MASTERARBEIT | MASTER'S THESIS

Titel | Title

A comprehensive survey of vegetation zones, thermal solar, and photovoltaic systems for rooftops in Austria against the background of the Triple Bottom Line Approach.

verfasst von | submitted by

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angestrebter akademischer Grad | in partial fulfilment of the requirements for the degree of

Master of Science (MSc)

Wien | Vienna, 2024

Studienkennzahl lt. Studienblatt | Degree programme code as it appears on the student record sheet:	UA 066 914
Studienrichtung lt. Studienblatt | Degree programme as it appears on the student record sheet:	Masterstudium Internationale Betriebswirtschaft
Betreut von | Supervisor:	Ass.-Prof. Dr. sc. ETH Alexandra Brausmann

Abstract:

Diese Masterarbeit erforscht das Potenzial von ungenutzten Dachflächen in Österreich, denn diese bieten die Möglichkeit für Vegetationszonen (VZs), Photovoltaik- (PV) und thermische Solaranlagen (TS). Die Studie nutzt qualitative Forschungsmethoden, wobei der Triple-Bottom-Line-Ansatz (TBL) als Rahmen dient. Das Ziel ist es H1a: "Welche Anlage der Vegetationszonen, Photovoltaik- und thermischen Solaranlagen (VPSS) wird in Österreich unter Berücksichtigung des TBL-Ansatzes die beste Auswirkung haben?" und H1b: "Inwieweit können die Dächer Österreichs dazu beitragen, die negativen Auswirkungen des Klimawandels durch den Aufbau von VPSS zu reduzieren?" zu beantworten.

Ergebnisse:

- **Die ökonomische Perspektive** zeigt, dass TS-Systeme die meisten Arbeitsplätze generiert. Aufgrund fehlender Daten konnte jedoch der Beschäftigungseffekt von VZs nicht gründlich untersucht werden. TS-Systeme tragen 75% zum Mehrwert Österreichs bei, während PV-Systeme einen Beitrag von 46% leisten. Derzeit ist die Nachfrage jedoch nach PV-Modulen signifikant höher, was zu höheren Einnahmen für PV-Planer und -Installateure führt.
- **Die ökologische Perspektive** zeigt, dass die Biodiversität zunimmt, wenn VZs auf den Dächern implementiert werden und TS-Systeme haben den größten Einfluss auf die Reduzierung von CO_2-Emissionen.
- **Die soziale Perspektive** zeigt, dass VZs die psychologische Gesundheit verbessern könnten, indem sie das Ausmaß von psychischen Erkrankungen wie Angstzuständen oder Depressionen verringern und die physiologische Gesundheit kann sich verbessern aufgrund eines geringeren Sterberisikos, weniger Krankheitstagen, weniger Lärm und eines reduzierten "Urban Heat Island"-Effekts. PV- und TS-Systeme haben im Vergleich hauptsächlich indirekte Auswirkungen auf die soziale Perspektive, da sie möglicherweise ein Gefühl des Wohlbefindens auslösen können. Ein Nachteil von PV- und TS-Systemen ist jedoch die potenziell schädlichen Auswirkungen aufgrund der Verwendung von seltenen Erden und giftigen Materialien.

Die Studie kommt zu dem Schluss, dass VZs die beste Option aus den untersuchten Kriterien des TBL-Ansatzes und weitere Forschung erforderlich ist, um das optimale VPSS-System zu bestimmen.

Abstract

This master's thesis explores the potential of unused rooftop spaces in Austria for the implementation of vegetation zones (VZs), photovoltaic (PV) systems, and thermal solar systems (TS). The study employs qualitative research methods, using the Triple Bottom Line (TBL) approach as its framework and aims to analyze H1a: "What arrangement of vegetation zones, photovoltaic, and thermal solar systems (VPSS) will have the best impact for Austria considering the TBL approach?" and H1b: "To what extent can the rooftops of Austria help reduce the negative impacts of climate change by building up VPSS?"

Findings:

- **The economic perspective** indicates that TS systems generate the most jobs compared to PV systems and VZs. However, due to a lack of data, the employment impact of VZs could not be thoroughly examined. TS systems contribute 75% to Austria's added value, while PV systems contribute 46%. However, the demand for PV modules is significantly higher, leading to a higher revenue for PV planners and installers.
- **The environmental perspective** shows that biodiversity will increase if VZs are implemented on rooftops. TS systems, in contrast, have the most significant impact on reducing CO_2 emissions.
- **The social perspective** reveals that VZs enhance the psychological situation by preventing mental health disorders like anxiety or depression and the physiological health can improve as well due to a lower mortality risk, fewer sick days, less noise, and a reduced UHI effect. PV and TS systems in comparison have mainly indirect effects on the social perspective and result in a sense of well-being. However, the main disadvantage of PV and TS systems is the potentially harmful effects due to the use of rare earth elements and toxic materials.

The study concludes that, based on the TBL approach, VZs are the best option among the evaluated criteria. However, further research is necessary to determine the optimal VPSS system.

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List of Abbreviations

Abbreviation	Definition
AC	Frequency Alternating Current
AI	Artificial Intelligence
BMK	Austria’s Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology
CAPEX	Capital Expenditure
CSR	Corporate Social Responsibility
DC	Variable Direct Current
EAG	Erneuerbaren-Ausbau-Gesetz
EoL	End of Life
ESG	Environmental, Social, and Governance
EU	European Union
OPEX	Operational Expenditure
PV	Photovoltaic
REs	Renewable Energies
SROI	Social Return on Investment
TBL	Triple Bottom Line
TS	Thermal Solar
VZ	Vegetation Zone
UHI	Urban Heat Island
VPSS	vegetation zones, photovoltaic, and thermal solar systems

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Introduction

Climate change and its impact on the whole world intensifies rapidly. The European Centre for Medium-Range Weather Forecasts showed that the temperature from 2023 has changed significantly between 1940 and nowadays (figure 1). The temperature in 2023 has been the warmest calendar year in global temperature data records since 1850 (Climate Change Institute, University of Maine, n.d.). The temperature increases in 2023 was 0.6°C higher than the average temperature between 1991-2020 and 1.48°C warmer than the pre-industrial level 1850-1900. This exceeds the assumption of the IPCC (2018) that stated that the world temperature will rise by 0.2°C yearly. Climate change is impacting the health and livelihood of people, and flora and fauna is endangered. Additionally, the diverse biological ecosystem is at risk while the consequences are not clear and could be irreversible (Knoll et al. 2022).

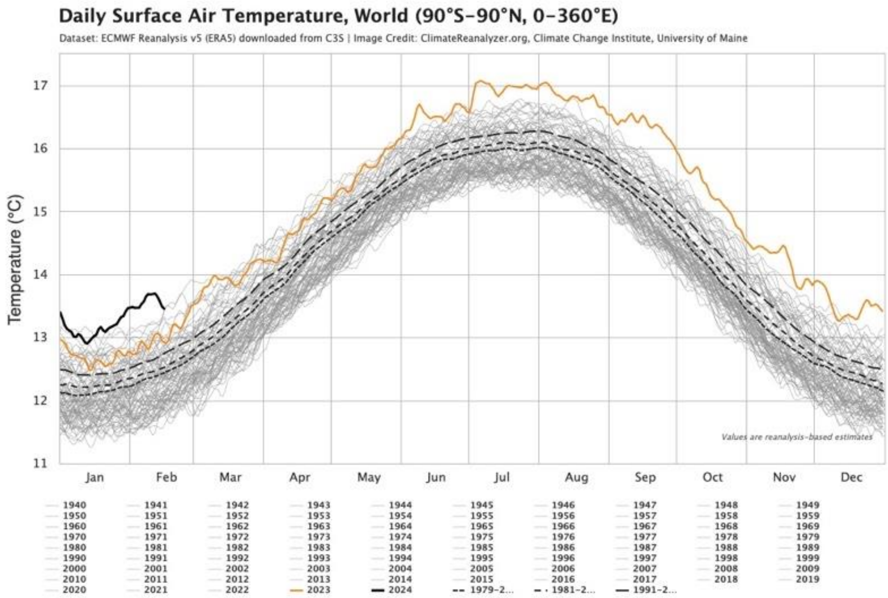

Figure 1: The daily mean surface air temperature between 1940 until today.

(source: Climate Change Institute, University of Maine. n.d. 'Daily Surface Air Temperature'. https://climatereanalyzer.org/clim/t2_daily/?dm_id=world. [Accessed: 24.02.2023].)

Especially in Austria, the rising temperature is higher compared to the worldwide average, and over the last decades heat days occurred about 50% more often in the state capitals of Austria. This has negative consequences, especially on city dwellers' well-being and health (Knoll et al. 2022). Steininger et al. (2020) states that the Austrian budget is supporting with round about €4 billion environmental harmful technologies like fossil imports, however, only €1 billion is invested annually into climate change adaption strategies. This contradicts Austria's goal because it is one of the first European Union (EU) countries that sets a clear guide to be climate neutral by 2040. The aim of Austria's Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology (BMK) is to have 100% renewable energy by 2030. This means that renewable energy capacities (REs) have to grow up to 27 TW_h, including 11 TW_h in PV, 10 TW_h in wind power, 5 TW_h in hydropower, and 1 TW_h in biomass. In addition, 14 topics of the guide have a special focus on cities, constructions, urban open spaces, and green spaces (BMK 2021; Knoll et al. 2022).

Cities in general experience huge problems regarding climate change because heat days will occur more often, there is a strong tendency towards urbanization, and there exists a greater land consumption in Austria compared to other EU countries (Enzi, Formanek, and Peritsch 2020; Grimm et al. 2008; Knoll et al. 2022). Especially sealed surfaces cause many problems. For example, radiant heat is reflected and prevents air exchange (Hutter et al. 2020), and the water retention is disturbed as in natural water cycles around 75% of precipitation water evaporates again in the same place, however, the proportion in cities is only around 5% due to the concrete surfaces (Fechner and Mayr-Ebert 2020). Additionally, the air quality decreases due to less filtering functions of plants (Knoll et al. 2022), and more people die because of heat (Vogl, Sattler, and Grgic 2021).

To address those problems, one of the defined 17 sustainable development goals of the United Nations is goal number 11: "Sustainable Cities and Communities". To achieve SDG 11 and reduce the major risks of climate change this Master-Thesis will examine how rooftops can contribute to the overall aim of being more sustainable. Especially unused spaces of rooftops can provide a big source for different solutions (IPCC 2007). Roofs could be important in cities in terms of climate change because their use would not require any additional areas. In densely populated cities in particular, all spaces are important resources that should not be left unutilized. One possibility to use this area is as a vegetation zone (VZ) because rooftops could provide a space for green areas and plants inherit many advantages regarding the mentioned problems of climate change. Secondly, rooftops could provide a surface for REs like photovoltaic (PV) or thermal solar (TS) systems. PV and TS technologies on roofs are exposed to a lot of sunlight which has a positive effect on the outcome of produced electricity, and those surfaces are already sealed which means that no additional open area has to be built on. Furthermore, it would contribute a major step towards Austria's goal to have 100% renewable energy by 2030.

The thesis will be structured as followed: First, the methodology of this paper will be explained. Followed by the explanation of the Triple Bottom Line (TBL) Approach and the research questions that will be answered. Secondly, Austria's roof area potential is analyzed and explained. Thirdly, the analysis explains the vegetation, photovoltaic, and thermal solar system (VPSS) and discuss which of them will be the most suitable in consideration of the TBL approach. Finally, a conclusion is drawn, and policy implications are given.

The Methodology

To evaluate the topic and analyze every perspective of the VPSS, qualitative research will be conducted. The Triple Bottom Line Approach (TBL) will provide a framework because it analyses the issue from the economy, ecology, and social awareness perspective. The investigation covers a broad literature, and six interviews with Dipl.-Ing. Susanne Formanek, Priv.-Doz. Dipl.-Ing. Dr. Ulrike Pitha, DI Vera Immitzer, Cornelia Daniel, Dr. Klaus Reisinger, and DI Roger Hackstock to get a wide-reaching knowledge.

Dipl.-Ing. Susanne Formanek and Priv.-Doz. Dipl.-Ing. Dr. Ulrike Pitha provide insights for VZs. Formanek is specialized on sustainable building with a focus on energy efficiency and climate change adaptation measures and in 2017 she founded the GRÜNSTATTGRAU innovation laboratory, which is considered as the competence center for VZs on roofs and facades. Pitha is specialized in the fields of structural greening, sustainable construction and vegetation technology and regularly publishes on these subjects. Furthermore, she is also head of the Vegetation Technology and Green Infrastructure working group at the Institute of Engineering Biology and Landscaping while she lectures about these topics at the BOKU University in Vienna.

DI Vera Immitzer helps to shape the political agenda in the field of REs in various committees and has a particular focus on the specialized field of photovoltaics. Aside of this, she has been the managing director of the Austrian Photovoltaic Association since 2019. Cornelia Daniel is the founder of Dachgold e.U. and co-initiator of Tausend und ein Dach. Due to her expertise in the PV industry, she gives guest lectures within the discipline "Sustainability-Entrepreneurship" at the Karl-Franzens-University Graz and was named “Austrian of the Year” in the field of climate in 2020. Therefore, Daniel and Immitzer were interviewed to provide a deeper understanding of PV technologies.

Finally, Dr. Klaus Reisinger and DI Roger Hackstock have been interviewed because of their expertise in the field of TS systems. Reisinger was appointed to the board of IG Lebenszyklus Bau in 2018 while he also founded the company ClimatePartner Austria. He is specialized in climate-neutral building and is also a lecturer at the Pinkafeld University of Applied Sciences in the "Energy and Environmental Management" course. Hackstock in comparison is the managing director of the Austria Solar Association, which brings together all of Austria's leading suppliers of solar thermal systems. These cover over 90% of the Austrian solar market and include 160 solar partner companies. In total, the association represents the interests of more than 200 companies in the solar sector and Hackstock therefore has deep insights into the industry.

The Triple Bottom Line Approach

The TBL Approach will be used as a theory to evaluate which of the VPSS are best to consider for rooftops in Austria. The TBL was coined by John Elkington in 1994 and since then the term has been widely adopted and the approach is approved in practice and research (Boubaker et al. 2018; Lerman et al. 2021; Milne and Gray 2013; UNIDO, n.d.). Traditionally, it was solely important for companies to make profit and to be only financially sustainable. However, Elkington (1998) stated that success cannot be only measured in terms of profit. A company is only successful if it minimizes its negative environmental effects that occur due to the activities the business does, and it also must consider the wellbeing of the people that are affected by its outcome. Therefore, the TBL is used to measure and report the corporate performance against the social, environmental, and economical outcome of a firm (UNIDO, n.d.). The overarching goal of a company should be to be sustainable in terms of "to be the best for the world" instead of "being the most profitable company in the world". The TBL is thus a "genetic code" that aims to sort unsustainable solutions and companies out (Elkington 2018).

Many other models used the TBL approach as its basis. For example, the "Environmental, Social and Governance" (ESG) framework, the "Environmental Profit & Loss approach", the "Social Return on Investment" (SROI), and the "Corporate Social Responsibility" (CSR) program of the UNIDO, and others relate their criteria to the TBL concept. Besides, the approach is also widely used in the financial market to assess sustainability of companies, industries, and institutions on the stock market (Boubaker et al. 2018). This indicates that the approach is already accepted and used by many companies and institutions. To get a better perception of the three criteria, each of them will be explained in detail and placed in the context of this thesis.

The economic criterion also considered as the "profit variable" focuses on the financial factors which are, for example revenue, rentability, and the shareholder value. Profit is termed as a firm's success that mainly depends on the financial performance it achieves for its shareholder (Miller 2020). To study the economic criterion, this thesis will examine how the instruction of each VPSS will affect the employment rate in Austria by trying to analyze how many employees are needed to build and maintain the VPSS. Secondly, the general supply chain of the arrangements will be considered to evaluate if the main profits will be generated within Austria or abroad.

The social criterion places its importance on the “People”. In sustainable states there are fewer conflicts and the focus shifted from the shareholders to all stakeholders (Gavin 2019; Miller 2020). The societal influence means that solutions should be respectful towards the whole community and their wellbeing. Furthermore, the word “social” is defined as an activity “in which you meet and spend time with other people” (Cambridge Dictionary, n.d.). Thus, VPSS will be evaluated beyond those dimensions and places its importance on the psychological and physiological health of city dwellers.

Thirdly, the environmental criterion of the TBL considers the impact on the “Planet”. Historically, companies have been the greatest contributors to the rise of carbon dioxide (CO_2) and climate change. Therefore, this criterion places importance on the carbon footprint, the utilized material, and its impacts (Miller 2020; Spiliakos 2018). To evaluate the effect of the VPSS on the environment, the focus will be laid on biodiversity and the effect VPSS can have on how much CO_2 each of the arrangements initiate and capture due to photosynthesis for example.

Overall, the TBL approach has been mainly used by companies to write their business reports in which they explain how they are sustainable in all three categories. However, next to the positive aspects, the rising awareness, and utilizations of the TBL concept there exist also some criticism. Milne and Gray (2013) for example argue that the TBL approach is an insufficient condition “for organizations contributing to the sustaining of the Earth's ecology”. In contrast, it could lead to greater levels of unsustainability and a business-as-usual. Critical voices suppose also that it has been successful as an organized principle, but failed in practice (Engelen and McElroy 2011). After 25 years the author of the TBL approach, expressed his opinion on the criticism. Elkington argues that many companies understood the approach as a balancing act by adopting a trade-off mentality, which leads in a false direction because within the concept it does not exist a weighting between the pillars. Besides, the occurring models afterwards which are in relation to the initial TBL concept provide an alibi and a bewildering range of options so that customers won’t understand it and companies won’t act. Finally, he withdrew the TBL approach as long as it is seen by companies as an accounting system only which means firms should instead evaluate every criterion equally strong and see the TBL approach in its entire way. However, he calls for action and a new capitalism that spurs the regeneration of the economy, society, and biosphere (Elkington 2018).

