demand for a product that performs better than existing ones on the market. In the urban environment, parkings and bus stops have proven to be great places to apply PV technology. This lies in the fact that these structures have mostly large unused sloped roof surfaces. This project is considered a pilot study of the NS Solar Carport.

This project was carried out by Jari Dijkema as a master thesis graduation project of the Building Technology master track at the Faculty of Architecture and the Built Environment of TU Delft (Dijkema, 2019).

6.3.2.2 Research and Development process

Step 1: Project scoping and definition – Understanding the clients' expectation

In this project, we worked closely with the project partner (NS) to understand the main goals, intentions, and essential considerations that needed to be taken into account to develop a suitable and feasible concept for their P+R locations. In addition, we had to understand the context of the project, including limitations, challenges, opportunities, and resources available. This information was collected in the early stage through interviews with NS stakeholders, to define the scope and evaluation criteria of the project. Some of parameters that are discussed as design decision in Chapter 3, has been used as underlying questions for the stakeholder. One example was the preference of NS to hide or expose the PV system. Another was the surface they intend to use for installing PV systems.

As a result of the interviews with NS, it turned out that the stakeholder had the ambition to make their train stations energy neutral by generating enough power on their real estate portfolio. To achieve this goal, they needed to use on-site renewable energy technology on every asset they own as the train lines are already running with renewable energy they procure from sustainable sources. One of these assets were the P+R parking lots near stations. They wanted to explore the possibility of implementing photovoltaic technology onto the carport structure because these are places easily accessible to install solar panels. However, NS believed that the current designs of solar carports do not instil the image they desire. Therefore, the stakeholder highlighted the design aspects of the product that could be linked to the image of the company. In addition to the design aspect, other aspects were mentioned by NS:

- As these P+R plots are bare parking spots next to the train stations across the Netherlands, the integration of PV technology into the structure should be carried out in a way that the parking plots are kept at maximum functionality.
- The system should have a maximum energy yield, being minimally dependent on orientation, while having nice designs that fit well into the context.
- The circularity and recycability aspect and material efficiency have a high priority.
- The modularity of the design for deployment on all P+R parking lots is very important.

Based on criteria outlined by NS, the research team defined a project goal as follows: the design of a modular structure for cars, taking into account the integration of solar panels into the structure with maximum solar gain in different orientations and with special attention to the design and image of NS whilst keeping the functionality of a parking lot.

Step 2: Exploration – benchmarking the existing concepts and prior-art

In the second step, the team researched technical aspects and considerations associated with the product development. The research covered different aspects, including existing PV technology, the structural capacity of PV modules, and alternative materials for the structure. It was followed by a comparative analysis of the other projects where PV technology was used in car parkings.

To investigate the existing technology and to compare them, an inventory of existing technology was developed. Different technologies needed to be studied that could fit the criteria selected by the client. As explained in Chapter 5, we adopted AHP method, and the results showed multi/polycrystalline silicon (p-Si) found to be the best suited.

To study the structural capacity of PV modules, we investigated the different characteristics of individual modules. These aspects allowed understanding of the structural behaviour of PV modules. These aspects are a) The type of module and its structural capabilities, b) The type of mechanical connection of the modules, and c) The type of materials suitable for the column structure.

The last part was a case study analysis of existing car shelter designs with PV. In this step, the goal was to learn and be inspired by different design approaches and to gain knowledge of contemporary carport designs. In this part, we analysed and compared these cases based on the PV technology used and the structure's material.

The findings from this part provided several inputs and considerations for concept development. These findings are summarised in Table 6.1.

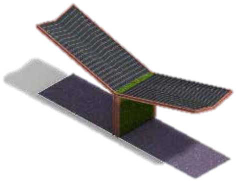
TABLE 6.1 Concept requirements and considerations found in the exploration phase

Requirements from Stakeholders	**Modular design** • The design should be suitable for every P+R location of the NS. **Suitable for different orientation** • The variety of site conditions of different P+R locations and consequently, orientations required for the PV, the design must be highly adaptable. **Flexible for replacement of PV** • The replacement of PV that is broken or the possibility of upgrading to newer, more profitable PV panels should be considered. **Transparent design** • To discard the need for lighting during darker days and to create a sense of security. **Demountable elements** • Due to the possibility of recycling elements when the structure is dismounted. **Sustainable appearance** • The design should have a sustainable (green) appearance.
Structural research	**Edge beam** • To allow a structure fully covered with PV, an edge beam is needed to lower the stress and deflection of the structure. **Linear supports** • To distribute the stress over the whole cross-sections of the glass. **Glass-glass modules** • For extra strength and to protect the solar cells a glass-glass module is the best option. **PV can't withstand its load** • The analyses of the mechanical resistance of modules showed that a structure made only from solar panels is not possible.
PV Module customisation	**Minimal angle** • The minimal angle at which no dirt will build upon the module is 15 degrees. **Blunt edges** • The modules should avoid being designed with sharp corners and edges to prevent lamination from occurring on them. **Rectangular shape** • The optimal shape for a PV panel is rectangular; when diverting from this shape the largest rectangular surface becomes the area at which PV cells can be operated. **Avoid cut-outs** • The module design should avoid cut-outs.
Benchmark with existing designs	**Maximum energy gain** • The purpose of these designs was to generate as much electricity as possible without compromising on the functionality of the parking lot. **Cost-effective steel aluminium structure** • Most of the structures are made from steel or aluminium; these materials are easily made into profiles and therefore cost-effective. **Similar appearance, lack of design** • Analysed designs are similar in the appearance to the solar cells, the structural material. These are typical examples of engineered carports that lack an influence of design. **Lack of added to value to the surroundings** • Beside the functionality of a shelter for cars and generating electricity, these designs do not add any value to the context or the experience of the parking lot.

Step 3: Design Development: design of different alternatives concepts

Based on the information collected in the previous step, 3 conceptual design alternatives are developed (Dijkema 2019). Each of the alternatives focused on one of the main aspects requested by the stakeholder. The team evaluated these alternatives to understand the pros and cons of the different options. Table 6.2 includes an image from each of the design alternatives, the main feature considered in their design and pros/cons. The result of these analyses later fed into the development of the final design.

TABLE 6.2 Design alternatives developed by (Dijkema 2019)

Design Alternative	Key features	Pros	Cons
Cost-effective design 	• Orientation independent • Maximised energy yield • standardised solar panels • Aluminium structure	• The system cost is at the lowest level • The system is modular and independent from the orientation	• A shift in the module has compromised the shelter functionality as rainwater can pass through the system • Poor module design • High material demand
Architectural Design 	• Social connection between design and user • Connection between design and stakeholder • Focus on openness of design • Use of wooden beam to hold the modules.	• The placement of the wall parallel to the parking spot is a beneficial. • Nicer Modular & design • Higher costs of panels customisation and structure • Less material and less environmental impact	• extra reinforcements materials for solar panels are needed • over-shadowing of the module
Sustainable Design 	• Use of retired rail track for column structure • Customised panels • Addition of green wall on the structure to collect rainwater	• Use of end-of-life rail tracks as structure • Additional function to the design	• Higher weight because of use of upcycled steel • Orientation dependency of the design

During consultation with the stakeholder, the three alternatives and features were presented, and we received feedback. During this consultation, a problem was raised by the stakeholder on the water drainage issues on the NS P+R, which could be addressed by adding a green wall to the structure. Moreover, for the stakeholder, the possibility to use old railway track material was very interesting from a circularity perspective.

Finally, based on the evaluation made on the different design alternatives and feedback received from the stakeholder, we decided to continue with the 3rd option (sustainable design) with some influences from the 1st and 2nd concepts.

Step 4: Optimization – Designing an improved final product based on client preferences and simulation outputs

In the last step, the concept was developed in detail and materials were selected. The rationale behind the use of the selected PV technology came from the analysis made with the AHP method developed in Chapter 5. As explained in detail in Chapter 5, we have applied the AHP method in this study to see how this method can support the combination of different priorities into the decision-making process of selecting the ideal PV technology to be used in the concept.

Including the specifications of the selected materials, the final design was modelled in a digital architectural modelling software (Dijkema 2019). Such modelling allowed optimisation and fine-tuning, as well as validation of the concept in regard to design and functionality. The software used also allowed further optimisation and validation of modularity features of the concept, solar energy engineering, orientation independence of design, structural design, mechanical strength, and connections of the modules.

The final design can be seen in Figure 6.8

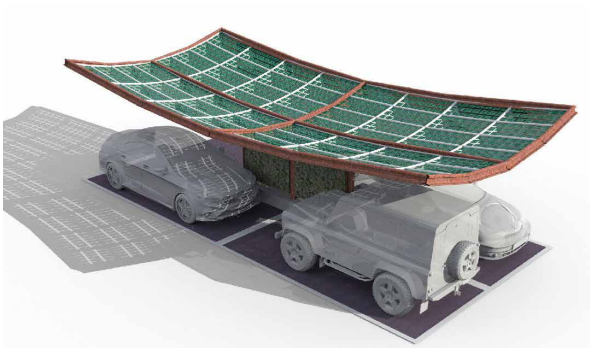


FIG. 6.8 Final design (Dijkema, 2019)

6.3.2.3 Lessons learnt, reflection on the approach and recommendations

Figure 6.9 presents the process in the concept development. As discussed, the main goal of this project was shaped around the development of a carport structure with PV technology for a defined client. Therefore, the focus was on the design and structural aspect of the concept rather than on optimal PV performance.

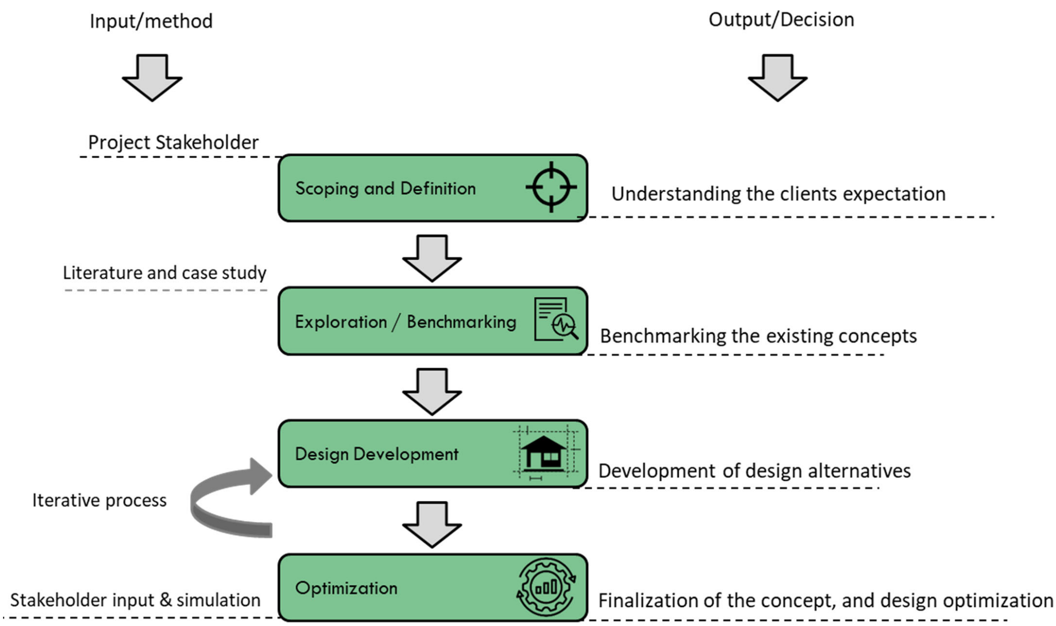


FIG. 6.9 Solar carport Research and Development process

In this project, we worked closely with external stakeholders with a clear mandate, goal, and requirements for the product development process. This close contact allowed us to have an iterative process and a high user-centric approach within the project. The method we applied resembles the classical practice of the architectural design process when architects work closely with the client and, after exploration, come with alternatives that eventually converge into one design concept. Therefore, the decision making was based on qualitative information from stakeholders and data collected from literature.

In this project, we considered integration in the context of functional integration. In other words, we envisioned PV modules to replace the roofing material of the shelter structure. As part of the research, we also explored the possibility that the

PV module withstands its mechanical load and replaces the beams and columns in the shelter structure and assesses the structural integration, which was shown to not be feasible.

6.3.3 PV Chimney

6.3.3.1 Project Background

In recent years, heat management of PV modules has been a subject of several studies within the PV industry (Zhang et al. 2020). The significance of these studies lies in potential improvement of the annual energy yield and life expectancy of PV modules (Ritzen et al., 2015). However, this issue is becoming a more critical concern for building applications as they suffer from a lack of side exposure to ambient temperature to dissipate the heat.

On the other hand, one of the growing R&D trends is the reduction of cooling and ventilation demands in buildings. Ventilation and cooling in buildings account for around 20% of energy consumption in a building (IEA, 2021). One of the approaches to passively ventilate the buildings is through a solar chimney system (Lal et al., 2013). A solar chimney is a passive ventilation approach that captures the solar radiation within a transparent enclosure on the building façade or dark surface. Heated air within the enclosure offers natural ventilation to the building and reduces reliance on mechanical ventilation systems (Harris & Helwig, 2007).

Furthermore, as highlighted in Chapter 1, in many countries, use of on-site renewable energy technology is becoming mandatory, and for multi-story buildings we need products and building components that enable utilisation of solar energy from vertical surfaces. However, as highlighted in Chapter 4, historically, architects tend to believe that photovoltaic potential on façades is significantly lower than on roofs, while countries as the Netherlands have a low angle of incident and, therefore, a higher yield can be expected from solar radiation arriving on vertical surfaces of buildings, rather than from rooftop applications. Defaix et al. (2012) calculated the potential generation of building-integrated PV (BIPV). A potential of 8 TWh was found for Dutch façades, estimated to be roughly 8% of the total electricity demand in 2030. Apart from the total quantitative advantage, Brito et al. (2017) found that façades can play an important role in spreading the PV-peak production over a day during summer and can double the PV production during winter.

