Analysis of a Solar Pavement Prototype and an Assessment of its Viability in the Venetian Market

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Abstract

Solar energy is central to an energy transition, but integrating solar panels in historic centers is challenging. A solution to this is solar pavements, solar panels incorporated into the ground. BYS Italia, the sponsor of this project, sought recommendations for their solar pavement prototype and its viability in the Venetian market. We conducted surveys, material comparisons, energy production evaluations, and cost analyses. Conclusions suggest the technology is not yet economically viable. Universities show interest, yet practical challenges hinder installation in Venice. Recommendations include exploring other university campuses, improving public understanding of pavements, and considering alternative renewable energy strategies like solar roof tiles and windows for historical cities.

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Executive Summary

To address rising energy demands, there is a pressing need to transition towards more renewable energy sources. Solar energy emerges as a promising solution to this transition as it is found abundantly in most places and is a reliable way of harnessing sunlight for power generation (Guangul & Chala, 2019). However, integrating solar energy outside of conventional settings such as on rooftops or large open fields presents difficulties. Historic centers in particular can pose unique challenges due to constraints and preservation concerns; innovative approaches to integrating solar energy have potential in such areas. One example of this approach is solar pavements, which are solar panel systems directly incorporated into the infrastructure of roads and other paths.

Italy, a country with many historic areas that is investing in solar power, could leverage solar pavements to meet its goals. Despite government support for solar energy, widespread adoption of solar pavements remains limited (Hu et al., 2021). BYS Italia was established in 2019 by Infinityhub SpA Benefit, with the goal of creating solar pavements. Their prototype, developed through the MITdesignX program, is installed on San Servolo island. Assessing its technical, social, and economic aspects could be important for future adoption.

As of April 2024, the energy production of the prototype had remained untested leaving BYS unsure about its potential. BYS wanted to see if other technical improvements could be made such as improving or replacing the current glass with another material to improve its durability, and whether any other changes could be made to enhance its functionality. Finally, BYS sought insights into feasibility within the Venetian market and was looking for improvements to their business model.

Project Goal and Methods

The overall goal of the project was to provide recommendations to BYS by evaluating their solar pavement prototype and its viability in the Venetian market. This goal was achieved with the following objectives and methods:

1. **Assess the views of university professors and students on solar pavements in the Venetian market.**
   We wanted to help BYS determine the interest levels of universities through professors' insights and help BYS understand social acceptance through a sample of university students' perspectives. We conducted surveys with university professors and students to gather their opinions

2. **Conduct a performance analysis of BYS' prototype, including a materials comparison and an evaluation of theoretical energy production.**
   We compared BYS' current glass with other potential materials suitable for the solar pavement's surface. We analyzed these materials based on specific properties to

determine their suitability. We also calculated the theoretical energy production of BYS' prototype.

3. **Perform a cost analysis of BYS' technology from their perspective and the customer's perspective.**
   We did a competitor analysis of the other existing solar pavement prototypes in comparison to BYS in terms of cost and energy production. We also created a Photovoltaic Potential Calculator to help BYS explore potential pricing strategies to improve their business model. The pricing strategy refers to how BYS plans to charge its customers, whether that is through an initial payment, a monthly rental cost, or a combination of the two. Through this calculator, BYS can generate multiple scenarios to identify the optimal pricing strategy.

Findings and Conclusions

Based on the completion of these methods, we present the following findings:

1. Soda lime silicate glass is a favorable material for BYS to continue to use. BYS' glass performs well for most properties compared to the alternative materials. It has a much lower cost, a much higher hardness, and is ranked high for both transmissivity and weather resistance. The only property that did not perform as well was tensile strength. However, the tensile strength of BYS should suffice for their application of cycle-pedestrian paths.

2. BYS' technology is not economically viable in northern Italy and would best be developed as a demonstration technology. Given its current theoretical energy production and its cost, there is currently no pricing strategy where both BYS and the customer can break even within the 20-year lifespan of the technology. Figure 1 presents three potential scenarios: one where BYS breaks even, one where the customer breaks even, and a middle ground between the two. The values of net profit or loss for the customer were calculated by subtracting the monetary equivalence of the energy produced by the pricing strategy BYS chooses. For BYS, the net profit or loss was identified as the difference between the technology's total cost and the selected pricing strategy.

	Rental Price for Customer	Incurring Loss at 20 years
Scenario 1: BYS break-even	€4,850 per month	Loss to Customer: €800,000
Scenario 2: Customer break-even	€1,500 per month	Loss to BYS: €800,000
Scenario 3: Middle ground	€3,175 per month	Loss to each: €400,000

Figure 1. Three scenarios for a monthly rental pricing strategy

3. Universities with sufficient resources could be promising early adopters of this demonstration technology. Survey results suggest that sustainability is a positive driving factor for solar pavements. Over 90% of the university professors who responded to our survey claimed that sustainability was very important to their university. Similarly, when students were asked how implementing solar pavements would affect their campus, sustainability emerged as the driving factor. This suggests that there is a strong institutional emphasis on sustainability practices. Further, as indicated in Figure 2, professors believe their university would be more likely to install solar pavement technology due to the university's reputation and spreading awareness about renewable energy. This indicates that the primary purpose of installing these pavements on university campuses may not necessarily be to meet all the energy demands of the university but rather to serve as a representation of the institution's commitment to sustainability.

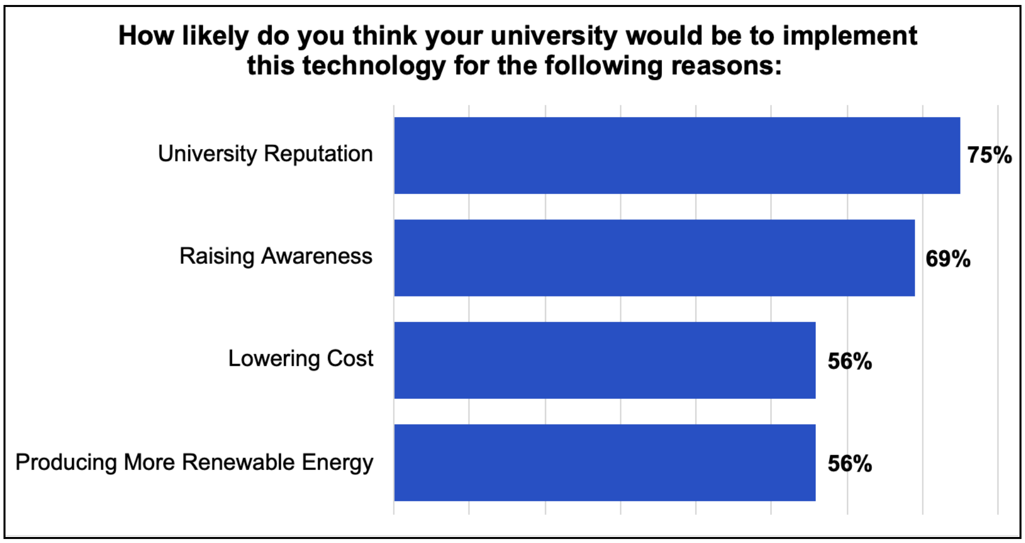


Figure 2. Bar chart of professors' responses to the question "How likely do you think your university would be to implement this technology for the following reasons?"

4. Implementing solar pavements on campuses in Venice is hindered by the ability to identify practical locations. When asked about whether there are potential locations where professors think their university could implement these solar pavements, 62% of responding professors replied that they did not believe there were any. One professor explained that there are no bike lanes in Venice and there are constraints on the placement of photovoltaic panels. Therefore, while there is an interest in solar pavements as a sustainable solution for universities, addressing practical challenges is required for their successful implementation.

Recommendations

Based on the findings of this study, we propose the following recommendations:

1. **We recommend that BYS look into other universities outside of Venice to assess potential adopters of their solar pavement.** It seems that it will be difficult to find locations on campuses in Venice to implement this type of technology; therefore, looking into other Italian universities might be a better fit. Moreover, municipalities and shopping centers could be potential stakeholders for further exploration to assess the solar pavements' viability.

2. **We recommend that BYS make more information about the pavements easily accessible to the public so they can learn more about their functionality.** Both responding professors and students expressed considerable concern about the slipperiness of solar pavements. This highlights worries about safety and the importance of addressing this issue in the design, implementation, and promotion of these pavements. People may have biases about the glass being slippery from previous interactions. Therefore, providing results from anti-slip tests or showing a piece of the prototype for people to feel may make the concept of this technology more clear to them.

3. **We recommend future researchers look into alternative strategies for cities like Venice with a high density of historical buildings.** Additional strategies for implementing solar energy into historic centers could include the integration of solar panels into windows, or solar roof tiles, as these are more seamlessly incorporated into buildings. This would help preserve the historical features of cities such as Venice while also contributing to the solar energy initiatives in Italy.

<u>**Table of Authorship**</u>

Section	Primary Author	Primary Editor
Abstract	VN	AK
Acknowledgments	KS	VN
Executive Summary	KS	AK
Chapter 1: Introduction	AK	JJ
Chapter 2: Background		
2.1 - Introduction to Solar Photovoltaic Systems	VN, AK	JJ
2.2 - Economic and Social Factors Affecting Solar Power Installations in Italy	KS, JJ, VN	KS
2.3 - Solar Pavements as an Emerging Technology	JJ, KS	VN
Chapter 3: Methodology		
3.1 - Assessing the Views of University Professors and Students on Solar Pavements	AK	KS
3.2 - Evaluating Prototype Performance	VN, JJ	KS
3.3 - Performing a Cost Analysis	JJ	AK
Chapter 4: Findings		
4.1 - Views of Solar Pavements by University Professors and Students	AK	KS
4.2 - Material Comparison and Review of Energy Production	VN, JJ	AK
4.3 - Cost Analysis of BYS' Technology	JJ	VN
Chapter 5: Conclusions and Recommendations		
Chapter 5 - Conclusions and Recommendations	AK	VN

Table of Contents

Table of Figures

Table of Tables

1. Introduction

Fossil fuels are the primary source of energy being used and produced globally. They emit significant amounts of carbon dioxide into the atmosphere and contribute to the global warming crisis (Soeder, 2021). To help mitigate this problem, there is a pressing need to transition towards more renewable energy sources, such as solar energy. It is a clean and renewable energy source found abundantly in most places, and a reliable way of harnessing sunlight for power generation (Guangul & Chala, 2019).

Although there is a high demand for solar energy, implementing it in historic places can pose unique challenges due to preservation concerns. However, solar energy comes in many forms, such as solar farms, rooftop solar panels, and photovoltaic (PV)/solar pavements. Notably, solar pavements are an innovative approach for integrating solar energy into daily life. They are solar panel systems that are directly incorporated into the infrastructure of roads and other paths (Hu et al., 2021). Despite being in the developmental phase, solar pavements have demonstrated promising potential. One example is the solar sidewalk in Budapest, powered by Platio, that provides energy to nearby buildings and electric vehicle charging stations (Hu et al., 2021).

Italy is an example of a country that has made significant investments in solar power generation and could benefit from solar pavement installations to meet its long-term goals. `Currently, about 19% of Italy's energy consumption is fueled by renewables. According to the National Plan for Energy and Climate (PNIEC), it is expected to reach 27% in 2030 (Topic: Renewable energy in Italy, n.d.). While this demand has led to the installation of conventional solar panels in the country, there have been no alternative solar pavements implemented past the early testing stages (Hu et al., 2021). One company that is exploring solar pavements is BYS Italia. This startup company is aiming to create PV cycle-pedestrian paths and has created a prototype to help introduce this new technology to Italy.

Our research goal for this project was to provide recommendations to BYS by evaluating their solar pavement prototype and its viability in the Venetian market. To accomplish this we assessed the views of university professors and students on solar pavements in the Venetian market. We also conducted a performance analysis of BYS' prototype, including a materials comparison and an evaluation of theoretical energy production. In addition, we performed a long-term cost analysis of the technology. We then provided recommendations to BYS regarding the viability of their prototype. We hope these recommendations will enhance the competitiveness of their solar pavement technology, fostering its wider adoption in the future.

2. Background

The global energy demand continues to rise, driven by factors such as population growth, economic development, and technological advancements. However, relying on fossil fuels to meet this demand poses significant environmental risks (Soeder, 2021). In response, there is a growing need to transition towards renewable energy sources. Solar energy stands out as a particularly promising option due to its abundance, cleanliness, and accessibility (Guangul & Chala, 2019). In this chapter, we discuss the importance of solar energy as a renewable resource. We then examine economic incentives that drive renewable energy adoption as well as the economic impact of PV panels. Further, we consider the factors affecting the implementation of solar panels in historic centers. Finally, we explore the emerging technology of solar pavements, and we discuss BYS' current prototype and its features.

2.1 Introduction to Solar Photovoltaic Systems

In this section, we describe and evaluate the different types of solar panels currently available on the market and highlight the benefits and advantages they offer. Then, we explore how factors like geographical location, positioning, orientation, and other weather-related conditions impact solar PV systems.

2.1.1 Flexibility of Solar Panels and their Benefits

Solar panels can be placed anywhere that they have enough access to sunlight. A multinational group of renewable energy scholars made the case that "Solar energy is one of the best options to meet future energy demand since it is superior in terms of availability, cost-effectiveness, accessibility, capacity, and efficiency compared to other renewable energy sources" (Kabir et al., 2018, p. 898). There are many modern techniques regarding the utilization of space when implementing solar panels. These techniques include implementation on rooftops, pathways, and even integration into building materials such as windows and facades (Energy5, n.d.). There are also more innovative ways of implementing solar panels, such as floating solar farms and solar trees (Hyder 2018). All of these implementations have the potential to be beneficial because they do not obstruct the area around them and still contribute to the overall goal of utilizing more renewable energy sources.

In addition to their flexibility, solar panels encompass a variety of benefits. The process of electricity generation through solar panels simply relies on sunlight, which is available in most regions of the world. Solar power is also a clean source of energy that causes no harm or pollution to the environment, making it an effective solution to fight against global warming (Guangul & Chala, 2019). Also, solar panels don't need water to operate, which can be very beneficial in the event of water droughts or heat waves.

While solar panel systems can be expensive, the more research and work that is done into their technology, the less they will cost. Their initial costs are expensive but they operate at low maintenance costs. The graph in Figure 1 demonstrates how historically, the price of solar PV modules has decreased as production and research and development increase. For example, from 2011 to 2021, the cost per unit module was reduced from €1.2/Wp to €0.22/Wp.

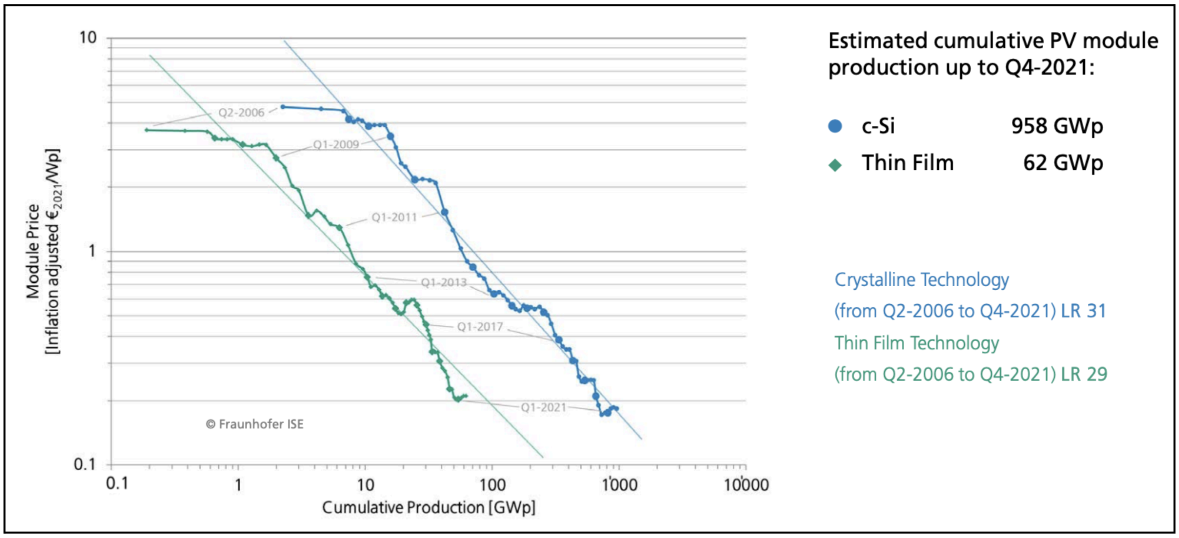


Figure 1. The decrease in PV module cost as the cumulative production increases (Benda et al., 2022).

2.1.2 Comparison of Types of Solar Panels

There are many different types of solar panels available on the market. Solar cells are the building blocks of solar panels, and Rathore (2021) describes three generations of solar cell technology:

- **First generation, wafer-based silicon solar cells:** Monocrystalline or polycrystalline
- **Second generation, thin film solar cells:** a-Si (Amorphous Silicon), CdTe (Cadmium Telluride), and CIGS (Copper-Indium-Gallium-Selenium)
- **Third generation:** Nanocrystal-based solar cells, polymer-based solar cells, dye-sensitized solar cells, perovskite-based solar cells, and concentrated solar cells

Each of these solar cells has its pros, cons, and levels of efficiency. The third generation is still in development, therefore we specifically focus on the first and second generation cells. As shown in Figure 2 the wafer-based silicon cells have much higher efficiencies than the thin film cells. However, the thin film cells are much more cost-effective than the wafer-based silicon cells. It can be difficult to decide between all these different types of solar cells, but ultimately it depends on the needs of the system and finding the most effective quality vs. cost ratio for the solar PV system.

<table>
<tr><th>Type of Solar Cell</th><th>Size</th><th>Cost</th><th>High temperature performance</th><th>Efficiency</th></tr>
<tr><td colspan="5">1st Generation - Wafer based silicon cells</td></tr>
<tr><td>Mono-crystalline</td><td rowspan="2">Requires less volume to produce same amount of power</td><td>More expensive crystalline silicon and two time more costly compared to thin-film solar cells</td><td>Does not perform good at high temperature (drops 10–15%)</td><td>17-18%</td></tr>
<tr><td>Poly-crystalline</td><td>Cheapest crystalline silicon and two time more costly compared to thin-film solar cells</td><td>Does not perform good at high temperature (drops 20%)</td><td>12-14%</td></tr>
<tr><td colspan="5">2nd Generation - Thin film cells</td></tr>
<tr><td>Amorphous Si Thin Film</td><td rowspan="3">Offering wide range of products design from flexible, light, durable</td><td>Cheaper and 50% less expensive than crystalline silicon</td><td rowspan="2">Performs good in cool as well as high temperature conditions (0% drops)</td><td>4-8%</td></tr>
<tr><td>CdTe Thin Film (Cadmium-Telluride)</td><td>Cheaper and 50% less expensive than crystalline silicon and most cost effective</td><td>9-11%</td></tr>
<tr><td>CIGS Thin Film (Copper-Indium-Gallium-Selenide)</td><td>Cheaper and 50% less expensive than crystalline silicon</td><td>Performs good in cool as well as high temperature conditions</td><td>10-15%</td></tr>
</table>

Figure 2. Comparison of first and second generation solar cells (Rathore, 2021).

In addition to there being different types of solar cells, there are also different ways to connect a solar PV system. There are stand-alone PV systems and grid-connected PV systems.

- **Stand-alone PV systems:** Contain an array of solar cells, a battery, charge controllers, and power conditioners. This system has no connection to the grid and uses the battery to store the excess energy that is collected for later use when it is needed.
- **Grid-connected systems:** Connect to the electricity grid and can be used by that or can be traded by electricity supply companies. During the nighttime when the PV system cannot generate electricity because there is no sunlight, the power is brought and stored from the local grid network in order to supply electricity (Rathore, 2021).

2.1.3 Effects of Geographic and Weather Conditions on Solar PVs

PV systems are influenced by multiple factors that affect their energy efficiency. One important factor is geographical location, including latitude, altitude, and weather conditions. The variation in latitude plays a crucial role in influencing solar radiation values. Places located near the equator experience higher solar radiation values, contributing to increased energy absorption by photovoltaic panels (Demirkiran & Karakaya, 2022). Temperature changes that are connected to differences in altitude can affect the efficiency of PV panels (Demirkiran & Karakaya, 2022). A study conducted in the south of Austria comparing solar power measurements in both alpine areas and an urban area site showed that in alpine areas there can be beneficial meteorological conditions for PV energy harvesting, which increases the energy yield of PV-power plants (Karpić et al., 2019). This means that PV systems operate best with high solar irradiation in cold environments (Karpić et al., 2019). These systems tend to perform more efficiently in places where there are abundant amounts of sunlight and the temperature is on the colder side, as opposed to very hot climates where excessive heat can reduce their efficiency. Therefore, solar UV radiation increases at higher altitudes as temperature decreases, making high-altitude mountainous regions prime locations.