In relation to this criticism the TBL approach is applied incorrectly. The general approach to provide a framework to assess equally actions on all three criteria instead of evaluating only the financial profitability, however, proved to be valid. Therefore, this thesis will evaluate the economic, social, and environmental criteria identically and use the framework as the author initially intended. The objective of this thesis is to sort the unsustainable options of the VPSS out and answer the hypothesis of this paper:

- H1a: What arrangement of vegetation zones, photovoltaic, and thermal solar systems (VPSS) will have the best impact for Austria in consideration of the Triple Bottom Line approach?
- H1b: To what extent can the rooftops of Austria help reduce the negative impacts of climate change by building up VPSS?

Austria's rooftop capacity, urban living, and the overall setting

The government of Austria developed a guide how to reach the goal of being climate neutral by 2040. However, the municipalities are mainly responsible for achieving this goal and evaluating the utilization of the land by allocating funds, for example. This leads to the issue that every municipality provides unstandardized data, subsidies differ, and many regulations are ruled individually (Knoll et al. 2022). For example, the city of Vienna provides a green rooftop cadaster that shows which roofs could be theoretically used to build up VZs (Pitha, interview; Stadt Wien, n.d.). The PV cadaster of Vienna shows all roofs within the city that have a solid orientation towards the sun so that they offer a source for PV panels or TS systems (Stadt Wien, n.d.-a). However, lower Austria for example does not provide such tools. In general, six out of nine federal states have their own solar cadaster including Burgenland, Carinthia, Salzburg, Styria, Tyrol, and Vienna (Mikovits et al. 2021).

To estimate the potential rooftop capacities for VPSS, there have been only a few studies to date that can be used as a valid source. Besides, many different approaches exist. Earlier studies used the population density or building insurance statistics to evaluate the possible rooftop capacity. However, recently the approaches have been more complex and accurate. Fechner (2020) chose a more precise approach that specifically determines Austria´s roof areas by following a 4-step approach and his research also provides a forecast. Firstly, he calculates the overall rooftops by taking the total number of buildings into account which were counted in 2011 and equaled 2.191.000 buildings. In 2018 the number of buildings increased up to 2.461.003 and equaled a rooftop capacity of 713 km^2 in Austria. Furthermore, he analyzed the number of rooftops that will be build up until 2030, as this is the year when

the federal state of Austria wants to rely solely on renewable energy. This means, that he included a potential growing number of buildings and calculated a possible efficiency increase of PV modules on top of each building category (family houses, multiple houses, or industrial buildings) and concludes that Austria's building rooftop capacity will be 738 km^2 by 2030. The next step was to consider the technical potential through the solar cadaster and parameters such as the building statics, electrical equipment, security requirements, the protection of historical monuments, and special static requirements which are for example that some rooftops are only allowed to use 50% of their roof or the ÖNORM B 1991-1-3:2006-04-01 which limits the load capacity of roofs. The third aspect considers the economic potential, as so far there is a priority for own cover which makes holiday houses or vacancy buildings unprofitable to build up solar technologies, for example. Lastly, the author estimated social and ecological reasons by including the willingness of the people to pay and install solar technologies (Fechner 2020).
The following thesis will rely on his conclusion and use the amount of 7.1 TW_h which equals 317.5 km^2 as it depicts the possible economic potential that is suitable for solar technologies in the year of 2030. However, for the vegetation perspective the possible roof capacity of 738 km^2 by 2030 can be used as a reference because this is the area which equals the overall rooftop capacity where VZs could be used. In this paper, the VPSS options are calculated as if only one option were feasible in order to be able to make a comparison. In reality, however, PV and TS systems can be implemented simultaneously with extensive VZs.

The VPSS – Explained

Photovoltaic

Since the Green Electricity Act in 2003, PV experienced an initial upswing but collapsed again in 2014 due to the capping of tariff subsidies. After an initial record growth in 2013 triggered by a subsidy anomaly, the PV market levelled off between 2014 and 2018 with annual installation rates of between 150 MW_{peak} and 190 MW_{peak}. In 2022 PV had an overall output of 1,009.1 MW_{peak} which led to an electricity supply of 3,7911.7 GW_h in Austria and is an increase of 36.4% compared to the prior year which can be seen in figure 2 (Biermayr et al. 2022).

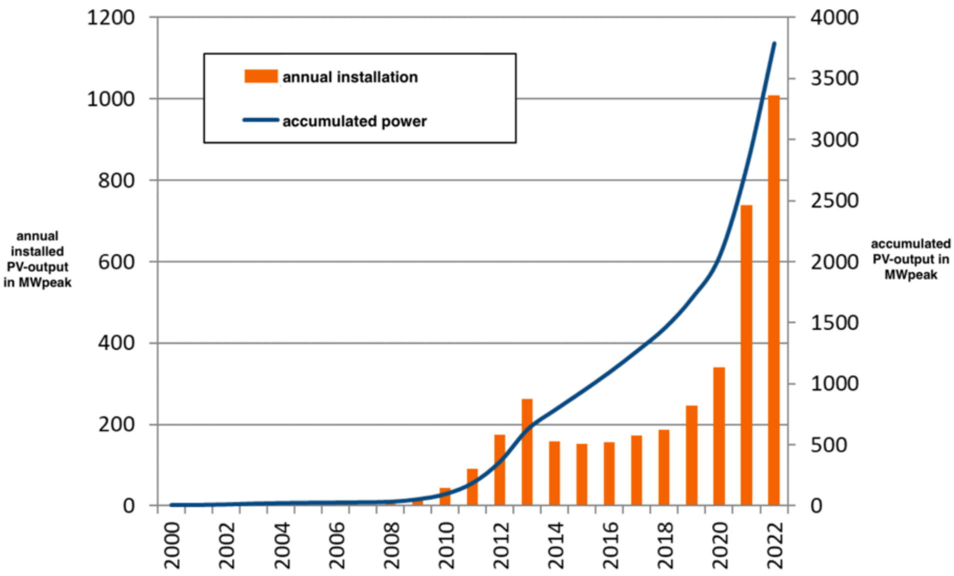

Figure 2: Annual PV capacity installed in Austria from 2000 to 2022.

(Source: Biermayr, P., S. Aigenbauer, C. Dißauer, M. Eberl, M. Enigl, H. Fechner, C. Fink, et al. 2022. 'Innovative Energietechnologien in Österreich: Marktentwicklung 2022'. 36a/2023. Vienna: Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie.)

At the moment there exist different types of PV panels. The solar cell is the basic component and, currently, 4 types exist. Polycrystalline silicon solar cells have a lower efficiency than monocrystalline silicon solar cells because they are made out of one silicon crystal; both systems are wafer-based modules. Monocrystalline silicon solar cells are therefore produced mainly despite being a bit more expensive (Biermayr et al. 2022; Vogl et al. 2021; Immitzer, interview). Besides, two PV cell types thin-film solar cells and special manufactured solar cells are also produced. They are very light and flexible, however, this results in less efficiency (Vogl, Sattler, and Grgic 2021). The PV module structure also consist out of 5 different construction types which are a standard module, a glass-glass module, a bi-facial module, the Plug-in module, and a module that can be built into house walls. The production gets more heterogeneous; however, the standard modules can be produced in large numbers and are the most installed (Biermayr et al. 2022). The average price is difficult to measure because special PV modules are more expensive, and prices fluctuate. Biermayr et al. (Biermayr et al. 2022) thus calculated the average price by including the electricity output of the PV modules and demonstrated that in 2021 the price was €317 per kW_{peak} while in 2022 the price increased up to 439€ kW_{peak} which equals a rise of 38.4%. The typical ready-for-use systems have fewer costs if their facility size increases. For example, a facility of 30 to 50 kW_{peak} costs approx. 31.66% less than a facility size of 5 kW_{peak} per kW. When observing a long-term trend, it can be seen that the price has fallen because the PV modules got more efficient, the production is more competitive, and innovative technologies made it cheaper. Additionally, Fechner et al. (2016) believe that the price will decrease even further.

Next to the PV modules there are other components which are necessary for the installation to work or to increase their efficiency. The power inverter converts the variable direct current (DC) output of the PV solar module into a utility frequency alternating current (AC) that is needed for the commercial electrical grid or the local off-grid electrical network. This AC can be used directly or can be stored in an electricity storage. Recently there has been a tendency towards the utilization of electricity storages because on average only 20 – 40% of the produced energy is used immediately (Biermayr et al. 2022). The rest of the produced energy can either be sold to the public energy grid or be used during the winter season because during that time the production of PV systems decrease up to 20 – 25% compared to the summer (Österreichs E-Wirtschaft and PWC 2022). However, during summer the best performance is at 25°C and with every additional 1°C the PV modules have 0.5% less output. The power optimizer which is integrated directly into the panel and monitors each module by preventing shaded modules from negatively impacting the performance of other modules or detecting dirt through an online tool increases the output in contrast (Vogl, Sattler, and Grgic 2021). PV modules usually have a life span of 25 years while the power inverter must be changed after 10 to 15 years. The cleaning process is only necessary if any problems occur, which depends on the surrounding area. A maintenance interval of 3 to 5 years is recommended while usually PV systems are maintenance-free (Immitzer, interview; Reisinger, interview). PV modules produce electricity; nevertheless, electricity can also be used to generate other forms of energy for example to heat up buildings through an electric heater or a heating pump.

Thermal Solar Systems

The initial boom of TS has been in 1980 to heat up swimming pools. Since then, the TS technology experienced a steady increase and was also utilized since 1990 for room heating. In 2009 TS have had the highest value of newly installed collectors with an area of 364.887m², which is equivalent to a performance of 255.4 MW_{th}. Since then, the amount has decreased. In the last two years there was only a small increase within the EU of newly installed collectors after a long time of recession, however, in Austria the value is still negative, with a decline of 16% between 2021 and 2022 (figure 3). The main problem of TS is that the price of PV is lower, only a few subsides exist, and the utilization of heat pumps is increasing (Biermayr et al. 2022).

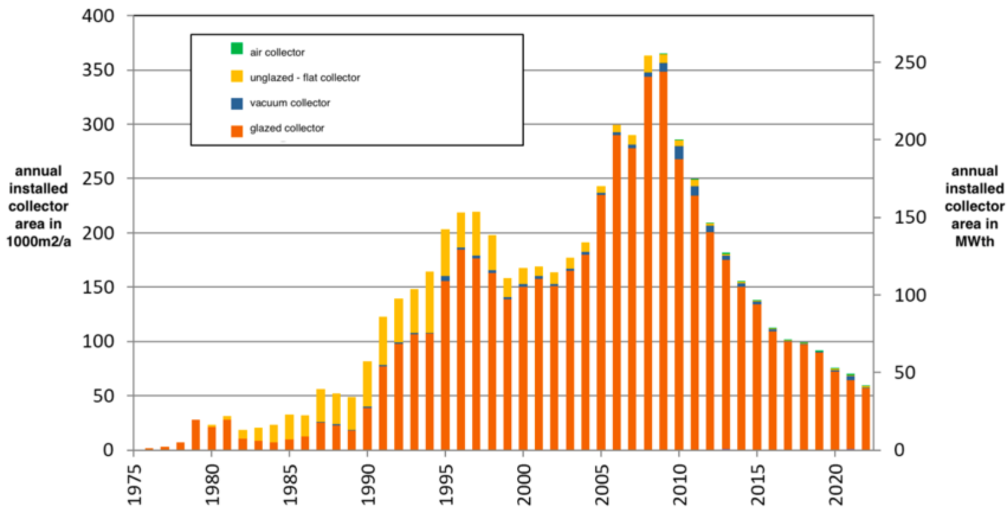

Figure 3: Annual installed collector area and capacity in Austria from 1975 to 2022 in m^2 and MW_{th} by collector type. (Source: Biermayr, P., S. Aigenbauer, C. Dißauer, M. Eberl, M. Enigl, H. Fechner, C. Fink, et al. 2022. 'Innovative Energietechnologien in Österreich: Marktentwicklung 2022'. 36a/2023. Vienna: Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie.)

Overall, the TS capacity by the end of 2022 was 4,6 million square meter of installed collectors in Austria, mainly assembled for one- or two-family houses for water heating and central heating assistance (Biermayr et al. 2022; Fink and Preiß 2014). Moreover, Austria is globally among the Top 10 countries regarding the installed TS capacity and ranks 4th within the EU by collector area per capita, which results in a useful heat yield of 2.063 GWh_{th} (Biermayr et al. 2022; Weiss and Spörk-Dür 2023).

Currently there are four types of TS technologies. First, evacuated tube collectors which are the most efficient by an annual energy yield of 450 – 650 kW_h/m^2 and cost circa three times more than the unglazed flat plate collector. Second, the unglazed flat plate collector, which is the cheapest and has an annual energy yield of 300 kW_h/m^2. Third, the most used collector type which is a glazed flat plate collector, which has an annual energy yield of 400 – 600 kW_h/m^2 and costs twice as much as the unglazed collector. And fourth, air collectors with the lowest heat capacity which are mainly used within the agriculture sector for air curing. The process of the heat production is very comparable between all collector types. The TS system absorbs the energy of the sun and converts it into heat. Afterwards the heat transfer medium will be transported to a heat exchanger and can be used again for a new cycle. In 2018, 97% of all collectors that have been assembled are glazed flat plate collectors. Next to the collectors there is usually a buffer storage or seasonal storage assembled to store the heat for a few days or save it for the whole winter season (Biermayr et al. 2022; Mieritz 2021; Vogl, Sattler, and Grgic 2021).

A solar system for only hot water preparation (6 m^2 collector area, 300 liters of solar storage) costs around €3,800 for the solar set, €500 for additional materials and €1,500 for installation.

A solar system for hot water preparation and heating (15 m^2 collector area, 1,000 liters of solar storage) costs around €8,100 for the solar set, €800 for additional materials and €2,700 for installation. However, the exact costs vary from facility to facility. The life expectancy of the collectors is around 20 to 30 years while the maintenance of the system is recommended every 3 years at the latest. One person needs about an hour and checks, for example, the pressure, the solar fluid, and see if there is any general damage. In principle, it can be said that the more frequently the system is inspected, the more efficiently it runs (Biermayr et al. 2022; Hackstock, interview; Lauf and Schneider 2019; Vogl et al. 2021).

Overall, even if there was a positive development the last couple of years, the market development is not that good in terms of sales figures compared to other renewable technologies. Besides, the production of electricity and cooling technologies is becoming an increasingly important topic. However, the production of electricity through TS systems is not economically lucrative and TS cooling is still a niche market because these systems are highly complex, very expensive and have a low output range (Biermayr et al. 2022; Haas et al. 2017; Hackstock, interview; Reisinger, interview; Weiss and Spörk-Dür 2023). This means that even if the energy yield of solar thermal energy is currently still three times higher than that of PV modules the diversity of collectors is declining and there is a general dwindling interest from residential developers due to unattractive or missing subsidies, as well as higher prices in comparison to PV modules (Biermayr et al. 2022; Formanek et al. 2023; Reisinger, interview).

Vegetation Zones

Vegetation Zones are experiencing an upswing because more municipalities indicate that green roofs are highly relevant to diminish many disadvantages of cities due to the climatic shift. Every 5th municipality in Austria has already specific rules to make green roofs mandatory under certain circumstances while 11% already initiated a municipal funding for green roofs. 87% of cities maintain an urban tree register and 84% are already planting additional urban trees as an action to adapt to climate change. However, only 2% have a specific cadaster for green rooftops and only 13% can estimate their currently installed green roofs. Besides, some municipalities consider greening mainly as a method to make public spaces more attractive but not as a possibility for climate policies, although VZs can provide many advantages to enhance residents' city life (Enzi, Formanek, and Peritsch 2021; Knoll et al. 2022). Plants improve the environment through photosynthesis and by reducing the air temperature in two ways: They prevent solar radiation from heating up surfaces below and provide shade. Also, plants convert energy to latent heat through the transpiration of water which releases through the stomata of their leaves. However, the effects of these two options differ in their effectiveness as the transpiration effect is depending on many other side effects, such as tree crown size, density, the optical property of their leaves, the composition of the soil, and the climatic conditions (Kong et al. 2016; Pace et al. 2021). Therefore, shading has a greater effect on the temperature than the transpiration (Loibl et al. 2020; Pace et al. 2021; Shashua-Bar et al. 2023). This shows that plants could potentially increase the overall well-being of city dwellers.

