Chalmers University of Technology

Solar Energy: from Photons to Future Societal Impact

Transparent Photovoltaic Windows

An overview of cadmium telluride transparent photovoltaics to assess the future potential of transparent photovoltaic windows

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Abstract

The rapid development of photovoltaics has inspired new innovative ways to capture the sun's energy. One such measure, that has proven benefits but has remained a niche and whose future potential is relatively unknown, is transparent photovoltaics (TPV). Current research is mainly focused on integrating windows with TPV since it could lead to a significant increase of available area for photovoltaics, especially in dense cities.

This project provides an overview of TPV windows utilizing CdTe thin films in order to assess the future potential of TPV windows, identify barriers that hinders the technology from diffusing and determine potential environmental impacts associated with production and utilization.

The project concludes that TPV windows exhibits great potential regarding energy output in climates with high solar radiation. Development is rapid with different materials and techniques looking like viable options in the future. However, the short life-span and the challenge to maintain efficiency in larger windows hinders the technology's diffusion. There are also signs of potential environmental impacts for CdTe TPV in the form of toxicity windows but further research is required to draw weighted conclusions.

Contents

1 Introduction

As population and overall consumption increases all over the world, so does the demand for energy [1]. This global pressure means it is more important now than ever to transition away from fossil fuels towards more renewable sources of energy. The only renewable energy source that has shown the capacity to cover any possible level of human consumption is solar energy [2]. It is only recently that solar cells have been utilized in a larger scale, due to an increase in conversion efficiencies and a decrease in manufacturing costs. This has led to a widespread deployment of photovoltaics such as building-attached solar photovoltaics on roofs and on the exterior walls of buildings. However, as the technology is becoming cheaper and more efficient, research is now being devoted to find new ways to use photovoltaics that would help capture more of the potential solar energy.

1.1 Development and Applications of Transparent PV

One measure to utilize more of the potential solar energy is transparent photovoltaics (TPV). TPV open up new possibilities as it can be applied on surfaces that also require some form of transparency [3]. Current research is mainly focused on the possibility of generating energy by integrating windows with TPV. This would significantly increase the available area for photovoltaics in dense cities as glass skyscrapers are now becoming more common, on which building-attached solar photovoltaics are less desirable. Considering that buildings consume large amounts of energy (41% of the total energy consumption in the US), TPV could work as an innovative solution to better meet this demand [4]. TPV may also be applied on other structures or products such as green houses, vehicles or mobile phones where smaller variants of TPV have the possibility to continuously power essential parts of the system [3].

The development of TPV has been thoroughly investigated but the technology remains as a niche and its future potential is still relatively unknown, despite the proven benefits. As higher efficiency comes with the cost of lower transparency, TPV are yet to perform at high enough standards to be used commercially. To make the necessary improvements, many aspects such as choice of material, manufacturing methods, potential risks, social and environmental barriers has to be acknowledged. This study aims to investigate such aspects and review the future potential of TPV as a viable option to provide renewable energy.

1.2 Aim of the Project

The general questions this report aims to answer are:

- What is the future potential of TPV windows with regards to supplying renewable energy?
- What challenges is the technology facing that hinders it from diffusing on a larger scale?
- What are the environmental burdens associated with the production and utilization of TPV windows?

2 Technological Background

In this chapter, the working principles of a photovoltaic cell is presented, followed by a more detailed description of band gap due to its importance when it comes to TPV. Lastly, the level of absorption in TPV and its effect when implemented in windows is described.

2.1 Principles of a Photovoltaic Cell

The function that every photovoltaic cell has to fulfill is to convert sunlight into electricity [5]. A scheme over such cell is shown in Figure 1. Conversion of sunlight into electricity is done with the use of materials that can conduct electricity, so called, semiconductors.

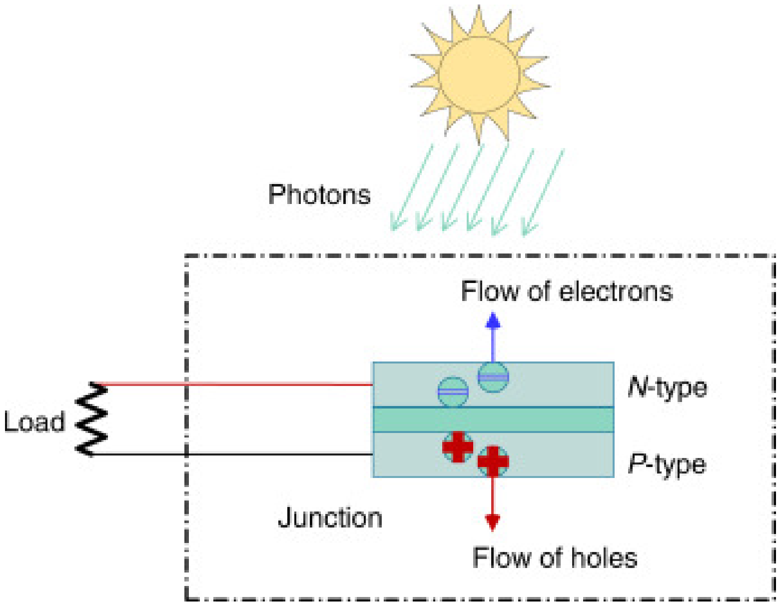


Figure 1: *A scheme showing the working principles of a PV cell [6].*

When photons with a certain energy come in contact with a semiconductor, a flow of electrons in such semiconductor may occur [5]. The photon's energy will be absorbed by the semiconducting material from which an electron will be ejected. The ejected electron will leave a hole which will be subsequently filled up by surrounding electrons. This is called p-n junction and semiconducting material in which holes will be created is of p-type while the one where electrons are in excess is of n-type. The described process is called photovoltaic effect and a device in which photovoltaic process occurs, is called a photovoltaic cell. In order to create a current by this cell the ejected electrons will be directed in one direction [7]. Since the energy absorbed from a photon will cause the electron ejection, the amount of absorbed energy will be proportional to the amount of created current. This means that the current coming from a photovoltaic cell will be varying, instead of being constant.

2.2 Bands and Band Gaps

A single, isolated atom has electrons which occupy atomic orbital with discrete energy levels [8]. When a molecule (consisting of two or more atoms) is formed, atomic orbitals of the atoms overlap and hybridize. The same goes for larger number of atoms, N, that are brought together and form a solid. One example of such a solid is crystal lattice. Discrete energy levels of N number of atoms will split into N levels possessing different energy. A real macroscopic object, piece of a crystal for instance, consist of $\approx 10^{22}$ number of atoms, which also means a large number of atomic orbitals. Thus, these atomic orbitals are spaced closely in energy with a difference between adjacent levels of $\approx 10^{-22} eV$. Since the difference is so small, the closely spaced atomic orbitals can be seen as a continuum, also called an energy band. Two different energy bands can be distinguished, a valence and conductive band. Valence band consist of occupied by electrons hybridized atomic orbitals while conductive band of unoccupied ones. Electrons of inner atomic orbitals do not contribute to a large extent to band formation due to their poor overlap with inner orbitals of other atoms.