Rainy and cloudy weather conditions also affect the efficiency of this technology. Although rain might seem like it would reduce levels of sunlight, it can actually have positive benefits for PV systems, especially in the spring and summer months. This is because the rain cools down the panels and prevents reflection loss (Del Pero et al., 2021). However, in the colder months, the cooling effect is not as important as the temperature is naturally colder. Nonetheless, frequent rain is still helpful as it prevents particles from building up on the panels, which positively affects the performance (Del Pero et al., 2021). Therefore, rain contributes to maintaining the efficiency of photovoltaic systems by keeping them clean and cool. Similarly, clouds and dust influence how much energy is produced by these PV systems. A study done on the effect of rain on PV systems found that the impact of cloud cover is an immediate decrease in the overall solar energy received and a drop in power output in the short term (Bonkaney et al., 2017). Dust on the panels has a similar effect, as it results in a decline in performance. Dust accumulation is a more gradual process that has long-term effects on the performance of PV panels as it reflects the incoming solar radiation reaching the solar module and decreases the energy output of the module (Bonkaney et al., 2017).

Although PV systems require direct sunlight, too much heat can create negative impacts. This is important as PV modules transform only 20% of solar energy into electricity, while the remaining 80% is converted into heat (Hasan et al., 2022). As the temperature of the PV panel's module rises, there is a significant decrease in its electrical efficiency. Hasan states that a study conducted in 2022 indicated that without cooling measures the efficiency of PV panels can decrease by 0.03% to 0.05% for every 1°C increase in temperature. This decline becomes even more significant as the temperature reaches higher levels, with a potential reduction in efficiency of up to 69% at 64°C (Hasan et al., 2022). Cooling methods help mitigate the impact of high temperatures on performance and allow for an increase in energy gain. Thermoelectric cooling can boost energy output by 18%, active water cooling by 15%, and natural ventilation by 2.5% (Hasan et al., 2022).

2.2 Economic and Social Factors Affecting Solar Power Installations in Italy

In the following section, we explain the different economic and social factors affecting photovoltaic technology installations in Italy. We start by exploring the economic incentives for renewable energy and then shift to the economic implications of solar energy. After, we discuss specific goals and regulations in Italian historic centers on renewable energy. Lastly, we scrutinize the factors that influence public acceptance of renewable energy.

2.2.1 Economic Incentives for Renewable Energy

In order to help motivate the energy industry to switch to renewable energy, many countries use economic incentives. The main tax incentives used in the European Union (EU) to promote renewable energy fall under direct, indirect, and other taxes used by specific countries. Direct taxes can be in the form of personal income tax, corporate tax, and property tax (Cansino et al., 2010). These taxes are applied to all, and then specific citizens are rewarded for generating renewable energy by deduction or exemption from these taxes. Indirect taxes can be in the form of value-added tax (VAT) and excise duty exemptions. Through these indirect taxes, both energy products and electricity are taxed and member states can then apply for exemptions or reduced tax levels depending on their renewable energy development. According to a 2010 study done by Cansino on the EU, most of the countries have different combinations of each of these tax exemptions to a varying degree, each with different effectiveness. The specifics of the tax exemptions that each country implemented also had a significant impact, as even two countries that had the same types of taxes saw differences in green energy production growth. As seen in the study, the Czech Republic completely exempts income and corporate tax on the sale of energy to the national grid. This promoted a growth of 269.84% in renewable energy production. In contrast, Belgium implemented a tax reduction system for income (40%) and corporate tax causing a growth of 87.75%. (Cansino et al., 2010).

As of 2019, Italy had a well-developed set of incentives for renewable energy, focusing specifically on PV development. There was a large spike in incentives mainly due to the “Conto Energia”, a set of five energy incentives over the period of 2005-2012. At the start in 2005, the incentives were exclusively given for electricity generated and self-consumed. After changes made in 2007, these incentives were extended to energy generated and delivered to the network (Bianco et al., 2021). According to a study done by Bianco (2021), after this initial spike in incentives, there was a slight gradual decrease in specific incentives for PV energy, from just under €400/kW in 2012 to about €300/kW in 2019. However, the total incentives remained strong at about 6,000 MC. Bianco (2021) states that as of 2024, the amount of incentives allows for a more gradual increase in PV plants, continuing the incentive overall to install and create new plants just at a smaller installation rate, as well as smaller installations on roofs or free surfaces. The incentives in Italy resulted in rapid growth in solar power generation, such that Italy accounts for almost 20% of the share of PV electricity generation in the EU in 2019, with Germany being the only country higher at about 28% (Bianco et al., 2021).

2.2.2 Economic Impact of Solar PVs

The economic implications of incorporating solar panels into the energy grid are multifaceted, encompassing installation costs, location-specific factors, and grid pricing structures (Ghaith et al., 2017). For grid-tied household solar panels, there is a fine balance that must be held between structure prices and energy production to keep them economically competitive. According to a study done by Ghaieth, neither type of household solar panels studied was economically competitive. In order for either to become competitive with grid-provided electricity, grid prices would need to increase by 420% to 444% (Ghaith et al., 2017). Furthermore, location-specific factors like variations in annual use estimates, production, and associated costs significantly influence the economic consequences of grid-tied household solar PV systems (Ghaith et al., 2017). The economic impact extends to the revenue of utilities, with a utility serving households operating 4 kW solar PV systems without net metering potentially experiencing a reduction in gross revenue, averaging around €280 per household annually (Ghaith et al., 2017).

Additionally, the economic impact of solar panels goes beyond the initial investment cost, involving factors such as technology, capacity, area, storage capacity, and installation location (del Sol & Sauma, 2013). A comprehensive study on the annual cost of electricity for households in Chile found that, on average, grid-tied solar panels were not economically competitive across the five locations examined. While the households weren't competitive, Chile emerged as an economically favorable country for solar power plant installations, with specific technologies exhibiting the lowest investment costs in their respective categories. From this information, we can conclude that the nature of solar power economics is dependent on local contexts, and market conditions are all dynamic. However, the larger solar power plants seem to be able to withstand this fluctuation slightly better. This highlights the need for policymakers and solar PV manufacturers to consider these factors for effective power system planning and expansions (del Sol & Sauma, 2013).

Larger PV systems seem to be faring better in Palestine's specific market conditions as well. A more recent study done by Ibrik (2019) outlines a year-long assessment of a peak performance of 7.68 kW grid-connected PV systems installed on the rooftops of three schools in Palestine. The evaluation revealed an average performance ratio (PR) of 78%, with each system generating an average annual energy output of 10.93 MWh/year. Economic analyses indicated promising results, suggesting that the adoption of such PV school systems should be expanded given they have a payback period of less than 5 years, a cost of around 0.1 US dollars per kWh produced, and an internal rate of return of approximately 20% (Ibrik et al., 2019). Additionally, the paper examines the impact of these PV school systems on the electric grid, including reductions in losses, voltage level improvements, and their environmental effects.

While these larger solar implementations can perform more favorably in their markets, it is still important to pay attention to the environment of power markets when planning new solar PV installations (del Sol & Sauma, 2013). Local context and conditions can markedly affect the payback period for solar PV installations, as illustrated by a comparison of installations in Chile and Palestine. Also, the change in prices and payback periods over time can have a drastic effect on economic competitiveness. As seen by comparing these two studies, the payback period for installing PV systems reduced drastically in the 6 years between 2013 to 2019. The PV systems were economically non-competitive for households in Chile in 2013, whereas they had a payback period of less than five years for schools in Palestine in 2019.

2.2.3 Renewable Energy Goals & Solar Regulations in Italian Historic Centers

Governments often set goals for increasing the amount of renewable energy used in their countries. In Italy, the Constitution states that energy-related topics are delegated between the states, regions, and provinces, therefore allowing regional authorities to make rules regarding energy-related decisions as long as they follow the requirements of the EU regulations. In 2020, the Italian National Plan for Energy and Climate (INECP) was created in response to the requirement set by the EU legislation that all EU countries had to create a 10-year National Energy and Climate Plan (NECP). The INECP set goals for 2030, which are to have 30% of energy production be from renewable energy resources, a 43% reduction in primary energy consumption compared to that of 2007, and a 38% reduction in greenhouse gas emissions compared to 1990 (Formolli, 2022). For solar energy at the national level, there are goals of 28,550 MW for 2025 and 52,000 MW for 2030. For reference, the capacity of installed solar PV plants in Italy in 2023 was 29,557 MW, which suggests they are on track to meet these goals (Terna, 2024).

Formolli discusses further how the hierarchy of Italian legislation allowed municipalities to be able to set their own energy-related regulations in buildings, depending on regional laws (2022). Mostly these regulations are present in historical centers and non-historical urban areas. The historical centers have regulations which include the prohibition of installing PV panels in places that would affect the visual presentation and preservation of the buildings, and require approval before installing PV systems on buildings in constructions that may have landscape or heritage protection. In non-historical urban areas, PV systems are required to be integrated into the buildings and follow the existing inclination of the roofs (Formolli, 2022).

2.2.4 Factors Influencing Public Acceptance

Social acceptance is a significant limiting factor that can delay the installation and operation of renewable energy plants. Understanding community reactions to potential installations is crucial, as the reputation of the organizations installing renewable energy projects is influenced by public perception; thus, building trust and addressing community concerns is essential for long-term support. A study by Segreto et al. explained that the main factors influencing social acceptance include trust in governance, distributional justice, siting issues, and socio-demographic factors (Segreto et al., 2020). In the context of this study, distributional justice refers to costs and benefits being fairly distributed between residents and developers, as well as financial compensation. Siting issues include issues with potential environmental or health impacts and attachments to specific places. Socio-demographic factors involve political atmosphere or community characteristics that will vary by location (Segreto et al., 2020).

The study noted that people respond well to transparency, as it builds trust between the government and the public, creating a sense of reliability and accountability. Community distrust is attributed to a lack of knowledge of the effectiveness of renewable energy and the developmental process involved (Segreto et al., 2020). This suggests that effective communication and proper education efforts are essential in bridging the gap between communities and renewable energy initiatives. Similarly, the study discussed that public participation helps to lower levels of concern and increase the sense of mutual trust between both parties (Segreto et al., 2020).

An effective incentive for community acceptance is a financial benefit for the potential inconvenience of installing a renewable energy source nearby (Segreto et al., 2020). A 2020 study by Segreto et al., included a qualitative analysis of 25 case studies on renewable energy projects across Europe. Segreto et al. concluded that financial incentives had the most impact on public acceptance compared to other factors previously explained. People often react positively to financial incentives as they provide tangible benefits that directly address their needs or concerns. Further, siting is another major determinant of social acceptance. Siting includes concerns about effects on human health, the environment, and community preferences. The study concludes that aesthetics were a common concern for residents and might influence their reluctance to live near renewable energy plants, as it can disturb the aesthetic quality of the landscape (Segreto et al., 2020). People may be receptive to renewable energy as a concept but might have a different attitude when they are personally affected by the installation of a plant. Overall, addressing community concerns, fostering transparency, and offering financial incentives can help overcome barriers to social acceptance. Making careful decisions about the locations of the installations is crucial as well as for minimizing negative impacts.

2.3 Solar Pavements as an Emerging Technology

In this section, we discuss different aspects of solar pavements, including their potential and limitations. Then, we showcase different implementations of these pathways around the world, while focusing on aspects like their energy production and applicability.

2.3.1 Advantages and Limitations of Solar Pavements

PV pavements are a recent development in the application of solar energy systems. Solar pavements are a cutting-edge approach that leverages renewable energy in infrastructure. They typically consist of three layers as seen in Figure 3: a surface translucent layer, a middle-level PV layer, and a bottom protective layer which can have either solid or hollow plates (Hu et al., 2021). The surface layer is integral to the system as it needs structural robustness to withstand pedestrian and traffic loads. It also needs to endure environmental factors to ensure traffic safety while also meeting functional criteria like flatness and wear resistance to facilitate electricity generation (Hu et al., 2021). This layer requires a degree of transparency to allow sunlight penetration for power generation purposes. Common materials used include inorganic options like glass and toughened glass, as well as high molecular polymers such as polycarbonates (Hu et al., 2021). Below this layer lies the middle-level photovoltaic layer, which converts sunlight into electricity and integrates various components like solar cells, LED lights, heating elements, and microprocessors (Hu et al., 2021). Solar cells commonly used include crystalline silicon and thin-film batteries, while embedded LEDs serve for road markings and signs, and heating elements aid in anti-icing (Hu et al., 2021). Sometimes, microprocessors are employed for load sensing and controlling various functionalities. For stable and balanced structural support, there is a bottom protective layer that safeguards the power generation layer, distributes collected energy, and transmits data signals. Materials used here include toughened glass, concrete slabs, and polymer plates (Hu et al., 2021).

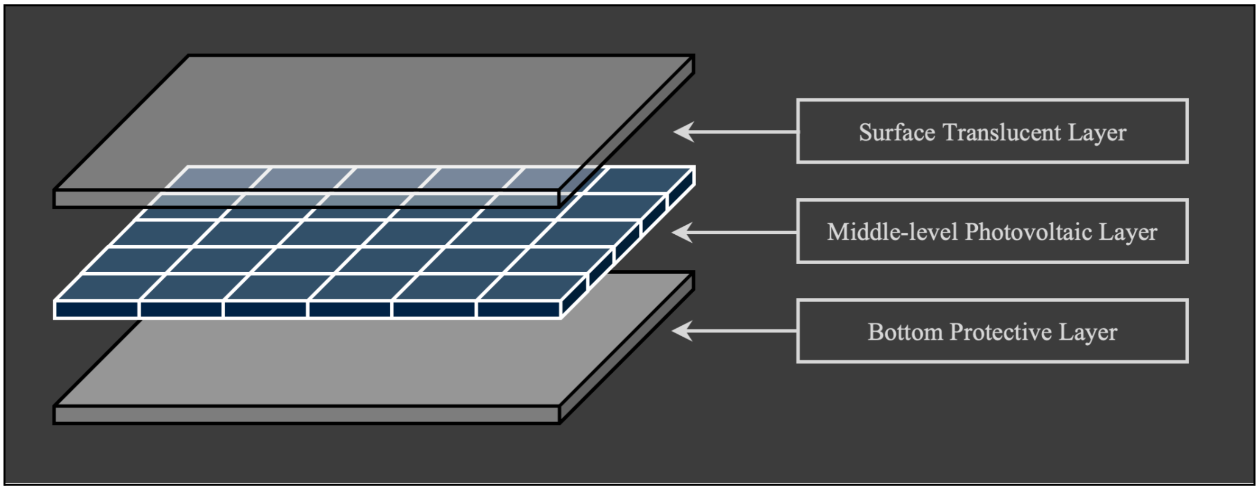


Figure 3. Typical construction of a solar pavement module.

The solid plates on the solar pavements exhibit robust bearing capacity and stability but encounter challenges with the placement of high-efficiency monocrystalline silicon cells. On the other hand, hollow plates offer flexibility in placement angles, yet necessitate advanced packaging technology and improved water resistance (Hu et al., 2021). As with any application installed in the environment, challenges related to these types of pavements are affected by factors such as heavy traffic loads, material degradation over time, and harsh environmental conditions (Hu et al., 2021). However, factors such as cost and positioning of the pavement are important for this type of application.

Cost poses a significant obstacle to the widespread adoption of solar pavements (del Sol & Sauma, 2013). Case studies highlight the high costs associated with these pavements, prompting questions about their economic viability. It is crucial to note that current costs do not reflect industrial-scale installation expenses, and as materials and technology progress over time costs are expected to decrease. The economic feasibility of solar pavements depends on achieving a lower Levelized Cost of Electricity (LCOE)[1], especially for structures like the Hollow slab, which already demonstrates lower material and production costs (Hu et al., 2021). Comprehensive life cycle cost-benefit analyses are essential to understand the complete environmental impact of solar pavements, encompassing CO2 emissions from raw materials to recycling stages.

Further, it is important to also understand how solar pavements' flat positioning can present limitations in terms of energy production. For example, a performance study was conducted on PV panels based on transparent resin-concrete. The study measured the output

[1] The LCOE is the price where the generated electricity should be sold in order for the system to break even by the end of its lifetime.

power of both traditional solar panels and solar pavement modules in Changsha, China. The test period was from 8:00 am to 5:00 pm in November, and the study found that the optimal orientation for solar panels in the Changsha area is 30 degrees south by west, and the best inclination angle is 20 degrees, which was used for testing (Hu et al., 2022). After performing the necessary tests, the study concluded that the daily power generation of the traditional solar panel was 0.934 kWh/m^2. In contrast, the solar pavement module generated only 0.152 kWh/m^2 per day, approximately 16.3% of that of the conventionally oriented solar panel (Hu et al., 2022). These findings suggest that while solar pavements offer potential benefits for integrating renewable energy into urban infrastructure, their flat positioning limits their energy generation capabilities compared to traditional solar panels.

Despite these challenges, the potential positive impact of solar pavements is considerable. They contribute clean energy for areas close to these pavements and reduce energy losses associated with long power lines. Additionally, solar pavements can play a role in advancing smart transportation, electric vehicle development, and mitigating environmental issues such as urban heat islands (Hu et al., 2021).

2.3.2 Existing Implementations of Solar Pavements

One way to analyze the potential benefits and limits of these pavements is by evaluating previous implementations. The installation of an innovative solar sidewalk in Budapest, developed by Platio, signifies an advancement in sustainable urban infrastructure as seen in Figure 4. Platio's pavement system integrates solar cells and recycled plastic, which not only transforms conventional sidewalks into energy-generating surfaces but also demonstrates a dedication to environmental responsibility by addressing plastic waste concerns (Hu et al., 2021). In contrast to conventional solar pavements using solid plates, the Budapest solar sidewalk employs a versatile design that incorporates recycled glass, anti-slip technology, solar cells, anti-cracking safety glass, and rubber. This approach not only enhances the overall performance of the pavement but also underscores its commitment to sustainability. The geometric surface design optimizes sunlight exposure to the solar panels and the hydrophobic coating ensures self-cleaning for sustained efficiency (Hu et al., 2021).

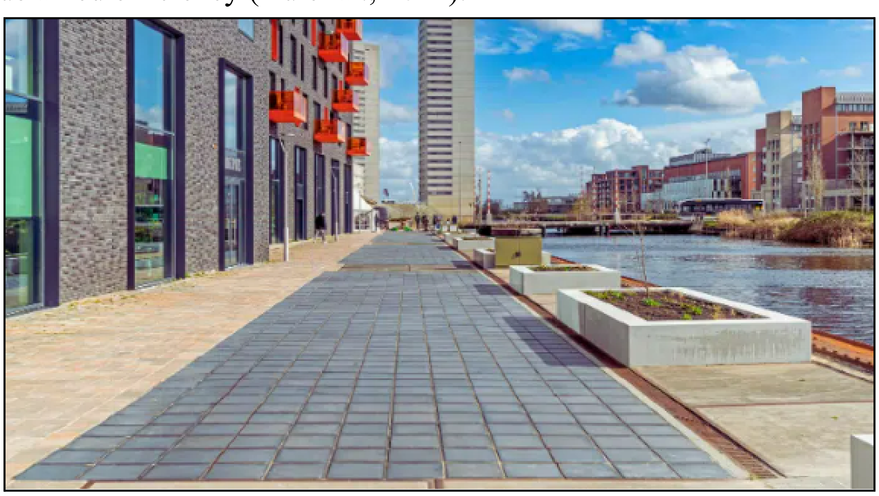


Figure 4. Platio Solar Sidewalk Panel in Budapest (PLATIO Solar Pavement - a New Source of Solar Energy, n.d.)

However, despite the promising features of the Budapest solar sidewalk, challenges persist. Issues such as the potential fracture of PV panels under driving loads, the inability to adjust panel tilt angles, suboptimal heat dissipation, and high costs are crucial considerations for the widespread adoption of solar pavements in urban landscapes (Hu et al., 2021). Since the Budapest solar sidewalk stands as a real-world application, addressing and overcoming these challenges is crucial to the continued development of solar pavements.

In 2017, China achieved a milestone in sustainable infrastructure by integrating a 3-layer solar road featuring transparent resin-concrete. The analysis presented in the research paper by Hu et al. (2022) delves into the determination of glass gradation and resin dosage, impacting critical factors such as compressive strength, optical performance, density, and porosity of the transparent resin-concrete pavement modules. Hu et al. (2022) also provided a basic overview of the structural design of the PV system as shown in Figure 5. This structural outline is designed for cohesion and involves a transparent resin-concrete, an unsaturated polyester resin-based transparent protective layer, waste glass, and an integrated solar panel. The solar panel module is fully encapsulated by the transparent resin-concrete, creating a unified structure that enhances overall stability. When sunlight illuminates the module's surface, it undergoes PV processes within the built-in solar panels which convert the light into electricity.