Green rooftop constructions differ regarding their possible assembly due to insulation effects and the slope of the roof (Pitha, interview). Roofs with a slope of 1.8% – 58% (which corresponds to an inclination of 1 degree to 30 degrees) can be planted, but from a slope of 9% measures such as anti-slip or shear protection must be taken into account to inhibit the slipping of the root protection and waterproofing installations. From a gradient of 26% upwards, additional actions must be done in order to secure the entire structure (Vogl, Sattler, and Grgic 2021). The slope of the roof then rules which kind of VZ can be planted. One option is an extensive rooftop VZ. This is best for rooftop constructions with a 0 – 35% slope. The height of the plants can be between 10 and 20 cm, the weight when saturated with water is approx. 90 to 250kg/m^2 while they have a water storage capacity volume of approx. 25 to over 60 l/m^2. In addition, extensive VZs require low maintenance and care and have overall lower investment cost. Intensive VZs in comparison are only for rooftop constructions with a 0 – 5% slope. Additionally, a high-quality structure and a stable substructure is necessary. The height of the plants can be between 15 and 200 cm, which could provide an additional space on the roof for private roof gardens. The care is therefore significantly more intensive, and the costs are very high. The weight when saturated with water is approx. 200 to 3,000kg/m^2 and the water storage volume is approx. 60 to over 150 l/m^2 (Fechner and Mayr-Ebert 2020). Next to these two types of VZs the rooftop needs some special extra layers to protect the building (figure 4). These extra layers are a roof sealing which usually has a root penetration protection and an extra layer for waterproofing. The drainage and storage layer, which regulates heavy rain events and enables the storage of rainwater. A filter layer that prevents the displacement of soil particles and finally the substrate layer, which serves as the root area of the plants (Vogl, Sattler, and Grgic 2021).

The price of extensive VZs starts at €25/m^2, with maintenance costs of around €9/m^2 per maintenance procedure. The production costs for intensively used VZs are around €50 – €100/m^2 and there is practically no upper limit. Depending on the type of use, the price can be as high as €1.500/m^2. However, it should not be forgotten that the property value increases by around 2 – 5% because of the utilized space, and people are willing to pay more for this additional leisure space (Bianchini and Hewage 2012a; Enzi, Formanek, and Peritsch 2021; Teotónio et al. 2020).

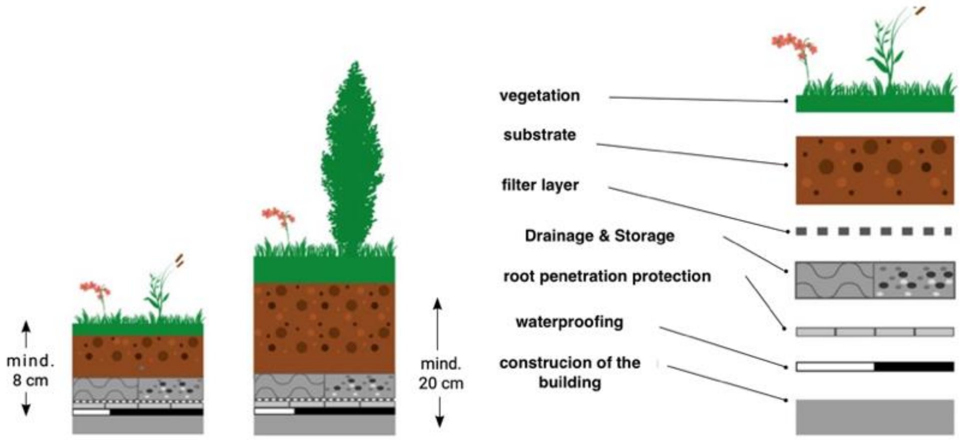

Figure 4: The extensive and intensive VZ structure.
(source: Enzi, Vera, Susanne Formanek, and Manfred Peritsch. 2020. 'Green Market Report Kompakt; Bauwerksbegrünung in Österreich'. 67. Wien: Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. https://gruenstattgrau.at/neuer-download-positionspapier-zur-bauwerksgebruenungsbranche-in-oesterreich/.)

Finally, the life expectancy of VZs is between 40 and 55 years but if the layers are not broken or can be fixed spot-specifically the life span can last up to 80 years and longer. The maintenance is required annually independent of their type (Bianchini and Hewage 2012a; Formanek, interview).

Discussion

The discussion will be structured by considering the economic, environmental, and social perspective while within every dimension first the PV criterion will be investigated. Followed by the TS systems and VZs on roofs. The order of the differential criteria is used because of the alphabetical order and has nothing to do with prioritizing or weighting the individual factors which are analyzed.

The economic perspective

To evaluate the economic perspective of the TBL approach the focus will be set on two main criteria to identify if Austria will benefit economically. Firstly, the effect that VPSS has on the employment rate will be evaluated, because the work force is a good indicator for economic growth. The Okun Law for example describes an empirical correlation by saying the employment rate rises if the production growth is increasing (Huang and Yeh 2013). Generally, Okun's Law can be seen as a valid relationship, however, the results can vary if different methodologies are used, which suggests that the relationship should be also seen with caution (Lee 2000). Huang and Yeh (2013) analyzed that a tradeoff generally exists in the short-run and also in the long-run while Frick and Lampart (2007) specified that the real GDP growth must be more than 1.8% to have a positive effect on the employment rate. Other studies also indicate that in principle there is a positive tradeoff between economic growth and the employment rate (Bartolucci et al. 2018; Lee 2000). Therefore, the required work force of VPSS will be compared and evaluated by trying to consider the employment rate of each system.

Secondly, the aspect of the supply chain of all VPSS will be taken into account by investigating where the main parts of each system are produced, and whether the supply chain is mainly dependent on international suppliers or if VPSS components are primary produced in Austria. Taking the supply chain into account enables to have a closer look at the contribution to the GDP of each VPSS in Austria. The GDP by its definition of the OECD is "the standard measure of the value added created through the production of goods and services in a country during a certain period" (n.d.) and thus makes it a key indicator. Besides, if a high production within Austria leads to higher exports this could have an additional advantage as exports increase economic growth and are a source for increasing investments, productivity, and consumption (Emery 1967).

In addition to these economic factors there are a number of other important external aspects that should be briefly considered. Right now, Austria's buildings are carrying the load of 40% of the CO_2 emissions and some studies predict that the need for energy will even increase in the future. Experts believe that next to the energy which is used to heat up buildings during the winter season the demand for cooling systems will be as high as the demand for heating systems, because the temperature will rise sharply in Europe within the next 20 years (Enzi, Formanek, and Peritsch 2020; Formanek 2022; Österreichs E-Wirtschaft and PWC 2022). Besides, many households might install their own charging station for electric cars which will lead to more electricity consumption. Concluding that even if the efficiency increases in energy production the problem remains that the electricity demand might double from year 2020 to 2040 in Austria (Österreichs E-Wirtschaft and PWC 2022). PV or TS systems could not solely meet these demands; however, they could serve a part of the high demand in a sustainable way and diminish the negative impacts on the climate in comparison to fossil fuel technologies.

The main difference between PV and TS lies largely in their output. PV produces electricity while TS systems are mainly used for heating up drinking water or as a domestic heating backup. Even if the electricity demand will increase significantly, the final energy

consumption in 2011 shows that the biggest share of the final energy consumption is used for heating and cooling (52,1%) followed by the energy used for mobility and transportations without electricity (34,7%), and finally 13,2% for the electricity demand. A more precise breakdown of the heating and cooling consumption shows that only 0.7% was required for air conditioning in 2011 (Fink and Preiß 2014). Nevertheless, the amount of cooling energy will increase. In particular the proportion of cooling energy required for residential buildings in the private sector will rise. Austria's cooling demand might increase between 6 and 28 TW_h, depending on climatic changes and optimized building insulation, in 2050 (Natiesta 2021). This shows that the final energy consumption of electricity is rather low in comparison to the necessary heating capacities today; however, the demand for electricity will increase significantly. Both technologies can produce both demanded products (heating and electricity); but the system needs to be adapted for the desired application area and this is not economically advisable. Hachchadi et al. (2023) showed that in Montreal the annual thermal effectiveness of TS is between 2 and 3 times higher than that of PV water heaters. This means that the area of PV modules must be 2 to 3 times larger than the area of TS collectors to produce the same amount of energy. Despite its low annual thermal efficiency, PV systems are still more efficient from a techno-economic perspective due to their lower CAPEX which are the major long-term expenses of a company and a lower OPEX which are a company's day-to-day expenses. Furthermore, the shift towards more electricity, shows that PV could better meet the increasing electricity demand and that the growth in cooling consumption in particular is better served by PV panels (Weiss and Spörk-Dür 2023).
Additionally, the PV industry shows that over the last years the technology improved significantly. The PV technology itself could enhance their degree of efficiency between 1955 and 1985 from 2% to 20%. Artificial Intelligence (AI) helps also to utilize data from the self-generated energy and coordinates it with the available energy resources. This means that AI links production steps with high energy consumption with those hours of the day when a particularly large amount of energy is available. Besides, many different types of PV technologies are currently on the market because the cells can be very flexible, and their range of application and the adaptability is high. This is in contrast to TS systems because their diversity significantly decreased over the last years and less innovative efforts have been done. It means that TS is less well adapted to the market situation and less flexible in terms of the demand. (Biermayr et al. 2022; Fechner 2020; Fechner et al. 2016; Hackstock, interview; Reisinger, interview). PV and TS systems, however, are in stark contrast to a VZ because possible improvements of the latter are partly bound to biological functions. Research is being

carried out into improved technologies that affect the subsoil or AI functions to improve the yield of plants. More innovative species are also being sought within the plant world. For example, there is now a type of leaf that shimmers slightly silvery to improve the albedo reflection which describes the ratio between the radiation reflected from a surface and the radiation incident on it or trees that hardly need any water to minimize the consumption of this resource (Formanek, interview).

Further important factors, when considering the economic perspective, are the aspect of costs, output, and planning capability. PV is one of the cheapest energy sources and the acquisition costs of the systems have fallen dramatically in recent years. The fall in prices is due to technological progress, economies of scale and learning effects, leading to a price-experience curve effect, and therefore to a drop in the price of around 90% between 2010 and 2020 (Wirth 2023). The PV market out of the RE market is currently the fastest growing, which shows that the sale of electricity is becoming an increasingly important issue. Revenues from the sale of electricity by PV system operators are estimated to over €638.82 million in 2022 in Austria (Biermayr et al. 2022). However, the energy self-consumption priority continues to prevent PV system operators from expanding their PV systems. Electricity suppliers usually purchase the remaining energy from their own customers. However, no energy producer is obliged to purchase the electricity. The OeMAG is the only buyer which has to purchase the electricity at the market price. To this end, the "Erneuerbaren-Ausbau-Gesetz" (EAG) adopts new initiatives that enhance the energy transition, strengthens PV and initiates funding programs for the technology.

TS systems, on the other hand, are not considered in the EAG and a closer look at the subsidy landscape in relation to TS also shows that subsidies have declined significantly over the past years (Biermayr et al. 2022; BMK 2021). The price development of TS systems has not fundamentally decreased for the end consumer, although production costs have fallen dramatically. With a doubling of the market in Europe since 1980, production costs were reduced by 23%, whereas the average annual price reduction for the end consumer was -1,9%. The reason behind it lies in the fact that there exists no competition between TS installation companies. This stands in stark contrast to the PV market because of a strong competitive pressure between them. This affects the price and leads to a price difference which is depicted by a margin for PV of around 4 – 8% while the margin for TS modules is around 25% (Fink and Preiß 2014). The margin of companies that build VZs on roofs is not publicly known, but it can be said that the price has remained constant in recent years (Formanek, interview; Pitha, interview). The effect of a VZ on roofs on the economy requires also a different perspective, because other side-effects lead to the probability that the profit could exceed the costs (Bianchini and Hewage 2012b). Firstly, there are energy savings due to the additional insulating effect, which depends on the type of the VZ. According to calculations, a green roof with a construction height of 10 – 15 cm is said to have 3 – 10% less heat loss (Formanek et al. 2023; Senatsverwaltung für Stadtentwicklung 2010). Green roofs also have consistently a more stable temperature throughout the day. As a result, the heat inside buildings could be stored much better in winter and was therefore 0.1 – 0.7°C warmer compared to buildings with a conventional roof. In summer, the opposite effect could be measured and led to 0.1 – 1.1°C cooler temperature indoors. This leads to less energy consumption of approx. up to 12% to 15% annually (Alves et al. 2019; Bevilacqua et al. 2017; Foustalieraki et al. 2017). However, another study came to the conclusion that if the overall construction is already well insulated, the effects on the heating energy requirement and the influence on the room temperature is insignificant (Loibl et al. 2020). Overall, this shows that there are many different aspects between VPSS and other factors are influencing the economical perspective and the profitability of every system.

Employment criterion

The unused rooftops of Austria and the potential utilization will create new jobs in all three VPSS. So far, the space is not considered at all and any VPSS is better than the status quo because the installation of VPSS would require additional workforce for their production, installation, and maintenance.

The relation of PV and TS systems and the employment rate have to be seen from another angle as well as these two systems would substitute other jobs. Austria's energy sources overall rely mainly on oil, gas, and coal; oil is especially utilized in the mobility sector. The electricity production in Austria is already mainly driven by green energy sources but the heat production is still reliant on fossil fuel energy sources. Since Austria committed to 100% REs by 2030 this would mean that the hazardous energy sources would be substituted by PV and TS, for example, and might lead to job losses in their industry (ILO 2012). Taking this into account, three things have to be considered. First of all, fossil fuels are mainly imported to Austria which means that the main production, workload, and revenues are abroad (Goers et al. 2020). Secondly, the substitution to REs is expected to lead to a net increase within the employment rate and the jobs are of better quality or of equivalent to those in the fossil fuel industry (BMK 2023; ILO 2012; Wei, Patadia, and Kammen 2010; Wien Energie, n.d.). And thirdly, the current job losses within the fossil fuel industry has been principally because of rising automation and labor productivity and not because of an increase in renewable energy sources (ILO 2012). Thus, concluding that the substitution would not lead to a major economic downturn in Austria. In contrast, there is a high chance that Austria will benefit from the installation of new REs which can be seen by the expanded employment rate between 2007 and 2011 from round about 2.3 million to approx. 5 million indirect and direct jobs worldwide (ILO 2012).

Measuring the employment potential can be done by estimating the jobs created per unit of produced capacity. On a global level PV creates the most jobs in contrast to other renewable energy technologies per unit of electricity output, however this is also influenced by the demand and governmental support through subsidies (Wei, Patadia, and Kammen 2010). Upon closer examination of renewable energy sector employment, it was found that within Europe, 24% of the workforce was required in the photovoltaic (PV) technology field while only 4% of work force was needed for the TS systems. The large number of jobs within the PV industry relies on the rapid expansion of the industry in comparison to TS. However, the main workforce of PV systems is captured in China because there are many manufacturing sites. Over the last years the market is undergoing a shift from European to Asian companies which has consequences for the employment rate of manufacturing the PV panels. Nevertheless, the installation, sales, and jobs that relate to the maintenance are by their very nature always on a local level and therefore contribute to the GDP of Austria. This indicates that countries that expand their installed PV capacity will continue to increase the employment rate even if it is just in the downstream PV value chain (ILO 2012). The same applies for TS technologies, however, their impact on the employment rate is considerably low. This lower workload is caused by the fact that the costs of the TS systems are higher in comparison to PV panels which results in less demand, less installations, and less needed work (ILO 2012).

The job occupations for PV systems include a variety of employment opportunities. Hamilton (2011) reported the different jobs for PV systems for the USA, and this can also be transferred to Austria. Firstly, a major part of work force is needed within the scientific research area because chemists, physicists, engineers, and material scientists are trying to increase the efficiency, reliability, and the aesthetics of the modules. Secondly, the process of manufacturing requires a lot of skilled workers including computer-controlled machine tools that must be overseen by workers. Thirdly, the building of a PV plant relies on people who work as a real estate broker, scientist, and constructer to procure land and ensure that the environmental ecosystem is protected. Finally, once the site has been chosen, workers are needed to install the PV panel and ensure that the systems work by maintaining them on a regular basis.

A survey of Austrian system planners and installers examined the average jobs per installed MW_{peak} and projected it on the basis of the newly installed PV modules in 2022 which has been a capacity of 1.009,1 MW_{peak}. The result shows that because of the newly installed PV panels the employment rate within the industry increased, resulting in 4.236 additional PV planners and installers, 1.051 additional manufacturing jobs for the inverters and components for PV, 471 new jobs within the research and development area, and 317 new jobs on behalf of the module producers. This overall shows a significant increase of 6.075 additional full-time jobs which can be seen as an increase of 34,1% compared to 2021. This high number can be traced back to the large amount of new installed PV panels and the report concludes that 4,2 jobs are needed to install one MW_{peak}. However, this result has to be seen with caution because many producers do not manufacture their products exclusively for the PV sector. That means that potentially the number of additional full-time jobs can be higher. (Biermayr et al. 2022). Besides, two important factors have been neglected in their survey. Firstly, the maintenance of PV panels has not been considered even if this would involve additional work force and secondly, the whole End of Life (EoL) has not been included which would also have an impact on the required work. Goers et. al. (2020) analyzed the effects on the employment rate through additional investments. They state that due to the import of fossil fuels, the revenues usually flow abroad but REs are anchored more strongly domestically. Besides, there are additional round effects in the economy, as more employment generates higher domestic production, higher wages, rising consumption, rising investments and, in turn, a higher GDP. With an expansion of PV systems of +11.4 TW_h by 2030, they conclude that it could be associated with an annual investment of €1.3 billion, an annual GDP increase of €2.3 billion and an annual increase of 30.000 employees by 2030.

The interviewed expert states that a private PV system of around 8 kW_{peak} can be installed in one day by a team of three people which equals around 5 people per MW_{peak} in terms of the installation alone. The costs and the frequency per m² for recurring inspections is not possible to estimate because they vary depending on the region, the size of the system, the type of inspection, local regulations, and the place of the module. For example, if the system is located near a chimney that emits a lot of smoke regular cleaning is essential, as soiling can impair electricity production. This thesis will rely on the opinion of Vera Immitzer as her statement is the most up to date and it equals the study of Biermayer et. al. which is also one of the latest studies and can therefore be seen as a validation. The estimated employment rate solely for the installation would result in 35.500 necessary jobs right now if all rooftops in Austria would be used for PV panels.