A band gap is defined as a leftover range of energy which is not covered by either valence of conduction bands due to their finite width [8]. The width of a band is highly dependent upon the overlap degree between adjacent atomic orbitals in a crystal. Therefore, the band gap of a certain material can be determined by its molecular (crystallographic) structure. The arrangement of atoms in crystalline atomic structure allows for classification of materials as insulators (non-conducting), conductors or semiconductors [9]. Mentioned classification arises from the fact that the size of a band gap is material specific and will therefore differ between different materials. This is schematically shown in Figure 2, where *metal* represents a conductor.

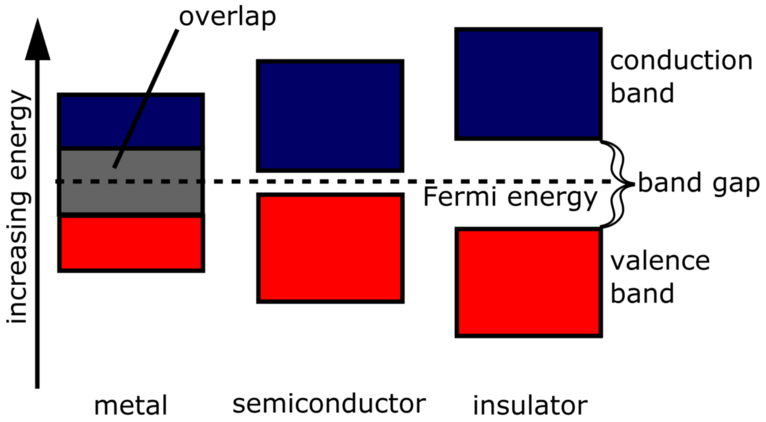


Figure 2: *A scheme showing differences in band gap sizes between conductors, semiconductors and insulators [9].*

The valance band, represented by the red box in Figure 2, is the outermost layer that electrons in an atom can occupy when they are not excited [9]. The conduction band, represented by the blue box in Figure 2, is the lowest layer or band that electrons can jump to when they get excited. Band gap is also defined as a distance between the valence band and the conduction band, i.e. the minimum energy required to excite an electron from valence band to conduction band [9]. The excitation will cause a material to become conductive. As can be seen in Figure 2, for a material that is a conductor, valence and conduction bands are overlapping, which allows for continuous electron flow. For a semiconductor there is a band gap between conduction and valence bands, which hinders electrons from the valence band to move freely to the conduction band, which is the case in conductors. In order to obtain a conducting material with a band gap present, a certain energy - determined by the band gap - needs to be provided in order to excite an electron from valence band to conduction band. Insulators on the other hand, have large band gap which causes them to be unable to become conductive.

2.3 Solar Energy and Ideal Band Gap

Energy coming from the sun, called electromagnetic radiation, spreads from X-rays (with short wavelengths) up to radio waves (long wavelengths) [10]. The irradiance, i.e., the radiant flux that reaches a surface per unit area, is in UV, Visible and Infrared regimes, as presented in Figure 3. From Figure 3, it can be approximated that the high values of irradiance spans over photon wavelength of ≈ 400 to 1200 nm which corresponds to photon energy of ≈ 1.0 to 3.1 eV. The highest irradiance of photon energy though spans over ≈ 1.0 to 2 eV.

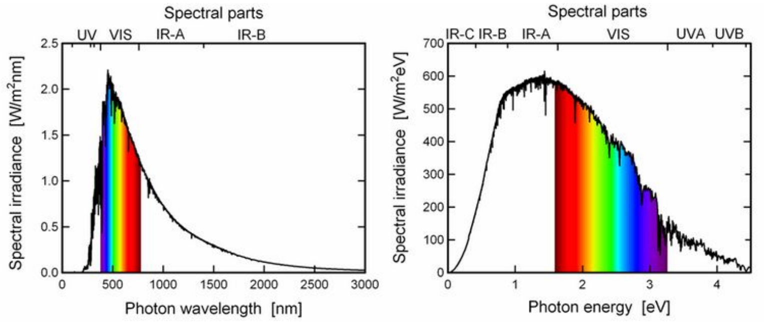


Figure 3: *Spectrum of Solar Radiation [10].*

A semiconductor that is used in a solar cell should absorb as much of the electromagnetic radiation as possible which means that a band gap of lower values of eV is more desirable [11]. On the other hand, in order to have a large built-in voltage, it would be more desirable to have a larger band gap. By compromising these two requirements, the concept of an ideal band gap for a solar cell has been introduced. This concept assumes a band gap of 1.0 to 1.7 eV as being ideal for an effective semiconductor. The ideal band gap for a certain solar cell is therefore definied as the value corresponding to the maximum absorption of solar energy for this particular solar cell.

2.4 TPV for Window Applications

PV windows absorber design can be categorised into low- and high-visible light transmittance (VLT) regimes [12]. VLT=1 means there is total transperancy where 100% of sunlight has been transmitted through a cell. The low-VLT regime corresponds to transparency of less or equal to 0.3. Therefore, low-VLT regime absorbers would result in semitransparent PV windows in which absorber materials like silicon (Si), perovskite or cadmium telluride (CdTe) could be used. In order for these materials to become semitransparent, they have to be thinned or patterned. Ideal band gap for such absorbers would be ≈1.35 eV.

The second absorber category, high-VLT regime, corresponds to transparencies higher than 0.3 [12]. This regime has the ideal band gap value increasing from 2 to 3 eV as VLT increases. Moreover the color of the cell goes from yellow through orange to red. Due to the fact that transparency is reduced for the sake of efficiency and vice versa, practically all TPV has some form of decreased visibility. To facilitate, this report will from now on also include semitransparent PV when referring to TPV.

3 Materials for TPV

There are several types of materials available to produce TPV such as crystalline silicon (c-Si), gallium arsenide (GaAs), cadmium telluride (CdTe) and much more other variants that come in form of thin films [4]. Due to their reduced thickness, thin films are a suitable choice of material for TPV since they increase the transparency while maintaining high efficiency. A thin film is constructed of a thin semi-conductive layer that has a solid backing material which results in lesser quantities of material needed for production [5]. The thickness of the film usually ranges from a few nanometers to tens of micrometers. Some thin film technologies are already commercial, while others are emerging and still in an experimental state. In the following sections, two commercial thin films and two emerging thin films will be described to provide an overview of different material options for TPV.