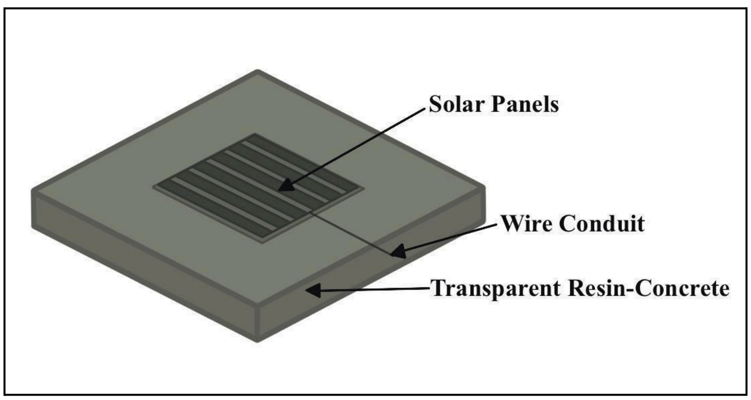


Figure 5. Panel prototype for the solar pavement based on transparent resin-concrete

Another implementation of a solar pavement is a solar cycling path in the Netherlands, specifically in Krommenie near Amsterdam, which is an installation of SolaRoad (SR) technology. The SR bike lane incorporates 27 precast concrete elements, divided into two halves—one equipped with solar modules and the other featuring a traditional concrete surface. These modules, comprising polycrystalline silicon with 80 wafer-based cells, exhibit a rated output ranging from 293W to 313W.

The electrical system's schematic overview, illustrated in Figure 6, demonstrates that the total direct current (DC) power generated by the 54 SR modules is directed to six parallel operating grid-connected inverters through module-level DC/AC converters. In the event that the predicted DC power exceeds multiples of the individual inverter rating of 2.5 kW, an additional inverter is employed to redistribute the SR power output (Shekhar et al., 2018).

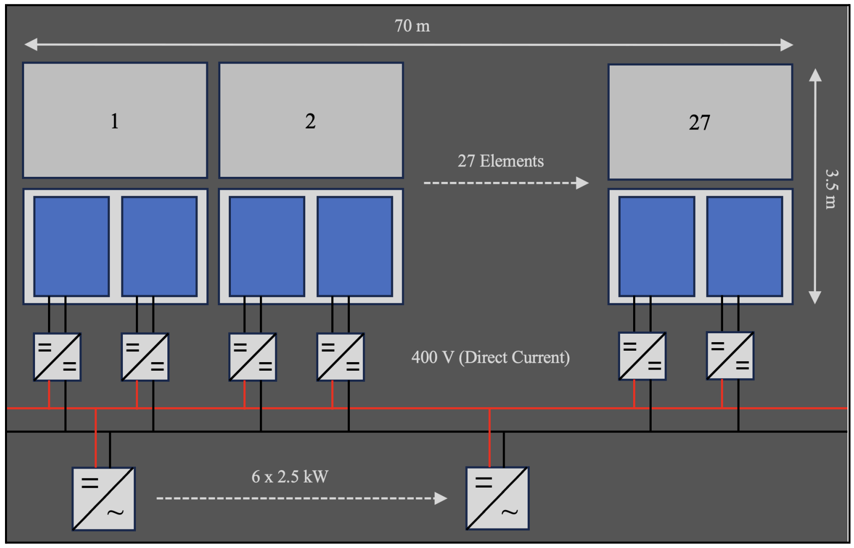


Figure 6. Geometrical and electrical layout of the installed SR bike path.

There are also other implementations of solar pavements currently in the development phase. Specifically, a company called BYS Italia is currently working on its own unique incorporation of solar panels into urban infrastructure in Italy.

2.3.3 BYS Italia and Its Solar Pavement Prototype

BYS Italia is a startup company formed in 2019. They were first established by Infinityhub SpA Benefit, with the goal of creating photovoltaic cycle-pedestrian paths. Their project was selected for the MITdesignX accelerated program, to help them refine and enhance their project (“BYS – BICYSOLARSTREET Italia”, 2024).

BYS’ current PV pavement prototype is still early in its developmental journey, as the team and prototype itself are only a few years old. As shown in Figure 7, the current prototype covers 35.7 meters of a main pathway and an additional side pathway of 11.4 meters. It consists of 53 PV panels containing multiple solar cells covered in an anti-reflective and anti-slip glass. The design can currently hold 550 kg/m2 as its maximum surface load. In 2023, BYS successfully installed their prototype on San Servolo island, located in the Venetian Lagoon, although it is still not connected to the grid.

Figure 7. Prototype of BYS on San Servolo

As of April 2024, the energy production of the prototype remained untested leaving BYS unsure about its potential. BYS wanted to see if other technical improvements could be made such as improving or replacing the current glass with another material to improve its durability, and whether any other changes can be made to enhance its functionality. Finally, BYS sought insights into market feasibility within the Venetian market and was looking for improvements to their business model.

3. Methodology

The research goal for this project was to provide recommendations to BYS by evaluating their solar pavement prototype and its viability in the Venetian market. To achieve this goal, we developed three supporting objectives:

- Assess the views of university professors and students on solar pavements in the Venetian market.
- Conduct a performance analysis of BYS' prototype, including a materials comparison and an evaluation of theoretical energy production.
- Perform a cost analysis of BYS' technology from their perspective and the customer's perspective.

In this chapter, we describe the methods we used to achieve these objectives. The results of the analysis will allow us to develop recommendations for BYS.

3.1 Assessing the Views of University Professors and Students on Solar Pavements

One aspect that we needed to consider was understanding the perspectives of potential stakeholders for solar pavements. BYS highlighted universities and municipalities as their potential stakeholders. We wanted to know how likely they would be to support the implementation of a product such as BYS' prototype at their institution. In order to assess university professors' and students' views of solar pavements in the Venetian market, we answered the following questions:

- How do the university professors view the technology?
- How likely are the potential stakeholders to implement a product such as BYS' prototype into their institution?
- How do university students perceive BYS' prototype and its functionality?

We answered these research questions by conducting surveys to gain insights about potential acceptance by university professors and students. Based on the results of these surveys, we hoped that BYS could use this information to assess how viable these markets are. We wanted to help them determine the interest levels of these stakeholders and how suitable these locations are for their technology.

3.1.1 Understanding Perspectives of University Professors

In order to explore the potential market, we considered conducting semi-structured interviews with university professors at Ca' Foscari University of Venice and IUAV University of Venice, as well as members of the Venice Sustainability Foundation (VSF) who represent municipalities. We originally chose to use semi-structured interviews as they offer flexibility and rich qualitative data. While they would likely have yielded more personalized responses, we were advised by BYS to use semi-structured surveys. They assumed respondents were more likely to complete the surveys and would feel more comfortable answering questions in Italian. Surveys also allowed us to reach out to more people in the given time. Our survey included a mix of questions following a 5-point Likert scale and a few open-ended questions. This gave us a balance between quantitative and qualitative data. We were aiming for a short response time and convenience for these stakeholders, as their time is valuable. Hence why the survey was provided in both English and Italian ensuring the respondents felt comfortable with the questions. To see the details included in our survey refer to Appendix A.

BYS attempted reaching out to VSF members; however, we did not receive any responses. Therefore, our focus became centered on university professors. To find potential professors to survey, we viewed the university websites and found one hundred professors from various departments related to Sustainability, Environmental Economics, as well as Architectural and Urban Composition. We chose these departments because we believed these professors would have a better understanding of the effects of solar pavements, considering they conduct their work in fields related to sustainability and architecture. Each of the professors was sent a personalized email with a link to the survey, and a follow-up reminder a week after the original email. To analyze the data, we used descriptive statistics to summarize their opinions and concerns. We assessed these professors on whether they think their universities would implement solar pavements. However, they are not the decision-makers for their universities, so it is difficult to conclude whether or not these universities could be a potential market for BYS.

3.1.2 Understanding Perspectives of University Students

In order to understand whether solar pavements would be accepted by users in the institutions where they are implemented, we set out to learn the views of university students. We wanted to understand their perspectives, including whether or not they would be accepting of this new technology. We hoped that this would allow BYS to see the potential acceptance of their pavements if they get implemented.

To achieve this, we made a survey to send to the university students. However, the university administration was not allowed to distribute the survey to the students for us, due to their policies. Instead, we visited Ca’ Foscari and IUAV University to approach students directly. We explained our project to them and asked if they would be willing to fill out a brief survey by scanning a QR code. We offered these surveys in both Italian and English, depending on the student’s preference. One advantage we found from conducting surveys in person was that students were more willing to respond, compared to surveys being sent by email.

We conducted the survey with questions using a 5-point Likert scale. We aimed to keep the surveys short while still getting the information we needed. During our time spent at the universities, we approached around 75 students in person. Before conducting this survey we pilot-tested it with a native Italian student to ensure clarity and effectiveness. Our anonymous survey included a set of statements regarding the students' familiarity with PV pavements, their opinions, and concerns. There were a few challenges when using surveys instead of interviews. One challenge we faced was that we were unable to follow up with the students if we had any questions about their responses because the survey was anonymous. Also, findings from our surveys are based on a limited number of responses and could reflect our inability to communicate in Italian. To see the details included in our survey refer to Appendix B.

3.2 Evaluating Prototype Performance

In order to evaluate the material and energy performance of BYS' prototype, we sought to answer the following questions:

- What types of materials are viable for the surface of a solar pavement?
- How do the properties of these materials compare to the glass that BYS uses?
- What is the theoretical energy production of the prototype?
- How does irradiance and temperature affect the efficiency of the prototype?

We answered these research questions by performing a comparison of the types of materials that can be used for the surface of a solar pavement and analyzing the theoretical energy production of the prototype.

3.2.1 Performing a Potential Materials Analysis

Another aspect of the current prototype that we looked into was its glass surface. This is an important factor to look at since pedestrians and bicycles are crossing the pavement, so safety was a key consideration. The prototype is made out of thermally toughened soda lime silicate glass. We performed an analysis of alternative materials in order to understand whether or not the current glass that is being used for the prototype is the most suitable considering its functionality.

As part of this analysis, we researched other materials that could be viable for the surface of a cycle-pedestrian path. Using the Ansys Granta EduPack materials database and other research libraries online, we found the properties of each of the materials we compiled (V23.1.1). We made a table comparing those properties, with a focus on their cost, strength, hardness, transmissivity, and weather resistance. Once the table was completed, we analyzed the differences between all of the materials and made conclusions about which material we thought should be used for the surface of the prototype. The materials analysis was limited by the small number of possible materials we were able to identify.

3.2.2 Evaluating Theoretical Energy Production of BYS' Prototype

We wanted to provide BYS with some data on the energy that their prototype could produce, as this is a significant factor in determining its effectiveness. We intended to do some physical testing with four of the monocrystalline solar panels at the testing site in Padua; however, there was a delay in the start of testing. Therefore, we calculated the estimated energy production with theoretical values.

We estimated the energy production of the BYS prototype by using a first-principles calculation (Kazem, 2017) as well as a reputable online calculator (PVGIS). BYS' current panel is the "Pista Ciclabile" from VGS PV Solutions. Obtaining values from its documentation, we used the following first-principles equation (Equation 1) to estimate photovoltaic power, PPV(t):

$$Equation\ 1:\ PPV(t) = (P_{peak} \times (G \div G_{standard}) - \alpha T \times (T_c - T_{standard})) \times PV_{eff}$$

- PPV(t) is the amount of watts produced by a PV panel as a function of time
- P_{peak} is the peak power that the PV cell is rated for. This is 280W for BYS' current panel.
- G is the Global Horizontal Irradiance (GHI) and T_c is the air temperature. To find these, we obtained "Global Horizontal Irradiance" (W/m^2) and "Air Temperature" (C^o) data from SolaCast Time Series Requests. We gathered irradiance and temperature values for the coordinates of Venice from 01/01/2023 to 12/31/2023.
- $T_{standard}$ and $G_{standard}$ represent the standard test conditions for solar radiation and cell temperature respectively for BYS' current panel which are 25 ^oC and 1000 W/m^2 respectively.
- αT is the temperature coefficient of the PV module power. This is 0.387 for BYS' current panel.
- PV_{eff} is the rated efficiency for BYS' current panel which is equal to 17.11%

Once we found the power output as a function of time, we converted this to energy produced in kWh per day for the panel using Equation 2.

$$Equation\ 2:\ E_{day}(d) = PPV \times L_{day} \times \frac{1}{60} \times \frac{1}{1000}$$

- $E_{day}(d)$ is the amount of energy produced in kWh by the panel per day as a function of the given date.
- PPV is the power value found in Equation 1 in Watts.
- L_{day} is the length of the day for a particular date in minutes. To obtain this value we used the "Duration of Daylight/Darkness Table for One Year" dataset provided by the Astronomical Applications Department.
- The division by 60 is a conversion from minutes to hours and the division by 1000 is to convert Wh to kWh.

We then summed all the daily energy production values for each month to get the monthly energy production as seen in Equation 3. We also wanted to find the total energy produced throughout the year which is represented in Equation 4.

$Equation\ 3:\ E_{month} = \sum_{d=1}^{L_{month}} E_{day}(d)$	$Equation\ 4:\ E_{year} = \sum_{d=1}^{365} E_{day}(d)$
• E_{month} is the total energy produced by the panel in a month in kWh • d represents the day of the month • L_{month} represents the length of the given month (L_{month} = 30 for January, L_{month} = 28 for February, etc.)	• E_{year} is the total energy produced by the panel in a year in kWh • d represents the day of the year • 365 is the number of days in a year

As a check on the first principles method and to compare our values for E_{month} and E_{year}, we also used the PVGIS online calculator with the inputs below:

- Location of Venice
- Incline of panel (0º)
- Rated Power in MWh (280 kWh = 0.28 MWh)

All of the methods showcased above aided in finding the estimated monthly and yearly energy production for BYS' technology.

3.3 Performing a Cost Analysis

In order to evaluate the viability of BYS's prototype, we answered the following questions:

- What is the monetary equivalence of the theoretical energy produced?
- What is the value proposition for the customer?
- What is the cost per meter squared of BYS' prototype compared to their competitors?

We answered these research questions by conducting multiple data analysis methods to gain insight into the viability of BYS's prototype.

3.3.1 Performing a Cost Analysis for Customers

We performed a cost analysis from the customer's perspective to understand the current value proposition of the BYS system. In order to do this, we estimated the energy production potential of BYS' panels based on radiance and temperature throughout the year.

The Prezzo Unico Nazionale (PUN) is the wholesale reference price of electricity purchased on the Italian Power Exchange (IPEX) and was used in the calculations to find the monetary equivalence of the energy produced over time as seen in Equation 5 below.

$$Equation\ 5\!: M_{eq} = E_{month} \times \frac{PUN}{1000}$$

- M_{eq} is the monetary equivalence of the energy produced in €.
- E_{month} is the energy produced by the panel in a month in kWh as derived by Equation 3.
- PUN is the price of electricity in €/MWh. This needs to be divided by 1000 to match the unit of E_{month} which is in kWh.

We proceeded by assessing the break-even point for customers, factoring in production costs for BYS and the potential rental prices for their product. Through graphical representation, we derived a trajectory of net profit against time and repeated this process for different pricing strategies. The pricing strategy refers to how BYS plans to charge its customers, whether that is through an initial payment, a monthly rental cost, or a combination of the two.

To achieve this, our team developed a Photovoltaic Potential Calculator (PVPC). The calculator aims to provide long-term information for BYS' product including energy produced (kWh) by an inputted number of panels, net cost (€) incurred by the customer, and net cost (€) incurred by BYS. The user experience with the PVPC is described below.

This calculator includes six input fields:

1. The energy produced by one panel for one day, which will be tested by BYS in the future.

2. The date on which the test was done, which gives a frame of reference to the calculator to understand what radiance and temperature conditions the panel was tested under. This information allows the calculator to extrapolate the energy production to an estimate for that month. The energy prediction for that month is divided by the panel's expected theoretical output for the month to determine the performance ratio that can be used in calculations moving forward.
3. The number of panels BYS wants to calculate production for. Its value is multiplied by the energy produced for one panel to provide the total energy produced by the number of panels given to the calculator.
4. The initial cost, in euros, of a system with the specified number of panels.
5. The rental cost, in euros/month, of the system. Both the fourth and fifth values are used to calculate the net price for BYS and the net cost for the customer.
6. The period over which to perform the calculations. For example, 20 years could be used as it is the predicted lifespan of the technology.

The output of the calculator is as follows:

1. A graph predicting the energy produced by BYS over time, along with the value for total energy produced for the specified time period.
2. A graph of the net cost incurred by the customer (total monetary equivalence of the energy produced per month subtracted by rental and initial prices) over time. The graph showcases a net-negative as a red curve and a net-positive as a green curve. Also indicated is a date representing when the customer starts incurring a loss and the total amount of money lost/gained by the customer for the specified time.
3. A graph of the net cost incurred by BYS (rental and initial prices subtracted by cost for panel production) over time. The graph showcases a net-negative as a red curve and a net-positive as a green curve, along with a date representing when BYS breaks even and the total amount of money lost/gained by BYS for the specified time.
4. A graph of net loss/profit by the customer and BYS as a function of rental price. This is represented as one curve with a negative slope (for the customer) and one line with a positive slope (for BYS) which meets in the middle. This meeting point represents a rental price for the technology that distributes the loss across both the customer and BYS equally.

The energy production and cost calculations involve many assumptions regarding system performance, system lifetime, and specific installation. They assume that the pavement is placed in an open field and does not account for the shading from nearby buildings or the foot traffic on the pavement. We also assumed that the irradiance was the maximum clear-sky GHI for a day and that the price of electricity stays constant, equivalent to the value retrieved on the day of the test. In addition, the calculator does not allow BYS to change their pricing strategy after initially setting it. The input for the pricing strategy is limited to an initial cost and/or a constant monthly rent.

3.3.2 Performing a Cost Analysis for BYS

We performed a cost analysis for BYS' product to find the cost per area for producing large amounts of solar pavements and how their price compared to the competitors. To do this, we used a financial statement that included estimated costs provided by BYS for 1 km of the technology. With this, we compared the total cost/m^2 of BYS to its competitors' cost/m^2 found in the research paper by Hu et al (2021), and represented these values on a table.

4. Findings

In this chapter, we first present findings on the opinions of university professors and students on the implementation of solar pavements in the Venetian market. Then, we identify viable materials that could be used for the top layer of the solar pavement and the strengths and weaknesses of each in different areas. Next, we present the theoretical energy production of BYS' panels. Finally, we describe the costs and revenues for both the customer and BYS using several different pricing scenarios, and the competitiveness of BYS compared to similar products.

4.1. Views of Solar Pavements by University Professors and Students

Surveys of both professors and students revealed a moderate level of familiarity with solar pavements. Over half of the professors indicated that they had prior knowledge of solar pavements before completing the survey, and the remaining did not. Similarly, among students, there were varying levels of agreement regarding their familiarity with solar pavements. Some expressed agreement, others disagreed, and the remaining were neutral.

Both professors and students indicated that sustainability could be a positive driving factor for solar pavement technology. Over 90% of the university professors who responded to the survey claimed that sustainability was very important to their university. This helped assess the likelihood of universities implementing solar pavements because if sustainability is deemed very important, it suggests that there is a strong institutional emphasis on sustainability practices. The high percentage of professors who prioritize sustainability implies their potential support for environmental initiatives. The majority of surveyed students expressed that the implementation of solar pavements on campus would enhance the sustainability of their university. When asked about how implementing solar pavements would affect their campus, sustainability emerged as the driving factor exceeding considerations such as modernization, innovation, attractiveness, or unappealing aspects.

Professors suggested that the symbolic value of solar pavements may motivate the implementation of this technology on their university campuses. The primary purpose of installing them may not necessarily be to meet all the energy demands of the university but rather to serve as a representation of the institution's commitment to sustainability. Figure 8 shows the professor's responses regarding motivations for implementing solar pavements. Enhancing the university's reputation and promoting awareness of renewable energy emerge as prevalent factors, followed by the goals of increasing renewable energy production and reducing overall electricity costs. The complete breakdown of each category can be seen in Appendix C. While students were not asked about reputation, they were asked about solar pavements increasing awareness of renewable energy on campus. 86% of students agreed or strongly agreed that these pavements on their campus would increase awareness.