The market situation of TS systems in comparison has not experienced a sustained increase in installed capacities due to the decline in revenue between 2010 and 2021 from €420 million to €147 million. This was also associated with a reduction in jobs from 4.700 employees to 1.200 employees. In addition, the development of TS companies in Austria shows that the number of manufacturing companies has fallen from 18 in 2010 to 9 in 2022. However, the recent increase in exports of Austria in 2022 led to an expansion in turnover to €151.6 million and an increase in jobs to 1.300 full-time equivalents (Biermayr et al. 2022). Goers et al. (2020) again analyzed the effect if +1.5 TW_h were to be additionally installed until 2030. They concluded that from 2020 onwards there would be 8.300 additional full-time jobs annually needed, and a GDP increase of €0,6 billion on an annual basis as well. Currently, the employment rate which is needed to establish 1 MW_{th} is 31 full-time employees (Hackstock, interview). Therefore, the estimated workforce would result in 220.100 employees right now if all rooftops in Austria would be used for the installation of TS systems.

Regarding the maintenance of the system, it can be said that the TS system require less maintenance in practice. Only the boiler will be checked on an annual basis if everything is still functioning while the collectors on the roofs are inspected sometimes even less frequently than the recommended three years. Comparing the required work between TS and PV systems it can be said that TS systems are less maintenance intensive and fewer employees are needed for the inspection (Reisinger, interview).

The greening market in contrast to the TS technology decline is evolving. Currently, the industry consists out of 550 companies and 1.200 employees only within the direct value chain. The average growth rate between 2014 and 2018 was 9,9%. If 50% of the overall Austrian flat roof market will be used for VZs it could lead to 6.500 additional jobs by 2030 (Enzi, Formanek, and Peritsch 2020). Furthermore, the ÖNORM L 1131 dictates that there has to be a regular maintenance of the plants and the instructions between 1 to 2 times a year which generates additional work force. This leads to required work of around 30 minutes for one employee for extensive roofs and for intensive roofs it can be a workload of around 4 hours of 3 to 4 employees annually for a roof of 100 m^2. The maintenance of a VZ is therefore in comparison to PV and TS systems more intensive and more frequent. Besides, there exists a maintenance obligation while PV and TS manufacturer usually only give a recommendation when it would be necessary to check if the functionality of the system is still achieved (Pitha, interview). In terms of the installation alone it can be said that on average 3 to 4 people are necessary to build up an extensive or intensive VZ (Formanek, interview; Pitha, interview; Vogl et al. 2021). The main problem of the calculation, however, is that this number cannot be converted to square meters, because the employees are required per roof area regardless of how large or small the rooftop is. This means that a calculation in relation to the 738 km^2 roof area is not possible. Even the number of the roofs is not sufficient on its own because depending on the composition, and potential obstructions like chimneys and skylights, any assertion made would lack precision (Formanek, interview). The only estimate that can serve as a possible comparative figure is the number of 13,000 additional jobs calculated by 2030 by Enzi et. al.. However, this number should be viewed with caution, as this statement does not take into account the latest standards and it considers solely the flat rooftop market while the maintenance of the system has not been considered (Enzi et al. 2020; Formanek, interview). This thesis will proceed with the estimated required workforce regarding the installation alone because the maintenance heavily depends on the area and data is less available.

Supply chain criterion

The supply chain criterion requires an analysis of the global market situation of each VPSS technology.

PV technologies are particularly dependent on China because the country is the global market leader in the supply of PV panels and components. Despite some constraints in the value chain, China is managing to expand its own market and installed more PV modules in 2022 with a cumulative total output of around 414.5 GW_{peak} which corresponds to over a third of global installed PV capacity. The EU was the second-largest global PV market in 2022 with a newly installed PV capacity of 39 GW_{peak}. China has captured the largest market share because the country employs the most people in this field. However, this achievement may also depend on demand and potential investments facilitated by China's subsidies. The low wages within China put high pressure on countries that have, on average, a higher wage as it is the case within the European countries for example. The wage differential results in competitive constraints and disadvantageous conditions for the PV market in Austria. Despite the different situation of each national market and its local labor conditions, there has been a significant rise with an annual increase in newly installed PV capacities of around 38% in Austria. By the end of 2022, 9 European countries were already able to cover more than 10% of their electricity consumption with PV electricity. However, Austria could only cover 6.6% which is well below the EU average of 8.7% (Biermayr et al. 2022; ILO 2012).

The value creation for Austria of a 5 kW_{peak} PV system consist out of the module itself (39%), the inverter (18%), the installation (22%), and other necessary components with a share of 21% of the whole system. This indicates that the regional added value for Austria will mostly be above 50% if at least one of the two components (inverter or the module) is made in Austria. The worst-case scenario would be that both components are produced abroad, and thus only 43% of the whole value chain can be credited to Austria. The installation and planning is usually done by Austrian companies which led to approx. €1,684.1 million revenue in 2022 solely for the domestic PV-planner and PV-installers (Biermayr et al. 2022; Fechner 2020). The domestic production, however, in Austria has fallen in recent years, meaning that the domestic market benefited by 9.5% less in 2022 compared to the previous year (figure 6). In 2022, PV modules with a total output of 208.3 MW_{peak} were produced and of those 112 MW_{peak} were exported, which corresponds to an export rate of approx. 53,8%. However, the domestic market rose again that year to 1,008.6 MW_{peak}, meaning that many PV systems had to be imported in order to meet the domestic demand. Therefore, in 2022, there was a net import of 912.4 MW_{peak}, which corresponds to an import rate of 90,5% to fulfill the whole domestic demand (Biermayr et al. 2022).

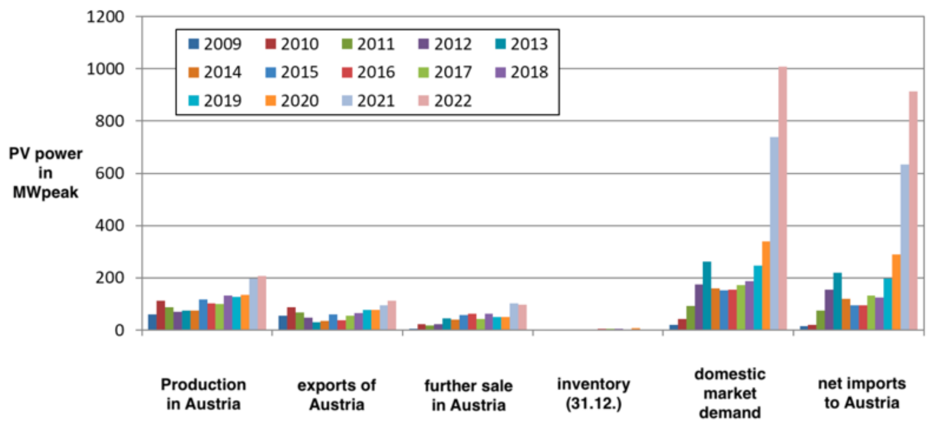

Figure 5: Austrian PV module production from 2009 to 2022.

(Source: Biermayr, P., S. Aigenbauer, C. Dißauer, M. Eberl, M. Enigl, H. Fechner, C. Fink, et al. 2022. 'Innovative Energietechnologien in Österreich: Marktentwicklung 2022'. 36a/2023. Vienna: Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie.)

The high level of imports indicate that, the PV industry of Austria is mainly reliant on countries abroad; however, there is still a regional added value because the planning and installation can only be realized in Austria. Cornelia Daniel emphasizes additionally, that high-quality European and Austrian alternatives are available, although they tend to be somewhat more expensive. For many customers the quality is important, and they favor European products. The decision between European or Asian components depends heavily on their individual preferences and their cost considerations (Daniel, interview). Concluding that although the installation, assembly and maintenance are carried out in Austria, many components and materials tend to be non-European.

TS systems, on the other hand, had a cumulative solar thermal capacity of around 540 GW_{th} worldwide in 2022, which corresponds to around 771 million square meters of TS systems and an annual energy yield of around 440 TW_h. However, solar thermal energy is experiencing an overall decline in annual growth rates, with only a slight increase in 2021, followed by a global decline of around 10.4% in 2022. This decline was mainly caused by two countries. Firstly, because of massive markets slumps in India due to changed subsidies and a stronger competition (-21%) and secondly because of the lockdown in China (-12,4%). On a global level, the revenues were around €17,400 million in 2021. The top 5 countries in terms of their total installed capacity by the end of 2021 were China, Turkey, the United States, Germany, and Brazil. But per capita, the top 5 countries are Barbados, Cyprus, Israel, Austria, and Greece (Biermayr et al. 2022; Weiss and Spörk-Dür 2023). The value creation of installed TS systems includes five areas: The technology production, the planning, assembling, and handling of the system, installation, and maintenance. The Austrian production of glazed flat-plate collectors, vacuum tube collectors and air collectors is spread across 9 companies, with over 90% of production being in the hands of just one company. This company is not only the largest manufacturer in Austria but also the largest worldwide. The company with the second largest production share is at 4%.

This means that Austria's export share in the field of TS systems is very large, and the domestic demand is not dependent on imports because they hardly play a role. Almost 95% of the flat-plate collectors manufactured in Austria in 2022 were exported, 77% for air collectors, and for vacuum tube collectors there exist no data. This equals 535,285 m^2 of a collector surface which has been exported in 2022 which is an increase of 16% compared to 2021 (figure 7). Austria's most important export markets are Germany (47%), Italy (24%) and France (10%). Concluding, that the main added value of the production and installation is in Austria in comparison to PV (Biermayr et al. 2022; Hackstock, interview; Reisinger, interview).

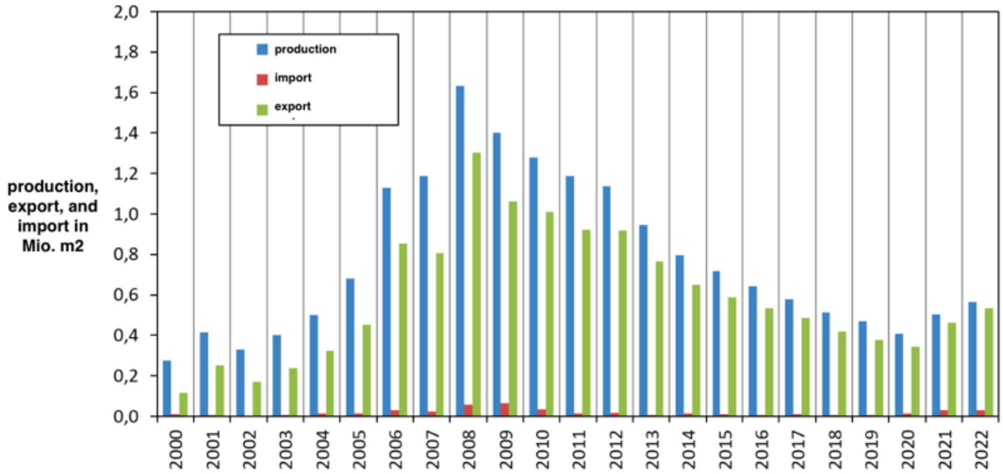

Figure 6: Production, export, and import of TS collectors in Austria between 2000 and 2022.

(Source: Biermayr, P., S. Aigenbauer, C. Dißauer, M. Eberl, M. Enigl, H. Fechner, C. Fink, et al. 2022. 'Innovative Energietechnologien in Österreich: Marktentwicklung 2022'. 36a/2023. Vienna: Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie.)

However, it must be considered that despite the high exports and the recorded increase between 2021 and 2022, the production of new TS systems is on an overall downward trend. The turnover of €151.6 million for the entire solar thermal industry in Austria in 2022 is also significantly lower compared to the turnover of €1,684.1 million achieved by PV planners and installers alone (Biermayr et al. 2022; Fink and Preiß 2014)

Overall, despite the strong domestic production and the large export share within the TS market, Austria generates significantly less turnover for the domestic market in contrast to the profits from the PV industry because of its higher demand. If the added value is considered independently of the current demand, TS systems would have an advantage, because their added value is 75% per square meter. PV systems, on the other hand, only have an added value share of 46% per square meter for Austria (Hackstock, interview).

The current position of the VZ industry in an international context is difficult to quantify because fewer surveys exist and the units of the entire system is by its very nature mostly domestic. The interviewed experts say that the main profits are realized domestically or within Europe. The substrate is mainly from Germany; however, the main components like the plants or the Drainage are produced primarily in Austria. This means that the economic profits are mainly generated within Austria and enhances its GDP (Formanek, interview; Pitha, interview).

When considering the domestic market, the industry's total turnover in 2014 was around €65.3 million and rose to €90.5 million by 2018. Therefore, the average annual sales growth in the period between 2014 and 2018 across all submarkets was around 9.6%. The largest clients are in residential construction, commercial properties, and the public sector, while private clients

only account for 10%. Companies are also noticing the stronger demand and are increasing their specialization in the industry. The industry's value chain is divided into research & development, planning, the production of basic materials as well as producing components for the system integration, and the installation and maintenance. On the manufacturing side of the substrate, 28 companies are currently active in Austria, and they increased their volumes by about 6.22% between 2014 and 2018. However, it is striking that the volume growth of substrate manufacturers is not as high as that of the distributors. This indicates that a large share of the substrate supplies is imported. Furthermore, root-resistant waterproof roof layers are also an important factor for the installation of VZs. Currently, there are a total of three different variants to choose from (bitumen, plastic, or elastomers). Those suppliers also have a considerable discrepancy between the amount of produced root-resistant waterproof roof layers and the installed number of green roofs. A possible explanation for this could be that some of the covers must be pre-produced and two layers are necessary to protect the roof appropriately. The sales growth of this industry between 2014 and 2018 was 4.67%.
In addition, a constant expansion can be seen on the manufacturer side because more companies are dedicating themselves to the industry (Enzi, Formanek, and Peritsch 2021; 2020).
Concluding that between VPSS, PV contributes the largest turnover nationally, followed by TS and VZs. However, the production of TS and VZs are mainly domestic, while the production of PV modules is strongly dependent on China.

The environmental perspective

The environmental perspective of the TBL approach is analyzed by taking into account the impact that VPSS has on biodiversity and on the amount of CO_2 in the atmosphere.
Biodiversity is especially important for the functioning of the whole ecosystem as it increases the resistance to climate extremes, and stabilizes the productivity of the environment (Isbell et al. 2015). A collapse of the ecosystem and a further loss in biodiversity are one of the greatest threats that society faces now. The decline of biodiversity can be traced back to four primary direct drivers which are pollution, climate change, invasive alien species, and changes in the land and sea use. The danger of biodiversity loss is that it activates a feedback loop whereby climate change accelerates a decline of the variety of species, and this in turn accelerates climate change. The extinction of some animals causes many severe problems because species are highly interdependent and closely linked to the environment in general (Dumitru and Wendling 2021; Urban 2015). Therefore, it would be a great gain for the environment if Austria's rooftops could contribute to the preservation and improvement of biodiversity.

Secondly, CO_2 is the main driver of climate change and is consequently particularly important to consider. The amount of greenhouse gases are increasing steadily and cause a temperature rise which in turn initiates many other problems such as extreme weather scenarios resulting in thunderstorms, heat, and floodings as well as the loss of biodiversity, poor harvests and many others (IPCC 2018). The thesis will mainly investigate those two criteria by asking: What impact could VPSS have on biodiversity, and how much do they influence CO_2 if they are installed on the roofs in Austria?
Other than these two dimensions, VPSS influences the environment in many other ways. PV systems for example contain rare and toxic materials and therefore exploit and damage the environment. Innovative solutions are already existing to prevent this problem but the exploitation of rare earth elements continues to harm the environment (Kang and Kang 2020). Especially, the battery of the PV system is responsible for the most environmental impact because they have got a relatively short lifespan, require a lot of rare earth elements, and a large amount of energy for their production (Tsoutsos, Frantzeskaki, and Gekas 2005). The entire TS system requires toxic materials and therefore they harm the environment as well. Experts, however, state that the production of the collectors do not require any toxic nor rare earth elements and thus the collectors are not dangerous (Hackstock, interview; Reisinger, interview). VZs in contrast do not need any rare resources and their impact on the environment is in comparison to PV and TS systems considerably low (Formanek, interview; Pitha, interview). This effect is also covered in detail within the physiological criterion of the social perspective of the TBL approach.
Furthermore, extreme weather scenarios will occur more often, which can influence the environment to varying degrees due to the structure of VPSS. Extreme weather scenarios have got detrimental effects on the environment as they lead to a greater frequency of reproductive failures and declines the longevity of living organisms (Moreno and Møller 2011). PV and TS systems might not cause any changes during extreme weather scenarios because they are in principle just another layer on top of the roof so heavy rain or hail would run off for example. VZs in comparison can handle extreme weather scenarios like rain better because the rainwater is temporarily stored in the ground (Fechner and Mayr-Ebert 2020). Rainwater retention of 30 – 160 l/m^2 can be stored by 65 – 70% on average per year for an extensive VZ, 60 – 99% for an intensive VZ and only 18% for a gravel roof. In addition, green roofs can store the water during heavy rainfall and release it with a time delay, placing significantly less pressure on the local stormwater network. VZs therefore lessen the consequences of heavy rainfalls (Enzi et al. 2016; Knoll et al. 2022). Another problem of extreme weather scenarios

are the increasing temperatures. This negatively impacts animal species because heat stress is detrimental for their health, decreases their libido, the embryonic survival, and fertility (Collier et al. 1982; Crescio et al. 2010; Gonzalez-Rivas et al. 2020; Klockmann, Günter, and Fischer 2016; Teixeira et al. 2013). PV and TS systems do not have any direct influence on the occurrence of heat while a VZ can actively reduce the heat pressure because plants provide shade and evaporate (Enzi et al. 2020; Daniel, interview, Formanek, interview; Hackstock, interview; Pitha, interview; Reisinger, interview).