3.1 Commercial Thin Films

3.1.1 Silicon Thin Films

Silicon is the most common material used in solar cells overall, and also the most common material in thin films [4]. This is largely due to the material's non-toxicity and abundance in nature. When used in thin film PV, the silicon can be amorphous (a-Si) or crystalline (c-Si). The c-Si solar cells can be used to create TPV for windows. However, the cells themselves are not transparent, they are instead placed in a pattern that makes the window act more transparent while maintaining an efficiency of 16-22% [13]. The a-Si thin films on the other hand can be directly utilized as a TPV, with an efficiency of up to 12%.

3.1.2 Cadmium Telluride Thin Films

Cadmium telluride (CdTe) is currently the second most used material in solar cells, after crystalline silicon [14]. Due to its ideal bandgap that is tunable from 1.4 to 1.5 eV, thin film based CdTe has a large absorption coefficient that is optimal for generating electricity. The results from a previous assessment of CdTe as TPV utilized in windows showed efficiencies ranging from 6% to 22.1% [15] with a transparency between 7% [16] and 43% [17]. Even though manufacturing of these solar cells is cheap thanks to high throughput methods, the rarity of tellurium and toxicity of cadmium increases the overall production costs and makes the solar cells subject to strict recycling policies [18, 19].

3.2 Emerging Thin Films

3.2.1 Perovskite Thin Films

Perovskite solar cells absorb light in the near infrared region of the electromagnetic spectrum [5]. This means that the visible light passes through these cells, making them semi- or even fully transparent. Layers of metal oxide materials such as Al_2O_3 and TiO_2 are typically used in these type of solar cells to achieve high efficiency. A material that could withstand requirements of both high transparency and high efficiency is for example methyl ammonium lead halide perovskite. The efficiency of perovskite solar cells can reach up to 17% while maintaining a transparency of 60% [20]. One technique that can be used in order to achieve thin (less than 40 nm) solar cells is perovskite evaporation deposition [5]. The big disadvantages of the perovskite solar cells are the high cost of the materials and the low stability.

3.2.2 Organic / Polymer Thin Films

Polymer solar cells (PSC) uses conjugated polymers as a light absorber material [21]. These polymers serves both as electron donors and acceptors and/or contribute to the hole transport. The technology has been studied for a long time and the highest efficiency of PSC reported is approximately 17% [22]. Despite the high efficiency, PSC still manage to achieve a transparency of more than 50%, [23], while some sources have recorded a transparency of up to 66% [24]. PSC are continuously developing and current research is investigating new and more efficient polymers in order to achieve higher efficiency [21].

4 Manufacturing and Building Integration

In order to investigate the different aspects revolving the potential of TPV windows more thoroughly in the following chapters, one material was chosen to be assessed more in depth, namely CdTe. The low complexity of CdTe makes it easy to manufacture and suitable for production at industrial scale [14]. Barman et al. [16] states that CdTe has enormous potential in building integrated photovoltaic (BIPV) applications but lacks available research. These are incentives to study CdTe as a TPV material further as it may become the material in focus when development of TPV windows increases. This chapter presents the manufacturing process of CdTe TPV and the concept of building integration to use TPV in windows.

4.1 Manufacturing of CdTe TPV

4.1.1 Materials

Semi-transparent CdTe PV can be manufactured in different ways. The most common is the one in which these solar cells consist of p-n heterojunction structure [25], i.e., a structure in which in-going materials are conductors with dissimilar band gaps. The structure contains a CdTe layer which is p-doped and matched with an n-doped window layer like cadmium sulfide (CdS) or magnesium zinc oxide (MZO) as a front contact material [25, 26]. The schematic representation of a CdTe TPV is shown in Figure 4.

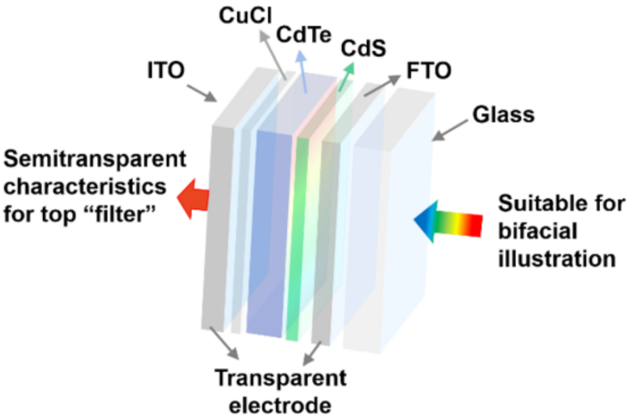


Figure 4: *A scheme showing CdTe TPV [15].*

The growth of CdTe absorber layers is generally performed on top of a conductive oxide layer which also needs to be transparent to allow the sunlight to pass through [25]. Such transparent conductive oxide (TCO) layer is usually tin oxide doped with fluorine (SnO_2:F) or indium tin oxide (ITO) [15, 25, 27]. As a final step, back electrical contact is implemented which involves positioning the entire emitter at the rear of the cell. For CdTe solar cells as a back electrical contact, combination of zinc telluride (ZnTe) and copper (Cu) containing carbon paste is used. In this combination, the ZnTe layer comes prior the paste which places Cu at the rear of the cell. The reason for having Cu in the rear of the solar cells is to achieve a proper hole concentration in the CdTe layer [28]. The thicknesses of the layers that CdTe TPV consists of are for example 400nm for p-doped CdTe leyer and 200nm n-doped CdS leyer [17]. These have been successively manufactured with a transparency of 43%.

4.1.2 Techniques

CdTe TPV that are used in windows are manufactured using different deposition techniques. Examples of such are sputtering, chemical spray pyrolysis, electrodeposition, as well as vapor-transport deposition (VTD) and close-spaced sublimation (CSS) [25, 29]. CSS and VTD are the most common techniques and will therefore be described in more detail.

CSS is a deposition technique that is typically used for manufacturing thin film CdTe solar cells due to its large-scale manufacturing suitability and production of high-efficiency thin films [29, 30]. In Figure 5 the CdTe CSS chamber is presented.