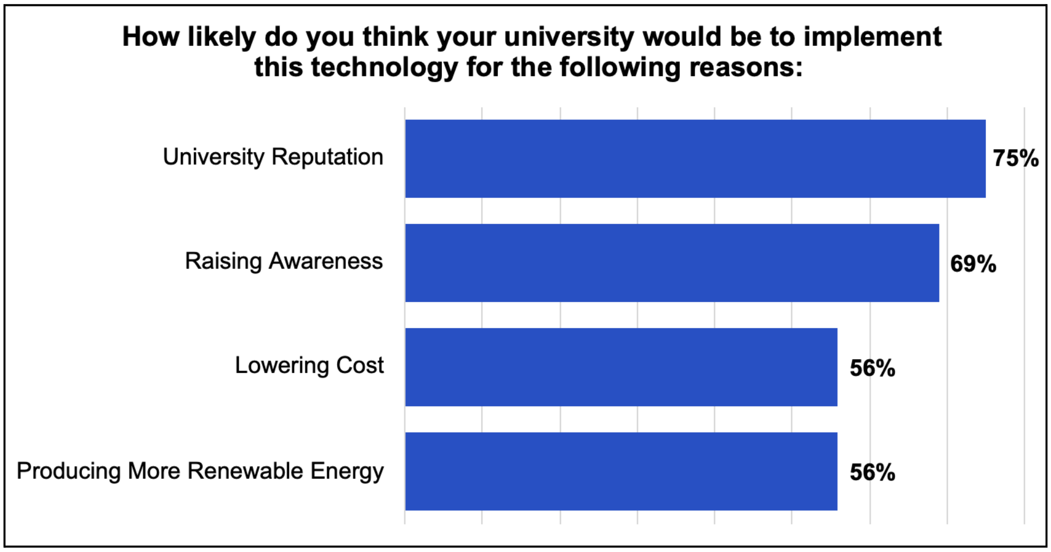
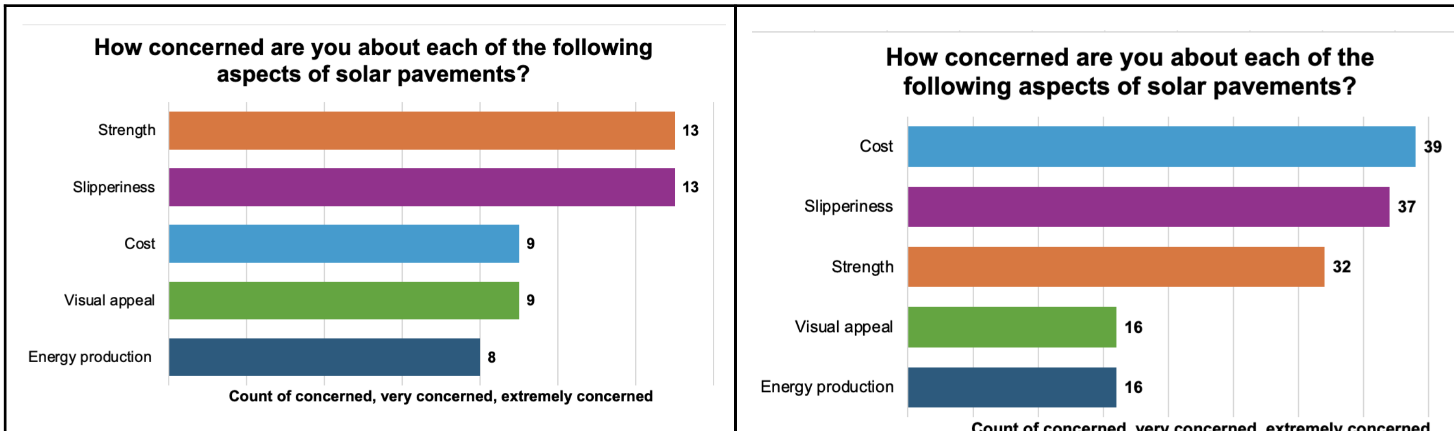


Figure 8. Professors' responses to the question "How likely do you think your university would be to implement this technology for the following reasons?"

Both professors and students expressed considerable concern about the potential slipperiness of solar pavements. Figure 9 reflects professor and student responses to five potential concerns; results include those that responded with concerned, very concerned, or extremely concerned. Slipperiness was among the top concerns for both groups. This highlights the importance of addressing this issue in the design implementation and promotion of solar pavements. Also, professors expressed high levels of concern about the strength of the pavement. This emphasizes the need for thorough testing and quality assurance measures to ensure the reliability and durability of the technology. Students expressed particular concern about the cost of this technology, signifying the importance of considering financial feasibility and affordability when planning for their implementation. Refer to Appendix C and Appendix D to see individual breakdowns of both the student and professor responses.



a) Professors Responses

	b) Students Responses

Figure 9. a) Professors' responses to the question "How concerned are you about each of the following aspects of solar pavements?"
b) Students' responses to the question "How concerned are you about each of the following aspects of solar pavements?"

Professors had difficulty identifying suitable locations for solar pavements on their campuses. When asked about whether there are potential locations where professors think their university could implement these solar pavements, only 38% of responding professors said there are. Of the professors who do believe they could be implemented, some suggested locations such as existing paths and the port area around the IUAV campus would be suitable. One professor explained, "There are no bike lanes in Venice and there are landscape and environmental constraints on the placement of photovoltaic panels." While there is an interest in solar pavements as a sustainable solution for universities, addressing practical challenges is required for their successful implementation.

Students expressed strong support for their university to fund solar pavements on their campus, even though some had difficulty imagining themselves using solar pavements. The university students overall were fairly positive about the idea of these pavements, with more than 75% of respondents saying they would like to see their university fund solar pavements on campus. Refer to Appendix D for the details of our results. While a majority express this desire, attitudes towards walking on solar pavements vary among students. As illustrated in Figure 10, 60% of the responding university students said that they somewhat agree or strongly agree that they could easily imagine themselves walking on a solar pavement, 20% said that they somewhat disagree or strongly disagree, and the remaining 20% expressed neutrality. However, when we looked at the 11 students who disagreed compared to the 35 that agreed, neither group appeared more worried about any of the five concerns previously mentioned. The people who disagreed had a smaller sample size, which made their responses to the concerns a slightly less accurate representation than the people who agreed. However, they still showed similar patterns of concern. This suggests that their inability to imagine themselves walking on a solar pavement might stem from a lack of understanding of the pavements, rather than specific concerns.

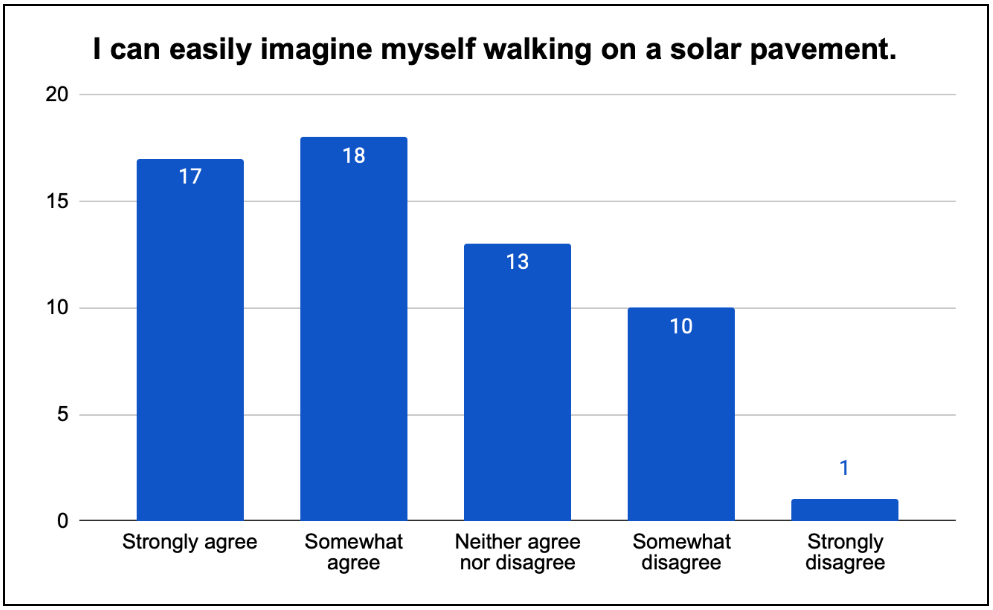


Figure 10. Students' responses to "I can easily imagine myself walking on a solar pavement." (n=59)

4.2. Material Comparison and Review of Energy Production

BYS' glass compares favorably to alternative materials in terms of cost and hardness. As can be seen in Table 1, the soda lime silicate glass that BYS uses exhibits superior performance with respect to cost and hardness when compared with acrylic, transparent wood, and polycarbonate. While the tensile strength of BYS' glass is less than that of the alternatives, it is sufficient for the application of pedestrian and bicycle paths.

Table 1. Materials comparison of three materials in addition to BYS' glass (Soda Lime)

	Cost per Panel (55kg)	**Tensile Strength**	**Hardness (Vickers)**	**Transmissivity**	**Weather Resistance**
BYS' Glass (Soda Lime)	€ 84[2]	31 MPa[2]	439-484 HV[1]	90%[2]	High resistance[2]
Acrylic (PMMA)	€ 123.75[4]	72 MPa[3]	16-22 HV[1]	92%[5]	High resistance[3]
Transparent Wood (PVA TW)	Unknown, not on the market	67-143 MPa[6]	2.97-8.28 HV[1]	91%[6]	Extremely low resistance[6]
Polycarbonate	€ 191.95[8]	65-131 MPa[10]	18-20 HV[1]	90%[9]	High resistance[7]

[1]Ansys® Granta Edupack, Version 23.1.1. https://www.ansys.com/products/materials/granta-edupack.
[2]Bys – BICYSOLARSTREET Italia, Infinityhub. (2024, January 30). https://www.infinityhub.it/applicazione/bys-bicysolarstreet/.
[3]Ali, U., Karim, K. J. Bt. A., & Buang, N. A. (2015). A Review of the Properties and Applications of Poly (Methyl Methacrylate) (PMMA). *Polymer Reviews*, *55*(4), 678–705. https://doi.org/10.1080/15583724.2015.1031377.
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[7]Danpal. (2022, November 17). Outdoor plastic sheets that can Stand Up To Weather | Danpal®. *Danpal*. https://danpal.com/outdoor-plastic-sheets-made-of-polycarbonate/.
[8]Mike. (2020, August 4). Polycarbonate price index. *Businessanalytiq*. https://businessanalytiq.com/procurementanalytics/index/polycarbonate-price-index/.
[9]*Polycarbonate (PC) - Properties, Uses, & Structure - Guide*. (n.d.). Retrieved April 15, 2024, from https://omnexus.specialchem.com/selection-guide/polycarbonate-pc-plastic.
[10]*Technical Data Sheet: Polycarbonate*. (n.d.). Laminated Plastics. https://laminatedplastics.com/polycarbonate.pdf.

Theoretically, one kilometer of BYS solar pavement could produce 170,000 kWh of energy in a year. This amount of energy is equivalent to the annual energy usage of approximately 67 households in Italy (Istat, 2023, Statista, 2022). This value was obtained by the calculations described in Section 3.2.2. Using the online PVGIS (Photovoltaic Geographical Information System), we found that the energy produced by BYS' panel for the location of Venice is 114,000 kWh for the year. This value was calculated based on the panel not being connected to the grid. Though the values obtained by both calculators are different, this could be attributed to the use of varying datasets. For future calculations, we used the value of 170,000 kWh that we obtained from Equation 1 from Section 3.2.2. This is because the PVGIS only factored in the rated peak power, system loss, and angle of inclination, whereas the calculator we developed uses additional specific details about BYS' panel like its standard testing conditions, temperature coefficient, and efficiency levels.

4.3 Cost Analysis of BYS Technology

Theoretically, BYS is competitive with other solar pavement prototypes in terms of cost and energy production. As can be seen in Table 2, companies like SolaRoad and Solar Roadways have higher manufacturing costs than BYS due to advanced technologies and direct incorporation into the ground. Wattway is in the middle between the more expensive prototypes and BYS, as it is a developed over-the-ground technology. BYS is similar to Wattway in the sense that they are above the ground and are installed on top of the pavement rather than installed in the ground. In terms of cost and energy production, BYS performs just as well as its competitors, if not a little better.

Table 2. Cost and energy produced per meter squared of BYS compared to its competitors

Prototype	Cost(€)/m^2	Energy production/m^2/year (kWh)
SolaRoad	13.000	78
Solar Roadways	9.500	71
Wattway	1.650	53
BYS	580	86 (theoretical)

BYS is not currently economically viable but could potentially be in the future. The three scenarios described in Table 3 suggest that after 20 years there is no scenario where both BYS and the customer break even. These scenarios assume no initial cost to the customer, just a monthly rental cost.

Table 3. Three scenarios for a monthly rental pricing strategy

	Rental Price for Customer	Incurring Loss at 20 years
Scenario 1: BYS break-even	€4,850 per month	Loss to Customer: €800,000
Scenario 2: Customer break-even	€1,510 per month	Loss to BYS: €800,000
Scenario 3: Middle ground	€3,175 per month	Loss to each: €400,000

Figure 11 shows the net income over time for BYS which adds the monthly rent to the production cost. As can be seen in red on 1/1/44, the break-even point is where the curve intersects with the axis.

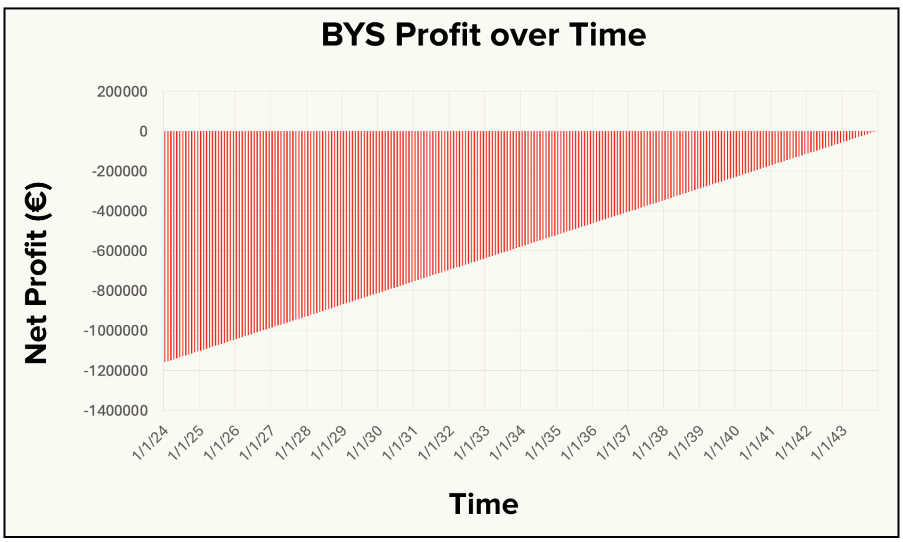

Figure 11. BYS profit over 20 years for €4,850 monthly rent

Similarly, as seen in Figure 12, the net negative is shown in the red curve, and the net positive in the green curve.

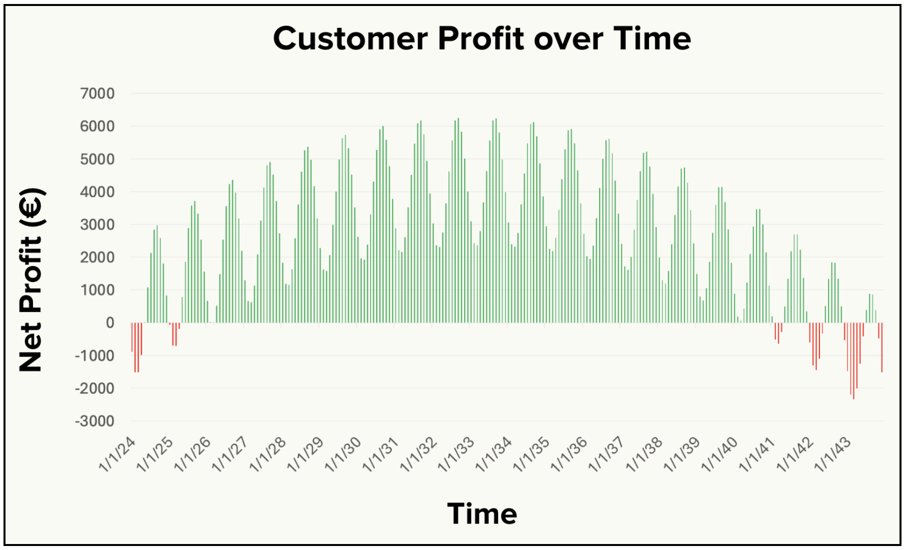

Figure 12. Customer profit over 20 years for €1,510 monthly rent

Figure 13 depicts the continuum of scenarios for different rental costs. Here, the orange line represents BYS' losses and profits as a function of the monthly rent at the end of 20 years. On the other hand, the blue line represents the customer's losses and profits as a function of the monthly rent at the end of 20 years.

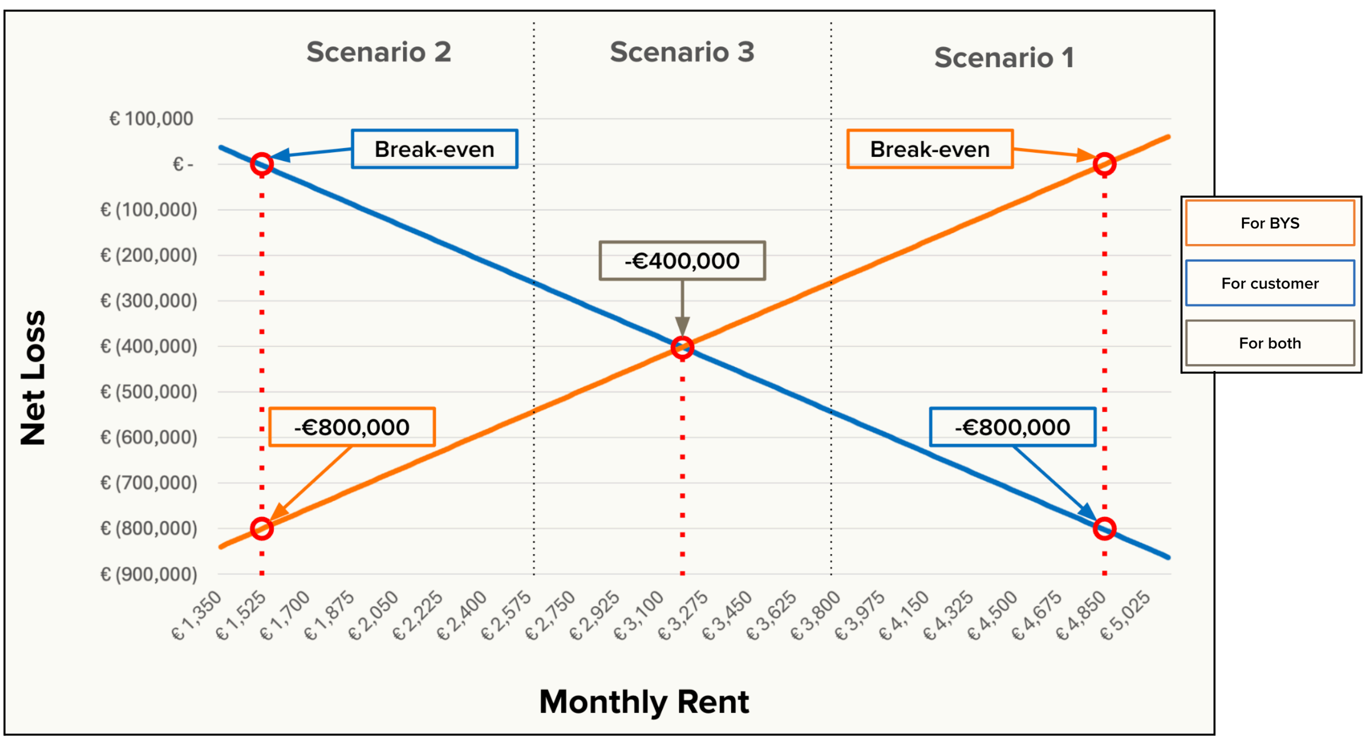

Figure 13. Three scenarios showcasing the net profit/loss as a function of monthly rental cost after 20 years

The first scenario involves BYS wanting to break even within their estimated 20 years of rent, which would require them to charge a monthly rental fee of €4,850. In this case, the customer will be incurring all of the loss. This may be viable for organizations such as universities as they may be willing to hold a loss if motivated by aspects like their commitment to sustainability rather than the energy production of the pavement.

The second scenario is one where the customer experiences a 20-year payback period for the pavement. In this case, BYS only charges €1,510 per month and absorbs the entire loss. This may seem counterintuitive initially, but it is possible that BYS might be willing to accept a loss for some initial installations so that the product could be tested and potentially gain acceptance. Over time, a combination of reduced solar panel costs and increasing energy value could make the technology economically viable.

The third scenario portrays the situation for a monthly fee of €3,175, in which case BYS and the customer equally share the cost over 20 years. This showcases a middle ground between both extremes explained in the previous two scenarios.

5. Conclusions and Recommendations

In this chapter, we present conclusions regarding the BYS solar pavement technology and offer recommendations for BYS' efforts going forward.

The BYS technology is not economically viable in northern Italy at this time. This study suggests that this technology does not make financial sense at this time and seems to be a long way from viability. There is no scenario where both BYS and the customer can break even within the given 20-year lifespan of the technology. However, the cost breakdown might change in the future. Solar panels are historically known to decrease in price as time goes on, meaning the price of solar pavements could follow a similar trend. The cost of electricity could potentially change as well, impacting the cost of solar pavements.

Universities with sufficient resources could be potential early adopters of this demonstration technology. Despite the lack of economic viability, the professors' responses led us to believe that if their university installed solar pavements, it would be for the university's reputation and spreading awareness about renewable energy. While there seems to be general support for this technology among responding staff and students, there are challenges in Venice that remain. Based on our results, universities that have the means to implement a technology like BYS in other locations in Italy may be interested in adopting it.

Providing evidence of slip resistance will likely be important for social acceptance of solar pavements. Given that slipperiness was a top concern for both university professors and students, it is evident that safety is an important consideration for individuals. This may stem from how new this technology is, making it challenging for people to envision its practicality and safety.