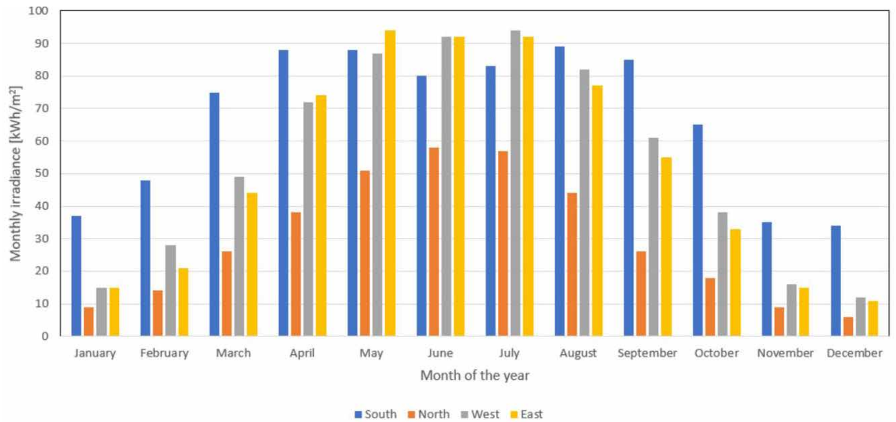


FIG. 6.10 Solar energy potential on vertical surfaces in the Netherlands (Wapperom 2019)

The starting-point of this project was the moment the research team conducted a site visit to one of the PV manufacturers in the vicinity of TU Delft. With a close look at the production line and process when PV cells are laminated between two glass sheets, the idea started to shape that what if we leave a few centimetres of air gap between the PV cell and the front and back glass sheets in a module for vertical applications, the stack effect could be used to let the air cool down the cells. Considering the dark colour of PV cells, this configuration could resemble a solar chimney system and other ventilated façade systems.

This project was initiated in collaboration with the Faculty of Architecture and the Built Environment (ABE), the Faculty of Electrical Engineering, Mathematics, and Computer Sciences (EEMCS), and the Faculty of Mechanical, Materials, and Maritime Engineering (3ME). In this project, we worked towards developing a novel application for PV technology, considering its architectural integration into the façade design and aiming for maximum use of the thermal and electrical energy produced by the modules as well as a reduction in the ventilation demands of the building. We worked with 4 graduate students to conduct this research and development process. Two of these students were from ABE, and the others were from EEMCS and 3ME. Due to the complexity of the concept, we divided the development steps between the students. In this process, we aimed to develop the concept until a business developer takes over, finds a business case, and conducts a financial feasibility study.

The core concept of this project was patented (PCT/NL2020/050422, 2020), and part of the technical feasibility research was published as a peer-reviewed journal (Ortiz Lizcano et al., 2020). The steps presented in the following section are a summary of the graduation projects of Sander Wapperom (2019) and Andri Lysandrou (2019).

6.3.3.2 Research and Development process:

Step 1: Project Scoping and definition

Due to the nature of this research based on a new configuration for PV modules, the project was defined to be explorative and started with proof of principle. As a basis for the study, we needed to make sure whether the proposed changes to the conventional system can have added value in terms of energy yield.

The potential concept entails the vertical application of PV modules on a building in a transparent enclosure to increase the potential energy yield and use the heat generated by the PV modules for stimulation of the stack effect and offer passive ventilation to a building.

Therefore, the project objectives were set are below:

- To prove that the proposed system can have a higher energy yield compared to standard situations;
- To find the optimal configuration in regard to the position of PV and depth of the cavity;
- To develop an experimental prototype to validate the simulated model and test the concept in the lab;
- To explore different architectural integration approaches;
- To place the system in a case study project and build a 1:1 scale of the concept with a potential client.

Step 2: Exploration – research on prior-art and methods to answer the research questions

In this step, the research team conducted literature research on various aspects of the concept. It included research on similar concepts, theories around heat convection, heat management in PV, and passive ventilation systems in buildings. Moreover, we explored different approaches and simulation tools used in the literature to measure the performance and thermodynamic behaviour of a similar system.

The findings showed the novelty of this concept and the potential for a higher energy yield. Moreover, it provided sets of practical information regarding the optimal geometry of such a chimney, the materials, and the modelling techniques adopted in similar projects.

Step 3: Proof of concept – Simulation and validation

Literature research showed that the simulation model should be developed in Matlab and based on a control volume approach.

The model was developed to function based on several inputs, including the local weather data, specification of the PV modules, and other materials (front glass and insulation material on the back wall) and also the geometry of the system (width, depth, and height). Following this, the model calculated the solar irradiance, which allowed for an understanding of the heat and mass flow and performance of the PV system. Eventually, the model could deliver the annual performance of the PV system, the thermal energy captured in the system, and stimulated airflow (Wapperom, 2019). Figure 6.11shows the process and model function.

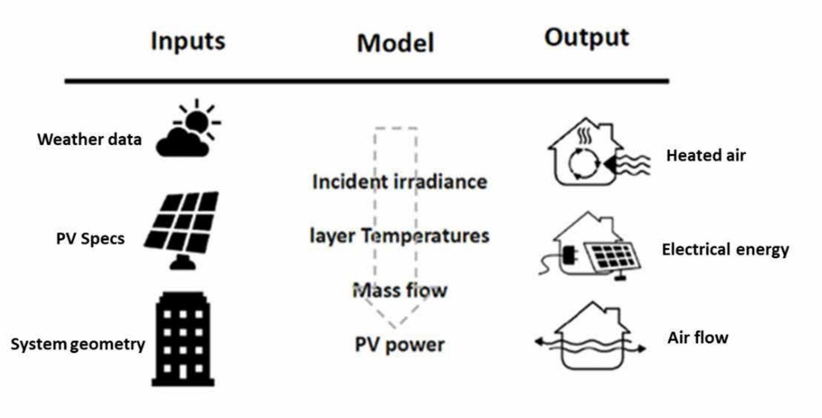


FIG. 6.11 Energy performance simulation model developed by (Wapperom 2019)

To validate the simulation model's reliability for understanding the proposed concept's performance, we needed to develop a lab-scale experimental prototype and conduct on-site measurements. Therefore, we built a physical model in the PVlab of TU Delft and placed it in front of a large-area solar simulator (LASS). In this experiment, the layers, from front to back, consist of glass, PV, and medium-density fibre (MDF) covered with insulation material. The frame was made from four cylindrical wooden poles, allowing depth adjustment of the PV module to measure the thermal behaviour of the system based on changes in the system's depth. The geometry of the model was defined based on available laboratory equipment including a glass-glass PV module (2 m x 1.6 m) and dimensions of the solar simulator, which we used in vertical position. Figure 6.12 depicts the built physical model and layout.

FIG. 6.12 Physical model in the lab

Once the model was built, we conducted several measurements in the lab by using various sensors on the model. As part of the model validation, the parameters below were measured in two configurations, once the PV was placed as the last layer (PVF) and once, the PV was placed inside and behind the front glass (PVI)

- Ambient temperature
- Mass flows inlets and outlets
- The stratified temperature of layers
- Irradiance of LASS
- PV module output

Comparing the data collected during the measurement with data derived from the simulation model developed earlier showed an acceptable level of accuracy in the simulation model. After this validation, the model could be a reliable source to predict the system's performance in actual situations.

Step 4: Optimisation – looking for optimal geometry and configuration

In the next step, it was essential to use the simulation model to understand how a different configuration and geometry influence the system's performance and how the concept could be optimised. To achieve this, the following points were studied:

- Optimal cavity depth for the air cavity to achieve maximum system efficiency
- Optimal place for PV inside the cavity to achieve maximum system efficiency

Moreover, a sensitivity analysis was conducted to find the effect of channel depth on the heat and electricity production on both PVF and PVI layouts. An optimum cavity for the PVF layout was expected to be between 0 and 0.1 m. For the PVI layout, a cavity depth between 0.2 m and 0.4 m was shown to be the most optimal configuration (Wapperom 2019).

The generation of electricity by the PV modules within a PVI layout was found to increase at positions closer to the building wall, whereas the heat flow increased in positions closer to the front glass. For the base case (total channel depth of 0.2 m), the optimal location for maximum system efficiency of the PV module in the channel was found to be in the middle, at 0.1 m. The results showed that in the configuration where the PV modules are inside the cavity (PVI layout), the electrical energy yield was reduced (due to glass absorption and increased temperature within the cavity), but the thermal energy yield was increased. Conversely, placing the PV as the front layer (PVF) decreased the heat generation but improved the electrical yield. Overall, PVI could offer a higher energy yield than PVF. This finding could be justified as firstly, PVF could dissipate part of the heat with the ambient environment and, secondly, additional glazing in the PVI configuration could reflect and absorb 8-10% of the incident irradiance and result in lower electrical yield.

To further study the performance of different types, we added a configuration when a cooling medium is placed behind the PV module while both are in the closed system and behind the glazing. The cooling feature could improve the electrical yield of the PV module and prevent faster degradation induced by increased temperatures. We simulated the new configuration and results showed such a system to be the best scenario compared to PVI and PVF. The cooling mechanism could make the PV module behave similar to the conventional PV-T system that could recover part of the excess heat in hot water. Figure 6.13 shows the comparison of the configurations and potential energy gain.

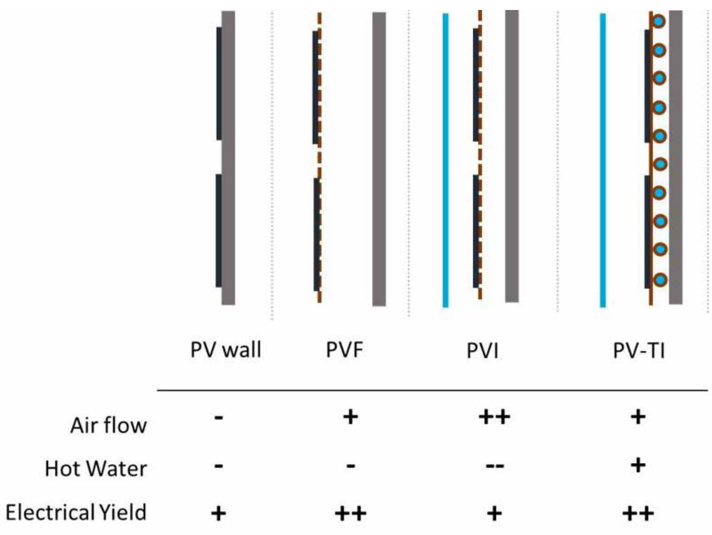


FIG. 6.13 Comparison of PV-TI with other systems in terms of value proposition

Step 5: Application design development- Design alternatives

In the next step, we investigated different possibilities to apply the proven concept to a practical application. We conducted this step by exploring the options to apply the concept to the façade of a case study building.

To make it happen, we joined forces with the TU Delft Solar Decathlon team to apply the concept to their prototype. To design and materialise the application of the concept, since the geometry of the concept is quite similar to that of a solar chimney, we reviewed the literature and similar projects to understand the important design parameters, challenges, and limitations that influence the performance of the system. The findings from literature research are summarised below:

TABLE 6.3 Important design parameters for Solar-Chimney

Parameter	Consideration
Glazing properties	• Glazing choice and layers depend on climate conditions. • Glazing transmittance can also affect ventilation rate. • Low-e coating increases heat absorption.
External wall properties	• Concrete is preferable above other construction materials. • An insulation layer improves the efficiency of the system in both winter and summer.
Vents	• The use of controlled vents increases the efficiency of the system. • Properly sized vents and additional fans can improve air circulation throughout the channel.
Building Local climate	• Solar radiation, orientation, and wind speed influence the system's performance.

From another angle, existing PV and PV-Thermal types and state-of-the-art technologies for vertical application along with their properties are investigated. The findings showed that an additional cooling medium with good thermal properties could significantly improve the PV efficiency and, consequently, the efficiency of the system. In Table 6.4, some of the considerations that are found to influence the system's performance are summarised.

TABLE 6.4 Important parameters on the PV-T technology

Parameter	Consideration
PV Glazing	• Unglazed PV/T systems have a higher electrical performance than glazed ones, while the thermal performance is higher in glazed systems. • High transmission and low emission glazing improves the system's electrical efficiency.
PV cell technology	• Polycrystalline cells perform better, electrically, than amorphous cells, while their thermal contribution is slightly lower. • Anti-reflective coating on the cells improve the total efficiency, while low-emitting coatings increase thermal efficiency while decreasing electrical efficiency.
Absorption medium	• Additional absorber coating on the medium improves the thermal conductivity. • An increase of collector's length can increase thermal efficiency while an increase of their diameter decreases their thermal efficiency. • The performance is higher when the collector's area is bigger than the PV area.

Following this, the team needed to see how the application can be fitted into different façade design styles. According to the "flatness" and openings on the façade, these variations are categorised into two main categories. The first category is named "Mask" as it includes the façades where the proposed system covers some parts of the building, creating a non-flat skin surface. The second category is named "Full Closed Mask", referring to the façades where the proposed system is merged with the rest of the façade components, creating a final flat surface. Then, the conceptual proposals of each category can be incorporated into pattern typologies according to the lines-shapes they create on the façade. These typologies are shown in Figure 6.14.

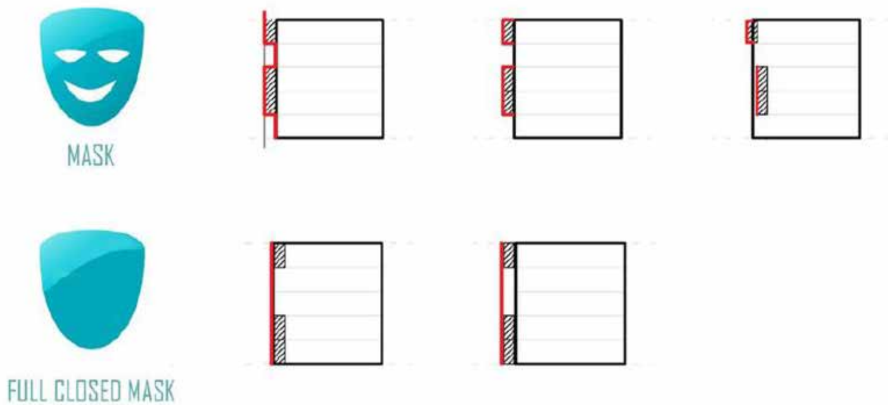


FIG. 6.14 Architectural possibilities of PV Chimney

In addition to the categorisation described above, we also explored different alternatives for positioning the concept on the façade with various patterns. Lysandrou (2019) explored the possibility of having "Floor Chimneys" and "Column Chimneys", as a system that would act as strips starting from ground level to the roof area, and the "Building Scale Chimney", the system on which the concept covers the whole façade as one compartment. Each of these systems would function differently, and the level of integration into building architecture and energy systems could be different.

Step 6: Prototyping – Development of a 1:1 in a case study building

As the next step of development, following the collaboration with the TU Delft Solar Decathlon team MOR, a multi-story apartment building in Rotterdam was chosen as the reference building. This building has 22 stories and a height of 90 m, a vacant office building built in the 1970s. The building required refurbishment and the proposed concept could be part of the passive and active strategy for increasing energy efficiency in the building.