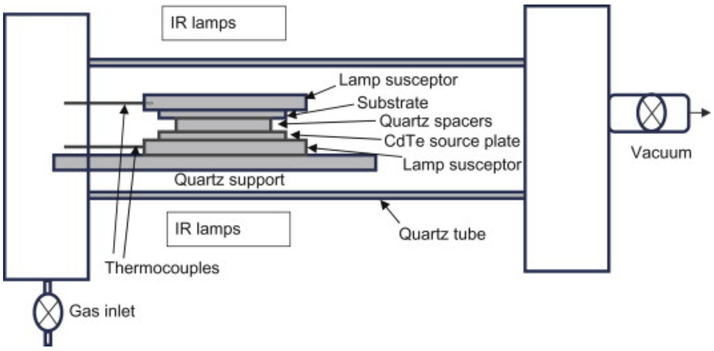


Figure 5: *A scheme showing a CdTe close-spaced sublimation chamber [30].*

As a first step in this technique, a CdTe source plate from a CdTe powder source of high-purity needs to be obtained [30]. This is done by a sublimation process. Next, a CdS-coated substrate, denoted *substrate* in Figure 5, is positioned in close vicinity to the CdTe source plate, separated by a quartz spacer. Lamp susceptors are used in order to absorb optical radiation from the lamps and allow for easier control of substrate temperature. Then, a heat treatment, so called hydrogen annealing, of CdS layer has to be performed. This is done at ≈ 400°C in the presence of $CdCl_2$ in order to decrease oxygen-induced defects and achieve cleaner surface for CdTe deposition [30, 31]. The temperature of the substrate is then lowered to 200°C and flows of oxygen gas and argon or helium are released into the sublimation chamber. The temperature of the CdTe source plate and the CdS-coated substrate is increased to over 600°C. Sublimation of the elemental gases from the source plate occurs followed by their recombination on the substrate surface of lower temperature than that of the CdTe source plate. In this way, a thin film of CdTe is deposited onto a CdS-coated substrate.

VTD is a thin film production technique with very high deposition rate which makes it suitable for high-throughput industrial manufacturing of CdTe thin film solar cells [30]. In this technique hot vapor saturated with Cd and Te is transferred onto a substrate surface of lower temperature. This causes a film of CdTe to form. A schematic representation of the CdTe deposition process is presented in Figure 6.

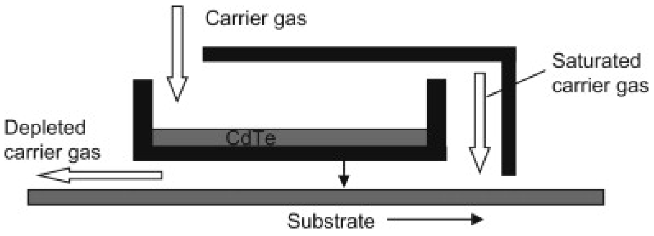


Figure 6: *A scheme showing the working principle of vapor-transport deposition technique [30].*

Gaseous Cd and Te can be generated from elemental sources by sublimation technique [30]. By adjusting parameters like chamber pressure, gas flow rate or temperature of the gases, control over the delivery rate of the heated gases can be achieved. VTD has been also compared to CSS and according to Petti et al. [30], this technique shows bigger improvements on an industrial scale.

4.1.3 Alternative Materials

During the manufacturing process of CdTe TPV, an important step is to anneal the CdS layer in the presence of $CdCl_2$ [31]. The use of $CdCl_2$ is however controversial due to two main factors. It is expensive but also demonstrates a potential risk to both environment and operators during the manufacturing process. This is because toxic cadmium ions being water-soluble. Major et al. [31] demonstrated that there is an alternative material which can be used as a replacement and does not show environmental or health concerns. $MgCl_2$ in a non-toxic and less expensive substitute candidate. It has similar impurity profile for Cl and O, elements important for p-doped CdTe. Moreover, the results of the study be Major et al. [31] show that $MgCl_2$ can be incorporated into the existing manufacturing process, without the need of a re-design, and behold the cell performance. Possible source of $MgCl_2$ is sea water where it can be recovered.

4.2 Building Integration

The concept of building-integrated photovoltaics (BIPV) assumes an integration between the materials used for PV and the overall appearance of the building [32]. This concept is important because it establishes a relationship between materials with different properties, both those used to construct buildings and those that enable the production of renewable energy.

In order to integrate TPV in windows, the elements used for its construction must not only have properties that allow for energy production, but also have the same properties as glass used for windows. These properties include, for example, protection against wind or rain, but also protection against noise and heat loss. An example of CdTe TPV integrated into a building envelope is presented in Figure 7.

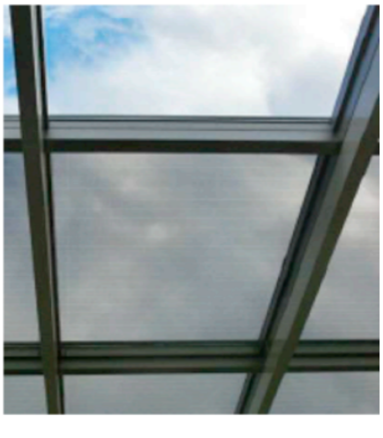


Figure 7: *Intergrated CdTe TPV [32].*

5 Performance and Cost Analysis

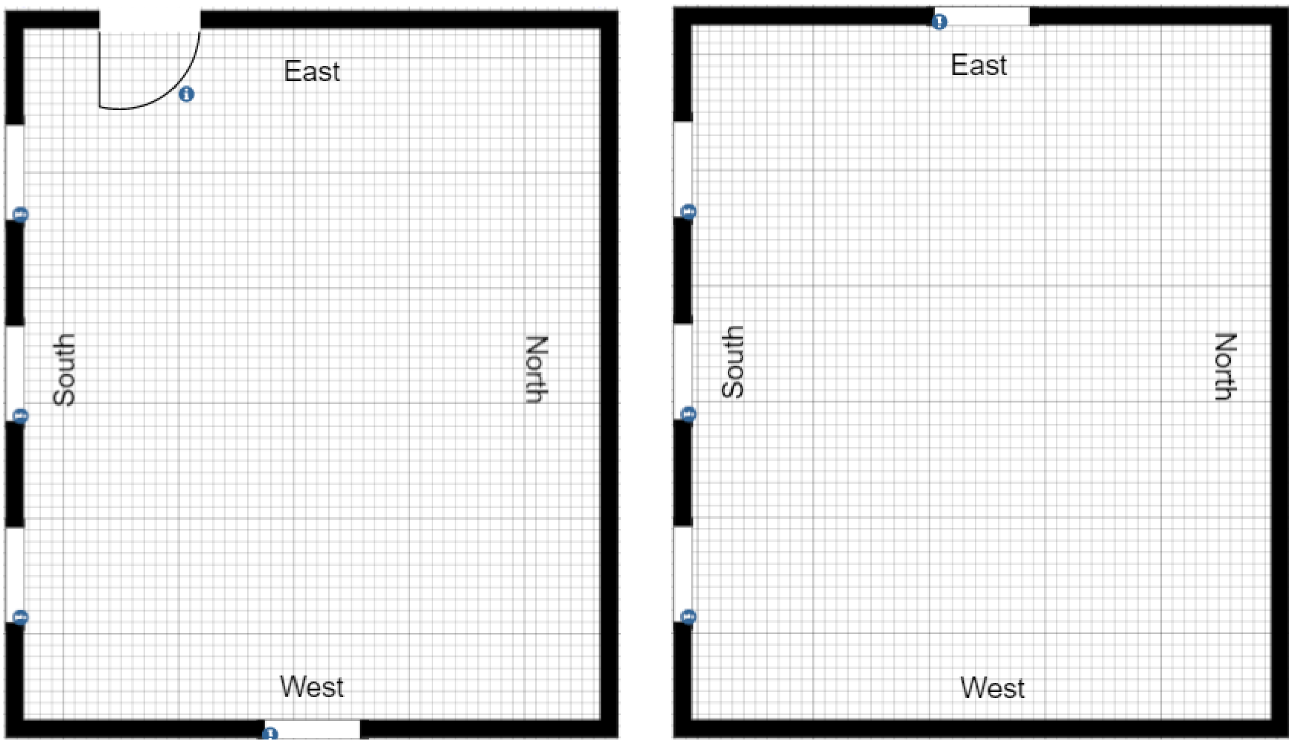
To get an understanding of how much energy that can be generated as well as how cost efficient CdTe TPV windows are, four different theoretical examples with various parameters were constructed to test their performance. The following chapter showcases how these tests were constructed, the limitations and the final results.