Biodiversity criterion

Climate change has a major impact on biodiversity, but REs can reduce these problems and its ongoing consequences. However, even if REs will enhance the situation, they could also cause some negative effects on the flora and fauna. PV and TS systems have got minor detrimental effects compared to other REs because they do not create any noise or chemical pollutants during their usage phase (Reisinger, interview; Tsoutsos et al. 2005).
Regarding their impact that PV or TS systems might have on biodiversity if they are installed on roofs there is currently not much research. However, a few studies searched if there could be an effect if they are implemented on an open space such as parks or green spaces in the neighboring areas of the city. Their results reveal that the impact on the wildlife depends highly on the location and their surroundings. For example, PV panels that are implemented on free landscapes are usually surrounded by fences which limits the free movement of animal species. Animals can only enter the area through small spots, and this prevents bigger animals like deer or wild boars to enter the habitat. Sometimes the area and the soil beneath the panels is cultivated with herbicides to prevent unwanted vegetation growth. A study in the UK showed that the grassland beneath PV was less diverse due to the different air temperature and cultivated soil. These outcomes are detrimental for the health and habitat of the animals and deteriorates the diversity of species (Armstrong, Ostle, and Whitaker 2016; Fthenakis et al. 2011; Walston et al. 2016). In contrast, however, most studies have come to the opposite conclusion because PV panels help to preserve plants during heatwaves and periods of drought. They provide shade and increase the diversity of the habitat which is in turn beneficial for animals. Additionally, the fence is seen as an advantage as it protects several species for external disturbance like humans or predators. Rare bird species like Wheatear, Hoopoe, Woodlark and Crested Lark were found again. These positive effects could be even enhanced by a wildlife-focused design and several adaptions during the installation (Blaydes et al. 2021; Henhofer 2021; Jarčuška et al. 2024; Peschel et al. 2019). Even if these results were conducted in solar parks and therefore their significance for sealed roofs is low, they still

show that PV modules in general do not affect animal species negatively. They underline instead that PV panels do not banish species or jeopardize the diversity of the animals.
There are hardly any studies that investigate the link of PV panels on the mortality rate of animals. One study in South-California measured in a rural area found a slightly increased mortality rate of birds due to PV and solar power towers (Walston et al. 2016). Another one underlined the danger of PVs for horseflies because they are lured to the panels due to the reflection. As soon as they touch the PV panel they get killed because of an electrical shock. The death of horseflies, however, is not seen as a major concern as their deaths are negligible when taking into account the large livestock (Blahó et al. 2012). Additionally, the light pollution of PV panels causes water insects to lay their eggs on the PV modules instead of natural waterbodies, however, special anti-reflective coatings can mitigate this problem (Daniel, interview; Immitzer, interview; Száz et al. 2016). Even if the effect of solar panels on birds is less studied, it is not generally seen as a major concern. A collision with PV modules might only exist with vertically positioned solar power towers or if they strongly reflect the sunlight at certain times (Bennun et al. 2021). Reincke (2021) mentioned that the installation of PV panels on rooftops should not be implemented only if rare bird species would use the rooftop as their breeding area.
These findings show that PV panels do not have a significant influence because the reflection of the PV panels can be prevented and the slightly higher mortality rate to insects or birds can be neglected. Additionally, the interviewed experts share the same consensus that the systems do not have an impact on biodiversity (Daniel, interview; Immitzer, interview).
TS systems and their impact on biodiversity is barely studied. The reason for this could be due to their negligible impact on the abundance of species. TS modules are not uniformly flat. They consist of individual tubes and because of that they do not create clear shade. The shade rather moves with the daytime and the amount of sunlight. This means that the animals do not really benefit from this as it provides no opportunity for a place that gets cooler compared to other spaces. An unstable shade has minor effects on the microclimate and the biodiversity (Reisinger, interview). Besides, no hazardous substances are produced during the utilization phase, thus the collectors are harmless during their operation (Hackstock, interview; Suuronen et al. 2017). The only concern lies in a pollutant which can occur through the coolant change. The small risk of an accidental water pollution because of a leak could lead to extreme high temperatures of the TS collectors and could initiate a fire. However, the coolant liquid should be replaced every 2 to 3 years only and a potential leakage can easily be controlled by good working practice (Reisinger, interview; Tsoutsos et al. 2005). This leads to a conclusion that

there is likely no effect on biodiversity from TS systems (Hackstock, interview; Reisinger, interview).
VZs in contrast to PV and TS are influencing the environment a lot, although their impact depends on the type of plants which are used. Generally, planted roofs in urban areas provide habitats for bees and insects no matter if these are extensively or intensively vegetated. Additionally, some species which are sensitive to drought and frost can survive in the long term and form nutrient cycles and food relationships if the substrate height is around 15 cm (Mann 1996). VZs which are designed to accommodate different nesting habitats and diverse native plants support bee conservation (Tonietto et al. 2011) and green roofs with a more complex vegetation enhance urban biodiversity for different arthropod species (Madre et al. 2013). Animal species, therefore benefit in general from greater plant diversity in urban areas leading to a flora and fauna composition that significantly correlates (Tonietto et al. 2011). However, according to some studies there is a difference between the ground-level and the roofs. The richness and abundance tend to be greater at the ground-level compared to green rooftops except for Heteroptera and especially leafhoppers because they were found almost twice as much on green roofs than on the ground-level (MacIvor and Lundholm 2011). Nevertheless, a VZ on roofs support a wide variety of insects and uncommon species (Braaker et al. 2017; MacIvor and Lundholm 2011; Tonietto et al. 2011). This leads to the general assumption that VZs on roofs increase and sustain biodiversity (Formanek, interview; Hietel et al. 2016; MacIvor and Lundholm 2011; Pitha, interview).
In summary, VZs will provide the most benefits for the abundance and richness of species. TS systems in contrast have been less studied but they might not have a significant effect on biodiversity while the interviewed experts also stress that there is not a correlation. PV systems in contrast have minimal negative effects. However, those effects can be prevented by using an anti-reflective coating, different materials, and by installing PV panels mainly horizontally. A possible extent of the impact VPSS would generate if they would be installed on all rooftops is hardly to guess. However, a ranking out of the VPSS technologies is clear: VZs are having the best impact on the abundance of animal species. Followed by PV because they can provide additional shade and their negative effects can be avoided. Lastly TS systems might not enhance nor deteriorate the situation.

Carbon dioxide criterion

Every VPSS system emits CO_2 during their production while it also leads to fewer CO_2 emissions because other forms of energy production which emit a higher amount of CO_2 are substituted. TS and PV are green energy sources and replace fossil fuel technologies. Treyer,

Bauer, and Simons (2014) showed that fossil fuel technologies are having the highest GHG emission factor per kW_h electricity within their whole life cycle of power generation with around 400 – 900g CO_2eq/ kW_h. Even if the fossil fuel power plants implement Carbon Capture and Storage (CSS), which is a future obligation implemented by the EU, their emissions are still around 120 – 190g CO_2eq/ kW_h. In contrast, nuclear and REs cause roughly 3 – 24 g CO_2eq/ kW_h. Besides, the solar energy systems emit zero air pollution during the usage phase of power generation (Aman et al. 2015; Reisinger, interview).
PV technologies release harmful gases only during their production. In some thin-film technologies, nitrogen trifluoride (NF_3) is sometimes still used for cleaning and coating, whereby some residual quantities can escape into the atmosphere. NF_3 is 17 times more harmful to the climate than CO_2 (Wirth 2023). One study calculates the CO_2 savings by comparing the produced green energy with the average Austrian energy mix. This includes the upstream emissions, i.e. all direct and indirect emissions that occur along the supply chain of PV and their downstream emissions. The results quantified a possible CO_2 saving of 0,2313 kg CO_2eq/ kW_h by taking Austria's energy mix from the base year 2021 as a comparable figure. This in turn results in a substitution of 1.642.230 tonnes of CO_2eq per year if one considers the economic potential (7,1 TW_h) of the rooftops. In other words, a saving potential of 33 kg CO_2eq calculated per square meter is possible (Formanek et al. 2023). Another study calculated the substitution factors for PV by using a simulation of the European electricity market. This means that the authors used the real European electricity market between 2013 and 2017 and compared it with a fictitious European electricity market without the renewable electricity production. Additionally, the highly fluctuating generation profile of PV was taken into account due to the pronounced diurnal and seasonal differences. However, although this study focused on Germany, their results show that in 2018, the electricity generation from PV diminished approx. 0,627 kg CO_2eq/ kW_h which avoided almost 29 million tonnes of CO_2eq GHG (Lauf and Schneider 2019). The difference of 0,3957 kg CO_2eq/ kW_h could be explained by the additional degree of efficiency that PV technologies experienced over the last couple of years and the utilized figures of the electricity market that improved towards more green energy sources in Austria (Daniel, interview; Immitzer, interview).
The TS system contributes also to a reduction of CO_2. By the end of 2021 the annual collector yield of all solar thermal technologies were 426 TW_h globally which corresponds to a final saving of around 145.4 million tons of CO_2 and 45.9 million tons of oil (Weiss and Spörk-Dür 2023). In Austria in 2019, 5 million m^2 thermal solar collectors produced 3,5 GW_{th} which equals a heat utilization of 2.081 GW_h and diminished the CO_2 amount up to 353.713 tons

(Vogl, Sattler, and Grgic 2021). Formanek et. al. (2023) calculated the CO_2 savings by comparing the generated heat with the average Austrian district heating mix, because this is the widespread form of generating heating in Austria. This was assumed because the district heating mix depicts the current representative energy mix. Their estimation included the upstream emissions, that occur along the supply chain containing direct and indirect emissions and the downstream emissions like the different options for disposal and possible recycling approaches again. The finding was a possible CO_2 reduction of 0,2022 kg CO_2eq/ kW_h by taking Austria's energy mix from base year 2021 as a comparable figure. This leads to a substitution of 3.870.544 tonnes of CO_2eq per year for the economic potential (7,1 TW_h) of the rooftops in Austria. Therefore, it exists a saving potential of 78 kg CO_2eq measured per square meter. The study of Lauf and Schneider in Germany again quantified a potential CO_2 saving of 2.198.858 tonnes, which equals a net-prevention factor of 0,247 kg CO_2eq/ kW_h. They calculated the annual final energy yield by considering the installed collector area, the utilization-specific yield factor, and the annual global solar radiation in Germany. This led to a heat supply from TS energy of 8.877 GW_h in 2018 while the substitution factor was the energy consumption of private households, and their heat generation from conventional energy sources. This result represents a complete vacuum tube collector or flat plate collector system which produces hot water, including hot water storage tank and control station. The slight difference between those two prevention factors is mainly due to the minimal difference within the conventional energy sources as their substitution factor.

Finally, VZs inherit a special role because plants sequester CO_2. Due to photosynthesis they convert CO_2 into glucose ($C_6H_{12}0_6$) and oxygen (O_2) which actively reduce the amount of CO_2 in the environment (Alves et al. 2019; Bevilacqua et al. 2017; Enzi, Formanek, and Peritsch 2020; Foustalieraki et al. 2017; Mann, Mollenhauer, and Westerholt 2023). Trees play a major role by diminishing CO_2 and thereby delaying climate change. The CO_2 absorption of extensive plants like moss, stonecrop, grass, or herbaceous plants absorb between 0,7 and 1,2 CO_2 kg/m^2. Intensive plants like shrubs, lawns, or trees can even absorb between 1,9 and 2,9 CO_2 kg/m^2 per year (Herfort, Tschuikowa, and Ibañez 2012). For example, the national average of CO_2 sequestration of urban trees in the United Stated is 22.8 million tonnes annually (Nowak and Crane 2002). In consideration of the rooftop potential in Austria a CO_2 absorption measured for an extensive rooftop within the first three years leads to at least 0,9 kg/m^2 less CO_2 due to the above-ground biomass only. Additionally, the potential savings within the substrate and the roots is estimated significantly higher because VZs enhance the situation by providing an additional insulation which in turn leads to less demand for heat production (Herfort, Tschuikowa, and Ibañez 2012; Enzi, Formanek, and Peritsch 2020). Next to these advantages there are also some negative effects of a VZ and their impact on pollution. The main problem lies within the polymer production of the different layers that are needed to install the VZ on the roof. Especially the manufacturing process of polypropylene and polyethylene needs a high amount of energy while toxic substances are released to the air. Since the layers of extensive green roofs are thinner, they require less material which therefore leads to less toxic substances compared to intensive rooftops. Therefore, green roofs can be only a sustainable option if they are planned on a long-term base, as it takes between 13 – 32 years to balance the produced air pollution during its production process (Bianchini and Hewage 2012a). Extensive green roof systems can make a major contribution to CO_2 reduction. The above-ground biomass of the plants can absorb up to 1.2 kg/m^2 of CO_2 with an optimal plant composition, considering the rotting process. Extrapolated to Austria's roof area of 738 km^2 as determined by Fechner, this corresponds to a CO_2 reduction potential of 885.600 tonnes of CO_2eq per year (Formanek et al. 2023; Herfort, Tschuikowa, and Ibañez 2012) which stands in the comparison to the volume of 61.49 million tonnes in 2022 in Austria (Ritchie, Roser, and Rosado 2020). This calculation, only considered the biomass celestial, however, especially the soil inherits a very large carbon pool as well (González-Pérez et al. 2004). Furthermore, the albedo effect has not been investigated as well. VZs have a higher albedo which means that they have a cooler surface temperature compared to gravel roofs or bitumen which in turn could lead to less energy demand within the building for example (Scharf, Pitha, and Trimmel 2012). This could diminish the CO_2 demand indirectly and would have a positive impact on the CO_2 calculation.

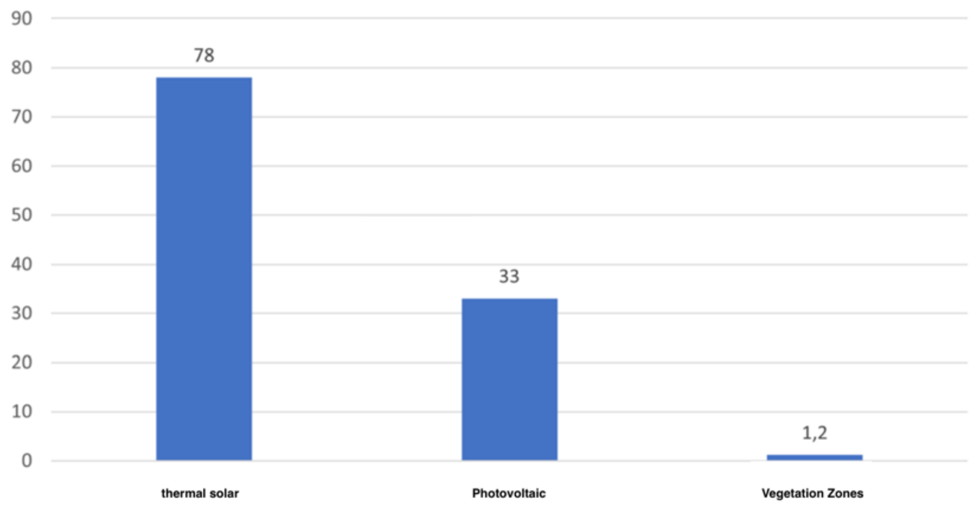

Figure 7: CO_2 saving potential in kg per m^2 and year.

(source: Formanek, Susanne, Andreas Dreisiebner, Florian Egger, Barbara Fontana, Roman Fritthum, Roger Hackstock, Alessa Klie, et al. 2023. 'Mehrwertorientierte Dachflächennutzung: Positionspapier für mehrwertorientierte Dachflächennutzung im Bestand und Neubau (2023) '. Wien: Grün statt Grau. https://ig-lebenszyklus.at/aktuelles/publications/mehrwertorientierte-dachflaechennutzung-positionspapier-fuer-mehrwertorientierte-dachflaechennutzung-im-bestand-und-neubau-2023.)

Taking these limitations into account it has to be noted that some values are still missing. Nevertheless, in relation to the investigation of Formanek et al. (2023) the CO_2 saving potential in kg per m^2 annually states that TS has the most potential (78 kg/m^2 of CO_2), secondly PV (33 kg/m^2 of CO_2), and finally green rooftops (1,2 kg/m^2 of CO_2) are having the lowest CO_2 saving outcome. Taking the huge differences into account the neglected values might only change the result slightly and therefore this thesis will consider their results for the analyses (figure 5). These figures also have to be seen in a wider context. Austria polluted the environment with 61.49 million tonnes of CO_2 in 2022, which corresponds to 6.9 tonnes per person per year (Ritchie, Roser, and Rosado 2020). If the possible saving potential of each VPSS on Austria's rooftops are related to the amount of CO_2 consumed in Austria, the result is that implementing TS could potentially lower the CO_2 balance by 2.67%, while PV and VZ could reduce it by 6.29% and 1.44%, respectively. However, this calculation does not solely apply to Austria's CO_2 consumption, as some production occurs abroad. This emphasizes that the use of roof surfaces with VPSS offers only a marginal contribution to reducing overall CO_2 emissions. Further research could explore how renewable energies and/or green areas might effectively diminish or even neutralize Austria's carbon footprint.