Recommendations

Solar pavements are a promising strategy for some urban locations, but to meet goals for renewable energy transition, alternative strategies will be needed for cities like Venice with a high density of historical buildings. We offer some recommendations for BYS and further research into solar implementations:

BYS should look into other universities outside of Venice to assess potential adopters. It may be difficult to find locations on campuses in Venice to implement this type of technology due to regulations in place to protect the city's historic character. Therefore, looking into other Italian universities might be useful for BYS. Municipalities and shopping centers could also be potential locations for further exploration to assess the solar pavements' viability.

BYS should make information about the pavements easily accessible to the public so they can learn more about them. People may have a preconceived notion about the glass being slippery from previous interactions with glass. Therefore, providing results from anti-slip tests or showing a piece of the prototype for people to feel may make the concept of this technology clearer to them. Introducing prototypes of the pavement for public interaction could play a pivotal role in alleviating these concerns and promoting greater acceptance of solar pavements.

BYS could use the PVPC (Photovoltaic Potential Calculator) to help find long-term energy production and decide on their pricing strategies. The calculator will be a useful tool for BYS once they get values from testing, where they will be able to input the actual energy production value and their chosen pricing strategy. The calculator will give them scenarios that are dependent on the values that are inputted. This will help BYS understand the long-term profit and loss of their technology and allow them to decide what changes they would need to make to their business model based on their desired outcome.

Further research into solar technologies should include the integration of solar windows or solar roof tiles as additional strategies for implementing solar energy into historic centers. This would help preserve the historical features of Venice while also contributing to the solar energy initiatives in Italy. Venice's unique historical character poses unusual challenges for implementing solar pavements. However, the social acceptance surrounding the concept of solar pavements suggests that there is potential for the integration of other types of solar energy systems. We hope that this study can aid in the development of solar pavements as a climate-friendly technology in other parts of Italy.

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Appendix A - Questionnaire for University Professors

Ciao!

This study, conducted in collaboration with BYS Italia s.r.l., explores the feasibility of a new type of solar technology. This survey will take you approximately 10 minutes.

We are students from Worcester Polytechnic Institute who are working with BYS Italia, a startup company established by Infinityhub, with the goal of creating solar pavements. Solar pavements are solar panel systems that are directly incorporated into the infrastructure of roads and the ground.

BYS' prototype can be seen in the image below.

We are conducting surveys with professors in universities to learn more about your perspectives on solar pavements and their implementation. Your participation in this survey is completely voluntary and will be anonymous. Please answer each question with as much detail as possible.

1) Have you heard about solar pavements before reading the description?

○ Yes

○ No

Display This Question:

If "Have you heard about solar pavements before reading the description?" = Yes

1.1) What is your opinion on solar pavements?

Display This Question:

If "Have you heard about solar pavements before reading the description?" = Yes

1.2) What specific projects or implementations have you heard of?

____

2) How important is sustainability for your university?

○ Not important

○ Somewhat important

○ Very important

3) How likely do you think your university would be to implement this technology for the following reasons:

	Very unlikely	Somewhat unlikely	Neither likely nor unlikely	Somewhat likely	Very likely
Raising awareness for renewable energy	○	○	○	○	○
Producing more renewable energy for the campus	○	○	○	○	○
The reputation of your university in terms of sustainability	○	○	○	○	○
Lowering overall cost spent on electricity	○	○	○	○	○

4) Solar pavements need to be placed in an area with adequate sunlight. Do you believe there are practical locations (walking paths, courtyards, gardens, etc.) in your university to implement solar pavements? Please explain.

____

5) How concerned are you about each of the following aspects of solar pavements?

	Not concerned	Somewhat concerned	Concerned	Very concerned	Extremely concerned
Cost	○	○	○	○	○
Visual appeal	○	○	○	○	○
Strength	○	○	○	○	○
Slipperiness	○	○	○	○	○
Energy production	○	○	○	○	○

6) What do you know about incentives (government or private funding) for utilizing renewable energy for your university?

____

7) If you are willing to have a brief follow-up interview about this topic, please leave your name and contact information here.

Name: ____

Email: ____

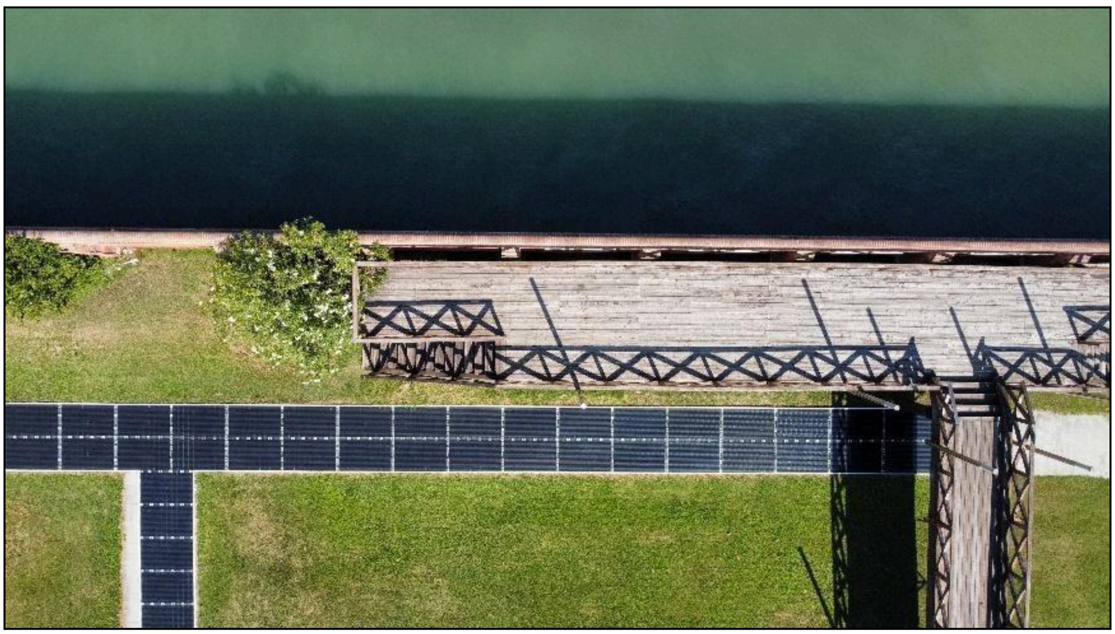
Appendix B - Questionnaire for University Students

Ciao!

This study, conducted in collaboration with BYS Italia, explores the feasibility of a new type of solar technology. This survey will take you approximately 5 minutes.

We are students from Worcester Polytechnic Institute who are working with BYS Italia, a startup company established by InfinityHub, with the goal of creating solar pavements. Solar pavements are solar panel systems that are directly incorporated into the infrastructure of roads and the ground.

BYS Italia's prototype can be seen in the image below.



We are conducting surveys with university students to learn more about your perspectives on solar pavements and their implementation. Your participation in this survey is completely voluntary and will be anonymous.

Solar pavements are solar panel systems that are directly incorporated into roads and the ground.

1)	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I am familiar with solar pavements.	○	○	○	○	○

2)	Strongl y disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
Solar pavements on campus would increase the awareness of renewable energy at my university.	○	○	○	○	○

3)	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I can easily imagine myself walking on a solar pavement.	○	○	○	○	○

4) Solar pavements would affect my campus by making it more... (Check all that apply)

- Sustainable
- Innovative
- Modern
- Attractive
- Unappealing

5)	Strongl y disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongl y agree

I would like to see my university fund the implementation of solar pavements on campus.	○	○	○	○	○

6) How concerned are you about each of the following aspects of solar pavements?

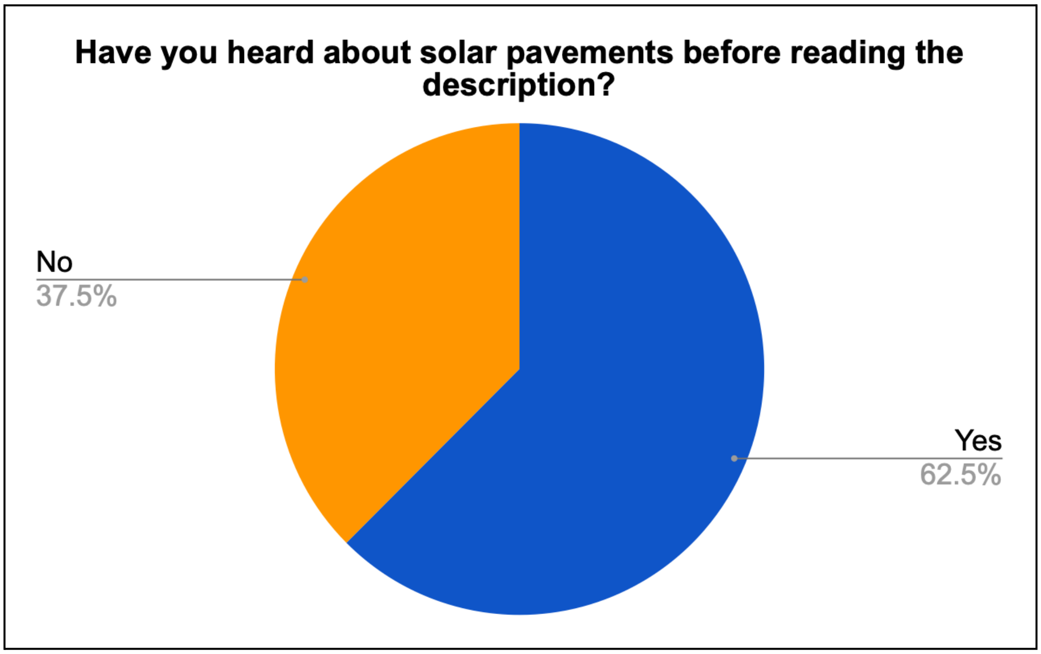
	Not concerned	Somewhat concerned	Concerned	Very concerned	Extremely concerned
Cost	○	○	○	○	○
Visual appeal	○	○	○	○	○
Strength	○	○	○	○	○
Slipperiness	○	○	○	○	○
Energy production	○	○	○	○	○

7) What additional questions and ideas do you have about solar pavements?

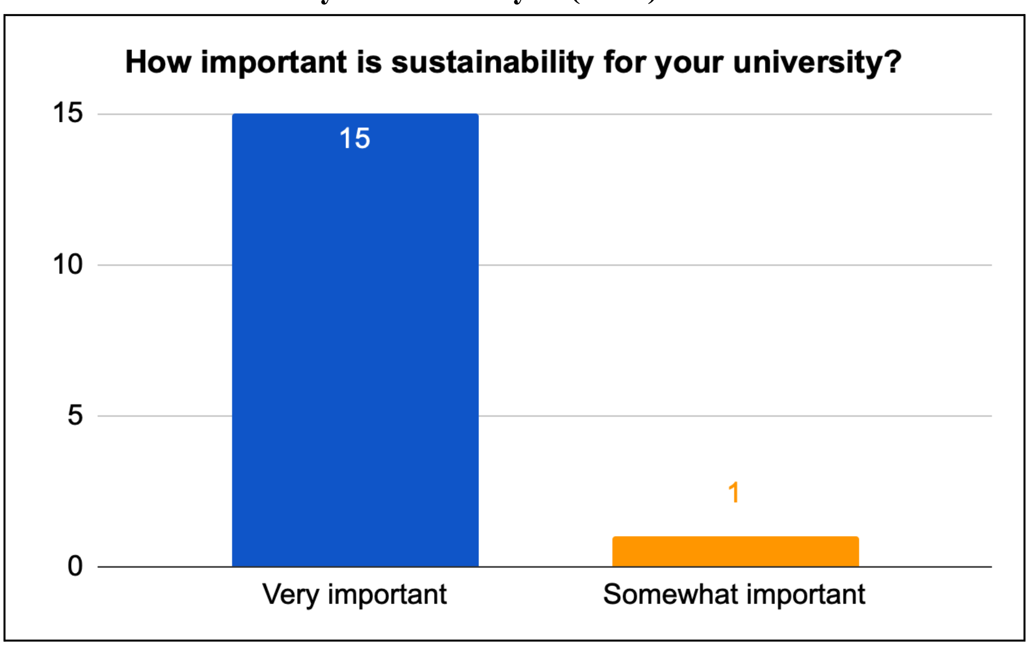
____

Appendix C - Results from University Professors Surveys

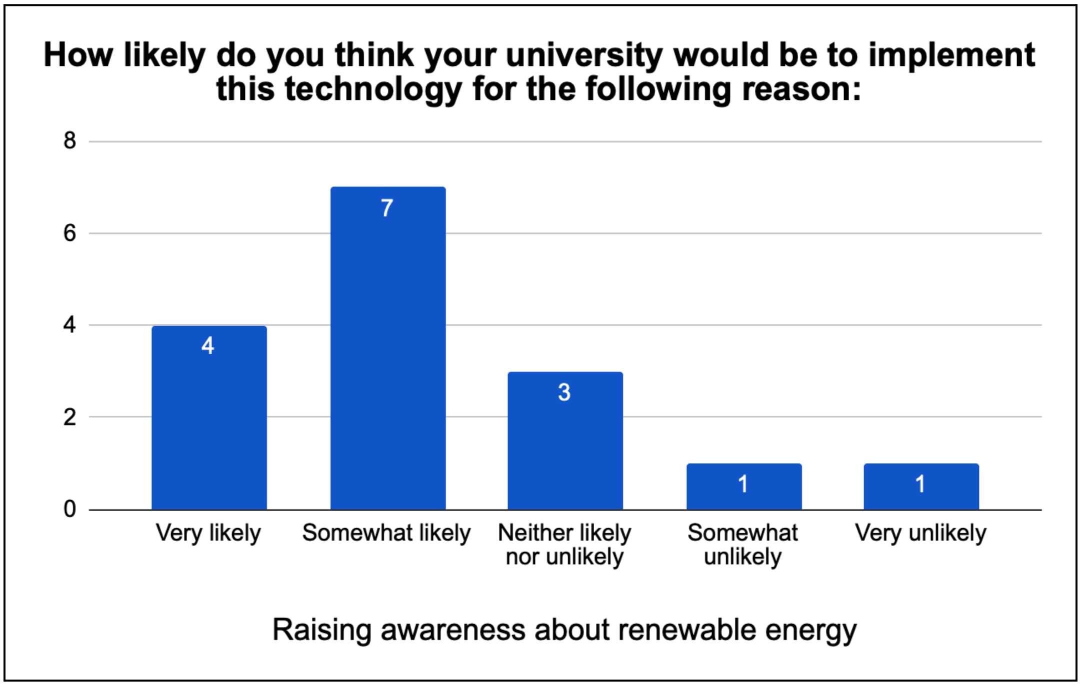
Pie chart of professors' responses to the question "Have you heard about solar pavements before reading the description?" (n=16)



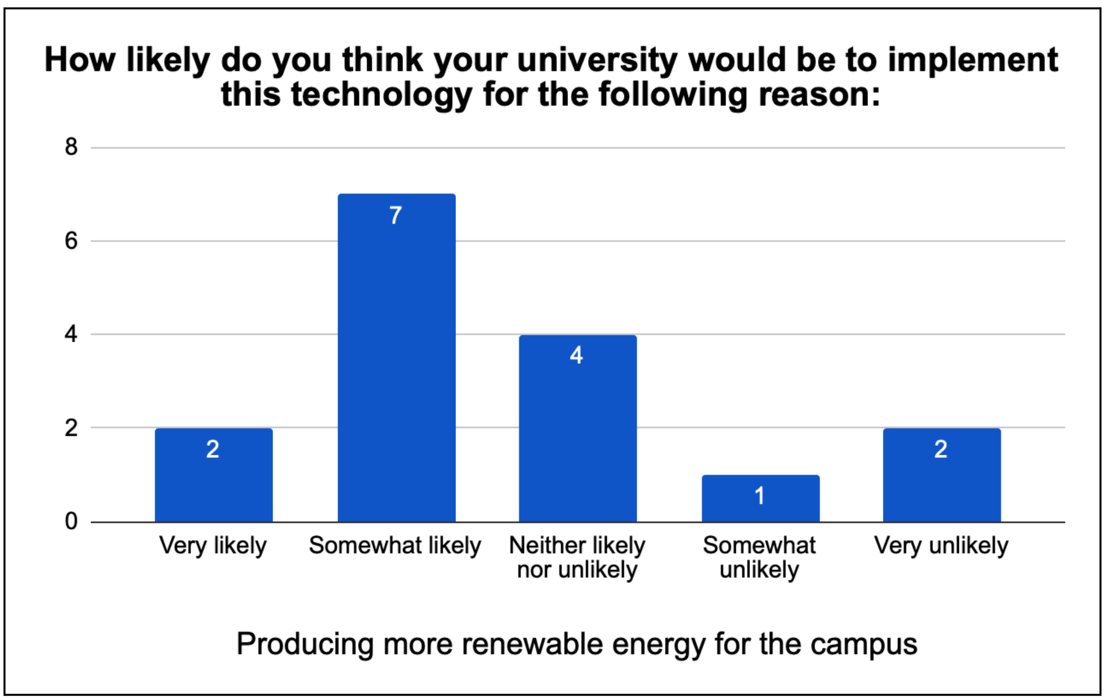
Bar chart of professors' responses to the question "How important is sustainability for your university?" (n=16)



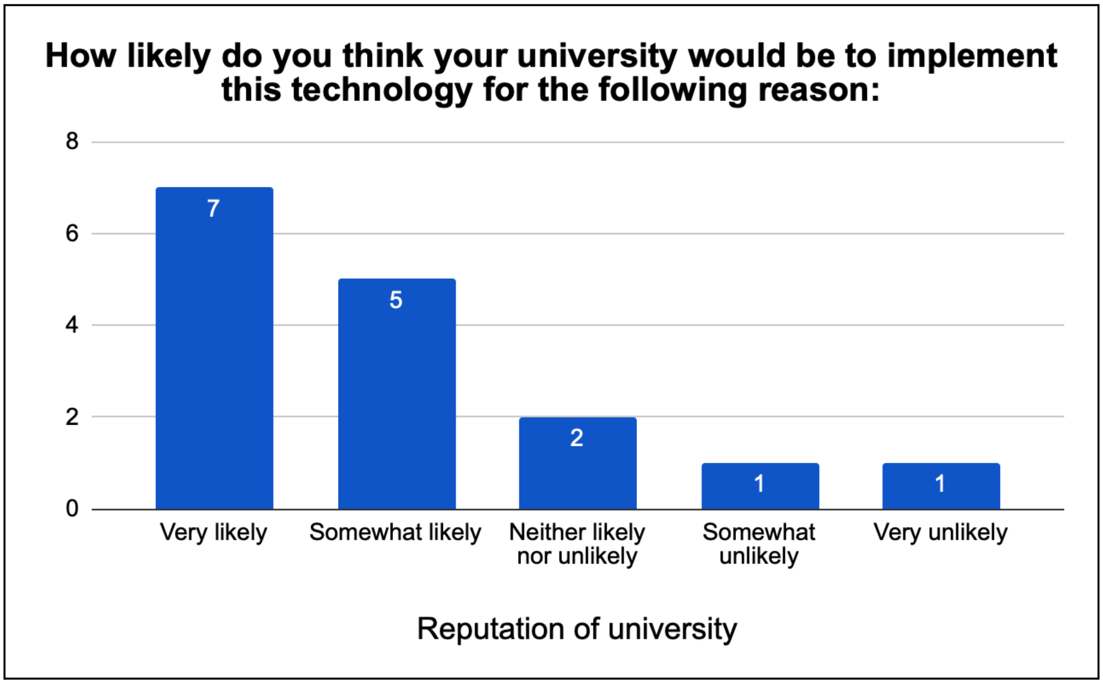
Bar chart of professors' responses to the question "How likely do you think your university would be to implement this technology for the following reasons?" (n=16)



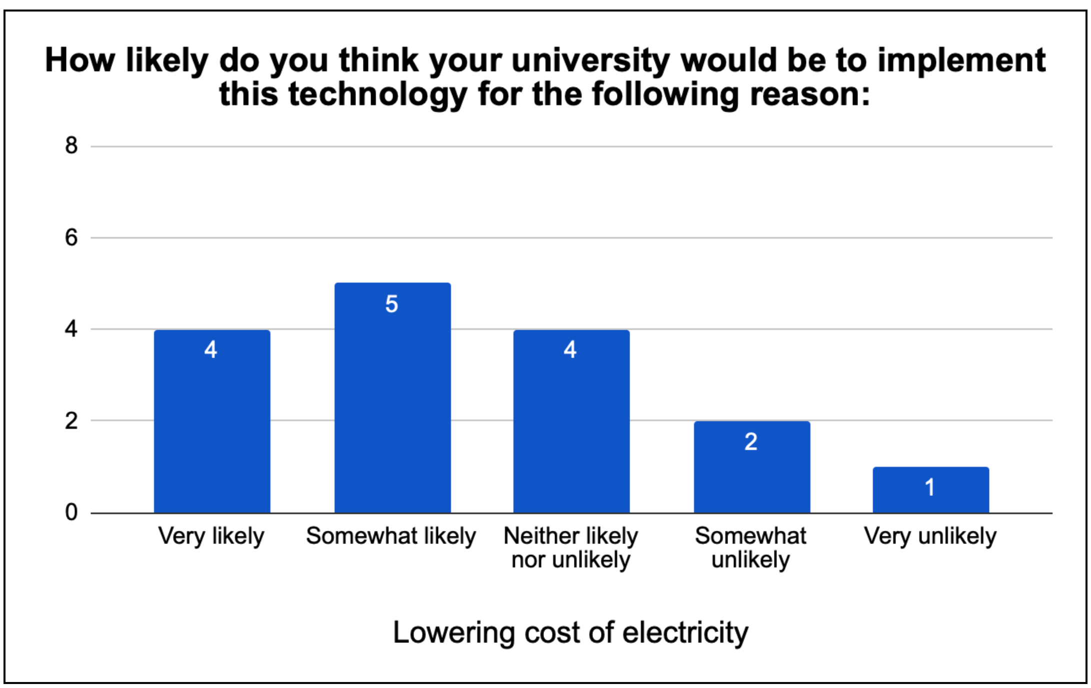
Bar chart of professors' responses to the question "How likely do you think your university would be to implement this technology for: Producing more renewable energy for the campus?" (n=16)