5.1 Method

For this analysis, a CdTe TPV with 6.04% efficiency and 32.7% transparency was chosen. This is the only CdTe TPV in the assessment by Barman et al.[16] which lies in the high-VLT regime and thus exhibits characteristics more similar to a regular window. The life span of CdTe TPV was assumed to be approximately the same as CdTe PV. This life span is estimated to be from 20 up to 30 years [33, 34]. The total cost of installing a TPV window is considered to be 9700 kr/m^2 [35]. The estimated cost is taken from a review article from 2015 [35], that in turn quantifies costs based on an article looking at TPVs in Italy, from 2011 [36].

The CdTe TPV windows were implemented in two different type of buildings which were placed in two different environments to investigate how the parameters affect the performance of these windows.

The first building is an average sized villa, presented in Figure 8, where six TPV windows are installed facing South, one facing East and one facing West. Each window has an area of 1 m^2 and is positioned with an angle of 90°. An average size villa that does not utilize electricity as a heating source consumes 5000 kWh/year [37].



(a) Level 1.

(b) Level 2.

Figure 8: A scheme showing an average size villa with 8 TPV windows installed facing East, West and South.

The second building is a commercial high-rise building, roughly 100 meters tall and 30 meters wide, with four equally sized perpendicular facades and a window-to-wall ratio of 60%. A scheme over such high-rise building is presented in Figure 9. All windows facing South, East and West would be installed as TPV windows, resulting in a TPV window area of 5400 m^2. Regarding installation costs, a mass discount would most likely be offered for a project such as this. For this example, a discount of 30% was chosen. For public buildings, the average electricity consumption is 111 kWh/year per square meter [38]. For this building, which has a square footage of 38,000 m^2, the total electricity consumption is 4,218,000 kWh/year.

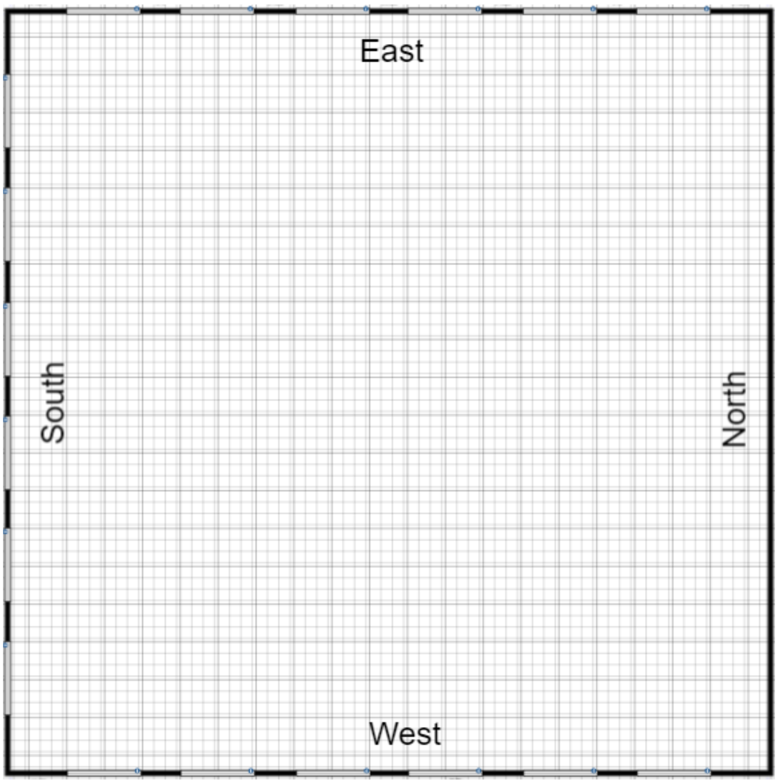


Figure 9: *A scheme showing a high-rise building with TPV windows installed facing East, West and South.*

The two buildings were first placed in Gothenburg where solar radiation is rather low at 1062 kWh/year [39], and the average cost of electricity in the region is 83.86 öre/kWh (see Appendix A). The buildings were then tested in Los Angeles, where solar radiation can reach up to 2500 kWh/year [25], and the average cost of electricity in 2022 was 259.17 öre/kWh (See Appendix A). The azimuth change was studied in both areas to calculate how the efficiency depends on which direction the windows are facing. The calculations are presented in Appendix B.

5.2 Limitations

Not only do TPV windows generate energy, they also save energy by reducing the need for cooling in buildings situated in warm climates [32]. Similarly, TPV windows increase the need for heating in buildings situated in colder climates. These types of additional energy savings and consumption are not accounted for in this analysis. Another factor that would affect the results but is not included in the calculations, is dirt accumulating on the windows, blocking the solar cells from being irradiated by sunlight thus lowering the efficiency. The extent to which these factors influence the results is difficult to pinpoint and would require more extensive research with practical studies to get an accurate estimation.

5.3 Results

The results from the calculations, illustrated in Table 1, show that TPV windows utilized in Los Angeles generates a significantly higher amount of energy compared to the TPV windows placed in Gothenburg. There is also a considerably large difference in years to reach payback depending on where the buildings are situated. The results also show that TPV windows installed in a villa will be able to cover a larger amount of the building's total energy consumption, compared to TPV windows installed in high-rise buildings.

	Total TPV window energy output (kWh/year)	**Share of energy consumption covered by TPV windows**	**Total amount saved by utilizing TPV windows (SEK/year)**	**Years until payback**
Gothenburg				
Villa	342	6.8 %	287	271
High-rise	189 046	4.6 %	163 063	225
Los Angeles				
Villa	682	13.6 %	1 768	44
High-rise	401 277	9.8 %	1 069 703	34

Table 1: Performance of CdTe TPV windows based on the four examples.