The PV chimney concept was realised as part of the framework of the Solar Decathlon Europe competition of 2019 and therefore became part of a complete renovation scenario. The proposed application was designed in detail and was constructed in a 1:1-scale prototype representing a cut-out of the 22nd floor of the building with all suggested changes and improvements. The development process with this case study was accompanied by various limitations imposed by the different stakeholders involved in the project. In the case study, we decided to use the floor chimney type to minimise the intervention into the existing building HVAC system and comply with the rules of the competition. In the built prototype, we could not test all the system's features and use all the energy harvested in the system. Figure 6.15 shows the pictures from the architectural design and MOR prototype (Lysandrou 2019).

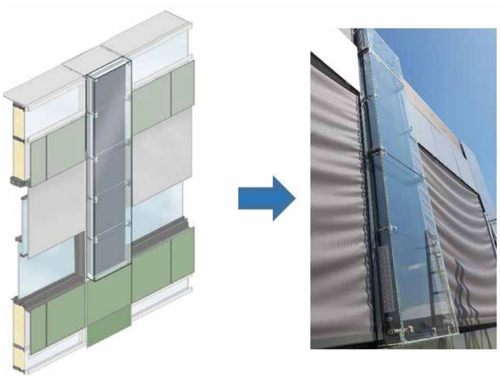


FIG. 6.15 PV chimney on the MOR prototype designed and developed by MOR team by (Lysandrou 2019)

The design, engineering, and construction of the prototype showed how such a simple idea on the conceptual level includes complexity in application when it involves several established and traditional disciplines in the practice of building construction. In the first place, such a concept required the consent and flexibility of the architectural team for the accommodation of the chimney onto the façade; then the HVAC design team needed to know how the system would influence the performance of the designated HVAC system in the building. In the next level, the PV engineer had to see how the PV was positioned, how the interconnections were handled, and where to accommodate the inverters and batteries. Eventually, the structural designer was responsible for mounting the system onto the façade. Simply put, the experience demonstrated the complexity and multi- disciplinary nature of the concept, making it a challenging task to develop further.

6.3.3.3 Lessons learnt, reflection on the approach and recommendations

Figure 6.16 presents the process during the concept development. This project had a broader scope in the development process than the other projects presented. The first phase is shaped around the demonstration of the technical potential of the proposed concept and evaluation of the performance by the development of a simulation tool and validation of it through a lab-scale prototype. In the second phase, the focus shifted from technical performance in the conceptual level to the design, development, realisation, and testing of the application.

As reflected in the project background, this project was initiated as an innovative idea based on a problem and insight into the building energy demand. In other words, by identifying the demands and issues in a business-as-usual fashion, we combined (integrated) different proven technologies and techniques to match the demand and production more intelligently and effectively.

In this project, we worked with several students and, consequently, the limited time for their graduation project highly influenced the scope of each project. However, we divided different milestones/work packages among different students from a diverse set of backgrounds and skills. On the other hand, it showed the multidisciplinary aspect of this concept, which also reflects its complexity during detail planning and construction of a 1:1 prototype.

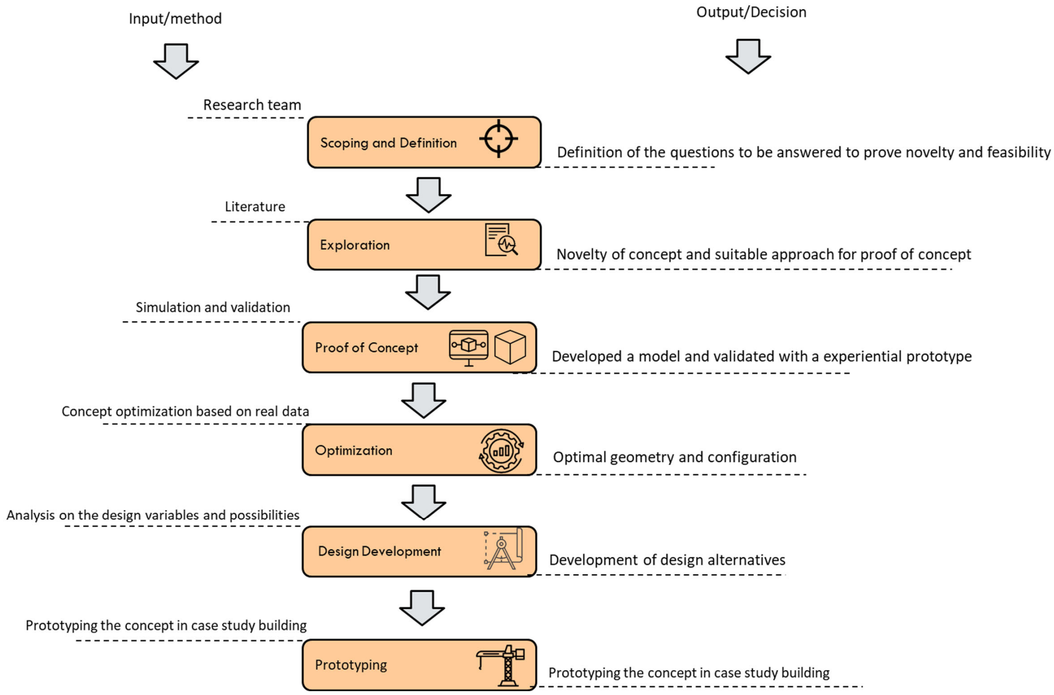


FIG. 6.16 PV Chimney Research and Development process

Regarding the technology itself, within the research process, we did not focus on a specific PV technology, as from the beginning, we were more interested in using existing and proven technology in new configurations with new value propositions. In addition, during the second phase, we realised that architects are much more comfortable working with glass on the façade instead of an opaque PV module. Therefore, it opens up room for better acceptance of the concept amongst architects.

In this project, we have seen integration differently compared to the other examples. Integration, in this case, is defined as an approach in which PV technology and other technologies/techniques come together to connect to the building HVAC system and accommodate new housing on the building façade that could speak the same language as other architectural elements.

The third project is an example that shows that for increasing the acceptability of PV in the building sector, we do not always need a customisation possibility on the conventional PV modules, and by thinking holistically, new applications can be developed.

6.4 Discussion on the product development process and case studies

6.4.1 Differences in the starting points and influences on the process

After analysing the concept developments, we can see that each has a different starting point and motivator. The first one is driven by a new technology that strives to offer its value propositions through a new application. The second one is driven by market demand for an application that can solve/address a problem or need in the marketplace. The third evolved around linking the value propositions generated through the synergetic relation of a few technologies to supply/respond to demands and challenges in the marketplace and vice versa.

Looking into the fundamental science of innovation, these approaches could be seen as a technology push, market pull and technology-market linked (Brem et al., 2009). In these approaches, we see how different drivers led to innovation and, in some cases, complemented each other. According to Brem (2009) the for a successful product development, it is essential that both forces - technology push and market pull- comes together to result in concepts that offers latest technological possibilities next in response to predefined market demand.

In this context, we have many technological innovations and efficient solar technologies that need to be applied in products to transition towards renewable energy. On the market side, we have abundant potential and demand for a clean source of energy to be used in the urban environment and clear demand for products that enable different surfaces on and around the buildings to become energy producers. This is where we need to develop more concepts for architectural application. On the technology-market linked, we have proven technologies that need integration in application that results in the creation of a product with higher performance in every aspect and greatest alignment with user desires.

Looking deeper into the implication of this categorisation in this context, it can be concluded that during the evolution of PV technology, we have noticed mainly the technological push approach. In other words, during the last few years, advancement of PV technology has been experiencing a steep incline, with key concerns surrounding reliability, efficiency, feasibility, stability, optimal configuration, and affordability of PV modules. We addressed the problems with using conventional PV technology in the built environment once it is added to the roofs of buildings as a result of a blind technological push. We also reflected on the low acceptability of so-called integrated products as a result of the market pull for such products, but perhaps the solution for such a problem is implementing a third approach where both market pull and technology push meet each other. In particular where concerns of aesthetic integration, low efficiency, and durability are all being addressed through one application and the PV system becomes part of the architectural element in the façade. Perhaps, in that situation, we could see the most comprehensive approach in regard to integration.

6.4.2 Differences in the R&D processes

As shown in the previous sections, each project went through a different process in the research and development phase. This difference lies in the nature of development and the starting points that were outlined earlier.

Under examination, it is possible to map these processes and compare them based on the steps followed in each project. In Figure 6.17, we have mapped these steps. In the PVcurtain project, as we were developing a concept that would be placed on a surface that is not optimal for PV functionality, we needed to study and evaluate the technical performance of the concept in order to see whether, from the technical perspective, the energy gained from the usage of bi-facial PV cells on the building envelope can be feasible. The next step after validation of solar technical feasibility, would be product design where all aspects related to the design and functionality can come together and result in a product that is acceptable by end-users.

In the PV-carport phase, however, we did not need to prove the feasibility of the use of PV in such a structure. Instead, we needed to add design aspects and work closely with the client in an iterative process to invent a concept that fulfils the demands of the stakeholders. Finally, in the PVchimney, we needed to focus on two points. First, proving the efficiency of such a system once we insert PV into the cavity and second, exploring the architectural possibility of accommodating the system onto the façade and developing an application for such a concept.

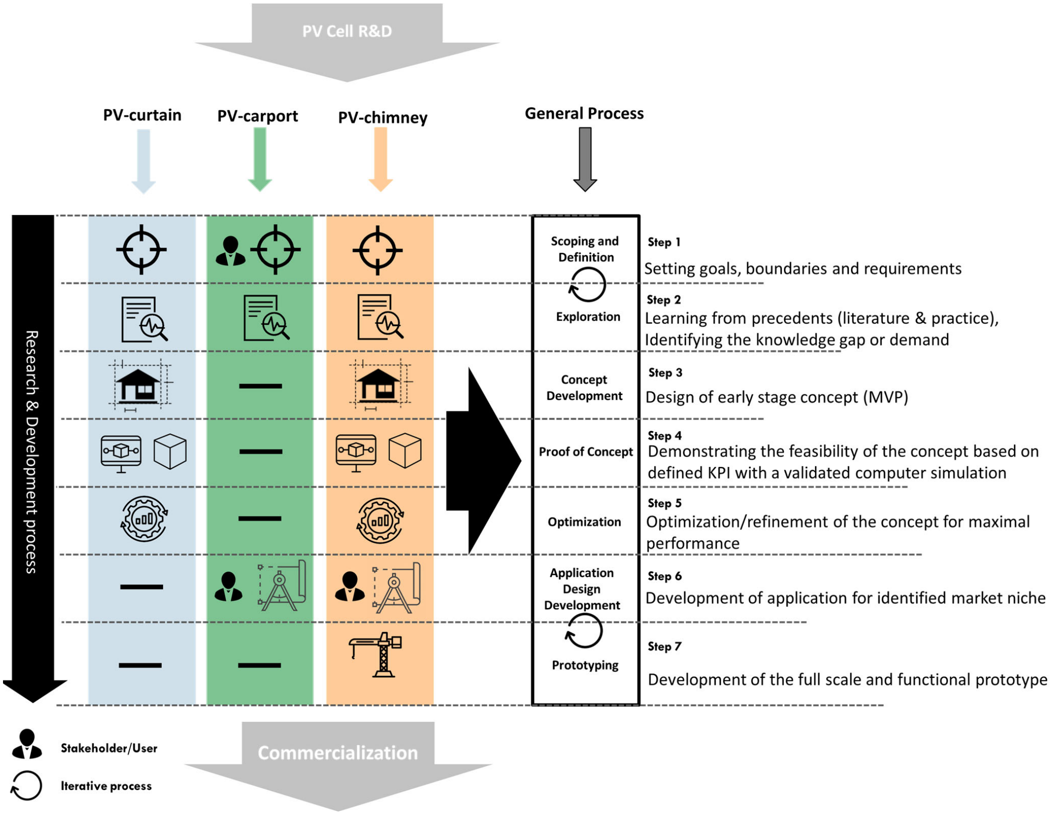


FIG. 6.17 General Research and Development process

Based on the steps followed for each project, we can think of a general approach that can be considered for other concept development for architectural photovoltaic application. Despite the differences and limitations in the scope of development of these projects, we used them as representative cases. Indeed, not many PV products in the market have gone through the complete research and development process. Therefore, we needed to rely on our experiences to formulate a holistic approach.

The general process after the R&D development of cell technology and before commercialisation can include 7 steps. Some of these steps can be ignored based on the nature and starting point of the project. Some are closely linked to previous steps and might be involved in a greater iterative process that complements each other. There may come a situation where stakeholders will be involved throughout the development process and provide direct feedback. It should be noted, however, that stakeholder input will be more helpful after the proof-of-concept stage, as the proof of concept is meant to assess the concept in standard test condition (STC) and not in practical situations. As a limitation of this approach, the fact that these projects were carried out in the academic environment distinguishes them from industry practice. In practice, these processes and steps might happen in a different sequence or in another setup.

Moreover, the differences in the process can be seen from metrics like technology readiness level (TRL). Both the PVcurtain and PVchimney started from lower TRLs, as proof of principle and feasibility was essential before product development, but the PVcarport started from a higher TRL, as the function of PV on the carport had already been studied and tested several times and in this process, we were more focused on the product development itself.

6.5 Conclusion

In this chapter, we presented results from 3 case study projects to explore different approaches and steps for concept development with PV technology for architectural application.

The different case studies depicted various approaches to concept development with photovoltaic technology for application into architecture. Each project's significance lies in the novelty and results generated in the research and development process. In these projects, we have implemented different research methods. The findings of some of these projects are very interesting and encouraged the team to follow up with further development. In some cases, these results are disseminated in the form of journal papers, conference presentations, and patents, contributing to the field of concept development with PV technology.

Alongside the mentioned findings, in this chapter, we could analyse these projects based on their starting point, to show how different starting points have influenced the research and development, scope, and ultimate goal of the project. We found that there is semblance to existing theories regarding the drivers of innovation and what we experienced within these projects

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Analyses on the approaches following these projects showed that despite the differences in the scope, objective, and nature of the concept, there were several similarities that could be used in a generalised approach for concept development for architectural application. This generalised process, derived from these case studies, can be used for the development of new products.

The findings of this chapter together with the findings of the earlier chapter provide a set of information on the adoption of existing PV products in architecture and the process that can be followed to develop new concepts for the application of PV on and around buildings.

Terra Expo 2020, Dubai, Grimshaw Architects, Author's personal collection.

7 Conclusion and Recommendations

In this dissertation, we explored different aspects related to the use of PV technology in buildings. Included is a general framework for effectively introducing PV into a project, the design decisions in said process, the experiences of architects in working with PV, and, finally, approaches used in the development of PV products. The final chapter summarises and highlights the main findings of the dissertation and synthesises some of these findings in sets of recommendations.

Chapter 7 first begins with answers to research questions drawn that shaped the framework of this dissertation. It is followed by recommendations for adoption and product development to assist architects and product developers.