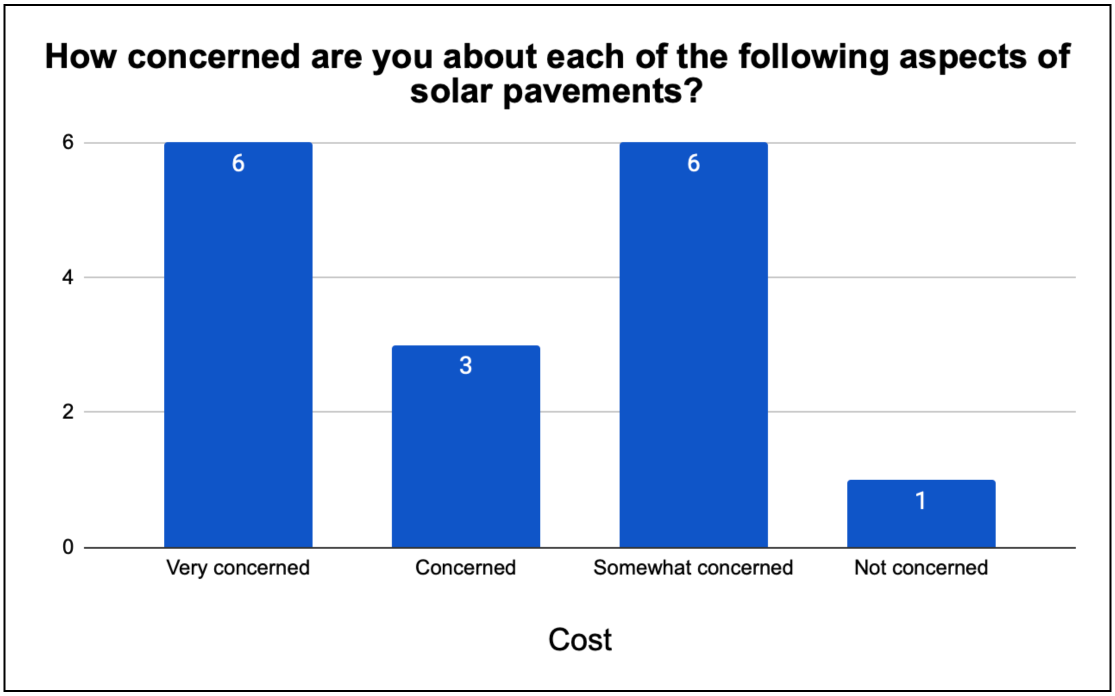
Bar chart of professors' responses to the question "How likely do you think your university would be to implement this technology for: Reputation of the university?" (n=16)



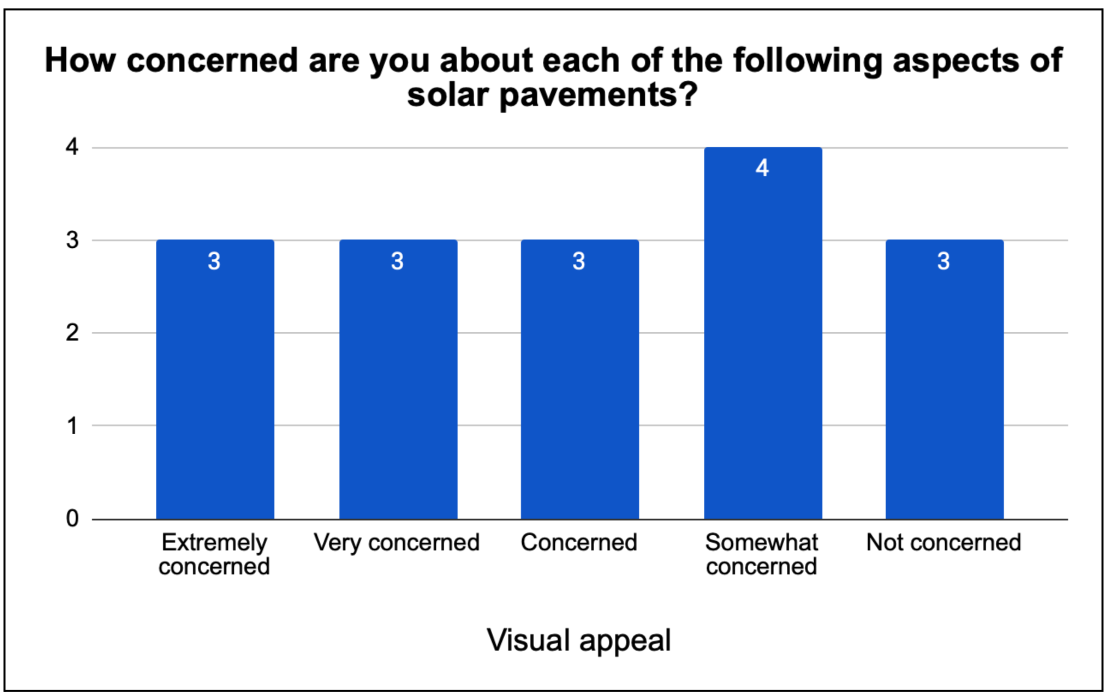
Bar chart of professors' responses to the question "How likely do you think your university would be to implement this technology for: Lowering the cost of electricity?" (n=16)



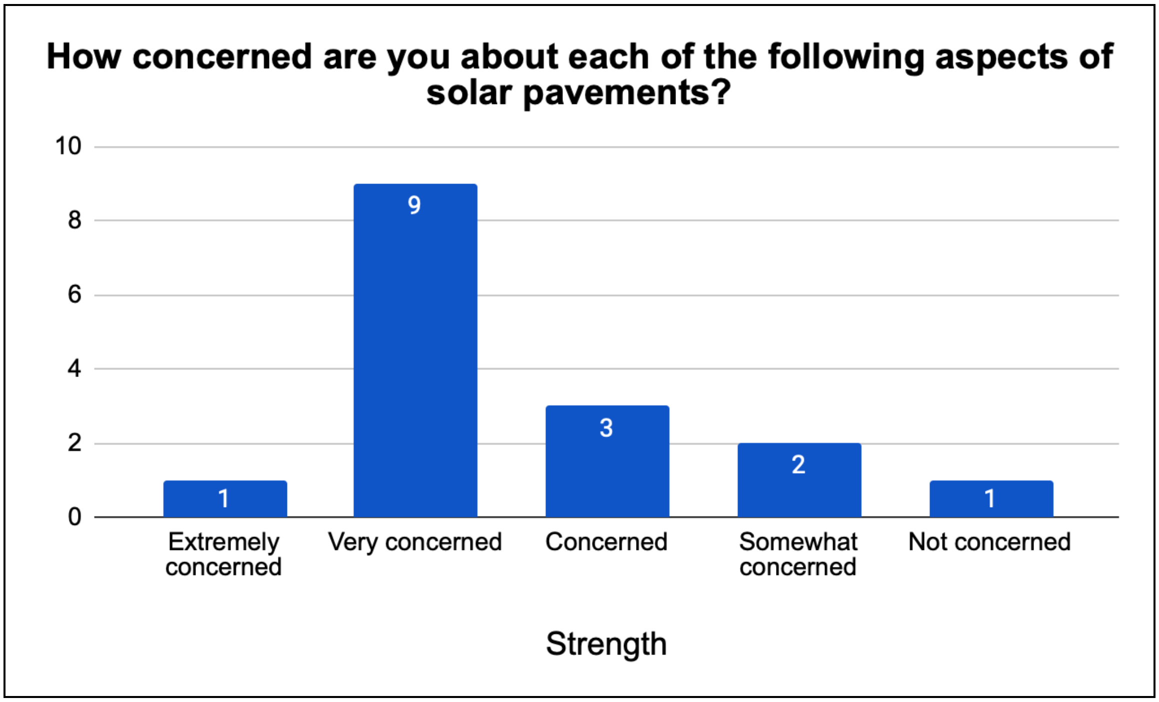
Bar chart of professors' responses to the question "How concerned are you about each of the following aspects of solar pavements: Cost?" (n=16)



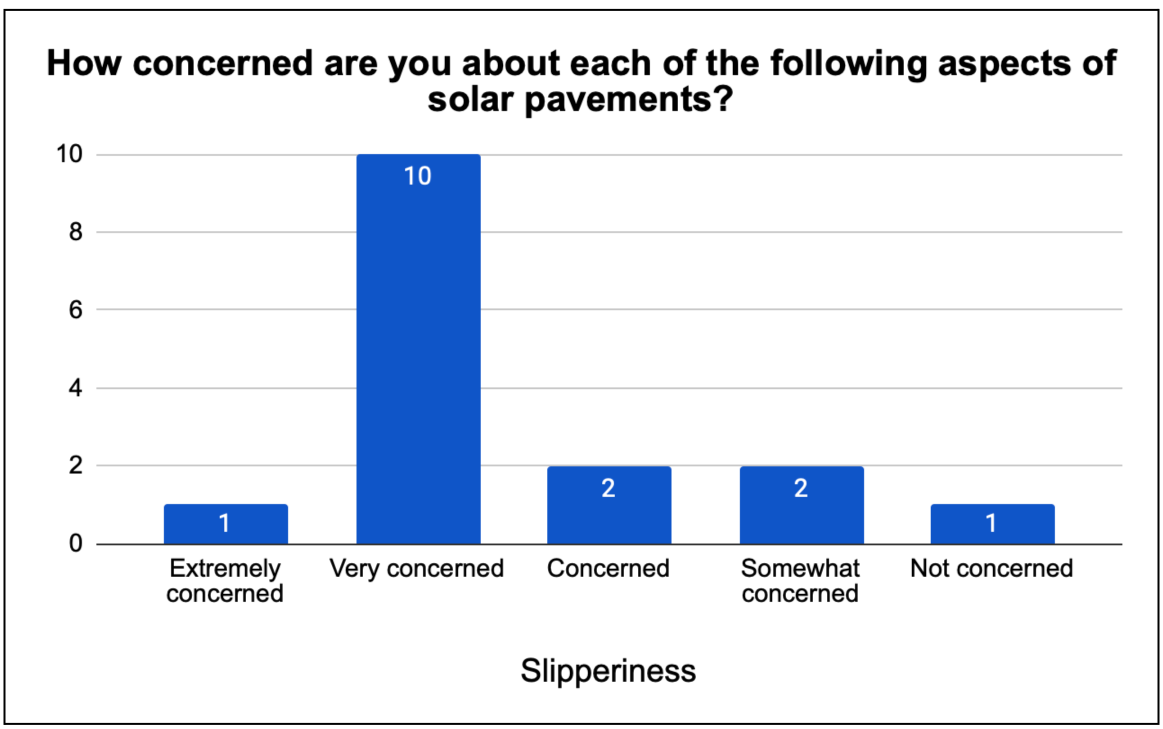
Bar chart of professors' responses to the question "How concerned are you about each of the following aspects of solar pavements: Visual appeal?" (n=16)



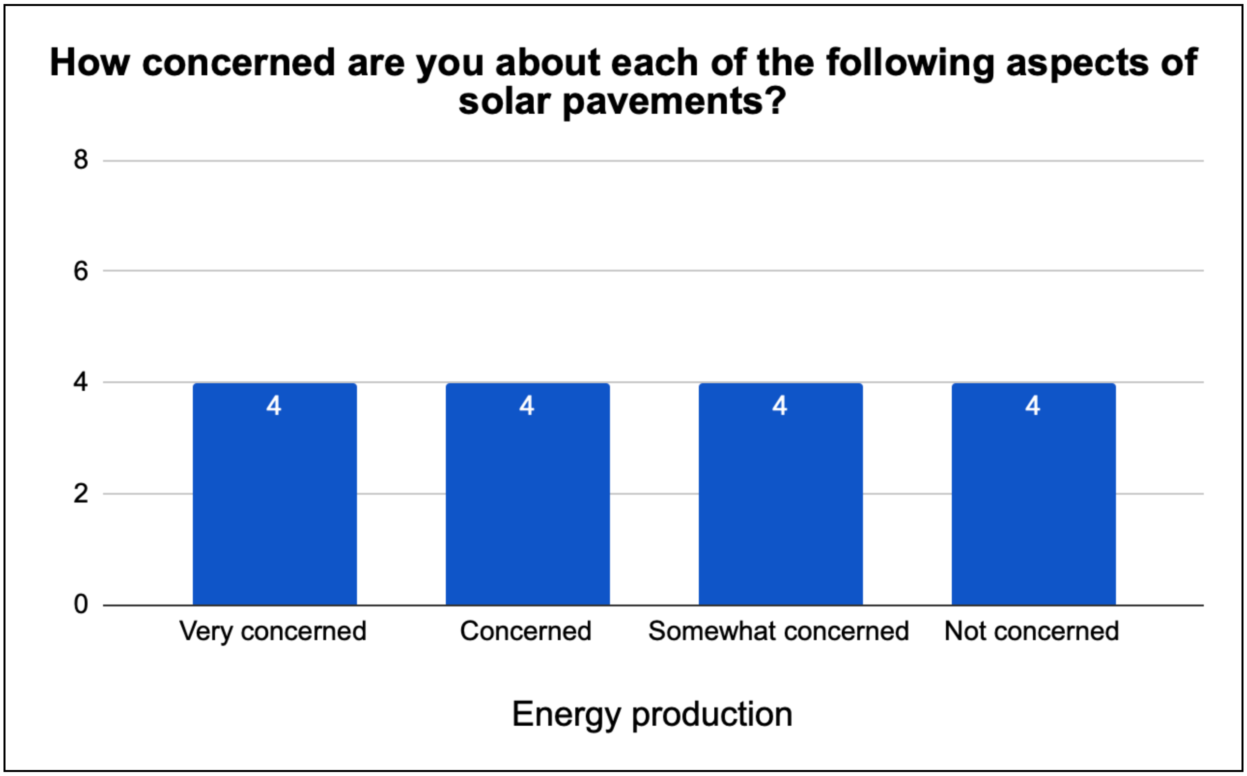
Bar chart of professors' responses to the question "How concerned are you about each of the following aspects of solar pavements: Strength?" (n=16)



Bar chart of professors' responses to the question "How concerned are you about each of the following aspects of solar pavements: Slipperiness?" (n=16)



Bar chart of professors' responses to the question "How concerned are you about each of the following aspects of solar pavements: Energy production?" (n=16)


How concerned are you about each of the following aspects of solar pavements?
8
6
4
2
0
4
4
4
4
Very concerned
Concerned
Somewhat concerned
Not concerned
Energy production

Responses from questions 1.1 and 1.2 of the university professors survey in Italian

Q1.1 - Qual è la sua opinione sulle pavimentazioni solari?	Q1.2 - Di quali progetti o implementazioni specifiche avete sentito parlare?
ottima. ancora troppo impegnativa economicamente.	piste ciclabili solari
Buona	3-4
I do not have a well formed opinion	Motorways
Se efficienti, uno strumento in più per l'incremento della quota di rinnovabili. A patto che non diminuiscano la superficie permeabile (sarebbe bene in genere ricorrere a sistemi di pavimentazione drenanti).	Nessuno
Dipende dal contesto in cui vengono inserite	passerelle ciclo-pedonali
positiva	costruzione di piste ciclabili
positiva, ma non conosco le performance tecniche	Isola di San Servolo
Non ho un'opinione precisa	Una realizzazione nel nord Europa
sono poco applicabili	solo letto descrizioni generali
è una buona idea	nessun progetto specifico

Responses from questions 1.1 and 1.2 of the university professors survey in English

Q1.1 - What is your opinion on solar pavements?	Q1.2 - What specific projects or implementations have you heard of?
Excellent. Still too challenging economically	Solar bike lanes
Good	3-4
I do not have a well-formed opinion	Motorways
If efficient, one more tool for increasing share of renewables. As long as they do not decrease permeable surface area (it would generally be good to use draining pavements systems).	None
Depends on the context in which they are placed	Bicycle and pedestrian walkways
positive	Construction of bicycle paths
positive, but I don’t know the technical performance	San Servolo Island
I do not have an accurate opinion	An achievement in northern Europe
Are not very applicable	Only read general descriptions
Is a good idea	No specific project

Responses from questions 4 and 6 of the university professors survey in Italian

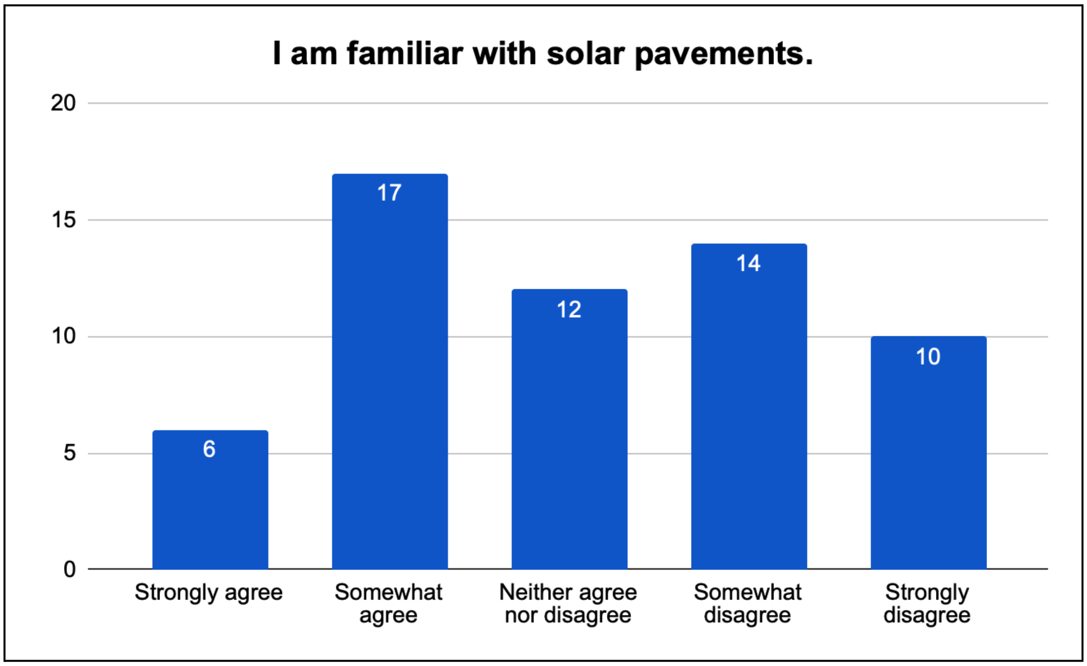
Q4 - I marciapiedi solari devono essere collocati in un'area con una luce solare adeguata. Ritiene che nella sua università vi siano luoghi praticabili (percorsi pedonali, cortili, giardini, ecc.) per l'installazione di pavimentazioni solari? Si prega di spiegare.	Q6 - Cosa sapete degli incentivi (finanziamenti statali o privati) per l'utilizzo di energie rinnovabili nella vostra università?
Sì, siamo a Venezia, quindi non c'è sovrapposizione col traffico automobilistico	nulla
Si fuori dal cotonificio	Niente
There are already cycle paths surrounding the university while inside the campus there are paths with good exposition to solar irradiation. Indeed there are already solar panels dedicated to e-bike recharging.	Little
Area portuale	Non ho conoscenze approfondite
Nelle sedi in terraferma, il centro storico ha limitate aree scoperte di pertinenza e sono comunque vincolate.	-
Gli spazi esterni di pertinenza dell'università non sono molti, più che altro sono spazi comunali	Niente
Essendo inserita in un contesto storico, dubito che la pavimentazione in oggetto sia realizzabile	Poco informata
sì	abbastanza
Penso che sia possibile teoricamente sia a San Giobbe che a Mestre	Poco
L'università Iuav ha sede nel centro storico di Venezia, dove l'utilizzo del fotovoltaico è quasi sempre impedito dalla sovrintendenza ai beni architettonici e al paesaggio. L'immagine che proponete è sì riferita all'isola di San Servolo, qui a Venezia, ma il contesto è diverso. Mi sempre comunque stupito che a San Servolo ne fosse stata concessa l'installazione.	Non me ne occupo
Si	poco
A Venezia non ci sono piste ciclabili e esistono vincoli di carattere paesaggistico e ambientale per l'inserimento di pannelli fotovoltaici.	niente
Essendo Iuav collocata in centro storico a Venezia, difficilmente può utilizzare pavimentazioni che non rientrano tra quelle autorizzate	personalmente non moltissimo, ma in passato sono stati fatti interventi importanti in tal senso e so che altri nuovi dovranno essere affrontati (su più di un edificio)
No	Non molto.
si esistono	potrebbero essere utili
nella nostra Università no perchè a Venezia non possono circolare le biciclette ma nell'area portuale limitrofa potrebbe essere possibile	non sono informato