6 Societal Drivers and Challenges

To get a more complete understanding of the potential of CdTe TPV windows, this section investigates drivers and challenges that might affect the development and diffusion of CdTe TPV windows. Relevant literature was gathered to assess how CdTe TPV windows might affect occupants in the buildings. To learn more about the interest of stakeholders, a semi-structured interview was conducted with a person who will be referred to as Jane for the sake of anonymity. Jane is working for a deep-tech company that is currently developing TPV and is thus knowledgeable in the field. This company does not specialize in CdTe TPV but Jane provided useful insight regarding the general development of TPV.

6.1 Stakeholder Interest

There are not only several different types of TPV technologies, as seen from chapter 3, but also many different companies developing and producing them all over the world. Some of the leaders in the field are Onyx Solar in Spain, Brite Solar in Greece and Ubiquitous Energy in USA. During the interview, Jane explains how TPV have been able to advance quickly because of the many companies involved and the heavy focus on R&D. *"There is a pressure on us to move as fast as possible but what we want is to find bigger companies interested like a glass company that can take on the manufacturing processes and do it themselves."*

According to Jane, there is a lot of interest from smaller actors because of the capacity to power smaller appliances at home. However, the future market depends on these larger actors looking to invest in bigger projects. *"We do have a lot of interest from smaller actors but I wouldn't call that a big market, the market is the tall buildings that have such high surface area of windows."*

Jane believes that some of the main challenges that needs to be addressed are the difficulties to manufacture larger TPV and the short life span of TPV windows. *"What we are working on now is to increase the sizes... We can make it transparent but how do we extract that charge from the middle of the window? If you cannot extract it, then it is not as efficient."* Jane estimated that dynamic TPV windows, which can alter its transparency for optimization, will be commercially viable in three to five years from now.

6.2 User Experience

Like any product, TPV windows have to appeal to the "users" who are affected by these semi-transparent windows. Unlike solar panels placed on a building's roof or facades, TPV windows will more directly affect the occupants of the building. This has to be taken into consideration when implementing TPV windows, especially on buildings where there is a high window-to-wall ratio, such as office buildings. Studies have shown that natural lighting in buildings creates a luminous environment in which the occupants experience more satisfaction and higher productivity while also affecting their mood and well-being [40–42]. There is also a correlation between work attitude and the available view from the windows. For a CdTe TPV windows, which has a rather low transparency, natural lighting would decrease and the view would be more limited which could result in negative effects for people in the building.

However, research also shows that an excess amount of sunlight through windows can cause serious problems for the people exposed [42]. Occupants experiencing an uncomfortable glare for longer periods during the day may feel distress and discomfort which later on evolves into physiological symptoms like headaches. TPV windows open up an opportunity to find the optimal sunlight penetration which eliminates the glare while still providing sufficient natural light to enhance the positive effects. The optimal sunlight penetration does however vary with different factors such as the size of the room and the window as well as the position of the window [40]. This requires a purchaser of TPV windows to be more aware of their own conditions and needs before choosing what level of transparency they are looking for in the windows.

7 Environmental Aspects

In the following sections, different environmental aspects regarding CdTe TPV will be presented. CdTe is a chemical compound consisting of the two rare elements cadmium (Cd) and tellurium (Te). Cadmium is a metal that is found mainly as a by-product in other ores, such as zinc [43]. Tellurium is a metalloid, that is mined almost exclusively as a by-product of certain copper ores, where it occurs in low average concentration [44].

7.1 Toxicity

Cadmium is classified as highly toxic by the European Chemicals Agency (ECHA), both to aquatic life and humans [45]. It can be fatal if inhaled, and may cause cancer and damage to organs through prolonged or repeated exposure. This means that people that are working with cadmium in industries such as refining of ores as well as manufacturing of solar cells, might be at risk [46]. Tellurium is classified as potentially harmful to both aquatic life and humans by ECHA [47], although commercial-grade Te is not classified as toxic [48].

According to ECHA, CdTe is classified as very toxic to aquatic life with long lasting effects, and is considered harmful if swallowed, in contact with skin or inhaled [49]. However, as CdTe is a very stable crystalline compound, insoluble in water, it is claimed by several sources that CdTe is much less hazardous than for example cadmium by itself [50–52]. One study mentions that potential ecotoxicity impacts are around 3 orders of magnitude lower for CdTe than Cd [52]. However, more studies are needed in order to be able to draw certain conclusions [50]. Moreover, as mentioned in part 4.1.3, there are manufacturing steps when making CdTe windows that can be more likely to release Cd, such as when annealing the CdS layer in a solar cell with the presence of $CdCl_2$.

7.2 Safety Concerns

There have been concerns regarding the safety of installing windows containing CdTe in buildings, as it has been thought to pose a possible risk to both humans and the environment. There is not a lot of research on CdTe TPVs specifically, however, Fthenakis et al.[53] produced a review article regarding safety for regular thin film CdTe PVs. They came to the conclusions that in the case of fire of CdTe PV, only around 0.05% of the Cd is released into the environment, as most Cd were encapsulated into molten glass. There was an experimental modeling, where the worst case scenario was analyzed, assuming all Cd in the CdTe roof mounted PV were released. This modeling showed, using Gaussian dispersion, that Cd concentrations in the ground level downwind from the solar cells, were below the threshold for concern for human health. Similar research has been done regarding the leeching of Cd from broken panels. No critical increase of Cd in the soil - neither for humans nor the environment - was reported in this case either.

7.3 Availability of Material

According to the US Geological Survey, Te is a critical material [54]. There is not a shortage as of now, as enough Te is mined as a by-product at the moment - the main source is refinement of copper. However, if the demand keeps going up, mining of Te by itself, and not as a by-product might be needed [55]. This is something that could potentially increase both price and environmental impact [56]. The recovery of Te through recycling could become critical. As

CdTe PV have a long lifetime, most of them have not reached their end of life, but when they do there might be an increase in recovered Te[54]. Cd is not classified as a critical material, and enough is mined as by-product to satisfy the demand for the foreseeable future.

7.4 Recycling

As there is little to no information regarding recycling of CdTe TPV, information regarding recycling has been collected for conventional non-transparent CdTe PV. In a literature review by Maani et al [57], the recycling process of CdTe was investigated. The authors looked into the energy needed in order to recycle the different materials in the solar cells by considering different types of recycling processes and comparing them to the production of CdTe using virgin material. The results show that in general, the recycling process has little impact on the life cycle of the PV, contributing only to around 3-4% according to LCA results. Regarding choice of the recycling method, thermal-based methods performed better than both mechanical and chemical methods, in terms of environmental impacts. Finally the article suggested that some materials should be prioritize in recycling due to their high environmental and economic benefits. These materials in CdTe PVs are Te, Cu and glass.