The social perspective

The social perspective will be investigated by focusing on the impacts that VPSS have on the psychological health and the physiological health of city dwellers. These two criteria have been selected for several reasons. According to the Cambridge Dictionary (n.d.) the word "social" is defined as an activity "in which you meet and spend time with other people". Thus, the different technologies will be evaluated beyond this definition and places its importance on the psychological health of city dwellers and how rooftops and the utilization of VPSS could increase the interaction of people. Secondly, the physiological health will be taken into account because it is one key dimension of the OECD (n.d.) well-being framework. The OECD measures the contentment of people by regarding eleven key dimensions of which five are closely linked to the mental health, four are linked to the economic stability, one stands for the ecological environment quality, and the final one measures health. The dimensions of the economy and ecological environment have already been partly covered by this thesis. However, the possible impacts VPSS could have on the health of city dwellers has not been considered so far. Therefore, the second aspect will be analyzed by investigating how VPSS might have an impact on the physiological health of humans.

The psychological health and the physiological health criteria, however, are also highly linked to each other because social connections significantly influence the long-term physiological health as they reduce the mortality risk (Holt-Lunstad 2021; White, Gaines, and Jha 2014). Keeping this in mind these aspects will be analyzed in the following.

In general, VZs and their impact on the social criterion have been investigated in detail while PV and TS systems are less surveyed because they contribute little to the social aspect of the TBL approach. However, it is worth noting that on a broader view PV systems could have an advantage globally because the technology can help address the electrification gap in some underdeveloped regions of the world. Many healthcare facilities are without any power provision and even basic services cannot be executed. PV could solve this problem and increase the reliable service provision, improve the quality of care, and enhance the health outcome (Dholakia 2018). Nevertheless, in Austria there are not any concerns of a lack of electrification.

Psychological criterion

Climate change has a direct impact on the ecological environment in which people and all species live in. The environment is deeply interconnected, so the effects of climate change can trigger additional issues, creating a snowball effect and leading to even more problems. The World Health Organization (2022) states that climate change "exacerbates many social and environmental risk factors for mental health and psychosocial problems, and can lead to emotional distress, the development of new mental health conditions and a worsening situation for people already living with these conditions." Therefore, one should be concerned about the mental well-being of the people in the context of climate change. The mental health of humans have also an impact on the economy because research shows that in Austria mental disorders result in healthcare costs that are 37% higher, total cost twice as high, and lost productivity costs 2.5-times higher than those without mental disorders. (Łaszewska et al. 2020; Shen 2023).

In relation to VPSS, PV and TS systems have no direct influence on the mental health of people (Daniel, interview; Hackstock, interview; Immitzer, interview; Reisinger, interview). They mainly cause an indirect effect. First, the problem of rising energy prices could increase a psychological burden because it puts additional pressure on the financial situation of private households. Second, those technologies are climate friendlier solutions which could develop the feeling of being part of the energy transition by the costumers. It might lead to a sense of control and a positive feeling because PV and TS systems generate a beneficial impact in the context of climate change. For example, Klaus Reisinger states in his interview that he feels extremely satisfied by having his own PV and TS systems on his roofs (Daniel, interview; Hackstock, interview; Reisinger, interview). Third, they slow down the progressive process of climate change. This in turn could diminish the negative effects that are caused by climate change such as heat stress and therefore delays the potential rise of mental health problems like depression, burnout, or anxiety.

A direct effect that could occur because of PV modules is a potential increased brightness and glare which leads to discomfort and visual inconvenience (Petherbridge and Hopkinson 1950; Shin, Yun, and Kim 2012; Wirth 2023). However, one guideline that must be followed when a PV module will be installed is dedicated to avoid potential dazzle and thus the possible risk can be neglected (Daniel, interview; Immitzer, interview). People in Austria tend to have a positive association towards PV systems in general because 71% would support an expansion of PV and 74% would favor PV systems on roofs (Hampl et al. 2022).

The correlation of TS systems on the mental health situation is barely surveyed which leads to the conclusion that there are not any positive nor negative effects that might influence the mental health of people directly. This has been also underlined by the interviewed experts (Hackstock, interview; Reisinger, interview).

VZs in contrast can increase the well-being of people in general. First, VZs reduce the temperature and therefore the associated thermal comfort of city dwellers. People feel more comfortable if they were surrounded by green areas. Their thermal well-being on roofs with a VZ increased from "hot" to "slightly warm" but this effect wasn't apparent on the ground level (Enzi et al. 2016). Nevertheless, higher temperatures are reduced on roof areas and the interaction of various types of vegetation across different levels is reasonable. This suggests that green roofs alone may not produce a noticeable effect at street level, but they constitute a crucial aspect of the comprehensive green infrastructure, thereby amplifying the positive impact (Pitha, interview). Residential greenspaces and lower temperatures increase the mental health, improve the sleep quality and the productivity outcome of people (Hou et al. 2023; Seppanen, Fisk, and Lei 2005; Stenfors et al. 2023). The productivity outcome in particular could generate an effect on the economy of Austria because an enhanced thermal well-being leads to an increased typing and thinking productivity of 46% (Kükrer and Eskin 2021). Another survey concludes that at optimal temperatures around 22°C the productivity of office workers can improve up to 18% (Ngarmpornprasert and Koetsinchai 2010) while relative productivity first increases and then decreases as the temperature varies from 16°C to 28°C (Geng et al. 2017). The improvement in productivity could than lead to more job opportunities, higher per capita income and a better quality of life (Hayward and Kuper 1978).

Secondly, VZs can mitigate noise levels by counteracting the sound reflection caused by urbanization, thereby reducing residents' exposure to noise. The result without VZs is that a reverberation effect occurs which is caused by oscillating sound waves. This has an impact on the overall volume and can create a chaotic noise pattern due to temporal shifts in the reflections. Noise effects on sleep quality impairs human communication and cohabitation so that the consequences are fatigue, insecurity, a lack of self-confidence, irritation, misunderstandings, and reduced performance at work. Children suffer particularly from noise in terms of their linguistic development, well-being and social behavior (Guillaume, Gauvreau, and L'Hermite 2015; Khomenko et al. 2020; WHO Europe 2018). According to the WHO (2018) an increase in the risk of ischemic heart disease can be observed above a daily time-weighted continuous sound level of 53 dB. However, in Vienna a large part of the urban population is exposed to a continuous noise level of between 55 – 60 dB during the day (Gartner and Ortner 2023). Plant growth on roofs, on the ground and on vertical surfaces in comparison can reduce the reflection of noise and thus the general noise level. A planted dry substrate can reduce the amount of noise by 8 dB, and if the soil of the substrate is wet noise can be reduced by up to 18 dB (Enzi et al. 2021; Guillaume et al. 2015; Markevych et al. 2017). This could also have an impact on the labor productivity because the productivity decreases up to 30% under the influence of constant noise of 70 to 95 dB and even a smaller noise level (50 – 60 dB) causes a significant psychological burden on the nervous system. Besides, if the noise level improves by 1 – 2 dB it leads to a reduction of 1% in labor productivity and harms the economy (Shirokov and Tikhnenko 2020). Hence, a decrease in dB resulting from VZs not only lowers the perceived noise level but also enhances the overall well-being and mental health of urban residents while it could potentially boost labor productivity and contribute to economic growth.

Thirdly, intensive VZs on rooftops could be used for urban agriculture or a space to interact with other people. Urban agriculture has got positive effects as it delivers food security. Especially, in lower-income regions, it creates a space to develop a network within the neighborhood, and thus enhances the well-being and mental health situation of people in general (Poulsen et al. 2015; Simon-Rojo 2019).

Finally, a 10-year longitudinal dynamic panel study in Wales showed that VZs enhance the mental health overall. The study tracked 2.3 million adults and revealed that having more green spaces nearby reduces the likelihood of experiencing mental health problems such as anxiety or depression by 7% for every 10% increase in access (Geary et al. 2023). Walks through parks increase the ability to reflect on a problem, and raise positive emotions (Mayer et al. 2009). This shows that green areas generally increase the positive well-being of people (Sarkar, Webster, and Gallacher 2018). Moreover, Vidal Yañez et al. (2023) studied the effect of the "Eixos Verds" Plan in Barcelona which mainly involves the establishment of street greening, some street furniture, and playgrounds. The authors showed that the exposure to greener areas prevented self-perceived poor mental health which led to 14% less visits to the mental health specialists, the usage of depressants was diminished by 8% and the antidepressant utilization of 13.000 annual cases could be prevented. Additionally, savings occurred economically because €45 million could be avoided annually due to the indirect and direct costs in the Spanish tax-funded healthcare system. This effect of a VZ on the economy should be viewed with caution as many external factors are difficult to consider and the results are very bound to local conditions, but in general the survey indicates that further positive feedback loops could be possible.

Concluding, VPSS can have an impact on the mental health of people. PV and TS systems mainly enhance the situation by having an indirect effect of humans and their mental health situation. VZs on roofs in contrast have more measurable effects. However, this effect mainly appears if humans are allowed to use the roofs as an additional space to relax and be surrounded by plants. If roofs are solely used extensively the impact could be very low as people are probably just seeing the green areas. Nevertheless, only the positive visual comfort of green areas could affect the mental health of city dwellers. This is highlighted by a longitudinal study carried out in Britain, revealing that individuals witnessed a notable enhancement in mental health by 1.5% in the initial year post-relocation, attributable to the positive visual ambiance (Alcock et al. 2014).

Physiological health criterion

The health threat of city dwellers is increasing due to the densely populated areas and fewer areas to unwind. Cities like Vienna are often not compliant with international standards in terms of air pollution, traffic noise, physical activity, heat, and green spaces. Such incompliances have a high impact on humans, for example human life expectancy is reduced by 199 days on average in big cities like Vienna. The cause for this earlier mortality is the high exposure to air pollution followed by less physical activity, too much noise, a lack of green space, as well as high temperatures (WHO 2016).

Starting with the aspect of air pollution it becomes clear that VPSS can increase life expectancy as a result of reduced carbon footprints as discussed in chapter "Carbon dioxide criterion" (cf. p. 34). An increase of CO_2 concentrations by 1 mg/m^3 corresponds to a 2.08% rise in the daily years of life lost due to non-accidental causes, cardiovascular diseases, respiratory diseases, coronary heart disease, stroke, and chronic obstructive pulmonary disease (Wang et al. 2021; Amuka et al. 2018). This suggests that TS could have a beneficial impact on the life expectancy of humans because it mitigates the most CO_2 in comparison to PV modules and VZs.

Taking a closer look at the noise level it is evident that almost a third of adults in Vienna are exposed to road traffic noise above 55 dB which exceeds the recommended maximum of 53 dB. However, once the noise level surpasses 65 dB, it triggers a more pronounced impact on physiological health. This results in individuals reporting various health effects, such as tinnitus, hearing loss, stress, vasoconstriction, and other cardiovascular impacts, as well as an elevated accident rate, and antisocial behavior (Yoshida et al. 1997). As mentioned before the noise level can be reduced by plants by approximately 8 dB up to 18 dB if the substrate is wet. PV modules and TS panels in contrast cannot diminish the amount of noise (Enzi, Formanek, and Peritsch 2021; Guillaume, Gauvreau, and L'Hermite 2015; Markevych et al. 2017).

In terms of days with high temperatures that are resulting in significant heat stress (32°C to 38°C), mortality rates are expected to increase by 12% and 7%, respectively, compared to days without thermal stress (26°C to 32°C) (Błażejczyk et al. 2018). High temperatures, however, can only be actively reduced by plants. The cooling impact of plants, predominantly influenced by factors such as species group, canopy cover, and the size has the potential to decrease air temperature by as much as 6.72°C (Feyisa, Dons, and Meilby 2014). PV modules and TS panels in comparison do not actively reduce the temperature. These systems simply absorb or reflect the sun light similar to an unutilized rooftop surface and therefore may not have any considerable impact on the temperature.

The final aspect of a higher mortality in cities mentioned by the WHO (2016) is that green spaces have an impact on the health of city dwellers. The increased morbidity risk could be partly prevented by implementing intensive VZs because even if green spaces enhance the overall wellbeing they are not reachable for about 80% within ≥ 0.5 ha and 300 m linear distance in Vienna although the WHO recommended that there should be universal access to VZs within 300 m linear distance (Khomenko et al. 2020; WHO Europe 2018). A study by Barboza et al. (2021) demonstrated that adhering to the WHO recommendation for access to green spaces could avert 42,968 deaths each year in Europe, accounting for 23% of total natural-cause mortality and 245 years of life lost per 100,000 inhabitants. Nonetheless, while parks at ground level may offer the most significant benefits, intensive VZs on rooftops accessible to the public could also generate a small impact. This indicates that cities in particular are places where people are vulnerable to climate change effects which results in an earlier mortality and could be diminished by implementing more VZs.

In addition to the factors identified by the WHO (2016) which lead to premature mortality in densely populated cities, such as too much noise, insufficient green spaces, and high temperatures, VPSS possess a range of other advantages and disadvantages regarding physiological health.

For example, REs can delay the ongoing process of climate change due to their more environmentally friendly life cycle (LC) in comparison to other energy sources such as coal, oil, or gas. Hence, it is crucial to compare TS and PV systems by taking their whole LC into account. A reliable LC should consider all stages like the raw materials, the production, transportation, installation, and the waste-management. An appropriate approach would be the "cradle-to-grave" analysis which has been done by Mahmud et. al. (2018). The researchers found major differences between TS and PV systems and their impact on the health of people. These differences within their LC can be traced back to several factors:

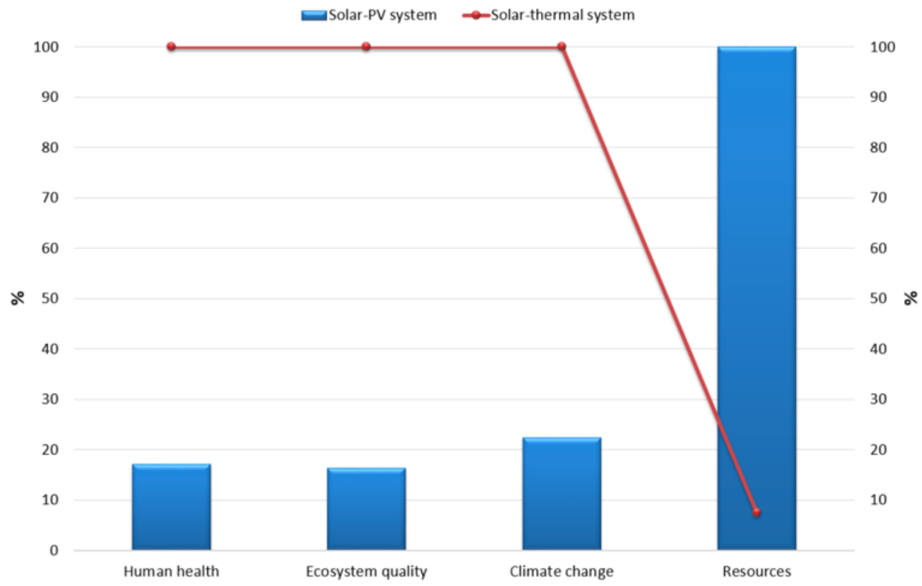

Figure 8: The cradle-to-grave impact comparison between TS and PV.

(source: Mahmud, M. A. Parvez, Nazmul Huda, Shahjadi Hisan Farjana, and Candace Lang. 2018. 'Environmental Impacts of Solar-Photovoltaic and Solar-Thermal Systems with Life-Cycle Assessment'. Energies 11 (9): 2346. https://doi.org/10.3390/en11092346.)

First, the impact that PVs have on human health is mainly due to their toxic materials and their EoL. The production of PV systems is energy intensive, and PV solar cells need toxic materials which have been restricted by the global environmental protection agencies like Cadmium, Lead, and Nickel (Aman et al. 2015; Tsoutsos, Frantzeskaki, and Gekas 2005). Toxic substances can leak from the modules over long periods of time if they are not checked frequently. The largest share of the market is made up of Wafer-based silicon modules which often contain lead but lead can be substituted at minimal additional cost (Wirth 2023; Immitzer, interview). Bakhiyi, Labrèche, and Zayed (2014) state that some hazardous chemicals could threaten PV manufacturing workers with health consequences through dust, smoke, vapor inhalation, and eye contact. However, Vera Immitzer (interview) emphasizes that there is not a risk for PV installers. The utilized toxic chemicals within PV systems and their impact on the human health during their operation is considerably low because they only become a problem if the PV module is severely damaged. This points out that as long as PV modules are not exposed to extraordinary forces and they are checked occasionally, the ecological impact is marginal (Daniel, interview).
Second, the LC of all PV components shows that the power meter, the cable, and the inverter are mainly responsible for the high impact on the environment. The cable and the inverter were primarily responsible for the main amount of hazardous nitrogen oxide and CO_2 emissions while the power meter needs a lot of energy to ionize electrons from atoms during its operation. This can be dangerous for the human body because ionizing radiation can affect

the DNA and potentially damage living cells (Mahmud et al. 2018). However, PV systems usually have no direct impact on the human health during their operation (Immitzer, interview).