7.1 Introduction

In order to realise the urban energy transition, it is imperative to make cities self-sufficient in terms of resources and energy. We must use building fabrics to absorb solar radiation and transform it into usable electricity. This requires thorough thinking into how PV can ascend its current position as a building service and become an integral part of a building's architecture.

The overarching goal of this dissertation is to support the decision-making process for the adoption and product development of photovoltaic technology for use in the built environment. The fundamental problem addressed in this dissertation is the lack of appropriate guidance and well-structured knowledge of the approaches and considerations needed to be deliberated in the design and decision-making process for realising architectural photovoltaic application.

To achieve this goal, various qualitative and quantitative research methods have been implemented to answer this problem. We divided the main research question into 5 sub-questions that are responded to separately in the first section. In the second part, we have synthesised the findings of the different chapters and presented sets of recommendations followed by the impacts of this research and the author's final words.

7.2 Answers to the research questions and general conclusion

In the first part sub-questions is answered, that followed by general conclusion as the answer to the main research question.

7.2.1 Rethinking on Integration

According to different definitions, what does 'integration' imply in the context of photovoltaics (PV) and architecture?

The integration has been used to overcome the negative aspects of placing industry-standard PV modules on the roofs of buildings specifically when aesthetic and functional aspects of the hosting structure are neglected. In response to this, a new category of PV product was developed, being referred to as the Building Integrated PhotoVoltaic (BIPV), with previous non-integrated modules being deemed Building Added PhotoVoltaics (BAPV).

Integration as a term, in general, has a wide range of meanings and can be defined and interpreted in various ways. However, considering the ultimate goal of the broader adoption of PV technology in architecture, we need to see how integration in the context of PV used in buildings is defined and whether this definition in practice can support achieving sustainability targets. Thus, in the starting chapter of this dissertation, we looked into the origins of the term integration in the context of PV technology in literature to understand in what context it was first used.

Scholars and stakeholders with different agendas, intentions, and motivations have distinct preferences in defining 'integration'. This can be traced in the requirements seen in our analysis of different definitions as presented in Chapter 2 and tend towards referring to integration in the context of replacement. It should be noted, however, that all of them, to some extent, agree that the current retrofitting practices of bolting PV modules onto the building roof or façade (the BAPV approach) is an undesirable approach for the future.

In the context of integration as replacement, a critical issue found was the focus on functional integration. In contrast, architectural integration has been overlooked, and despite the problems identified in the BAPV approach regarding aesthetics, in these narratives, architecture and design have not been properly addressed. We argued that through our existing perceptions and current understanding of integration, we are limited in the approaches we can utilise in adopting PV, as the architect is forced to work with products that already presume an unchanging secondary function. In addition, many of the scholars emphasised that aside from functional integration, i.e., having PV serve a secondary function in the building, such as cladding, architectural integration, that is, assimilating PV into the design concept, is an aspect that can hold weight in determining the scope of integration. In Chapter 3, we analysed many projects where the architect nicely blended conventional modules into their designs without delegating any constructive role to PV, therefore, one could conclude that integration does not prerequisite photovoltaic products to take the role of a construction material or serve a dual function. The PV modules can still be a part of the architecture and remain a building service and perform their primary function as a component in generating on-site renewable energy.

In Chapter 4, we conducted interviews with 30 architects and questioned them on their understanding of the concept of integration and found that some of the architects, contrary to other stakeholders, view integration as more oriented towards creating harmony in the design process rather than replacing a specific component of the building with PV modules. Put simply, architects are interested in seeing PV intertwining itself with the design concept itself. Assessing this quality, however, is mainly subjective and left to the architect’s discretion. In Chapter 6, while looking into concept development approaches, we noticed, in one example, that integration could be seen even more holistically, with the PV functionality fitting into the building’s energy system in a synergetic way while also seamlessly blending into the architecture.

Overall, looking into the definition found in the literature and standards presented in Chapter 2, the responses received from interviewed architects, and the approaches adopted during concept development in Chapter 6, a question could be raised on whether a redefinition of this term can be helpful or if this concept is inevitably going to be discarded with further progress in the adoption process and product development of PV technology. One way to investigate this question is to look at history and the way similar technologies were introduced to buildings (e.g., elevators and radiators). In almost all cases, we do not use the term integrated in similar contexts. The hope is that soon, we can expect PV to become standard practice and a natural part of building services.

This dissertation suggests recognising the role of PV technology in buildings as building service (i.e. as boilers, radiators and HVAC units) and, regarding integration, leaving it at the discretion of architects and designers to accommodate PV systems within the anatomy of the building’s architecture: either exposed and part of the architectural language or concealed and hidden somewhere out of sight without thinking about having them as a misfit to buildings and other surfaces in the urban environment.

7.2.2 Design Decisions

What are the Design decision in realisation of APA?

Regardless of the discussion around integration, architects have deployed PV technology onto buildings in various ways. These numerous approaches are outcomes of different decisions made by either the architects themselves, or other project stakeholders during the design process. As part of an exploration into the state-of-art, we needed to explore these approaches in order to gain an overarching view of all the possibilities and the decisions that are made during the adoption process.

We surveyed projects in which PV technology has been adopted and mapped based on similarities and differences regarding design approach and position of the PV and building. Similarities, to group them and reduce the number of samples and categories, and differences, to identify the different decisions made during the design process of those projects.

Based on these analyses, the following parameters were identified as design decisions that needed to be made by the design team:

- Visibility of the PV system, hiding or exposing PV modules in the design
- Mounting strategy, how to articulate the PV element onto the building
- Physical customisation of the PV modules, the extent to which the product will be customised
- Building fabric used for application, the surface on which the PV will be installed
- Additional functionality of the PV modules, whether the module used will serve an additional functionality in addition to energy generation

Interestingly, some of these choices are mentioned as requirements in the definitions presented for integration. Moreover, we noticed that some of the choices influence other decisions that need to be made, as there is an interrelation between these decisions.

As one of the outcomes, we developed a decision matrix that can be used to map all the approaches for using PV in architecture. The matrix can be used by architects and product developers to more easily see the different possibilities and make informed decisions in a reasonable timeframe.

7.2.3 Insights and Lessons learnt

Based on realised projects and architects, what are the motivations, lessons learnt, and perceptions regarding the adoption of APA?

We can find several projects that adopted PV technology on and around the building. In these projects, different PV technologies have been used in various types of products and diverse architectural styles and approaches. These approaches are mapped and analysed in the previous question. However, we must gather deeper insight regarding the experiences, lessons learnt, and perceptions of the architects in using this technology better to understand the bottlenecks, shortcomings, and challenges ahead in adopting PV technology in the built environment.

To respond to this sub-question, we conducted an explorative study aiming to collect a mix of qualitative and quantitative data from architects and other designers in the form of the in-depth interviews presented in Chapter 4. Based on the categorisation of these approaches developed in Chapter 3, we invited two groups of architects to join our study, once with experience in using PV technology and ones without experience.

As a result, we could see three kinds of motivations to use PV in architecture. One, related to external incentives (e.g., NZEB) that drive the project, another, a green architecture approach that is related to the interests and intentions of the architect to introduce environmentally friendly and climate-responsive technologies to the building, and the final one, a communicative gesture in which the use of PV is mandated by the project owner and PV is used as a symbol of sustainability. Based on these motivations, we concluded that there is a direct link between the moment when the PV is introduced to the design concept, the type of PV product used, and the surface used to apply the PV on. In other words, the timeframe when PV is decided to be used can influence the final approach. When it is considered early, higher freedom is granted towards the designer and a more symbiotic approach can be achieved.

Comparing the experiences of architects that had already applied PV in their designs and ones that had not, we could conclude that, in practice, working with PV technology was not as complicated as it is perceived. Overall, among the first group, 14 out of 15 interviewees positively expressed their experiences with the adoption of PV and willingness to continue using, even recommending it to their peers. In contrast, the second group mainly highlighted the challenges and hindrances they speculate on the process. Lack of diversity in reliable products produced by known suppliers followed by doubts on the complexity of execution, life span, long-term performance of modules, after-sale services, maintenance responsibilities, and safety are some of the concerns mentioned.

We found that versatility in colour, transparency, size, and reflectivity of modules are the most requested options by architects. In addition, the findings highlighted some of the considerations under lessons learnt as follows:

- Space required for ventilation and the cables of modules
- Overshadowing of the modules on tilted configuration
- Window-to-wall ratio, size of building openings
- Accessibility of the system for maintenance and cleaning of modules
- Safety considerations with PV modules and the supporting structure
- Weather resistance and tightness of the PV system

To summarise, we were able to document the experiences of architects when working with different types of PV technologies available for deployment in buildings. These insights are beneficial for other architects when they wish to utilise PV in their projects. Moreover, It is evident that adapting PV technology into the design process is easier than expected once an integrated approach is used.

7.2.4 Technology decision

What are the commercially available PV technologies, and how can we find the best-suited technology for APA?

The PV industry is experiencing steep growth in introducing new PV cell technologies, module manufacturing processes, and customisation techniques. Each of these technologies and techniques have different features and characteristics that make them suitable for a variety of applications. To make an informed decision during technology selection, it is essential to compare these technologies based on aspects that are important for the architect's preferred application. These aspects are identified in Chapter 4 as part of the inputs collected from architects.

Our exploration of commercially available PV technologies shows the first-generation technologies (c-Si) as the most advanced and the one holding the largest market share. In addition, it is the leader in terms of efficiency and technical performance. Such dominance allowed the technology to benefit from the economy of scale, extensive cost reduction, and accessibility with different module types. However, the physical flexibility of this technology for customisation on the cell level remains limited and, in this aspect, most of the development has focused on module manufacturing technologies. Regarding second generation technologies, higher temperature tolerance can make them better suited for applications that lack double sided ventilation. Automated production lines make customisation of size and shape fairly difficult; however, most are already lightweight, flexible, and have some level of transparency in contrast to the first generation. The third-generation technologies receive increased attention because, in research labs, they are reaching a state of competitive efficiency when compared to the 1st and 2nd generation, with lower production costs and reduced environmental impact. This makes them an interesting option for architectural application, although their limited service life expectancy remains an important consideration.

We noticed that applying different criteria during product selection is a complicated process for architects and product developers. Therefore, we have adopted an Analytic Hierarchy Process (AHP) method to see if this approach can be used for optimal selection of technology based on the priorities defined by stakeholders. Overall, despite the effort needed to develop the mathematical proofs, the benchmark showed that the results generated by the method are accurate and reliable.

The benchmark on the suitability of the AHP method can be seen from two angles: both for the adoption of PV products and new product development. However, when it comes to commercialised products with reliable and professional sale/after-sale services and safety certification needed for the architectural application, it is hard to make a clear conclusion on whether the effort required for the development method can be justified.

7.2.5 Concept development

What are the steps and processes in new product development of APA?

According to several reports and the interviews conducted in this dissertation, it is apparent that existing PV products cannot fulfil current market demands. Therefore, new products/applications need to be developed to facilitate the adoption of this technology in the built environment.

As part of this study, we investigated 3 projects in which new concepts using PV technology were developed. These projects all had different scopes and goals and we analysed them to see the different approaches in the research and development process.

The approaches reviewed resemble existing theories on the drivers of innovation when, in some instances, technological development is the driver for new product development. In such projects, the key question lays on the performance of the technology in the proposed concept. In another approach, demand in the market drives new concept development. In those cases, the process focuses on the demands of the stakeholder for the product and is less focused on the technology itself.

Analyses on the process undertaken in the 3 case studies showed that despite the differences in the scope, objective, and nature of the concepts reviewed, several similarities could be used in a generalised process for concept development. According to this analysis, the research and development process before the commercialisation phase can be divided into 7 steps. The sequence of these steps can be adjusted based on the starting point and the main objective.

7.2.6 General Conclusion

In this section, we have synthesised the findings discussed above and presented them as the answer to the main question of study.

What are the considerations in the development and adoption process of architectural photovoltaic applications (APA) that can be used to support design and decision-making in a wider utilisation of the solar energy potential in the urban environment?

A Architectural Photovoltaic Application

We started our research by looking at ‘integration’ as an alternative approach to using PV in buildings. We found that integration, as currently understood, cannot be used as a comprehensive definition to be adapted for different kinds of architectural styles and approaches. In addition, in the context of sustainability and building architecture, the term ‘integration’ is overused and can lead to severe confusion through different interpretations. Therefore, as the first recommendation of this dissertation, I would like to suggest moving on from the ‘integration’ approach. Based on the comprehensive research done into this issue that is presented in Chapters 2, 4, and 6, we would like to introduce architectural photovoltaic application (APA).

APA can be defined as an approach in which PV as a technology with primary function of on-site renewable energy production is considered as a building service in the built environment and is adapted to the building anatomy based on the design concept of the building. Through this method, PV does not need to assume any other role in the building; instead, it would be recognised as a component in the design process that needs to be accommodated in the design concept itself. Furthermore, APA emphasises the architectural features of the application rather than the functionality of the product.

B Considerations in the Adoption Process

This dissertation highlighted several considerations that architects mentioned as part of their experiences. To clearly summarise these considerations, we have collected the points that architects need to consider once they need/want to use PV in their buildings.

- **Visibility of the PV modules in the design concept**: The degree of exposure of the PV. The question on whether the architect and design team intend to show the modules or keep it hidden in the design. Different responses to this question would determine a different roadmap in the adoption process.

- **Mounting strategy**: How the PV product connects to the building fabric and the question on how the load of modules are being transferred to the building structure.

- **PV product type**: The level of flexibility towards the customisation of the PV product and the question on whether existing industry standardised PV products or customised products are to be used to better fit the building concept.

- **Building fabric used**: The building structure that the PV system is applied to or connected to and the question on the location, position, and orientation of the modules.

- **Functionality**: Delegation of an additional role to the PV product in the building system besides electrical energy generation.

All these considerations, along with the decision on the category of the PV technology, are key considerations in the adoption of PV.