Responses from questions 4 and 6 of the university professors survey in English

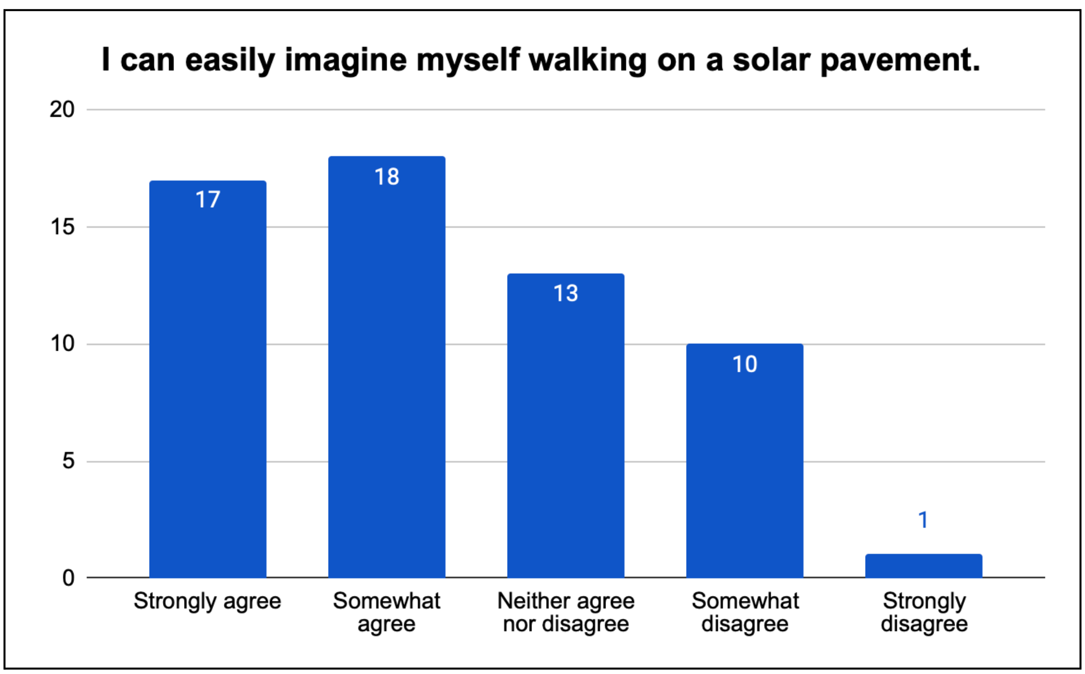
Q4 - Solar pavements need to be placed in an area with adequate sunlight. Do you believe there are practical locations (walking paths, courtyards, gardens, etc.) in your university to implement solar pavements? Please explain.	Q6 - What do you know about incentives (government or private funding) for utilizing renewable energy for your university?
Yes, we are in Venice, so there is no overlap with car traffic	Nothing
Yes outside the cotton mill	Nothing
There are already cycle paths surrounding the university while inside the campus there are paths with good exposition to solar irradiation. Indeed there are already solar panels dedicated to e-bike recharging.	Little
Port area	I have no in-depth knowledge
In the mainland locations, the historic center has limited uncovered areas of relevance and are still constrained.	-
There are not many outdoor spaces pertaining to the university, more like municipal spaces	Nothing
As it is included in a historical context, I doubt that the paving in question is feasible	Little knowledgeable
yes	Fairly
I think it is theoretically possible in both San Giobbe and Mestre	Little
Iuav University is based in the historic center of Venice, where the use of photovoltaics is almost always prevented by the Superintendence of Architectural Heritage and Landscape. The image you propose is yes referring to the island of San Servolo, here in Venice, but the context is different. I was always amazed, however, that San Servolo was allowed to install it.	I don't deal with it
Yes	Little
There are no bike lanes in Venice and there are landscape and environmental constraints on the placement of photovoltaic panels.	Nothing
Since Iuav is located in the historic center of Venice, it can hardly use pavements that are not among those authorized	Personally not very much, but major interventions have been made in the past in this regard and I know that other new ones will need to be addressed (on more than one building)
No	Not much
yes they exist	Could be useful
in our University no because bicycles cannot circulate in Venice but in the neighboring port area it could be	Not informed

Appendix D - Results from University Students Surveys

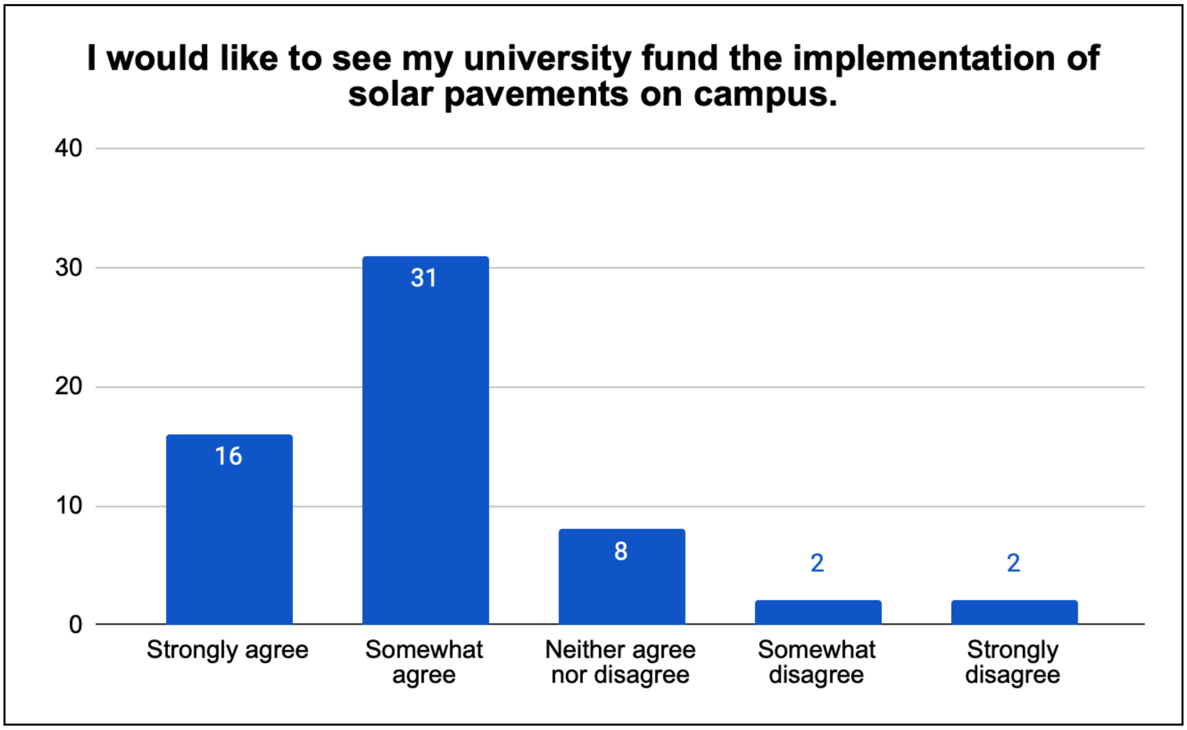
Bar chart of students' responses to the statement "I am familiar with solar pavements." (n=59)



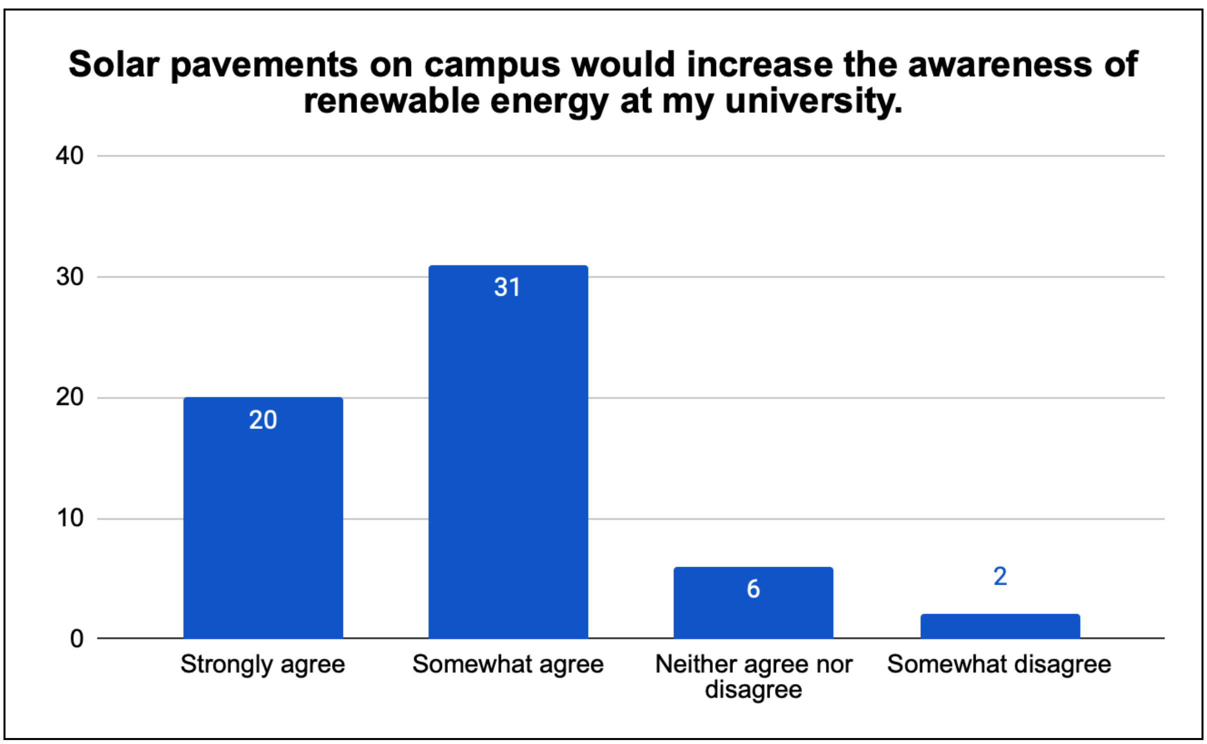
Bar chart of students' responses to the statement "I can easily imagine myself walking on a solar pavement." (n=59)



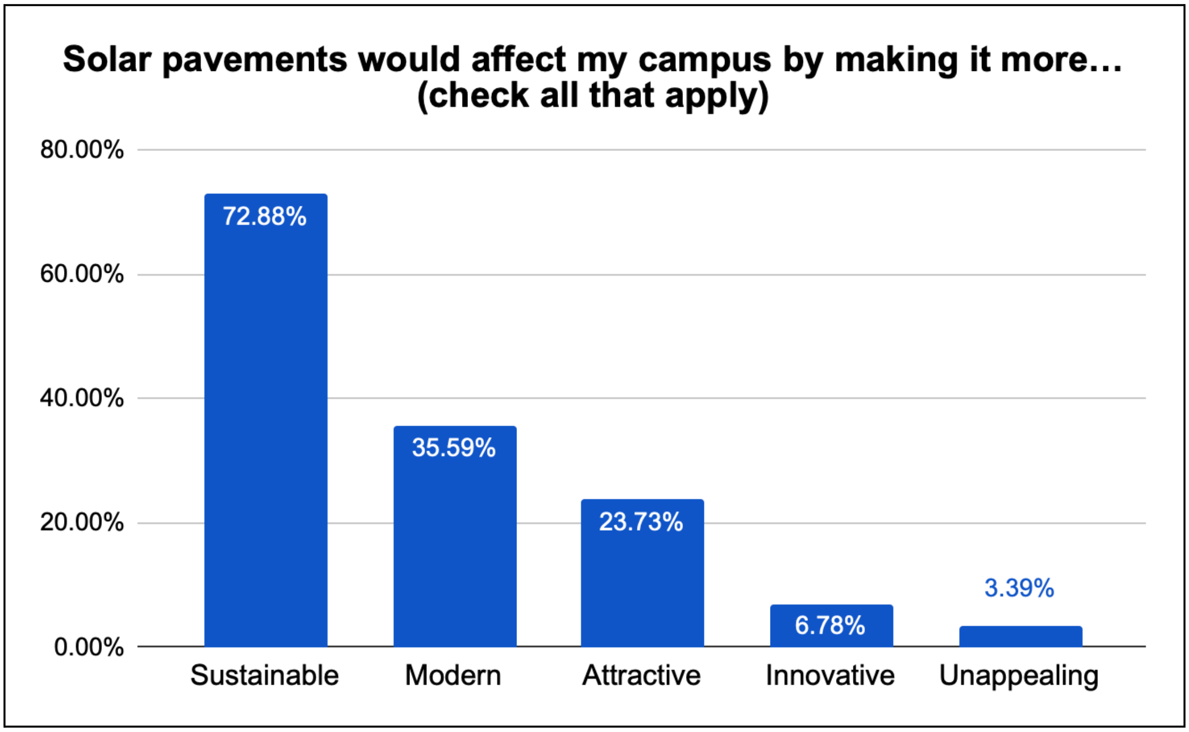
Bar chart of students' responses to the statement "I would like to see my university fund the implementation of solar pavements on campus." (n=59)



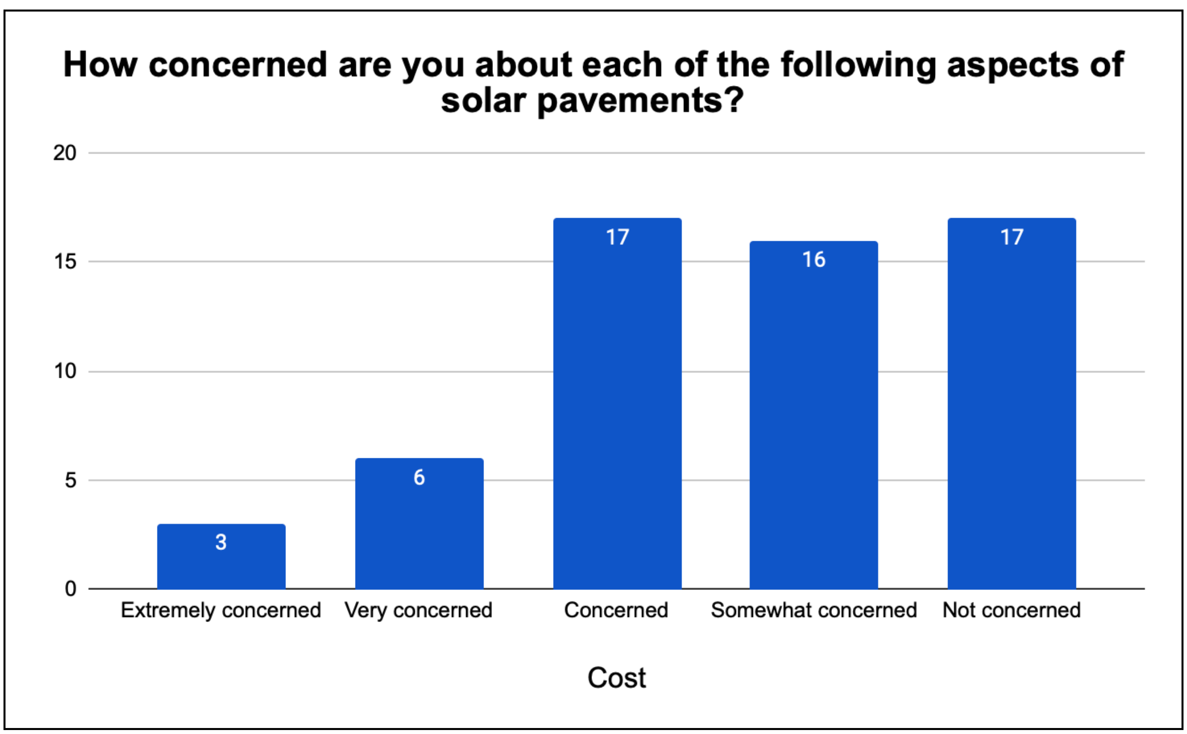
Bar chart of students' responses to the statement "Solar pavements on campus would increase the awareness of renewable energy at my university." (n=59)



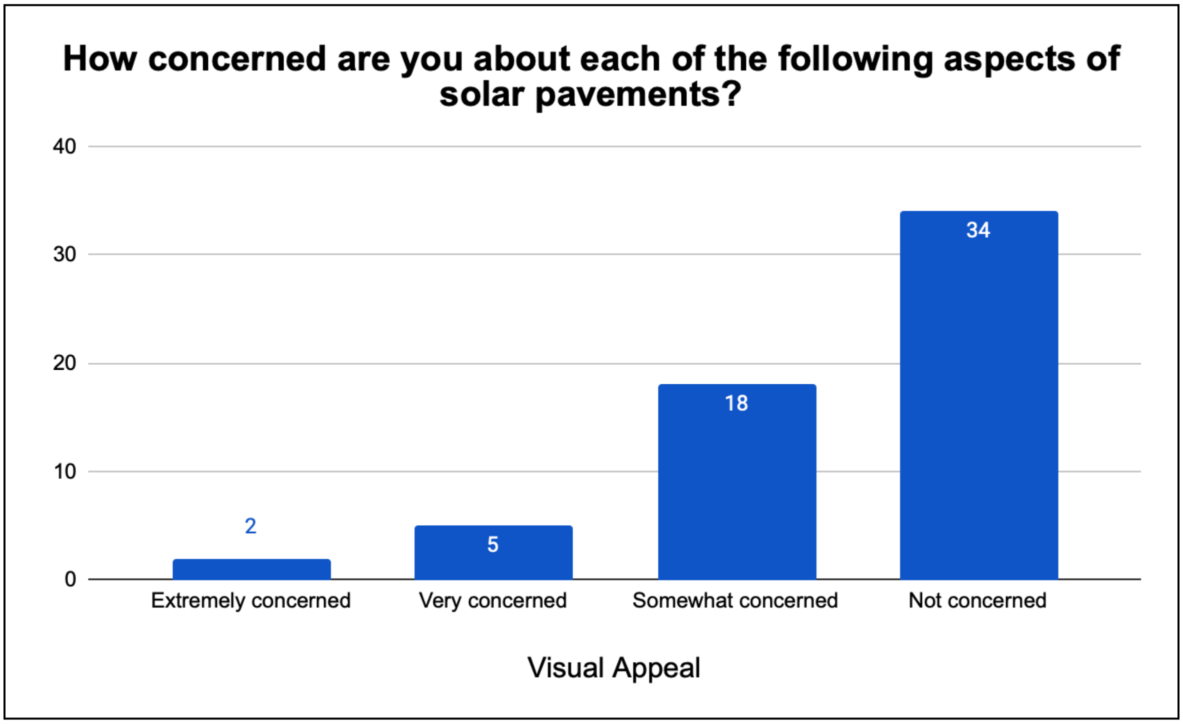
Bar chart of students' responses to the statement "Solar pavements would affect my campus by making it more…." (n=59)



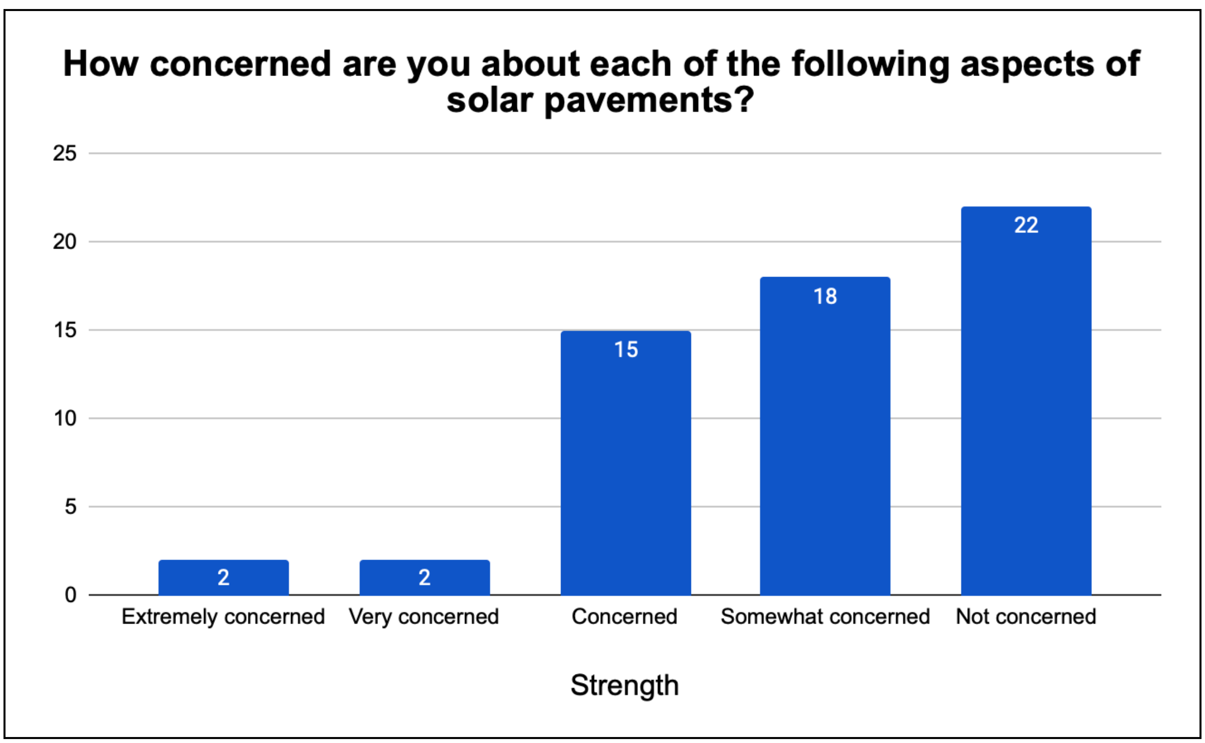
Bar chart of students' responses to the question "How concerned are you about each of the following aspects of solar pavements: Cost?" (n=59)