8 Discussion

In this chapter, methodological choices and results are discussed a long with other findings. Furthermore, a comparison between CdTe TPV and other TPV is made.

8.1 Performance and Cost

The results from the performance and cost analysis indicate that CdTe TPV windows have great potential when it comes to supplying energy in locations with high solar radiation, such as Los Angeles. However, considering the life span of the TPV windows, none of the windows would last until the payback back period. This might be crucial for home owners looking to make an investment. Another factor that greatly affects the payback period is electricity prices. One of the reasons for the significantly shorter payback period in Los Angeles is the high electricity prices. If the analysis were performed using a different area with similar solar radiation but lower electricity prices, the results would be very different. The base for calculating the cost of installing solar cells, is also based on an article over ten years old, which might have impacted the results as well. However, the reason for choosing this article is because there is a lack of information available.

It should be noted that the energy saved from reduced cooling, which was not included in the calculations, can have quite a large effect on the results. This is especially true for the case of CdTe TPVs since they low transparency prevents a lot of heating coming from the sun. This means that the CdTe TPV windows most likely perform better in practice than the results indicate. It should also be mentioned that the choice of CdTe TPV for the analysis is on the lower end regarding potential efficiency for this material. If a CdTe TPV with higher efficiency was chosen instead then, evidently, the performance would increase and the payback period decrease.

8.1.1 Energy Payback

Many articles on the topic of performance of solar panels look into Energy Payback Time (EPBT) and/or Energy Return on Energy Invested (EROI) [58, 59]. EPBT approximate how long the PV system must be in use, before the energy invested in it throughout its estimated life time is recovered. EROI estimates a ratio of energy returned to society to the energy necessary to produce that energy. These two metrics are the two most commonly used to measure energy performance of technologies. In this project, neither EPBT or EROI was calculated, but it could be valuable to do so in further studies. A cost analysis can provide important information, but it is also dependent on the current economy. EPBT and EROI on the other hand, measures energy efficiency, which will not be as affected by the changes in economy. It can therefore be an easier way to compare the performance of one technique to another.

8.2 Environmental Aspects

In chapter 7 the environmental aspects regarding CdTe TPV were considered. It seems that even though Cd is a highly toxic material, the use of CdTe TPV windows should not pose a safety risk to either humans or the environment, even in case of breakage or fire. However, the information is based on studies covering conventional CdTe PV, as data for CdTe TPV is lacking. There might therefore be a risk that CdTe TPVs mounted as windows could pose a safety hazard. For example, in case of a window breaking, the material would likely end up both inside and outside the building, which could potentially give another result.

Further, the result showed that the manufacturing of CdTe can cause a health risk for those working in the vicinity, as the Cd in this stage is not yet encapsulated in the stable formation of CdTe. Some processing steps could potentially be altered in order to increase safety, such as using $MgCl_2$ instead of $CdCl_2$ when annealing the CdS layer in the solar cells. However, Cd would still pose a potential risk for those working with refining the ores, and potentially also for those working with recycling the solar cells.

Lastly, the availability of material and recycling was covered. The results showed that in case of an increased demand, there could be a shortage of in particular Te, which could cause both price and environmental impact to increase. The recycling of CdTe PV should therefore be focused on recovering in particular Te, but also Cu and glass, as this will give the highest environmental and economic benefits. The recycling of CdTe PV are still low, but as more and more PV reach their end of life, the recycling will likely increase - especially if the demand for Te goes up.

8.3 Comparing CdTe TPV to Other TPV

When it comes to comparing the efficiency of the commercial thin films for window application, CdTe TPV seems to be a good competition for silicon based PV. While c-Si PV have their maximum efficiency between 16-22%, CdTe TPV can reach to similar values, 22.1% at most. The high efficiency of CdTe PV is a trade-off though, because it results in lower transparency. For window integration, it is rather more desirable if the transparency is kept at high level so that more of a day light would be able to pass through. Higher transparency could be reached with the help of the emerging thin film PV, perovskite or polymer thin films for instance. Their transparency reach up to 60 and 66% respectively, which is almost twice that of CdTe TPV. On the other hand, their efficiency is currently 17% at maximum, which is somewhat lower than the efficiency that could be reached with CdTe TPV.

When it comes to the costs of manufacturing CdTe TPV, they can be kept at a low level due to high-throughput methods. This is something that is desirable especially for home applications, because more people would be able to afford them and install TPV windows in their houses. However, low cost should not be treated as the only factor that drives the potential for home application of CdTe TPV. Other factors like awareness of materials and techniques used in manufacturing are also significant, since higher demand for CdTe TPV would mean more cadmium and tellurium, rare earth elements, being in use. Comparing to silicon based PVs, the problem of material availability is more urgent since silica is a more common element on Earth compared to Cd and Te. Therefore, CdTe TPV of high efficiency would be more desirable in windows applications so that they could be used in an effective way.

9 Conclusion

TPV windows exhibits large potential as a new and innovative way of utilizing photovoltaics. Development is well on its way where high efficiency and transparency are linked to emerging technologies utilizing materials such as perovskite thin films and polymer thin films. Commercial technologies, such as CdTe TPV, are already showcasing energy outputs that are sufficient to cover a reasonable share of the consumption in buildings situated in climates with high solar radiation. While there is a growing interest from stakeholders, there is still a challenge to develop larger TPV windows and increase their life span, which is essential for the technology to diffuse on a bigger market. There are also signs of potential environmental impacts, mainly in the form of toxicity, related to the extraction and refining of cadmium and tellurium used in CdTe TPV but more studies are required to draw weighted conclusions. Further research should also focus on potential environmental impacts associated with other TPV and their life cycles as the technologies differ and potentital impacts may vary.

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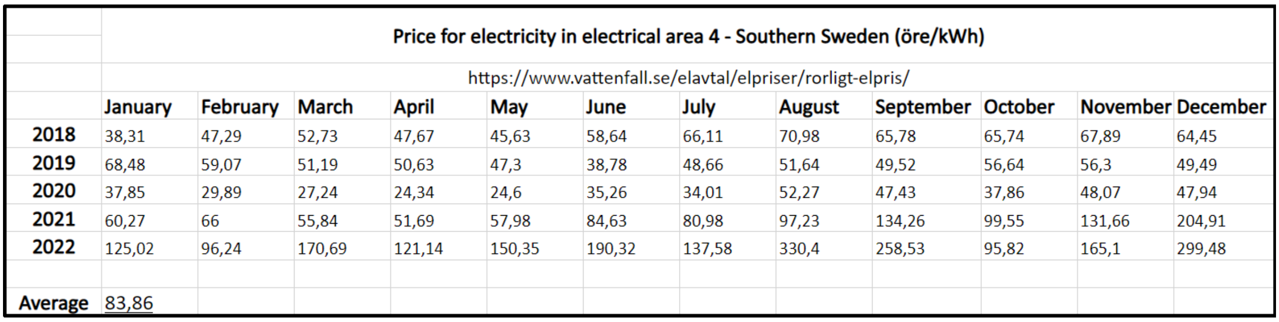
Appendix