The EoL of PV panels is another potential risk for humans, especially if their waste management is inappropriate. Modules that are dumped in landfills or are exported to developing countries (which normally do not have a good disposal system) come with a high health risk connected to hazardous metals, which should be removed carefully before PV panels are thrown away (Nain and Kumar 2020). If the leachate is contaminated, human health is endangered via the ingestion and the dermal pathway. Metals like Cadmium, Indium, Gallium, Molybdenum, and Tellurium are posing a risk to subpopulations through the soil-ingestion and soil-dermal pathway (Nain and Kumar 2020). The groundwater-dermal pathway above all increases the risk of cancer. Therefore, recycling technologies should be implemented. PV panels which are made out of recycled components require only 1/3 of the energy that would be used to build up a PV panel from scratch (Aman et al. 2015; Nain and Kumar 2020). This indicates that due to the toxic substances that are used in PV panels it is important to develop a recycling process to diminish the amount of required energy and decrease the possible dangerous effects on the physiological health. In 2012, the EU established the new WEEE – Directive (Waste Electrical and Electronic Equipment Directive) to obligate PV manufacturing companies to take their PV modules back and reuse their resources which is a step towards a better process overall. Besides, there are ongoing developments to increase the amount of the recycling rate (Aman et al. 2015; Bakhiyi et al. 2014; Wirth 2023; Immitzer, interview).

TS collectors in comparison do not have any toxic materials and therefore their disposal is easier. The TS collectors can be disposed in the same way as regular household waste and do not have to be regarded as hazardous waste, as it is the case with PV panels (Hackstock, interview; Reisinger, interview). However, by taking into account the whole LC of the entire TS system the result is different. Overall, the cradle-to-grave approach shows that the whole TS system on average is more dangerous to the human health, the ecosystem, and accelerates climate change (figure 8). The main reason for this is that the components of the entire TS technology rely on more hazardous materials and have got a higher impact on the land use, freshwater toxicity, acidification, ionizing radiation, marine and terrestrial eutrophication, and human toxicity. PV systems in comparison only consume more resources in this respect (Mahmud et al. 2018).

VZs in contrast utilize toxic materials like biocides, PVC, or redecides which inhibit that plants grow through the root resistant layer. However, producers are increasingly trying to eliminate the potentially hazardous materials by using mechanically active alternatives or other substances. Overall, toxic materials have, in comparison to PV and TS systems, very little influence and pose no danger to humans. Furthermore, nearly all components can be recycled, and the process continues to grow so that even the EoL stage has no impact on the human health (Formanek, interview; Pitha, interview).

Generally, VZs have a largely positive impact on the physiological health of humans. Firstly, natural environments increase the effect of the human well-being, enhance stress recovery, reduce the allostatic load, and harmonize the impact on the physiological stress reactions. Keeping in mind that stress is a subjective experience, individuals who report a substantial amount of stress in a study by Keller et al. (2012) have a 43% increased risk of premature death which could be prevented if VZs are in walkable distance. Secondly, due to photosynthesis plants reduce the amount of CO_2 and improve the air purification which creates a healthier environment and leads to fewer sick days (Alves et al. 2019). This indicates that being able to live in areas where green spaces are close by has a positive effect on the longevity and the occurrence of diseases which would speak in favor for intensive VZs on roofs (Haluza, Schönbauer, and Cervinka 2014; Takano, Nakamura, and Watanabe 2002). In numerical terms, enlarging the green space measured as in the Normalized Difference Vegetation Index by using a 500-meter zone is associated with a 0.95% reduction in overall non-accidental deaths (Villeneuve et al. 2012).

Finally, the Urban Heat Island (UHI) effect has a remarkable impact on the physiological health of humans as well. It describes an increased temperature due to overheating of the city compared to the surrounding suburbs because cities have a lower albedo value. A small albedo value results in buildings storing heat and acting as radiators at night so that the city does not cool down but remains hot (Formanek 2022). This means that if climate change continues, the Heat Island Effect alone could triple the number of heat-related deaths by 2080. Meanwhile the mortality rate among individuals with chronic health problems and elderly individuals is expected to be even higher (Wong, Paddon, and Jimenez 2012). This is illustrated by an increased death rate in the elderly from cardiovascular (3.44%), respiratory (3.60%), and cerebrovascular (1.40%) diseases due to a 1°C temperature rise (Bunker et al. 2016). Furthermore, another study found that for temperatures surpassing the optimal range, mortality rates rose by 0.47%, 1.86%, 12.82%, and 2.72% for malignant neoplasms, cardiovascular disease, respiratory diseases, and overall mortality, respectively, with every degree Celsius increase above the optimal temperature. Those optimal temperatures vary between younger individuals, below 65 years, with an optimal temperature of 15.5°C, and the elderly, above 65 years, with an optimal temperature of 16.5°C (Huynen et al. 2001). Heat-related mortality is already increasing in the inner districts of Vienna, as they are the most densely built-up area (Hutter et al. 2020). UHIs therefore lead to increased temperatures and trigger thermal discomfort in people which then causes stress and circulatory problems (Enzi et al. 2016). Plants provide a significant advantage in addressing this issue. They help cool the environment through transpiration, a process known as evaporative cooling and they convert more than 50% of absorbed solar energy into latent heat. (Enzi et al. 2016; Mann, Mollenhauer, and Westerholt 2023). This does not warm the surrounding air, which means that plants lead to significantly lower surface temperatures and a significant reduction in the Heat Island Effect (Knoll et al. 2022). Extensively planted roofs, however, have a small impact on the UHI effect, whereas intensively planted roofs contribute to a greater reduction in temperature. Besides, Loibl et. al. (2020) stress that greening should mainly be implemented at street level because city dwellers can benefit most from it. Nevertheless, even if VZs are planted on rooftops they can contribute to an improvement of the human health.

Summarizing the impact of VPSS on the physiological health of urban residents, VZs appear to have the most positive influence. This is because plants reduce illness occurrences by lowering stress reactions, decreasing noise levels, and mitigating the UHI effect, resulting in improved thermal well-being. In comparison to PV and TS systems, VZs utilize the least toxic materials, while PV systems rely on the most hazardous materials, which is particularly problematic if they are not properly recycled. Therefore, the main advantage would be generated if intensive VZs would be implanted on rooftops to improve the overall physiological health of humans.

Conclusion

This Master thesis explores the potential of rooftops in contributing to the overall sustainability goals, particularly in densely populated urban areas where every space is valuable. Unused rooftop spaces offer opportunities for various solutions, including VZs or RE systems like PV or TS. These technologies utilize the existing sealed surfaces of buildings, thereby eliminating the necessity for further land utilization. The study uses a qualitative research approach by evaluating a broad literature and conducting six interviews with experts such as Dipl.-Ing. Susanne Formanek, Priv.-Doz. Dipl.-Ing. Dr. Ulrike Pitha, DI

Vera Immitzer, Cornelia Daniel, Dr. Klaus Reisinger, and DI Roger Hackstock. Furthermore, the TBL approach offers a framework by analyzing the three main perspectives which are the economic perspective through the employment rate and supply chain, the ecological perspective through biodiversity and carbon dioxide levels, and the social perspective through psychological and physiological health criteria. Investigating these criteria aided to answer the hypotheses H1a: "What arrangement of VPSS will have the best impact for Austria in consideration of the TBL approach?" and H1b: "To what extent can the rooftops of Austria help reduce the negative impacts of climate change by building up VPSS?"

Concluding the economic perspective, TS systems would generate the most jobs in comparison to TS and VZs. However, due to a lack of data, the VZ perspective could not be examined appropriately enough to make a clear statement. The supply chain criterion shows a similar result, as TS systems contribute 75% to the added value of Austria, PV systems only 46%, and for VZs there cannot be drawn a conclusion again due to missing data. Currently the demand of PV modules, however, is significantly higher compared to VZs and TS. This leads to more installed PV modules and therefore the final revenue of PV-planners and PV-installers in Austria is notably higher (€1,684.1 million in 2022) than the revenue for the entire TS industry which equaled €151.6 million in 2022.

The environment perspective of the TBL approach reveals that the biodiversity will increase only if VZs are implemented on the roofs of Austria. In contrast, PV and TS systems do not have a direct impact on biodiversity. The second criteria of the environmental perspective about carbon dioxide reveals that TS systems enhance the situation the most because the amount of CO_2 that could be reduced by installing TS systems on top of Austria's entire rooftop space equals 3.870.544 tonnes of CO_2eq per year, followed by PV systems (1.642.230 tonnes of CO_2eq per year), and lastly by VZs with 885.600 tonnes of CO_2eq per year.

Finally, the social perspective indicates that VZs enhance psychological well-being by preventing mental health disorders like anxiety and depression, and improve physiological health by lowering mortality risk, reducing sick days, and mitigating the UHI effect for better thermal comfort. PV and TS systems, in comparison, only have an indirect effect or can be detrimental to human health due to the required rare earth elements, the utilized toxic materials, and the detrimental life cycle of the entire systems. Table 1 offers a concise summary of the primary benefits and drawbacks of each VPSS.

	Advantages	Disadvantages
PV	• Due to the highest demand, it generates the most revenue for Austria's economy (€1,684.1 million achieved by PV planners and installers alone). • The increasing electricity demand enhances the market situation of RE in the future which potentially leads to a greater demand in comparison to VZs and TS panels.	• PV has a high dependance on China because it produces main parts of the module. However, the regional added value for Austria will mostly be above 50%. • 4,2 jobs are needed per MW_{peak} which are less in comparison to TS (while there cannot be a conclusion of VZs because of missing data). • Potential negative effects on biodiversity. • Rare resources are exploited. • Less CO_2 reduction compared to TS and VZs by taking Austria's energy mix from the base year 2021 into account (33 kg/m^2 of CO_2 annually).
TS	• More efficient than PV modules in the production of energy. • 31 full-time jobs are needed per MW_{th}. • The production is mainly domestic with high export rates. • Reduces the most CO_2 in comparison to PV and VZ by taking Austria's energy mix from the base year 2021 into account (78 kg/m^2 of CO_2 annually).	• No data on the effect on biodiversity. • High prices due to less competition between TS companies. • Less demand results in a declining market, less R&D, and less funding. • More dangerous to the human health and the ecosystem due to the comparison of the whole LC. • Exploits rare resources.
VZ	• Increases biodiversity significantly.	• Less CO_2 reduction potential in comparison to PV and TS by taking

	• Diminishes the problem of extreme weather scenarios. • Diminishes heat stress for animals and humans. • Decreases the UHI effect which results in a better thermal well-being and fewer deaths. • Leads to a positive impact on the physiological and psychological health. • Increases the property value of 2-5%. • Less energy demand of 12-15% annually.	into account the above-ground biomass only (1,2 kg/m^2 of CO_2 annually). • Less data leads to an unclear situation about the impact VZs might have on the Austrian economy due to more jobs and a domestic or international supply chain. However, maintenance is more labor intensive in comparison to PV and TS.

Table 1: Conclusion of the main advantages and disadvantages of VPSS.

If the critics of the TBL approach are considered, the conclusion would be that VZs should be installed on the roofs of Austria because they have their main advantages in three categories (the biodiversity, the psychological, and physiological health situation of humans) of the investigated main criteria. TS systems have their main positive advantages in two categories (the employment rate, and the reduction of CO_2), and PV systems have their main advantage in only one category because they contribute the most to Austria's economy. However, this finding should be approached with caution. The higher economic value of PV systems is primarily due to their greater demand, leading to more installations and a higher revenue compared to TS systems and VZs.

Considering the two hypotheses of this thesis, the recommendation of the analysis is that in general VPSS systems enhance the status quo. Any system is better than an unused rooftop space. H1a explores which VPSS has the most favorable impact for Austria. Considering the Triple Bottom Line (TBL) approach, VZs emerge as the optimal choice. However, the potential higher demand of electricity in the future might increase the added value for PV systems. Furthermore, Klaus Reisinger (interview) stated that PV will probably prevail in the future because the demand rises, PV modules can easier provide heat with a heat pump, and the innovative possibilities offer more opportunities for adaptation compared to TS. Many surveys suggest that a combination of PV modules and a VZ on rooftops would get the most out of the surface. First, because plants would inhibit the overheating of PV modules so that their efficiency does not decrease (Mann and Mollenhauer 2021; Vogl, Sattler, and Grgic 2021). Second, plants profit from the provided shade of PV modules which results in less water stress and a healthier state in general (Tams, Paton, and Kluge 2023). Third, it increases the biodiversity even more because a combination would provide shade for the benefit of the animals due to the PV module and the planted space would provide a new habitat for animals (Vogl, Sattler, and Grgic 2021). Finally, the implementation of both technologies could have the greatest impact on the Austrian economy as it could create new jobs and generate more profit domestically even if the combined installation is more expensive.

To answer the question to what extent the rooftops of Austria could help to reduce the negative impacts of climate change (H1b) it can be concluded that an installation of every VPSS enhances the situation and delays the detrimental effects of climate change. This is mainly because they reduce the amount of produced CO_2. In addition, the advantage of VZs is particularly important because they can increase the richness of animal species, which helps inhibit negative feedback loops affecting the environment. However, to what extent each system helps to improve the situation cannot be said because of missing data.

Concluding, that that further research has to be done because the investigated criteria represent only a small subset of many factors. Nevertheless, they suggest that VZs are in comparison to PV and TS the most suitable option based on their outcomes.

Limitations and Policy Implications

The investigation of VPSS also inherits some challenges because the three systems are completely different in their production, their installation, and their outcome. Therefore, a comparison has to be made with caution. Nevertheless, rooftops provide a limited space for these systems and therefore a comparison is necessary. Furthermore, the existing literature is not always clear enough which type of collector or which type of PV module has been investigated. Therefore, the figures cannot be determined to one specific technology. However, this thesis compares TS, PV and VZs, which are fundamentally different so that the potentially minimal differing results due to the use of the different types within the technologies is negligible. Another important factor is that subsidies and political decisions have a strong impact on the demand which leads to more PV modules being purchased at the moment. The higher demand in the segment also leads to more research and more innovative solutions, which in turn might further increase demand. However, this could give a distorted picture of the end result because TS systems are in comparison to PV more efficient in their energy production. The question therefore arises which form of energy will be the most necessary in the future and which could possibly be best suited. The greatest limitation, however, of this thesis is that the literature has not been sufficient and specific enough to make an accurate statement. Even the interviewed experts were unable to address certain questions. The lack of data meant that no clear results could be calculated for Austria's roof areas. This underscores the necessity for further research and emphasizes the need for heightened attention to this matter, especially among policymakers. In view of the ever-increasing problems of climate change, it is essential to reach a conclusion quickly and then implement this solution promptly. The economy, the environment and people would benefit from this.

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Appendix

Interviews: Photovoltaic Systems

Cornelia Daniel

Cornelia Daniel is the founder of Dachgold e.U. and co-initiator of Tausend und ein Dach. Due to her expertise in the PV industry, she gives guest lectures within the discipline "Sustainability-Entrepreneurship" at the Karl-Franzens-University Graz and was named "Austrian of the Year" in the field of climate in 2020.
The interview has been conducted on the 07th of March 2024.

Catalogue of questions:

Krings: Over the years, PV systems have been optimized. Do you know whether this has led to additional potential CO_2 savings?

> Daniel: Yes, definitely. On the one hand, improved performance optimization enables more electricity to be generated. On the other hand, increasing performance of the modules plays a decisive role, as fewer modules are required to achieve the desired yield. This not only helps to reduce the CO_2 emissions generated during the module production, but also leads to a more efficient use of resources as fewer modules need to be used.

Krings: Why could it be currently uneconomical to feed all the electricity into the public grid due to the self-consumption priority?

> Daniel: The statement that it is uneconomical to feed PV electricity into the grid is clearly wrong. As long as the production costs are below the feed-in tariff, the system is always economical. As a rule, the production costs are always far below the electricity price and of course one may save even more if one saves the electricity price on the one hand and the grid costs and levies on the other.

Krings: What is the amortization period of the entire PV system including all necessary components like the inverter, cable, PV module, and so on?

> Daniel: We intentionally do not take the amortization period into account, as this is heavily dependent on the price of electricity. The higher the cost of grid electricity, the more economical a photovoltaic system becomes. As a rule, however, we can say that the amortization period for the entire system is between 8 and 15 years, assuming a system service life span of 30 years.

Krings: How often do you check whether it is still functional and how does this work?

> Daniel: A visual inspection between 3 to 4 years is generally recommended to ensure that everything is in order. More intensive cleaning is usually only necessary if problems occur.
> The location is particularly relevant. For example, cleaning plays a decisive role if the system is located near a chimney that emits a lot of smoke. In such cases, regular cleaning is essential, as soiling can impair electricity production. It is therefore important to take the location into account when determining the cleaning interval. Besides, if the system is not maintained and damage occurs, the insurance will be cancelled. Visual maintenance can always be carried out by the customer and should simply be carried out regularly.

Krings: How often does the entire system have to be replaced or when have the PV modules reached their End of Life?

Daniel: The modules must be completely replaced after 25 to 30 years.

Krings: How often do the roofs need to be checked? How many workers are needed and for how long? Do you also know much does this cost the installer per m²?

Daniel: The maintenance varies depending on the location. And regarding the questions about the required employees and costs, we don't have any data on this. In principle we can say that smaller systems can be installed in one day, while large systems may take a little longer.

Krings: How many jobs are required per MW_{peak} and to what extent could this be converted to m²?

Daniel: Unfortunately, I do not have any data to answer this question appropriately.

Krings: The production is mainly located in China, which according to research is the world's largest PV producer. To what extent does Austria's economy profit?

Daniel: Overall, high-quality European and Austrian alternatives are available in the photovoltaic sector, although they tend to be more expensive. However, many customers attach great importance to quality and favor products from Europe. The decision between domestic and foreign components depends heavily on individual preferences and cost considerations. Although installation, assembly and maintenance are carried out in Austria, many components and materials tend to be non-European, especially over the entire life cycle.