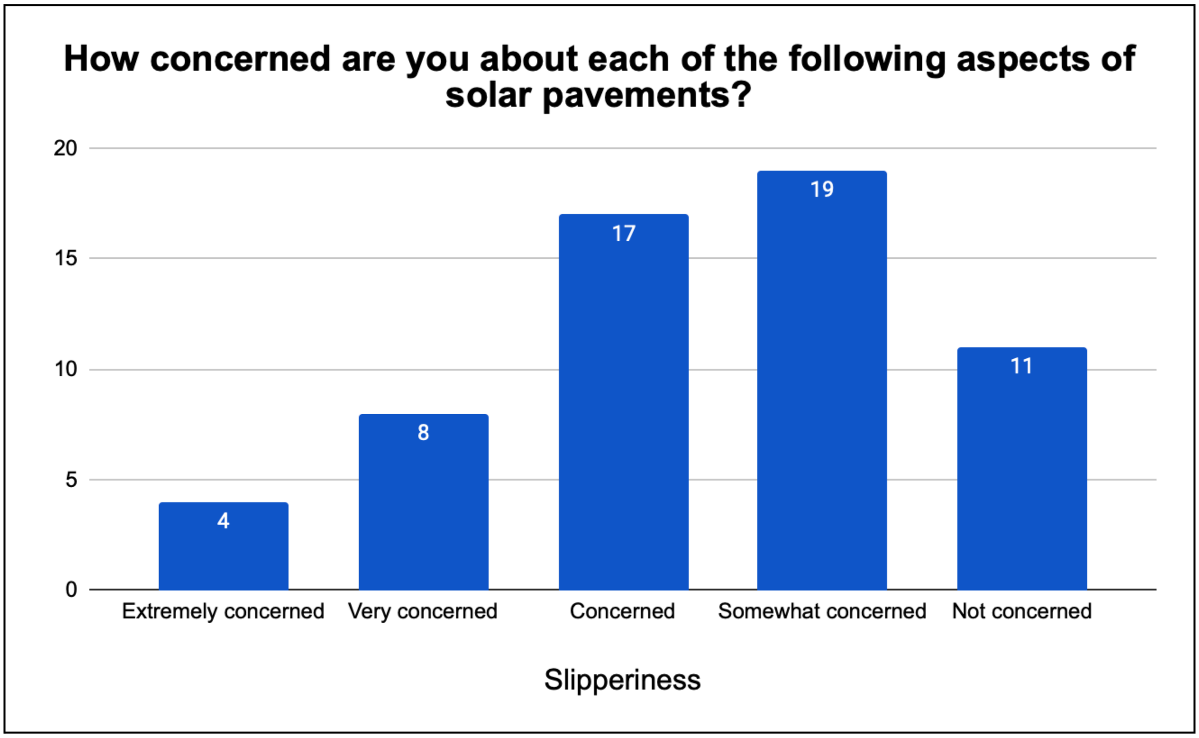
Bar chart of students' responses to the question "How concerned are you about each of the following aspects of solar pavements: Visual appeal?" (n=59)



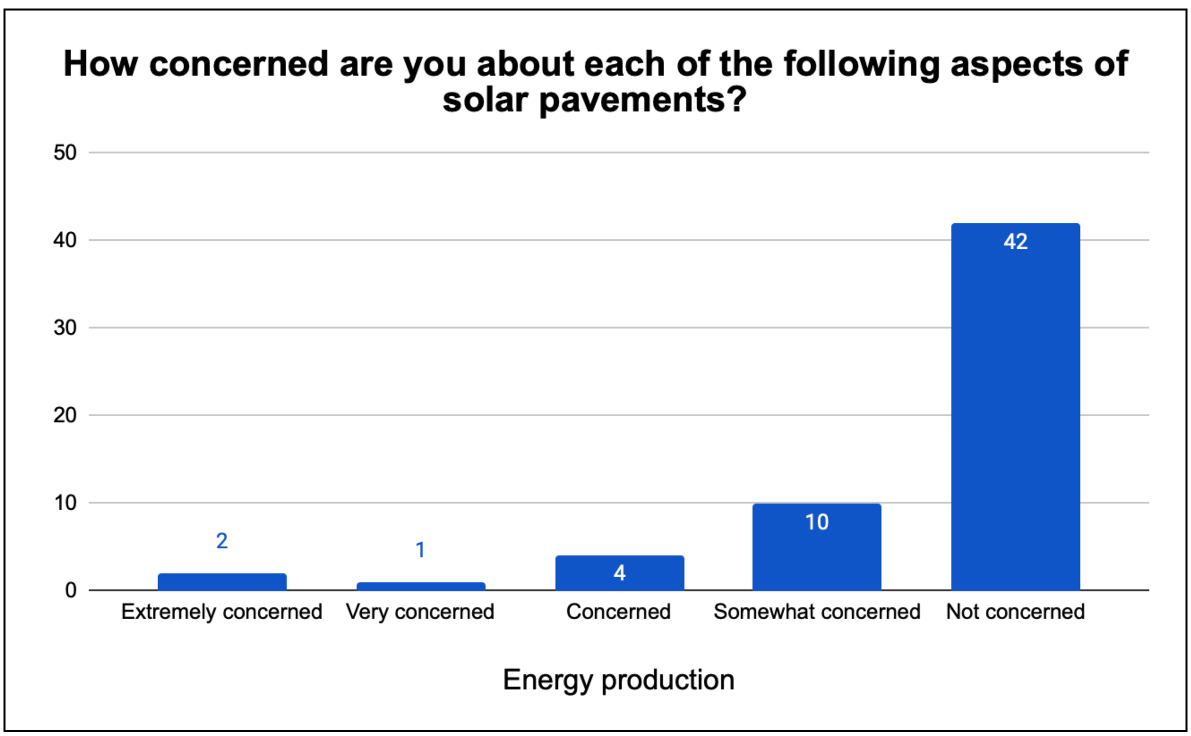
Bar chart of students' responses to the question "How concerned are you about each of the following aspects of solar pavements: Strength?" (n=59)



Bar chart of students' responses to the question "How concerned are you about each of the following aspects of solar pavements: Slipperiness?" (n=59)



Bar chart of students' responses to the question "How concerned are you about each of the following aspects of solar pavements: Energy production?" (n=59)



Responses from question 7 of the university students survey in Italian

Q7 - Quali altre domande e suggerimenti avete in merito alle pavimentazioni solari?
Le biciclette sono illegali a Venezia…
L'unica cosa che posso dire essendo veneziana è che penso sia una cosa complicata da realizzare a causa del tessuto storico-artistico- culturale ma anche progettuale, posso immaginare che Venezia sia una città complicata per questo tipo di innovazioni.
È un alternativa sostenibile considerata l'impossibilità di smaltimento delle batterie di accumulo?

Responses from question 7 of the university students survey in English

Q7 - What other questions and suggestions do you have about solar pavements?
Bicycles are illegal in Venice…
The only thing I can say being Venetian is that I think it is a complicated thing to do because of the historical-artistic-cultural but also design fabric, I can imagine Venice being a complicated city for this kind of innovation.
Is it a sustainable alternative considering the impossibility of disposal of storage batteries?

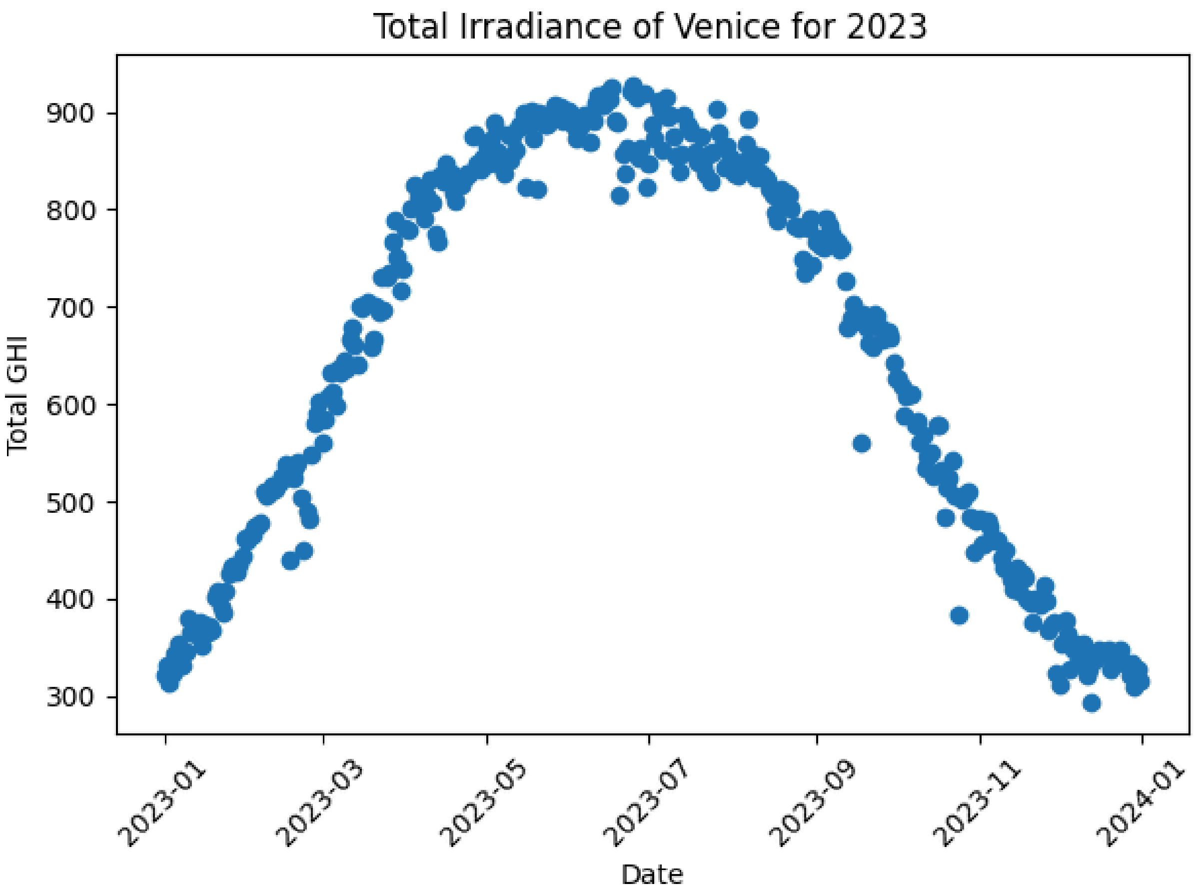
Appendix E - Cost Analysis Code

GHI.py: for reading the GHI database

```
# Import necessary libraries
import pandas as pd  # For data manipulation and analysis
import matplotlib.pyplot as plt  # For creating plots

# Read the Global Horizontal Irradiance (GHI) data from a CSV file into a
DataFrame
df = pd.read_csv('GHI.csv')

# Drop the 'period' and 'air_temp' columns from the DataFrame
df = df.drop('period', axis=1)
df = df.drop('air_temp', axis=1)

# Read the length of day data from a CSV file into another DataFrame
df_lod = pd.read_csv('length_of_day.csv')

# Drop the 'date' column from the DataFrame
df_lod = df_lod.drop('date', axis=1)

# Remove any unnamed columns from the DataFrame
df_lod = df_lod.loc[:, ~df_lod.columns.str.contains('^Unnamed')]

# Convert the 'length_of_day' column from hours:minutes format to minutes
df_lod = df_lod['length_of_day'].str.split(':').apply(lambda x: int(x[0]) *
60 + int(x[1]))

# Extract the 'period_end' column from df as 'date and time' and rename it
to 'date and time'
period = df['period_end']
df = df.rename(columns={'period_end': 'date and time'})

# Rename the 'clearsky_ghi' column to 'ghi'
df = df.rename(columns={'clearsky_ghi': 'ghi'})

# Convert the 'date and time' column to datetime format
```

```
df['date and time'] = pd.to_datetime(df['date and time'])

# Group the DataFrame by date and find the maximum GHI value for each date
df_grouped = df.groupby(df['date and time'].dt.date)['ghi'].max().
reset_index()

# Concatenate the grouped DataFrame with the length of day DataFrame
df_grouped = pd.concat([df_grouped, df_lod], axis=1)

# Round the 'ghi' values to two decimal places
df_grouped['ghi'] = round(df_grouped['ghi'], 2)

# Reindex the DataFrame with specific columns
df_grouped.reindex(columns=['date and time', 'ghi'])

# Rename the 'date and time' column to 'date'
df_grouped = df_grouped.rename(columns={'date and time': 'date'})

# Save the updated DataFrame to a new CSV file without the regression
df_grouped.to_csv('GHI_updated_no_regression.csv', index=False)

# Scatter plot of 'date' vs 'ghi' to visualize the total irradiance over
time
plt.scatter(df_grouped['date'], df_grouped['ghi'])
plt.title('Total Irradiance of Venice for 2023')
plt.xlabel('Date')
plt.ylabel('Total GHI')
plt.xticks(rotation=45)  # Rotate x-axis labels for better readability
plt.tight_layout()  # Adjust layout to prevent clipping of labels
plt.show()  # Display the plot
```

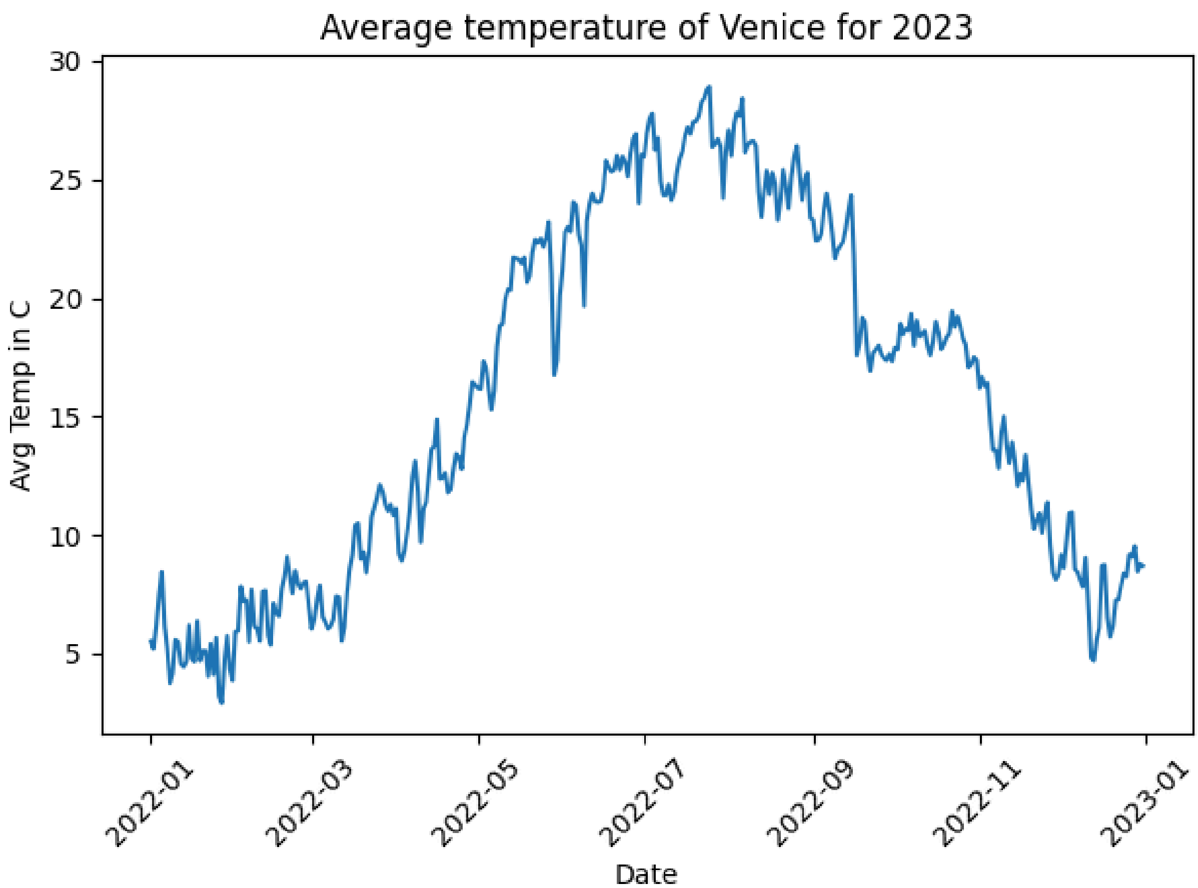
Output for GHI.py



AIR_TEMP.py: for reading the Air Temperature database

```
# Importing necessary libraries
import pandas as pd
import matplotlib.pyplot as plt

# Reading the CSV file into a DataFrame
df = pd.read_csv('AIR_TEMP.csv')

# Dropping the 'period' column from the DataFrame
df = df.drop('period', axis=1)

# Renaming the column 'period_end' to 'date and time'
period = df['period_end']
df = df.rename(columns={'period_end': 'date and time'})

# Converting the 'date and time' column to datetime format
df['date and time'] = pd.to_datetime(df['date and time'])

# Grouping the DataFrame by date and calculating the mean of 'air_temp'
df_grouped = df.groupby(df['date and time'].dt.date)['air_temp'].mean()
      .reset_index()

# Reindexing the columns of the grouped DataFrame
df_grouped.reindex(columns=['date and time', 'air_temp'])

# Renaming the 'date and time' column to 'date'
df_grouped = df_grouped.rename(columns={'date and time': 'date'})

# Writing the grouped DataFrame to a new CSV file without regression
df_grouped.to_csv('air_temp_updated_no_regression.csv', index=False)

# Plotting the data from the grouped DataFrame
plt.plot(df_grouped['date'], df_grouped['air_temp'])
plt.title('Total Irradiance of Venice for 2023')
plt.xlabel('Date')
plt.ylabel('Avg Temp in C')
plt.xticks(rotation=45)  # Rotating x-axis labels for better readability
plt.tight_layout()  # Adjusting layout to prevent clipping of labels
plt.show()  # Displaying the plot
```

Output for AIR_TEMP.py



PV_tracking.py: using the 2 datasets to produce daily energy production

```
# Import necessary libraries
import pandas as pd
import matplotlib.pyplot as plt
from IPython.display import display

# Read the solar radiation and day length data from the CSV file
df_ghi = pd.read_csv('GHI_updated_no_regression.csv')

# Read the air temperature data from the CSV file
df_temp = pd.read_csv('air_temp_updated_no_regression.csv')

# Drop the 'date' column from the temperature dataframe
df_temp = df_temp.drop('date', axis=1)

# Concatenate the solar radiation and temperature dataframes along the columns
df_pv = pd.concat([df_ghi, df_temp], axis=1)

# Calculate energy output using a formula based on solar radiation,
temperature, and day length
df_pv['energy output'] = (17.11/100) * (((280 * (df_pv['ghi']/1000)) -
      abs(-0.387*(df_pv['air_temp'] - 25))) * df_pv['length_of_day'] / 60 /
      1000)

# Convert the 'date' column to datetime format
df_pv['date'] = pd.to_datetime(df_pv['date'])

# Group the data by month and sum the energy output for each month
df_pv = df_pv.groupby(df_pv['date'].dt.month)['energy
output'].sum().reset_index()

# Save the processed data to a new CSV file
df_pv.to_csv('pv_out.csv', index=False)

# Plot a bar chart showing energy produced per month
plt.bar(df_pv['date'], df_pv['energy output'])
plt.title('Energy Produced by 280Wp rated PV panel per month in Venice')
plt.xlabel('Date')
plt.ylabel('Energy Produced in kWh')
plt.xticks(rotation=45)
plt.tight_layout()
plt.show()

# Plot a line chart showing cumulative energy production over time
plt.plot(df_pv['date'], df_pv['energy output'].cumsum())
plt.title('Total Energy produced by 280Wp rated PV panel in Venice, 2023')
plt.xlabel('Date')
plt.ylabel('Total Energy Produced in kWh')
```

```
plt.xticks(rotation=45)
plt.tight_layout()
plt.show()
```

Output for PV_tracking.py