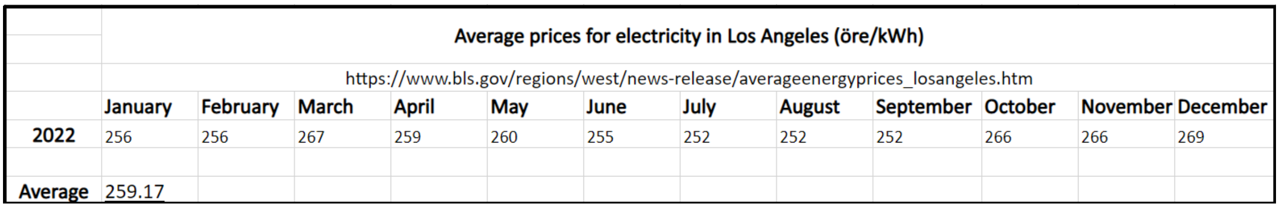
A Electricity prices



Price for electricity in electrical area 4 - Southern Sweden (öre/kWh)

https://www.vattenfall.se/elavtal/elpriser/rorligt-elpris/

	January	February	March	April	May	June	July	August	September	October	November	December
2018	38,31	47,29	52,73	47,67	45,63	58,64	66,11	70,98	65,78	65,74	67,89	64,45
2019	68,48	59,07	51,19	50,63	47,3	38,78	48,66	51,64	49,52	56,64	56,3	49,49
2020	37,85	29,89	27,24	24,34	24,6	35,26	34,01	52,27	47,43	37,86	48,07	47,94
2021	60,27	66	55,84	51,69	57,98	84,63	80,98	97,23	134,26	99,55	131,66	204,91
2022	125,02	96,24	170,69	121,14	150,35	190,32	137,58	330,4	258,53	95,82	165,1	299,48
Average	83,86											

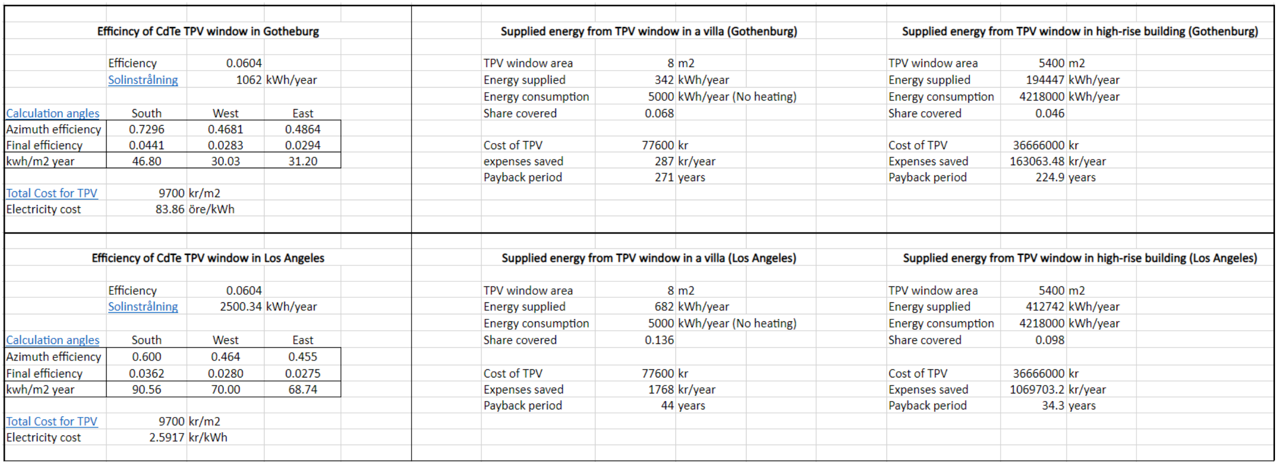


Average prices for electricity in Los Angeles (öre/kWh)

https://www.bls.gov/regions/west/news-release/averageenergyprices_losangeles.htm

	January	February	March	April	May	June	July	August	September	October	November	December
2022	256	256	267	259	260	255	252	252	252	266	266	269
Average	259.17											

B Calculations



Efficincy of CdTe TPV window in Gotheburg

	Efficiency	0.0604	
	Solinstrålning	1062	kWh/year
Calculation angles	South	West	East
Azimuth efficiency	0.7296	0.4681	0.4864
Final efficiency	0.0441	0.0283	0.0294
kwh/m2 year	46.80	30.03	31.20
Total Cost for TPV	9700	kr/m2	
Electricity cost	83.86	öre/kWh	

Supplied energy from TPV window in a villa (Gothenburg)

TPV window area	8	m2
Energy supplied	342	kWh/year
Energy consumption	5000	kWh/year (No heating)
Share covered	0.068	
Cost of TPV	77600	kr
expenses saved	287	kr/year
Payback period	271	years

Supplied energy from TPV window in high-rise building (Gothenburg)

TPV window area	5400	m2
Energy supplied	194447	kWh/year
Energy consumption	4218000	kWh/year
Share covered	0.046	
Cost of TPV	36666000	kr
Expenses saved	163063.48	kr/year
Payback period	224.9	years

Efficiency of CdTe TPV window in Los Angeles

	Efficiency	0.0604	
	Solinstrålning	2500.34	kWh/year
Calculation angles	South	West	East
Azimuth efficiency	0.600	0.464	0.455
Final efficiency	0.0362	0.0280	0.0275
kwh/m2 year	90.56	70.00	68.74
Total Cost for TPV	9700	kr/m2	
Electricity cost	2.5917	kr/kWh	

Supplied energy from TPV window in a villa (Los Angeles)

TPV window area	8	m2
Energy supplied	682	kWh/year
Energy consumption	5000	kWh/year (No heating)
Share covered	0.136	
Cost of TPV	77600	kr
Expenses saved	1768	kr/year
Payback period	44	years

Supplied energy from TPV window in high-rise building (Los Angeles)

TPV window area	5400	m2
Energy supplied	412742	kWh/year
Energy consumption	4218000	kWh/year
Share covered	0.098	
Cost of TPV	36666000	kr
Expenses saved	1069703.2	kr/year
Payback period	34.3	years

C Interview questions

1. Do you believe that the technology you have used in your project has the potential to be efficiently implemented in windows and have you compared it to other technologies/materials used for transparent solar cells?

2. Do you believe transparent solar cells in general will receive more attention and become viable enough to diffuse on a commercial scale?

3. What are the main challenges with developing transparent solar cells as well as getting the technology out on the market?