C Adoption and Product Development Process

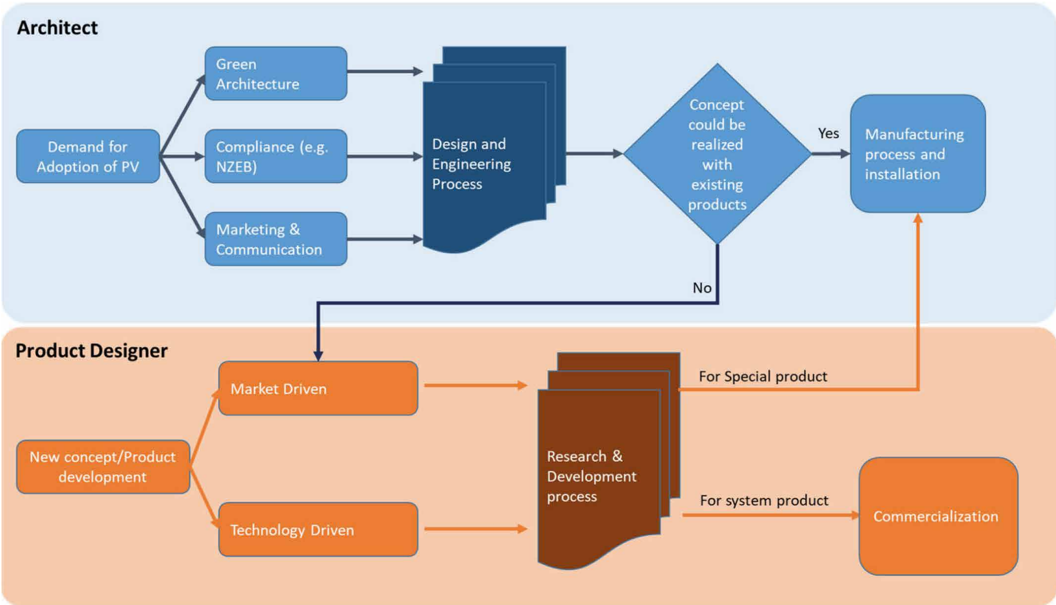

FIG. 7.1 Process map on adoption and product development

As the leading actor in the building design process, architects need a guideline to follow to properly realise APA in their projects. The starting-point and project mandate will define the reason for the use of PV and subsequently other decisions that they will make in the adoption process. If we funnel the findings of this dissertation regarding the adoption and development process, in addition to other insights gained throughout this PhD trajectory, a process map can be developed. In this process map – Figure 7.1- We envisioned three scenarios for the adoption of APA as explained in Chapter 4, namely, a) Compliance with Policies & Incentives, b) Green Architecture, and c) Marketing & Communication. Based on the applicability of these scenarios, the design and engineering process can vary. The design and engineering process entails several steps, including the design decision matrix developed where architects need to decide on aspects that can influence the design of the PV system. Asides from that, based on the scenario, there might be a need to conduct a quantitative assessment on the yield potential of each surface of the building and accordingly size the PV capacity needed to fulfil the target set. These two processes – design decisions and PV sizing - can be iterative, with the sequence being flexible for use in a variety of project conditions.

Once the design and engineering process is over, and if existing products in the market couldn't meet the expectations of the design team, a new product needs to be developed. In Chapter 3, we faced several projects where the architect designed a new product using PV to achieve a design or engineering target that was desired.

In addition to the market demand for a new product initiated by architects and designers, the emergence of new technology can also trigger a wave of product development.

In such a situation, instead a project being designed exclusively for a specific project, it might result in the development of system products (standardised) that can be used for different buildings or projects.

7.3 Impacts

The desired impact of this study is seen from two perspectives: social and scientific. Indeed, the energy transition will have many long-term social consequences, among the positives, cleaner and healthier cities, but in the process of achieving this goal, many people including politicians in displays of NIMBYism (Not In My Backyard) complained and obstructed the placement of distributed renewable technologies in landscapes and cities, believing it to disturb the skyline and environment (Wüstenhagen at al., 2007). These beliefs are not entirely unfound: We can often see an unpleasant image created when PV systems are randomly placed on the roofs in a BAPV manner, devaluing the aesthetic harmony of a neighbourhood. Certainly, the involvement of architects and highlighted design considerations in the adoption of this technology facilitates the social acceptability of these products and eventual contribution to energy transition towards carbon-free energy sources.

On a related note, if we manage to increase the market share of on-site solar energy production by increasing PV acceptability, aside from all the land saving and job creation potential for agriculture and housing instead of centralised utility-scale solar farms, fuel poverty in many cities can be tackled. A study done in Dundee, Scotland, a city with an above average fuel poverty rate, demonstrates that the use of PV and some energy efficiency measures can eliminate fuel poverty by 100% (Andreadis et al., 2013). So we are hopeful that the findings and information we provided in this dissertation pave the road for faster adoption and higher use of PV technology in buildings.

At the scientific level, this research contributes to developing new thinking strategies toward redefining the integration approach in this context. We highlighted the shortcoming and various interpretations of this approach in academia and practice. Furthermore, we contributed to this field by documenting and analysing the knowledge architects gained in realising projects with PV technology.

In the product development projects, we also introduced new concepts and applications for PV and contributed to the progress of the adoption of PV technology. In the case of PVchimney, we filed a patent as our proposed concept, using PV in a new configuration to increase the system yield that directly contributed to the field of PV heat management, falling under a new invention.

7.4 Reflection and Recommendations

In the trajectory of my PhD research and within the defined framework, I have managed to answer the questions raised and have shed some light on the gaps in knowledge and present findings that can be used for targeted audiences.

Based on the mandate suggested by the SolarUrban research programme and informed decisions during research design, we have chosen to keep this research broad in terms of the use of PV in buildings and have tried to keep the scope as wide as possible in order to arrive at a holistic conclusion instead of focussing on specific applications for a certain PV technology. However, such an approach entailed difficulties and limitations.

The main challenge was maintaining a bird's-eye view of the topic without getting too close or specific so that it results in having a generic conclusion linked to a certain type of PV technology or a certain surface of the building. However, on many occasions, we needed to zoom-in and uncover many aspects and afterwards zoom-out again and try to make a general conclusion based on the observations. This challenge can be seen particularly in Chapter 6 where we went through this process for every project; we attempted a final broadening of scope in order to identify patterns throughout the three studied cases. Furthermore, within the first three chapters, we tried to diverge to explore and include as much as possible and in a few cases, such as in Chapter 5 and 6, we converged to make concrete conclusions.

One of the limitations of this study also pertains to Chapter 6, where we showcased three concept development projects, while the findings of earlier chapters, including gathered parameters and considerations, were not implemented and validated in those projects. The reason behind this issue is rooted in the fact that these projects were developed in parallel to the research of some other chapters. In the other words, the research and data collection were not performed in a linear manner due to the nature of the projects and other practical considerations. Therefore, in some cases, we could not use the opportunity to validate the findings from one chapter in another. In particular, the findings of Chapter 3 could have been validated by the architects in Chapter 4, or having the later findings of Chapter 2, 3, 4, 5 implemented in Chapter 6.

As reflected in Chapter 4, conducting in-depth interviews as the method for exploration was also very challenging and time consuming. On top of that, again the scope of the research did not allow us to narrow down the projects or typologies selection. One other limitation relates to the selection of interviewees. Although we had the chance to include many renowned architects in this study, we were forced to remain in the European context and could not include architects from Asia and North America because of limitations with travelling. But overall, the findings are comprehensive and cover many types of projects, design approaches, and typologies, that make the findings credible.

As a recommendation for future research, I would suggest a study mapping the roles of different stakeholders in the process, in order to better understand needs and decisive factors. In this study we focused on the architects, but in fact, building owners and contractors can have different perspectives that need to be considered in the overall decision-making process.

One other recommendation would be continuing development of comparative and decision-making tools for selecting the right PV technology for different applications and climate zones. The tool could be developed and used as an online service for potential users.

Furthermore, considering the ever-rising energy prices, we should investigate alternative business models to finance different PV applications. Indeed, the use of PV in buildings can be seen as a profitable investment for building owners and investors and it can open many opportunities to better accommodate it in buildings and other urban fabrics. Based on the level of integration and the role PV plays in the building, existing business plans can be adapted. Therefore it warrants further investigation.

As highlighted in the beginning, we did not reflect much on the circularity issues associated with PV systems in the building. The reason behind this hesitation was existing complexity and challenges in the decision-making process. In all chapters of this dissertation the circularity could have become a key consideration. It is indeed a shortcoming and recommendation for future works. Looking into the definition of integration based on the product architecture principle could be an interesting topic for future studies. It can include design for disassembly, circularity, and reusability as possibilities.

On concept development, we have presented some missing concepts from the market and shown some of the opportunities for the introduction of new products. Each of these products would require deeper research and development and again could be considered as a topic for future studies.

As a side note, it is extremely important that we develop a new discipline around the energy production of buildings and in addition to designing systems to consume power, we create systems to produce and store generated energy on-site.

7.5 Final remarks

It is readily apparent that current BAPV methods are insufficient in realising the urban energy transition. The view of PV as an add-on to an existing structure that is merely attached into the roof or façade is leading to the urban energy transitions stagnation. In this dissertation numerous examples of how PV can be used in buildings are presented and many experiences of the architects that were involved in those projects are documented. As of current regulations, political pressures and as part of the compliance process of international goals for tackling climate change, there is no way around using PV on buildings. In order to wisely use these opportunities in mandatory PV usage, we must better equip architects with good products and decision-making tools in order to assist them in their usage of this technology. This is, by far, the most important goal of this dissertation.

In addition, in this book, I emphasised the role of architects in the adoption process as being in the centre of the decision-making. This role that has been neglected and undermined by many actors and, therefore, resulted in architects viewing PV as a highly complicated and alien technology and often, as an inefficient product.

If we want PV to become a staple in the architect's toolbox, we need to leave it to them on how they wish to use it, with other related actors, including engineers, policymakers, contractors… etc. supporting them in making the best use of it.

I would like to close this dissertation by referring to the same analogy I quoted at the beginning. I wish that the content me and my colleagues provided in this dissertation contribute to achieving this analogous view of the city.

Buildings in our urban ecosystems must carry out a similar function as trees in a forest. Collecting energy on its outer surface and transforming it for its own needs. This way of approaching the issue would reduce dependence on external energy sources, reducing them to a balancing force rather than a supplying one (Markvart & Castañer, 2013).

Bibliography

ABC News. (2018). Retrieved June 20, 2022, from https://abcnews.go.com/Technology/apples-headquarters-facilities-now-powered-100-percent-renewable/story?id=54362901

Abdelrazik, A. S., Al-Sulaiman, F. A., Saidur, R., & Ben-Mansour, R. (2018). A review on recent development for the design and packaging of hybrid photovoltaic/thermal (PV/T) solar systems. *Renewable and Sustainable Energy Reviews*, *95*(July), 110–129. https://doi.org/10.1016/j.rser.2018.07.013

Acuto, M., Parnell, S., & Seto, K. C. (2018). Building a global urban science. *Nature Sustainability*, *1*(1), 2–4. https://doi.org/10.1038/s41893-017-0013-9

Adamovic, N., Zimmermann, A., Caviasca, A., Harboe, R., & Ibanez, F. (2017). Custom designed photovoltaic modules for PIPV and BIPV applications. *Journal of Renewable and Sustainable Energy*, *9*(2). https://doi.org/10.1063/1.4979820

Adeeb, J., Farhan, A., & Al-Salaymeh, A. (2019). Temperature effect on performance of different solar cell technologies. *Journal of Ecological Engineering*, *20*(5), 249–254. https://doi.org/10.12911/22998993/105543

Adriano Biondo. (2017). Burckhardt partners. Retrieved June 19, 2022, from https://www.burckhardtpartner.com/de/projekte/detail/projekte/show/Projekte/neubau-buerogebaeude-und-hotel-grosspeter-tower-basel/?no_cache=1&cHash=3b383b8aa43c21283fa7ff2706f5c10a

Ajayan, J., Nirmal, D., Mohankumar, P., Saravanan, M., Jagadesh, M., & Arivazhagan, L. (2020). A review of photovoltaic performance of organic/inorganic solar cells for future renewable and sustainable energy technologies. *Superlattices and Microstructures*, *143*(April), 106549. https://doi.org/10.1016/j.spmi.2020.106549

Aksamija, A. (2017). *Integrating Innovation in Architecture : Design, Methods and Technology for Progressive Practice and Research*. New York, UNITED KINGDOM: John Wiley & Sons, Incorporated. Retrieved from http://ebookcentral.proquest.com/lib/delft/detail.action?docID=4814067

Alsema, E. (2012). Energy Payback Time and CO2 Emissions of PV Systems. In *Practical Handbook of Photovoltaics* (pp. 1097–1117). Elsevier Ltd. https://doi.org/10.1016/B978-0-12-385934-1.00037-4

Anderson, B. N. (1977). Solar energy: Fundamentals in building design. *New York*.

Andreadis, G., Roaf, S., & Mallick, T. (2013). Tackling fuel poverty with building-integrated solar technologies: The case of the city of Dundee in Scotland. *Energy and Buildings*, *59*, 310–320. https://doi.org/10.1016/j.enbuild.2012.11.032

ASCA. (2019). Solar street furniture installed at KAUST - Saudi Arabia | ASCA®. Retrieved May 9, 2021, from https://en.asca.com/projects/asca-city-en/solar-street-furniture-installed-at-kaust/

ASCA. (2020). Flexible solar cell & transparent photovoltaic film | ASCA®. Retrieved May 9, 2021, from https://en.asca.com/cell-solar-flexible-transparent/

Attia, S., Bilir, S., Safy, T., Struck, C., Loonen, R., & Goia, F. (2018). Current trends and future challenges in the performance assessment of adaptive façade systems. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2018.09.017

Bachman, L. R. (2004). *Integrated Buildings: The Systems Basis of Architecture*. https://doi.org/50669935

Bahaj, A. S., James, P. A. B., & Jentsch, M. F. (2007). Photovoltaics: added value of architectural integration. *Proceedings of the Institution of Civil Engineers - Energy*, *160*(2), 59–69. https://doi.org/10.1680/ener.2007.160.2.59

Ballif, C., Perret-Aebi, L.-E., Lufkin, S., & Rey, E. (2018). *Integrated thinking for photovoltaics in buildings*. https://doi.org/10.1038/s41560-018-0176-2

Barkaszi, S. F., & Dunlop, J. P. (2001). *DISCUSSION OF STRATEGIES FOR MOUNTING PHOTOVOLTAIC ARRAYS ON ROOFTOPS. Proceedings of Solar Forum.*

Bear ID Architects. (n.d.). Retrieved February 20, 2022, from http://bear-id.com/projects/langedijk-solar-homes/

Biyik, E., Araz, M., Hepbasli, A., Shahrestani, M., Yao, R., Shao, L., … Atlı, Y. B. (2017). A key review of building integrated photovoltaic (BIPV) systems. *Engineering Science and Technology, an International Journal*, *20*(3), 833–858. https://doi.org/10.1016/j.jestch.2017.01.009

Böer, K. W. (1974). SOLAR ONE THE DELAWARE SOLAR HOUSE AND RESULTS OBTAINED DURING. *International Conference Photovoltaic Power Generation 1974*.

Böer, K. W. (1978). Payback of solar systems. *Solar Energy*, *20*(3), 225–232. https://doi.org/10.1016/0038-092X(78)90101-9

Bonomo, P., Zanetti, I., Frontini, F., & Donker, M. N. van den. (2016). BIPV Products Overview For Solar Building Skin. In *33rd European Photovoltaic Solar Energy Conference and Exhibition BIPV* (pp. 35–40). https://doi.org/10.1109/ciced.2018.8592188

Brem, A., & Voigt, K. I. (2009). Integration of market pull and technology push in the corporate front end and innovation management-Insights from the German software industry. *Technovation*, *29*(5), 351–367. https://doi.org/10.1016/j.technovation.2008.06.003

Bristow, N., & Kettle, J. (2015). Outdoor performance of organic photovoltaics: Diurnal analysis, dependence on temperature, irradiance, and degradation. *Journal of Renewable and Sustainable Energy*, *7*(1). https://doi.org/10.1063/1.4906915

Butera, F. (2008). PART IV Transforming the Built Environment Chapter 14. *Urban Energy Transition*.

C.F.Moller. (n.d.). Retrieved June 19, 2022, from https://www.cfmoller.com/p/Copenhagen-International-School-Nordhavn-i2956.html

Castellanos, S., Sunter, D. A., & Kammen, D. M. (2017). Rooftop solar photovoltaic potential in cities: How scalable are assessment approaches? *Environmental Research Letters*, *12*(12). https://doi.org/10.1088/1748-9326/aa7857

Chen, D., Chen, Y., Wang, Z., Gong, J., Liu, C., Zou, Y., … Verlinden, P. J. (2020). 24.58% total area efficiency of screen-printed, large area industrial silicon solar cells with the tunnel oxide passivated contacts (i-TOPCon) design. *Solar Energy Materials and Solar Cells*, *206*, 110258. https://doi.org/10.1016/j.solmat.2019.110258

Creswell, J. W. (2009). *Research design: Qualitative, quantitative, and mixed methods approaches*. SAGE.

Dam & Partners. (n.d.). Retrieved June 19, 2022, from https://damenpartners.com/projecten/epo-new-main/

De Spakler - Amsterdam - Lingotto. (n.d.). Retrieved June 19, 2022, from https://lingotto.nl/projecten/de-spakler-amsterdam/

Defaix, P. R., van Sark, W. G. J. H. M., Worrell, E., & de Visser, E. (2012). Technical potential for photovoltaics on buildings in the EU-27. *Solar Energy*, *86*(9), 2644–2653. https://doi.org/10.1016/j.solener.2012.06.007

Dijkema, J. (author). (2019). The Transition: Design and engineering of a sustainable solar carport for the “Nederlandse Spoorwegen” LK - https://tudelft.on.worldcat.org/oclc/1108342117. Retrieved from http://resolver.tudelft.nl/uuid:6c7978a5-3f0c-4309-b493-208d8bb8623c

Ellis, M. F. (1983). Roof integrated photovoltaic module and system design. In *Solar collectors in Architecture*.

EN 50583:2016, Photovoltaics in buildings BIPV modules. (2016).

Energy Agency, I. (2021). *World Energy Outlook 2021*. Retrieved from www.iea.org/weo

Erban, C. (2011). KWH is not the main objective of phtovoltaic, (0), 49–50.

EU. (2010). Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). *Official Journal of the European Union*, 13–35. https://doi.org/doi:10.3000/17252555.L_2010.153.eng

Euroconstruct. (2019). Euroconstrcuct - Reports. Retrieved August 27, 2020, from https://www.euroconstruct.org/ec/reports

European Commission. (2020). 2030 climate & energy framework. Retrieved March 10, 2022, from https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2030-climate-energy-framework_nl

F. Frontini1, A. Scognamiglio2, G. Graditi2, C. Polo Lopez1, M. P. (2013). FROM BIPV TO BUILDING COMPONENT. *28th European Photovoltaic Solar Energy Conference and Exhibition FROM*, 4604–4615.

Farkas, Klaudia; Frontini, Francesco; Maturi, Laura; Scognamiglio, Alessandra; Munari Probst, Maria Cristina ; Roecker, C. (2013). Designing photovoltaic systems for architectural integration. Criteria and guidelines for product and system developers, 84.

Farkas, K. (2011). The art of photovoltaics. *30th ISES Biennial Solar World Congress 2011, SWC 2011*, *3*(Nasar 1998), 2052–2063. https://doi.org/10.18086/swc.2011.17.09

Farkas, K., Probst, M. C. M., & Horvat, M. (2010). Barriers and Needs for Building Integration of Solar Thermal and Photovoltaics. *Eurosun*, (7491).
Ferrazza, F. (2018). *Crystalline silicon: Manufacture and properties. McEvoy's Handbook of Photovoltaics: Fundamentals and Applications* (Third Edit). Elsevier Ltd. https://doi.org/10.1016/B978-0-12-809921-6.00004-5
Flisom. (2020). Fully Flexible Modules: eMetal, eRoll & eFlex | Flisom. Retrieved May 9, 2021, from https://www.flisom.com/products/
Frantzis, L., Hill, S., Teagan, P., & Friedman, D. (1994). Building-integrated PV-analysis and US market potential, 1204–1207. https://doi.org/10.1109/wcpec.1994.520180
Fraunhofer ISE. (2017). Photovoltaics report, (July).
Fraunhofer ISE. (2020). Photovoltaics Report, (September).
Frontini, F., Bonomo, P., Chatzipanagi, A., Verberne, G., Van Den Donker, M., & Folkerts, W. (2015). *BIPV Product Overview for Solar Facades and Roofs*. Retrieved from www.bipv.ch
Fuentes, M. (2007). Integration of PV into the built environment, 1–9.
Gagnon, P., Margolis, R., Melius, J., Phillips, C., & Elmore, R. (2016). Rooftop solar photovolatic technical potential in the united states: A detailed assessment. *Nrel*, (January), 82. https://doi.org/https://www.nrel.gov/docs/fy16osti/65298.pdf
Gaiddon, B., Kaan, H., & Munro, D. (2009). *Photovoltaics in the urban environment : lessons learnt from large-scale projects TT -. Earthscan*. London : Earthscan,.
Gevaerts, V. S. (2017). Organic PV module design and manufacturing. In *Photovoltaic Solar Energy: From Fundamentals to Application* (pp. 292–302). John Wiley & Sons.
Ghosh, A. (2020). Potential of building integrated and attached/applied photovoltaic (BIPV/BAPV) for adaptive less energy-hungry building's skin: A comprehensive review. *Journal of Cleaner Production*, *276*, 123343. https://doi.org/10.1016/j.jclepro.2020.123343
Grätzel, Richter Dahl Rocha & Associés. (n.d.). Retrieved June 19, 2022, from https://www.archdaily.com/491135/richter-dahl-rocha-develop-innovative-facade-for-swisstech-convention-center
Green, M. A. (2002). Third generation photovoltaics: Solar cells for 2020 and beyond. In *Physica E: Low-Dimensional Systems and Nanostructures* (Vol. 14, pp. 65–70). North-Holland. https://doi.org/10.1016/S1386-9477(02)00361-2
Green, M. A. (2018). *High-efficiency silicon solar cell concepts. McEvoy's Handbook of Photovoltaics: Fundamentals and Applications*. Elsevier Ltd. https://doi.org/10.1016/B978-0-12-809921-6.00005-7
Green, M. A., Dunlop, E. D., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., & Hao, X. (2021). Solar cell efficiency tables (Version 58). *Progress in Photovoltaics: Research and Applications*, *29*(7), 657–667. https://doi.org/10.1002/PIP.3444
Green, M., Dunlop, E., Hohl-Ebinger, J., Yoshita, M., Kopidakis, N., & Hao, X. (2021). Solar cell efficiency tables (version 57). *Progress in Photovoltaics: Research and Applications*, *29*(1), 3–15. https://doi.org/10.1002/pip.3371
GreenPix: Zero Energy Media Wall / | ArchDaily. (n.d.). Retrieved February 20, 2022, from https://www.archdaily.com/245/greenpix-zero-energy-media-wall?ad_medium=widget&ad_name=navigation-next
Hagemann, I. (1994). THE AESTHETIC AND ARCHITECTURAL INTEGRATION OF photovoltaic systems in buildings. In *12th European photovoltaic solar energy conference.*
Hagemann, I. (1996). Architectural Considerations for Building-in tegra ted Photovoltaics, *4*(May), 247–258.
Hagemann, I. (2004). Examples of successful architectural integration of PV: Germany. *Progress in Photovoltaics: Research and Applications*, *12*(6), 461–479.
Hagemann, I. B. (2001). BUILDING INTEGRATED PHOTOVOLTAIC (BIPV) ARCHITECTURALLY SMART INTEGRATION OF PV IN THE BUILDING ENVELOPE 3 . ACTION OBJECTIVES FOR FURTHER, (October), 2363–2366.
Hagemann, I. B. (2004). Examples of successful architectural integration of PV: Germany. *Progress in Photovoltaics: Research and Applications*, *12*(6), 477–483.
Hagemann, I. B. (2010). Building design and the potential of third-generation solar cells, 1–2.
Haghighi, Z., ORTIZ LIZCANO, J. C., ISABELLA, O., ZEMAN, M., & VAN DEN DOBBELSTEEN, A. (2020). *PCT/NL2020/050422*. European: World Intellectual property Organization.
Hanifi, Hamed; Schneider, Jens; Bagdahn, J. (2015). *Reduced Shading effect on Half-Cell modules - Measurement and Simulation*. Hamburg, Germany.

Harris, D. J., & Helwig, N. (2007). Solar chimney and building ventilation. *Applied Energy*, *84*(2), 135–146. https://doi.org/10.1016/j.apenergy.2006.07.001
Hegedus, S. S., & Luque, A. (2005). Status, Trends, Challenges and the Bright Future of Solar Electricity from Photovoltaics. In *Handbook of Photovoltaic Science and Engineering* (Vol. 1, pp. 1–43). Chichester, UK: John Wiley & Sons, Ltd. https://doi.org/10.1002/0470014008.ch1
Heinstein, P., Ballif, C., & Perret-Aebi, L. E. (2013). Building integrated photovoltaics (BIPV): Review, potentials, barriers and myths. *Green*, *3*(2), 125–156. https://doi.org/10.1515/green-2013-0020
Heinstein, P., Christophe, B., & Laure-Emmanuelle, P.-A. (2013). Building Integrated Photovoltaics (BIPV): Review, Potentials, Barriers and Myths. *Green*. https://doi.org/10.1515/green-2013-0020
Henemann, A. (2008). BIPV: Built-in solar energy. *Renewable Energy Focus*, *9*(6 SUPPL.). https://doi.org/10.1016/S1471-0846(08)70179-3
Herzog, T, Krippner, R., & Lang, W. (2012). *Facade construction manual*. Retrieved from https://books.google.nl/books?hl=en&lr=&id=OTrTAAAAQBAJ&oi=fnd&pg=PA5&dq=thomas+herzog+facade&ots=T-6kKyZ1X7J&sig=533lAYSUDUIoCQ4jQzk48liFuuw
Herzog, Thomas. (1983). PV in Architecture. In *First E.C. Conference on Solar Collectors in Architecture : integration of photovoltaic and thermal collectors in new and old building structures : proceedings of the international conference, held at Venice, Italy, 3-5 March 1983 / edited by W. Palz, V.* .
Hestnes, A. G. (1999). BUILDING INTEGRATION OF SOLAR ENERGY SYSTEMS. *Solar Energy*, *67*, 181–187.
Horsky, A. (2017). NEW-Blauhaus | kadawittfeldarchitektur. Retrieved June 19, 2022, from https://www.kadawittfeldarchitektur.de/en/projekt/new-blauhaus/
Horvat, M., Dubois, M.-C., Snow, M., Wall, M., Amado, M., Bouffard, É., Massart, C. (2011). *IEA-SHC Task 41: Solar Energy and Architecture Task 41-Solar Energy and Architecture Subtask B-Methods and Tools for Solar Design International survey about digital tools used by architects for solar design EDITORS*.
IEA. (2002a). International Energy Agency (IEA), 2002. Potential for building integrated photovoltaics. Report IEA-PVPS T7-4:2002 (Summary), IEA. Retrieved from www.iea-pvps.org.
IEA. (2002b). Potential for building integrated photovoltaics. *IEA-PVPS Task 7*, *2002*, 2–4. Retrieved from www.netenergy.ch/pdf/BipvPotentialSummary.pdf
IEA. (2017). *REthinking Energy*.
IEA. (2021). The Future of Cooling – Analysis - IEA. Retrieved November 1, 2021, from https://www.iea.org/reports/the-future-of-cooling
InifinityPV. (2020). Solar Tape. Retrieved May 9, 2021, from https://infinitypv.com/products/opv/solar-tape
INTEGRATE | meaning in the Cambridge English Dictionary. (n.d.). Retrieved February 4, 2021, from https://dictionary.cambridge.org/dictionary/english/integrate
International Energy Agency. (2012). IEA SHC Task 41 - SubtaskA. Retrieved from https://task41.iea-shc.org/publications
IRENA. (2019). *Future of solar photovoltaic: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation: paper). International Renewable Energy Agency* (Vol. November). Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Oct/IRENA_Future_of_wind_2019.pdf
IRENA. (2021). *Global patenting trends in RET. /inspire/Intellectual-Property-Rights/Global-Patenting-Trends-in-RET*. Retrieved from /inspire/Intellectual-Property-Rights/Global-Patenting-Trends-in-RET
J. R. Oster. (1979). *Residential Photovoltaic Module and Array requirement study*.
Janberg, N. (2018). bureau d'architecture greisch scrl Wallonie-Bruxelles Architectures. Retrieved June 19, 2022, from https://wbarchitectures.be/fr/architects/bureau-d-architecture-greisch-scrl/Tour-Paradis-a-Liege/895/
Jelle, B. P., & Breivik, C. (2012). The path to the building integrated photovoltaics of tomorrow. *Energy Procedia*, *20*(1876), 78–87. https://doi.org/10.1016/j.egypro.2012.03.010
Jelle, B. P., Breivik, C., & Drolsum Røkenes, H. (2012). Building integrated photovoltaic products: A state-of-the-art review and future research opportunities. *Solar Energy Materials and Solar Cells*, *100*(7465), 69–96. https://doi.org/10.1016/j.solmat.2011.12.016
JinkoSolar. (2021). JinkoSolar announces 23.01% efficiency for n-type monocrystalline panel – pv magazine International. Retrieved May 11, 2021, from https://www.pv-magazine.com/2021/01/12/jinkosolar-announces-23-01-efficiency-for-n-type-monocrystalline-panel/

Jošt, M., Lipovšek, B., Glažar, B., Al-Ashouri, A., Brecl, K., Matič, G., … Albrecht, S. (2020). Perovskite Solar Cells go Outdoors: Field Testing and Temperature Effects on Energy Yield. *Advanced Energy Materials*, *10*(25). https://doi.org/10.1002/aenm.202000454

Kaan, H., & Reijenga, T. (2004). Photovoltaics in an architectural context. *Progress in Photovoltaics: Research and Applications*, *12*(6), 395–408. https://doi.org/10.1002/pip.554

Kameleonsolar. (2020). ColorBlast® Colored Solar Panels - Kameleon Solar. Retrieved May 9, 2021, from https://kameleonsolar.com/colorblast/

Kenji Kobayashi. (n.d.). Kengo Kuma and Associates. Retrieved June 19, 2022, from https://kkaa.co.jp/en/project/toshima-ward-office-toshima-ecomusee-town/#gallery-1

Kennedy, D. M., Farret, F. A., & Simões, M. G. T. A.-T. T.-. (2006). Integration of alternative sources of energy, (July), 1–2. Retrieved from http://dx.doi.org/10.1002/0471755621

Kojima, A., Teshima, K., Shirai, Y., & Miyasaka, T. (2009). Organometal halide perovskites as visible-light sensitizers for photovoltaic cells. *Journal of the American Chemical Society*, *131*(17), 6050–6051. https://doi.org/10.1021/ja809598r

Kuhn, T. E., Erban, C., Heinrich, M., Eisenlohr, J., Ensslen, F., & Neuhaus, D. H. (2020). Review of Technological Design Options for Building Integrated Photovoltaics (BIPV). *Energy and Buildings*, 110381. https://doi.org/10.1016/j.enbuild.2020.110381

Kuhn, T. E., Tersluisen, A., Eisenlohr, J., Eggers, J., Jäger, F., Aßländer, O., Stark, T. (2019). Neuartige , teiltransparente BIPV-Module mit erhöhtem Gestaltungsspielraum Technische Grundidee.

Kumar, G., & Raheja, G. (2016). Design Determinants of Building Envelope for Sustainable Built Environment: A Review. *Scholar.Archive.Org*. https://doi.org/10.11113/ijbes.v3.n2.127

Kurtz, S., Haegel, N., Sinton, R., & Margolis, R. (2017). A new era for solar. *Nature Photonics*, *11*(1), 3–5. https://doi.org/10.1038/nphoton.2016.232

L.H. Slooff, J.A.M. van Roosmalen, L.A.G. Okel, T. et al. (2017). AN ARCHITECTURAL APPROACH FOR IMPROVING AESTHETICS OF PV. *European PV Solar Energy Conference and Exhibition EU PVSEC, 25-29 September 2017, Amsterdam, the Netherlands*, *4*(September), 9–15.

Labouret, A., & Villoz, M. T. A.-T. T.-. (2010). Solar photovoltaic energy (NV-1 onl, pp. 1–18). Stevenage : Institution of Engineering and Technology,. Retrieved from http://dx.doi.org/10.1049/PBRN009E

Lal, S., Kaushik, S., & Bhargav, P. (2013). Solar chimney: a sustainable approach for ventilation and building space conditioning. *International Journal of Development and Sustainability Online*, *2*(1), 277–297. Retrieved from https://www.academia.edu/download/35894072/ijds-v2n1-20.pdf

Larsson, D., Benson, J., Woess-Gallasch, S., Frederiksen, K., Hendrick, P., & Frieden, D. (2018). *Transition towards Sound BIPV Business Models Inventory on Existing Business Models, Opportunities and Issues for BIPV IEA PVPS Task 15 Subtask B-Transition towards sound BIPV business models*. Olivier Jung.

Lavrakas, P. (2012). *Encyclopedia of Survey Research Methods*. *Encyclopedia of Survey Research Methods*. Sage Publications, Inc. https://doi.org/10.4135/9781412963947

Lewis, N. S. (2007). Powering the Planet. *Materials Research Society Spring Meeting*, *32*(10), 808–820. https://doi.org/10.1557/mrs2007.168

Linden, J. (n.d.). Brooks + Scarpa Architects | ArchDaily. Retrieved June 19, 2022, from https://www.archdaily.com/340616/green-dot-animo-leadership-high-school-brooks-scarpa-architects

López, P. (n.d.). *ACCEPTANCE OF BUILDING INTEGRATED PHOTOVOLTAIC (BIPV) IN HERITAGE BUILDINGS AND LANDSCAPES: POTENTIALS, BARRIER AND ASSESSMENT CRITERIA*. Retrieved from http://www.supsi.ch

Lovins, A. B., & Lovins, L. H. (1982). *BRITTLE Energy Strategy for National Security*.

Lysandrou, A. (2019). *Investigation and implementation of the PV-Chimney'system on building emvelopes*. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3Abaf07691-9475-40d1-963e-f2eeb8604739

Madlener, R., & Sunak, Y. (2011). Impacts of urbanization on urban structures and energy demand: What can we learn for urban energy planning and urbanization management? *Sustainable Cities and Society*, *1*(1), 45–53. https://doi.org/10.1016/j.scs.2010.08.006

Marburg, K. (2014). opus Architekten BDA, Darmstadt. Retrieved June 19, 2022, from http://www.opus-architekten.de/

Markvart, T., & Castañer, L. (2003). Architectural Possibilities for PV Technology. In *Practical Handbook of Photovoltaics - Fundamentals and Applications* (p. 777). Elsevier. Retrieved from https://app.knovel.com/hotlink/khtml/id:kt0083EKG1/practical-handbook-photovoltaics/architectural-possibilities

Markvart, T., & Castañer, L. (2013). Chapter IA-1 - Principles of Solar Cell Operation BT - Solar Cells (Second Edition). In *Solar Cells* (pp. 3–25). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-386964-7.00001-9

Maturi, L., & Adami, J. (2018). *Building Integrated Photovoltaic (BIPV) in Trentino Alto Adige*. Retrieved from http://link.springer.com/10.1007/978-3-319-74116-1

Max Mittag, Matthieu Ebert, Helen Rose Wilson, T. F. (2018). MOSAIC MODULE CONCEPT FOR COST-EFFICIENT AND AESTHETIC BIPV MODULES, (September), 24–28.

Merriam-Webster. (n.d.). . (n.d.). Integrate. In dictionary. Retrieved , from. Retrieved April 13, 2020, from https://www.merriam-webster.com/dictionary/integrate

Mesquita, D. D. B., Lucas De Silva, J., Moreira, H. S., Kitayama, M., & Villalva, M. G. (2019). A review and analysis of technologies applied in PV modules. *2019 IEEE PES Conference on Innovative Smart Grid Technologies, ISGT Latin America 2019*. https://doi.org/10.1109/ISGT-LA.2019.8895369

Miasole. (2020). MiaSolé - Home. Retrieved May 9, 2021, from http://miasole.com/

Monte Rosa Hut. (2009). Retrieved June 17, 2022, from https://www.wicona.com/hu/baltics/references/switzerland/monte-rosa-hut/

Nayak, P. K., Mahesh, S., Snaith, H. J., & Cahen, D. (2019). Photovoltaic solar cell technologies: analysing the state of the art. *Nature Reviews Materials*, *4*(4), 269–285. https://doi.org/10.1038/s41578-019-0097-0

Nowak, S., Gutschner, M., Ruoss, D., Togweiler, P., & Schoen. (2002). *Potential for Building Integrated Photovoltaics, Report IEA-PVPS T7–4*.

NREL. (2020a). Cadmium Telluride Solar Cells | Photovoltaic Research | NREL. Retrieved May 9, 2021, from https://www.nrel.gov/pv/cadmium-telluride-solar-cells.html

NREL. (2020b). Copper Indium Gallium Diselenide Solar Cells | Photovoltaic Research | NREL.

NREL. (2021). Best Research-Cell Efficiency Chart | Photovoltaic Research | NREL. Retrieved May 9, 2021, from https://www.nrel.gov/pv/cell-efficiency.html

OECD/IEA. (2017). World Energy Outlook 2017 Executive Summary, 13. https://doi.org/10.1016/0301-4215(73)90024-4

Ohshita, Y., Onishi, K., Yokogawa, R., Nishihara, T., Kamioka, T., Nakamura, K., … Ogura, A. (2019). Ultra-Thin Lightweight Bendable Crystalline Si Solar Cells for Solar Vehicles. *Conference Record of the IEEE Photovoltaic Specialists Conference*, 1131–1134. https://doi.org/10.1109/PVSC40753.2019.8981291

Onyx Solar. (2018). Onyx Solar - Photovoltaic Glass for Buildings. Retrieved May 9, 2021, from https://www.onyxsolar.com/

Ortiz Lizcano, J. C., Haghighi, Z., Wapperom, S., Infante Ferreira, C., Isabella, O., v. d. Dobbelsteen, A., & Zeman, M. (2020). Photovoltaic chimney: Thermal modeling and concept demonstration for integration in buildings. *Progress in Photovoltaics: Research and Applications*, *28*(6). https://doi.org/10.1002/pip.3194

Ozdemir, S., & Sahin, G. (2018). Multi-criteria decision-making in the location selection for a solar PV power plant using AHP. *Measurement: Journal of the International Measurement Confederation*, *129*(July), 218–226. https://doi.org/10.1016/j.measurement.2018.07.020

Palz, W., Vianello, V., & Bonalberti, E. (1984). *First EC Conference on Solar Collectors in Architecture: Integration of Photovoltaic and Thermal Collectors in New and Old Building Structures*. D. Reidel Publishing Company.

Paolo Corti, Pierluigi Bonomo, & Francesco Frontin. (2020). *Building Integrated Photovoltaics: A practical handbook for solar buildings' stakeholders*. Retrieved from www.solarchitecture.ch,

Parida, B., Iniyan, S., & Goic, R. (2011). A review of solar photovoltaic technologies. *Renewable and Sustainable Energy Reviews*, *15*(3), 1625–1636. https://doi.org/10.1016/j.rser.2010.11.032

Pelle, M., Lucchi, E., Maturi, L., Astigarraga, A., & Causone, F. (2020). Coloured BIPV Technologies: Methodological and Experimental Assessment for Architecturally Sensitive Areas. https://doi.org/10.3390/en13174506

Peng, C., Huang, Y., & Wu, Z. (2011). Building-integrated photovoltaics (BIPV) in architectural design in China. *Energy and Buildings*, *43*(12), 3592–3598. https://doi.org/10.1016/j.enbuild.2011.09.032

Peng, J., Curcija, D. C., Thanachareonkit, A., Lee, E. S., Goudey, H., & Selkowitz, S. E. (2019). Study on the overall energy performance of a novel c-Si based semitransparent solar photovoltaic window. *Applied Energy*, *242*(January), 854–872. https://doi.org/10.1016/j.apenergy.2019.03.107

Polman, A., Knight, M., Garnett, E. C., Ehrler, B., & Sinke, W. C. (2016). Photovoltaic materials: Present efficiencies and future challenges. *Science*, *352*(6283). https://doi.org/10.1126/science.aad4424

Prabhudesai, S. (2019). *Modelling and Demonstration of a Bifacial PV Curtain for Building Applications*. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3A943bb96d-7177-4ddb-99b8-447bbe446964

Prasad, D K, & Snow, M. (2002). The Role of Emerging Technologies and Tools in ' Green ' Buildings. In *PLEA* (pp. 1–6).

Prasad, Deo K., & Snow, M. (2004). Examples of successful architectural integration of PV: Australia. *Progress in Photovoltaics: Research and Applications*, *12*(6), 477–483. https://doi.org/10.1002/pip.572

Prieto, A., Klein, T., Knaack, U., & Auer, T. (2017). Main perceived barriers for the development of building service integrated facades: Results from an exploratory expert survey. *Journal of Building Engineering*, *13*(April), 96–106. https://doi.org/10.1016/j.jobe.2017.07.008

R2M, Onyx Solar, Flisom, BEAR-iD, A. (2016). BIPV market and stakeholder analysis and needs Project report, (October 2016), 52. Retrieved from file:///C:/Users/xcybe/Downloads/report-bipv-market-and-stakeholder-analysis-and-ne.pdf

Ramanujam, J., Bishop, D. M., Todorov, T. K., Gunawan, O., Rath, J., Nekovei, R., … Romeo, A. (2020). Flexible CIGS, CdTe and a-Si:H based thin film solar cells: A review. *Progress in Materials Science*, *110*(August 2018), 1–20. https://doi.org/10.1016/j.pmatsci.2019.100619

Ramanujam, J., & Singh, U. P. (2017). Copper indium gallium selenide based solar cells - A review. *Energy and Environmental Science*, *10*(6), 1306–1319. https://doi.org/10.1039/c7ee00826k

Reijenga, T. (2000). ARCHITECTURAL QUALITY O . BUILDING INTEGRATION O . SOLAR ENERGY - CASE STUDIES IN THE NETHERLANDS ECN Petten new Zonnewende Langedijk ECN Petten retrofit, (March).

Reijenga, T. H., & Kaan, H. F. (2011). PV in Architecture. In *Handbook of Photovoltaic Science and Engineering* (pp. 1043–1077). John Wiley & Sons, Ltd. https://doi.org/10.1002/9780470974704.ch23

Reinders, A., Sark, W. Van, & Verlinden, P. (2018). Part one Introduction to Photovoltaics 1 . 1 . 1 Introduction to Photovoltaic Solar Energy. In *Photovoltaic solar energy : from fundamentals to applications.*

Rezaei, N., Isabella, O., Vroon, Z., & Zeman, M. (2018). Quenching Mo optical losses in CIGS solar cells by a point contacted dual-layer dielectric spacer: a 3-D optical study. *Optics Express*, *26*(2), A39. https://doi.org/10.1364/oe.26.000a39

Richter, C., Lincot, D., & Gueymard, C. A. (Eds.). (2013). *Solar Energy*. New York, NY: Springer New York. https://doi.org/10.1007/978-1-4614-5806-7

Ritzen, M. (2017). Environmental impact assessment of Building Integrated Photovoltaics: numerical and experimental carrying capacity based approach, 217.

Ritzen, M., Vroon, Z., & Geurts, C. (2013). Building Integrated Photovoltaics. In *Photovoltaic solar energy : from fundamentals to applications.* (Vol. 3, pp. 795–930). Retrieved from http://www.seia.org/policy/solar-technology/photovoltaic-solar-electric

Ritzen, M., Vroon, Z., Rovers, R., Geurts, C., & Blocken, B. (2015). Real Life Lab BIPV field testing in the Netherlands. In *2015 IEEE 42nd Photovoltaic Specialist Conference, PVSC 2015*. Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/PVSC.2015.7355634

Roecker, C., Affolter, P., Bonvin, J., Gay, B., & Muller, A. . (1995). PV building elements, *36*, 381–396.

Roecker, M. C. M. P. C. (2011). Architectural Integration And Design, *4258*(2008), 171.

Roy, P., Kumar Sinha, N., Tiwari, S., & Khare, A. (2020, March 1). A review on perovskite solar cells: Evolution of architecture, fabrication techniques, commercialization issues and status. *Solar Energy*. Elsevier Ltd. https://doi.org/10.1016/j.solener.2020.01.080

Røyset, A., Kolås, T., & Jelle, B. P. (2020). Coloured building integrated photovoltaics: Influence on energy efficiency. *Energy and Buildings*, *208*. https://doi.org/10.1016/j.enbuild.2019.109623

RPBW. (n.d.). Retrieved June 20, 2022, from http://www.rpbw.com/project/paris-courthouse

RPBW. (2016). Retrieved June 19, 2022, from http://www.rpbw.com/project/stavros-niarchos-foundation-cultural-center

Ruposov, V. L., & Belikov, A. (2021). New solutions for solar energy: aesthetics and return on investment. *IOP Conference Series: Earth and Environmental Science*, *751*(1), 012018. https://doi.org/10.1088/1755-1315/751/1/012018

Rüther, R., Knob, P. J., da Silva Jardim, C., & Rebechi, S. H. (2008). Potential of building integrated photovoltaic solar energy generators in assisting daytime peaking feeders in urban areas in Brazil. *Energy Conversion and Management*, *49*(5), 1074–1079. https://doi.org/10.1016/j.enconman.2007.09.020

Saaty, T. (1980). *The analytical hierarchy process*. (Mc Graw-Hi). New York.

SAIRQ. (2020). Productos – Siarq. Retrieved May 9, 2021, from https://siarq.com/productos/

SBAE | Ile Seguin Musical City. (2017). Retrieved June 19, 2022, from http://www.shigerubanarchitects.com/works/p31_IleSeguin/index.html

Schmid, J. (1983). Design consideration and economic aspects of photovoltaic modules for Architecture. In *Solar collectors in Architecture*.

Schulz und Schulz. (n.d.). Retrieved June 19, 2022, from https://schulz-und-schulz.com/en/projekte/katholische-propsteikirche-st-trinitatis-leipzig/media/7/

Scognamiglio, A. (2008). Starting point for new cultural vision of BIPV. *23rd EUPVSEC*, (September), 1–5.

Scognamiglio, Alessandra, Garde, F., & Røstvik, H. N. (2014). How net zero energy buildings and cities might look like? New challenges for passive design and renewables design. *Energy Procedia*. https://doi.org/10.1016/j.egypro.2014.11.1044

Scognamiglio, Alessandra, & Ossenbrink, H. A. (2014). *Photovoltaics forms landscapes : Beauty and power of designed photovoltaics*.

Scognamiglio, Alessandra, & Røstvik, H. N. (2013). Photovoltaics and zero energy buildings: a new opportunity and challenge for design. *Progress in Photovoltaics: Research and Applications TA -*, *21*(6), 1319–1336. https://doi.org/10.1002/pip

Shirazi, A. M., Zomorodian, Z. S., & Tahsildoost, M. (2019). Techno-economic BIPV evaluation method in urban areas. *Renewable Energy*, *143*, 1235–1246. https://doi.org/10.1016/j.renene.2019.05.105

Shukla, A. K., Sudhakar, K., & Baredar, P. (2017). Recent advancement in BIPV product technologies: A review. *Energy and Buildings*, *140*, 188–195. https://doi.org/10.1016/j.enbuild.2017.02.015

Sick, F., & Erge, T. (1996). Photovoltaics in Buildings - A Design Handbook for Architects and Engineers, 280.

Sijmons, D. (2017). Energie en Ruimte, 138.

Sijmons, D., Hugtenburg, J., Hoorn, A. van, & Feddes, F. (2014). *Landscape and energy : designing transition TT -. TA -*. Rotterdam : Nai010 Publishers,.

Singh, P., & Ravindra, N. M. (2012). Temperature dependence of solar cell performance - An analysis. *Solar Energy Materials and Solar Cells*, *101*, 36–45. https://doi.org/10.1016/j.solmat.2012.02.019

Sino-Italian Ecological and Energy Efficient Building / Photo by daniele-domenicali. (n.d.). Retrieved February 20, 2022, from https://www.archdaily.com/880371/sino-italian-ecological-and-energy-efficient-building-mario-cucinella-architects/59c9c8cdb22e38ca7c000092-sino-italian-ecological-and-energy-efficient-building-mario-cucinella-architects-photo

Solar Roof | Tesla Belgium. (n.d.). Retrieved July 1, 2022, from https://www.tesla.com/nl_be/solarroof

Solar Stadium in Taiwan. (2014). Retrieved June 17, 2022, from https://inhabitat.com/taiwans-solar-stadium-100-powered-by-the-sun/

Staebler, D. L., & Wronski, C. R. (1977). Reversible conductivity changes in discharge-produced amorphous Si. *Applied Physics Letters*, *31*(4), 292–294. https://doi.org/10.1063/1.89674

Stammers, J. R. (1983). Economics of use of solar energy in the UK.

Strong, S J. (1996). Power windows. Building-integrated photovoltaics. *IEEE Spectrum*, *33*(10), 49–55. https://doi.org/10.1109/6.540090

Strong, Steven J. (1983). Residential applications of photovoltaic in the united states. In *Solar collectors in Architecture*.

Sunpower. (2020). High Efficiency Solar Panels | Maxeon | SunPower Global. Retrieved May 7, 2021, from https://sunpower.maxeon.com/int/solar-panel-products/sunpower-maxeon-solar-panels

SunPower. (2010). MAXEON™ GEN III SOLAR CELLS Positive Electrical Grounding Interconnect Tab and Process Recommendations Cell Physical Characteristics. *Photovoltaics: Research and Applications*, (5), 46–352.

Sunrise_project. (2009). *BUILDING INTEGRATED PHOTOVOLTAICS > A NEW DESIGN OPPORTUNITY FOR ARCHITECTS*.

Súri, M., Huld, T. A., Dunlop, E. D., & Ossenbrink, H. A. (2007). Potential of solar electricity generation in the European Union member states and candidate countries. *Solar Energy*, *81*(10), 1295–1305. https://doi.org/10.1016/j.solener.2006.12.007

Swissinso. (n.d.). No Title. Retrieved August 14, 2021, from https://www.swissinso.com/technology

TAGO ARCHITECTS. (2012). Retrieved June 19, 2022, from http://tagomimarlik.com/?bL=sH1&gR=oK&id=39&cat=34&sid=866713309&l=lang1
The Edge. (n.d.). Retrieved June 19, 2022, from http://www.plparchitecture.com/the-edge.html
Thomas, Randall. Max, F. (2001). *Photovoltaics and Archtecture. Spon Press.* London: Spon,.
Tripathy, M., Sadhu, P. K., & Panda, S. K. (2016). A critical review on building integrated photovoltaic products and their applications. *Renewable and Sustainable Energy Reviews*, *61*, 451–465. https://doi.org/10.1016/j.rser.2016.04.008
Troldborg, M., Heslop, S., & Hough, R. L. (2014). Assessing the sustainability of renewable energy technologies using multi-criteria analysis: Suitability of approach for national-scale assessments and associated uncertainties. *Renewable and Sustainable Energy Reviews*, *39*, 1173–1184. https://doi.org/10.1016/j.rser.2014.07.160
Tsai, C. Y., & Tsai, C. Y. (2020). See-through, light-through, and color modules for large-area tandem amorphous/microcrystalline silicon thin-film solar modules: Technology development and practical considerations for building-integrated photovoltaic applications. *Renewable Energy*, *145*, 2637–2646. https://doi.org/10.1016/j.renene.2019.08.029
UNGA. (2016). New Urban Agenda, adopted by the United Nations General Assembly at its sixty-eighth plenary meeting of the seventy-first session on 23 December 2016, (January), 1–66. Retrieved from https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_71_256.pdf
UNStudio. (n.d.). Retrieved June 20, 2022, from https://www.unstudio.com/en/page/11994/hanwha-headquarters-remodelling
Urbanetz, J., Zomer, C. D., & Rüther, R. (2011). Compromises between form and function in grid-connected, building-integrated photovoltaics (BIPV) at low-latitude sites. *Building and Environment*, *46*(10), 2107–2113. https://doi.org/10.1016/j.buildenv.2011.04.024
Van De Kaa, G., Rezaei, J., Kamp, L., & De Winter, A. (2014). Photovoltaic technology selection: A fuzzy MCDM approach. *Renewable and Sustainable Energy Reviews*, *32*, 662–670. https://doi.org/10.1016/j.rser.2014.01.044
van Veen, L. (2020). *The "new" zero energy office building The impact of Dutch regulatory changes on the development of energy efficient office buildings*. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3Aa5771286-3c8e-41e4-9367-6035e2594748
Vellini, M., Gambini, M., & Prattella, V. (2017). Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels. *Energy*, *138*, 1099–1111. https://doi.org/10.1016/j.energy.2017.07.031
Virtuani, A., Pavanello, D., & Friesen, G. (2010). Overview of Temperature Coefficients of Different Thin Film Photovoltaic Technologies. *25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain*, (JANUARY), 4248–4252. https://doi.org/10.4229/25thEUPVSEC2010-4AV.3.83
Wang, J. J., Jing, Y. Y., Zhang, C. F., & Zhao, J. H. (2009). Review on multi-criteria decision analysis aid in sustainable energy decision-making. *Renewable and Sustainable Energy Reviews*, *13*(9), 2263–2278. https://doi.org/10.1016/j.rser.2009.06.021
Wapperom, S. (2019). *Energetic performance of a combined double skinfaçade with photovoltaic modules placed atvarious locations*. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3A31cb19b2-d98b-44d4-90b3-7ffc7fc0f34e
Weller, B. T. A.-T. T.-. (2010). Photovoltaics : technology, architecture, installation. Basel : Birkhäuser ; Retrieved from http://www.degruyter.com/isbn/9783034615709
Wilson, H. R. (2018). *IEA task 15-04: 2018 -International definitions of BIPV*. Retrieved from https://iea-pvps.org/wp-content/uploads/2020/02/IEA-PVPS_Task_15_Report_C0_International_definitions_of_BIPV_hrw_180823.pdf
Wu, W., Bao, J., Ma, L., Chen, C., Liu, R., Qiao, Z., … Liu, Z. (2019). DEVELOPMENT OF INDUSTRIAL N-TYPE BIFACIAL TOPCON SOLAR CELLS AND MODULES Weiliang. *36th European Photovoltaic Solar Energy Conference and Exhibition DEVELOPMENT*, (October), 2–5. https://doi.org/10.4229/EUPVSEC20192019-2BP.1.5
Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy*, *35*(5), 2683–2691. https://doi.org/10.1016/j.enpol.2006.12.001

Xu, Y., Li, J., Tan, Q., Peters, A. L., & Yang, C. (2018, May 1). Global status of recycling waste solar panels: A review. *Waste Management*. Elsevier Ltd. https://doi.org/10.1016/j.wasman.2018.01.036

Yeop Myong, S., & Won Jeon, S. (2015). Design of esthetic color for thin-film silicon semi-transparent photovoltaic modules. *Solar Energy Materials and Solar Cells*, *143*, 442–449. https://doi.org/10.1016/j.solmat.2015.07.042

Yin, R. (2009). *Case study research : design and methods* (4th ed.). Thousand Oaks Calif.: Sage Publications.

Zanetti, I., Bonomo, P., & Frontini, F. (2017). *Building Integrated Photovoltaic: Product overview for solar building skins*. Retrieved from www.seac.cc

Zhang, C., Shen, C., Wei, S., Wang, Y., Lv, G., & Sun, C. (2020). A Review on Recent Development of Cooling Technologies for Photovoltaic Modules. *Journal of Thermal Science 2020 29:6*, *29*(6), 1410–1430. https://doi.org/10.1007/S11630-020-1350-Y

Zhang, T., Wang, M., & Yang, H. (2018). A review of the energy performance and life-cycle assessment of building-integrated photovoltaic (BIPV) systems. *Energies*, *11*(11). https://doi.org/10.3390/en11113157

Ziar, H., Asaei, B., Farhangi, S., Korevaar, M., Isabella, O., & Zeman, M. (2017). Quantification of Shading Tolerability for Photovoltaic Modules. *IEEE Journal of Photovoltaics*, *7*(5), 1390–1399. https://doi.org/10.1109/JPHOTOV.2017.2711429

Zijlstra, R. (2016). Broekbakema. Retrieved June 19, 2022, from https://www.broekbakema.nl/en/projecten/energy-academy-europe-2/

Zumbuehl, R. (2015). Umwelt Arena. Retrieved June 17, 2022, from https://commons.wikimedia.org/wiki/File:2015-Spreitenbach-Umweltarena.jpg

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Work Experiences

06/2021 – Present | Senior Associate - Sustainable Corporate Solutions, Sustainalytics-Morningstar, NL

03/2017 – 06/2021 | Senior Researcher - Solarurban research project, TUDelft Faculty of Architecture, NL

02/2020 – 08/2020 | Consultant on Sustainability & Innovation - Foresight and Innovation team, Arup, DE

03/2013 – 08/2016 | Consultant on Sustainability & Renewable Energy, Various locations [Freelancer]

08/2013 – 08/2014 | Consultant on Sustainable Construction, CD2E, Lille, FR

2013- 2015 | Co-Founder, SolarCatch, Berlin, GER

Education & Qualifications

2017 – 2022 | Ph.D. Façade & Building Product Innovation, TUDelft, Netherlands
Dissertation title: Architectural Photovoltaic Application

2012 – 2013 | MSc Sustainability Engineering & Innovation Management, Paris-Saclay – France
Graduation project: Start-up business concept for Building-integrated photovoltaic shading product

2007 – 2011 | BArch Architectural Engineering, Tehran Azad University, Iran
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Architectural Photovoltaic Application

Zoheir Haghighi

The urgency to use renewable technologies within the built environment results in new interpretations of and approaches to Architecture. New building regulations, together with international pledges for addressing climate change, made the implications of photovoltaic systems (aka ‘solar panels’) in the buildings more crucial than ever. Moreover, the current mainstream of placing PV systems on the roof and façade of buildings is neither aesthetically appealing nor technically efficient and consequently not a sustainable, long-term, and reliable approach. In response to this issue, the concept of Integration is introduced as an alternative to this approach.

This research suggests the notion of Architectural Photovoltaic Application (APA) in response to the various shortcomings of the Integration, with its current definitions, for being adapted to different architectural styles and approaches. APA can be defined as an approach in which PV technologies are meant to be sources of on-site renewable energy and considered a part of building services that is also incorporated to the building anatomy through the design process. Through APA, PV systems do not need to play a role in the building construction, instead these systems are fully accommodated by Architects in the design process as another element of the building service.

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