Krings: Do PV systems on rooftops in Austria have an effect on biodiversity?

Daniel: No as far to my concern they do not have any impact on the biodiversity.

Krings: Do PV systems have a direct impact on human health? I am referring to whether there are any possible toxic materials in PV modules and if there is a risk for PV installers or people in general?

Daniel: Lead and cadmium are the main problematic materials in PV systems. However, it was found that the systems only raise environmental concerns if they are significantly damaged. To put it bluntly, the PV system would have to be smashed into pieces to cause danger for humans. As a rule, normal damage such as that caused by heavy hail has no impact on the PV system. This means that as long as the system is not exposed to extraordinary forces, the ecological impact is negligible. And employees are not exposed to any danger during installation either.

Krings: Can the glare from PV systems cause extreme disturbance to people?

Daniel: No, the potential occurrence of glare is taken into account and avoided at the planning stage.

Krings: Do PV systems have a direct impact on people's mental health?

Daniel: Well, I wouldn't say that directly. However, one could argue that in the view of rising energy costs, the issue of energy poverty is a psychological burden. Using a photovoltaic system undoubtedly involves investment costs, but it is a cost-effective way of generating electricity. It therefore offers a certain form of independence. In addition, PV systems could be seen as an opportunity to be part of the energy transition, especially in the context of climate change. It could provide a sense of control and therefore have an impact. Nevertheless, I wouldn't say directly that this plays a significant role.

Krings: To what extent is recycling already being carried out in Austria, thereby reducing risks to the environment and human health?

> Daniel: Unfortunately, I can't say anything about this. I just know that there is a company in lower Austria that takes into account this problem and recycles PV systems.

Vera Immitzer

DI Vera Immitzer helps shape the political agenda in the field of renewable energies in various committees and has a particular focus on the specialized field of photovoltaics. As a long-standing employee, she has supervised international research projects and national conferences in this context and has been the managing director of the Austrian Photovoltaic Association since 2019.
The interview has been conducted through a written exchange on the 5th of March 2024.

Catalogue of questions:

Krings: Over the years, PV systems have been optimized. Do you know whether this has led to additional potential CO_2 savings?

> Immitzer: Yes, over the years, PV systems have improved in terms of efficiency and performance. These improvements have contributed to PV systems being able to generate more electricity per square meter from sunlight than previous generations of systems. This reduces the need for electricity from fossil fuels, which in turn leads to a reduction in CO_2 emissions.
> The exact amount of CO_2 savings through the optimization of PV systems depends on various factors, such as the specific technology, the size of the system, the location and the period of use. However, studies have shown that more modern PV technologies can lead to significant savings in CO_2 emissions compared to older technologies. The energy amortization, i.e. the time within which the energy required to produce the PV module is generated by the PV system, is less than two years.

Krings: The OeMAG must purchase the electricity on a mandatory basis and is the only buyer in Austria. What is the monetary profit of a PV system per square meter per year if the electricity is fed into the public grid?

> Immitzer: 1 square meter generates around 180 kW_h per year. If this electricity is fed into the grid and sold to an energy supplier or the OeMAG, the system operator receives 18 euros.

Krings: Which type of solar cell was mainly installed in Austria? (e.g. in DE wafer-based modules with a market share of 90%)

> Immitzer: In Austria, mainly monocrystalline solar cells are installed. These provide a higher yield than polycrystalline or thin-film solar cells. A specific market share is not known. Both are wafer-based modules.

Krings: What is the amortization period of the entire PV system including all necessary components like the Inverter, cables, and the PV module for example?

> Immitzer: The amortization of a private PV system is given within 10 years.

Krings: How often do the roofs need to be checked? How many workers are needed and for how long? Do you know how much does this cost the installer per m²?

Immitzer: The inspection intervals are only partially prescribed but must be carried out at appropriate intervals. As far as we are aware, there is no legal or standardized maintenance interval for private households. However, for business an interval of 3 – 5 years is recommended and, in some cases, also prescribed in the notifications.
The costs for recurring inspections of PV systems can vary depending on the region, the size of the system, the type of inspection and local regulations. It is therefore not possible to estimate the costs per m². In general, the costs per m² are lower for larger roofs than for single-family homes. For the other questions regarding the employees and the costs I do not have any data.

Krings: How often does the entire system have to be replaced or when have the PV modules reached their End of Life?
Immitzer: The product warranties for modules can reach up to 25 years, the actual service life is probably longer, inverters in contrast have warranties of 10-15 years.

Krings: How many employees are needed to install the system and for how long?
Immitzer: A private PV system of around 8 kW_{peak} is installed in one day by a team of 3 people.

Krings: How many jobs are required per MW_{peak}? To what extent can this be converted to m²?
Immitzer: In terms of installation alone, it is currently calculated at around 5 people per MW_{peak} over the year. Although the number of people has fallen continuously in recent years due to efficiency improvements. As a rule, the installation time depends on various factors, including the type of the system, its technical requirements, the availability of labor and the experience of the personnel.

Krings: The production is mainly located in China, which according to research is the world's largest PV producer. To what extent does Austria's economy profit?
Immitzer: In Austria, the module production, the inverter production, and the production of substructures and cables could be made. However, jobs which are created in Austria are primarily in the planning and assembly of systems.

Krings: Do PV systems on rooftops in Austria have an effect on biodiversity?
Immitzer: Since biodiversity is only found in open spaces on grassland and forests for example there is no influence on biodiversity. PV panels on open areas however have a positive effect on biodiversity. Therefore, a combination with green areas could have an impact on rooftops as well.

Krings: Do PV systems have a direct impact on human health?
Immitzer: No

Krings: Can the glare from PV systems cause extreme disturbance to people?
Immitzer: There are guidelines that must be observed when planning PV systems. A special guideline is dedicated to the potential glare from PV systems in order to avoid this.

Krings: Do PV systems have a direct impact on people's mental health?
Immitzer: No

Krings: How many toxic materials are in PV modules? Which of them can be replaced? Is there a risk for PV installers or people in general?

Immitzer: Photovoltaic modules usually consist of different materials. When installing the components, there is no danger to the installers from the components as the products are harmless.
It is also important to note that the solar industry is trying to use environmentally friendly materials and implement sustainable manufacturing and disposal practices. Research and development in this area continues in order to further improve the utilization of materials.

Krings: To what extent is recycling already being carried out in Austria and thereby reducing risks to the environment and the human health?

Immitzer: There are legal requirements for the collection and recycling of PV modules and inverters, which the initial distributors must comply with. Currently, there are ongoing developments which means that the recycling rate is continuously increasing.

Interviews: Thermal Solar Systems

Roger Hackstock

In 1999, the Industry Association Austria Solar was founded, which brings together all of Austria's leading suppliers of solar thermal systems. These cover over 80% of the Austrian solar market, in total the association represents the intersects of around 160 companies in the solar sector. Thus Roger Hackstock, managing director since 2002, has a deep insight into the industry.
The interview has been conducted on the 12th of March 2024.

Catalogue of questions:

Krings: Have there been any technological improvements in the production of thermal solar systems in the last 10 years?

Hackstock: In the last 10 years, there have been no improvements worth mentioning within the smaller systems. However, considering the larger installed collector areas, it can be said that the installation got faster, systems have become more efficient and components harmonizing better.

Krings: It will get warmer in the future, so more cooling energy will probably be needed. How suitable are solar systems for producing cooling energy? Is this economically viable or would it make more sense to use a PV system?

Hackstock: In principle, it is possible to use solar thermal systems for cooling. Austrian companies developed projects in overseas regions mainly, where abundant sunshine and heat makes solar cooling more profitable. Austria it is not the best economic option for producing cooling energy by the sun.

Krings: What is the amortization period for the entire solar system including all necessary components like the storage tank, pipes, and the solar collectors for example?

Hackstock: The amortization time is an argument we hardly use as it is based on many assumptions such as government subsidies, fuel costs and much more. However, to answer your question anyway, I can say that the energy amortization time for PV systems and solar thermal systems is around 1 to 2 years. However, if you look at the economic amortization time, this is around 13 years for PV systems and between 4 and 8 years for solar thermal systems, assuming that fuel costs increase by 6% per year.

Krings: How often do the solar installations have to be checked? How many workers are needed and for how long? Do you know how much does this cost the installer per m^2?

Hackstock: Our recommendation is to check the solar system every three years. One person needs about an hour to do this and goes through a maintenance manual, for example measuring the pressure, checking the solar fluid, and looking for general damage. In principle, however, it can be said that there is no mandatory time after which a system must be checked. However, the more frequently the system is checked, the more efficiently it is in the long run. You can think of it as being similar to your own heating system at home. Regarding the costs I am not quite sure about specific data.

Krings: How often does the entire system have to be replaced or when have the collectors reached their End of Life?

Hackstock: So far, I am not aware of any system that has had to be replaced completely. We usually look if there are any individual components that need to be replaced and then change them individually instead of replacing the entire system straight away. Recently, for example, I was at a system that is already 40 years old, only the collectors have been replaced since. After 30 years, however, the collectors should be replaced because they lose their efficiency over the years.

Krings: Taking a closer look, how many jobs are needed per MW_{peak}?

Hackstock: According to the market statistics, a total of 1,300 full-time jobs are required for 41.4 MW_{peak}, which means that approx. 31 full-time jobs per MW_{peak} are needed.

Krings: That is a significant difference to the installers required for a PV system - what could be the reason for this?

Hackstock: The difference is possibly because firstly more solar thermal systems are produced in Austria and, in contrast to PV, many PV jobs are in China. Secondly, it takes longer to install a solar thermal system than a PV system and therefore more installers are needed. And thirdly in parallel to this more installers are required, which means that more labor time is booked per system.

Krings: Where is the most production taking place globally and how much does Austria's economy benefit?

Hackstock: In the case of solar thermal systems, the share of added value within Austria is 75% in relation to the total investment costs, including installation.
This share is significantly lower for PV systems due to the high level of imports that are required. The PV modules mainly come from China, which means that the added value is mainly due to the installation of the modules. For a long time this value has been 38%, but the fact that the systems have now become cheaper has shifted the percentage of added value in Austria's favor and is now 46% per square meter since 2022. This means that the added value within the PV industry is increasing. However, the direct comparison shows that Austria benefits more from the high level of exports within the thermal solar systems sector. It should also not be forgotten that solar thermal systems are more efficient than PV systems. To generate the same amount of energy, you need three times more PV modules than solar collectors. So, the question is always what you want to earn from the roof.

Krings: What is the effect of thermal solar panels on rooftops on biodiversity?

Hackstock: On roofs, the collectors have no effect on biodiversity. However, if the collectors are installed on open spaces, they can provide a safe space for beneficial insects in nature and can increase biodiversity.

Krings: Are harmful gases produced during the utilization phase?
Hackstock: No, no harmful gases are produced during the utilization phase.

Krings: Do solar systems require toxic materials or rare earths and what does this mean for the End of Life? Can the resources get recycled?
Hackstock: Thermal solar collectors do not require rare earths, nor are rare toxic chemicals used. Unlike PV systems, the collectors can simply be disposed and do not have to be considered as hazardous waste like PV panels.

Krings: Do solar systems have an effect on people's health?
Hackstock: No

Krings: Do solar systems have an impact on people's mental health?
Hackstock: No. At best, they can increase the sense of well-being of people who have installed a solar system.

Klaus Reisinger

Dr. Klaus Reisinger was Managing Director of ALLPLAN GmbH from 2003 to 2015 and founded ClimatePartner Austria in 2007. After working in the field of plant engineering for three years, he was a partner at iC consulenten Ziviltechniker from 2018 to 2022. In autumn 2018, Reisinger was appointed to the board of IG Lebenszyklus Bau. He specializes in "climate-neutral buildings" and is also a lecturer at the Pinkafeld University of Applied Sciences in the "Energy and Environmental Management" course.
The interview has been conducted on the 8th of March 2024.

Catalogue of questions:

Krings: Have there been any technological improvements in the production of thermal solar systems in the last 10 years?
Reisinger: No, there has been no significant improvement in the area of solar thermal systems in recent years. In contrast, PV has seen a significant improvement in efficiency. This is mainly due to the fact that more research has been carried out within the PV industry and that electricity, in contrast to heat, is the more valuable form of energy.

Krings: To what extent will solar thermal systems still be important in the future in consideration of the increasing demand for electricity?
Reisinger: Overall, it can be said that PV will probably prevail in the future, as this form of energy is likely to be in greater demand even if thermal solar systems are more efficient. In addition, PV systems can also provide heating and cooling next to electricity if they are coupled with a heat pump. A solar thermal system does not offer this possibility efficiently enough. Besides, PV modules can be adapted better due to their constant improvement in technology.

Krings: To what extent could the heat produced by the solar systems also be fed into a public grid as a form of energy?

Reisinger: This is possible in principle, but not economically lucrative and technically more complicated overall. The produced heat can only be stored temporarily in a storage facility and later used locally when required. Electricity, unlike heat, always finds a consumer and can be fed into the public grid. In this respect the solar thermal system is at a disadvantage.

Krings: What is the amortization period for the entire solar thermal system, including all the necessary components such as the storage tank, the cables, the solar collectors, etc.?

Reisinger: That is very site-specific and I'm not sure about that.

Krings: How often do the roofs have to be checked and how many workers are needed for how long?

Reisinger: Solar thermal systems hardly age at all. Taking the entire system into account, the collectors hardly ever need to be checked, whereas the boiler is checked for functionality once a year. In contrast to PV systems, the handling of the technology is still very analogue. With solar thermal systems, the necessary data can only be viewed analogue on the solar storage tank. PV systems, on the other hand, usually allow you to view the current electricity production digitally via an app. The control of the PV system is therefore easily recognizable and, if necessary, maintenance is carried out. Over the years, the system loses more and more of its performance so that it would have to be replaced after around 25 years. But to come back to your question of how often the roof needs to be checked, I can say that PV systems are checked less frequently than thermal systems. In practice, for example at my home, my PV system is actually maintenance-free and my solar thermal system is also checked far less than once a year.

Krings: How many employees are needed to install the system and for how long?

Reisinger: Unfortunately, I can't give a generalized answer.

Krings: Taking a closer look, how many jobs are needed per MW_{peak}? To what extent can this be converted to m^2 ?

Reisinger: I can't answer this question exactly either, but I can say that as soon as the energy transition really takes place, many new employees will be needed. In my opinion, however, PV will mainly be expanded and the solution to the energy problem will be the storage technology, as this will hopefully become even more efficient.

Krings: Is the added value mainly domestic or international?

Reisinger: The added value is mainly in Austria, which is also a big advantage over PV systems, because these are often imported from China.

Krings: Do thermal solar panels on rooftops have an effect on biodiversity?

Reisinger: No. Thermal solar collectors do not provide any meaningful shade in comparison to PV modules, and they do not harm any animals. Therefore, I would say that they do not have any influence.

Krings: Are harmful gases produced during the utilization phase or do the create any noise?

Reisinger: No. Thermal solar systems do not produce any harmful gases, nor do they create noise. The danger lies within the heat pumps because they require a refrigerant that can escape in the event of a leak. Synthetic refrigerants in particular are harmful, whereas these could also be replaced by natural refrigerants. Natural refrigerants such as ammonia, for example, are less efficient. However, a potential leak can also be easily avoided by carrying out regular checks.

Krings: Does the production of the collectors involve toxic materials or is there a potential risk to installers or people in general?

Reisinger: No, thermal systems do not contain any toxic materials that could pose a potential danger to humans.

Krings: Are the materials of the thermal solar panels recycled?

Reisinger: No, to my knowledge the resources are not recycled, and this is only possible to a limited extent, as the materials are neither harmful nor reusable.

Krings: Do solar systems have an impact on people's health?

Reisinger: Hardly. Only when the system gets extremely hot tiny explosions can occur. But this phenomenon is so rare that it can be disregarded.

Krings: Do solar panels have an impact on people's mental health?

Reisinger: No. The only thing is that that solar thermal systems might lead to a better conscience. For example, I find it very joyful to have a solar thermal system which makes me happy.

Interviews: Vegetation Zones

Susanne Formanek

Susanne Formanek graduated from the University of Natural Resources and Applied Life Sciences in Vienna in the field of timber industry. She headed the Green Building Cluster in Lower Austria and held a seat on the Lower Austrian Climate and Energy Programme. Since 2011, Formanek focused on sustainable building with a focus on energy efficiency and climate change adaptation measures. To this end, she co-founded the GRÜNSTATTGRAU innovation laboratory, which is a competence center for greening of roofs and facades.
The Interview has been conducted on the 5th of March 2024.

Catalogue of questions:

Krings: Do you know what the margin of the companies is to install an intensive or extensive roof?

Formanek: The data to this question is available, but it is confidential company data, and we would not have the confidence to quote a price or give a guideline. Firstly, because the prices vary so much due to the raw material prices and secondly because they naturally differ between the systems depending on their size and roof. Even after consulting the board, I am unfortunately unable to give you information's because it wouldn't be right for the market to quote prices.

Krings: Is there something like an amortization period of the entire system which includes all necessary components because for green roofs it could be difficult to measure something like this. What are your thoughts about this?

Formanek: The ongoing debate about amortization is not unfamiliar to us, particularly due to the fundamental fact that green roofs do not, in principle, have a direct amortization as photovoltaic systems do. The dilemma lies in the fact that the benefits result mainly from three other aspects which aren't related to an amortization time. Firstly, the green roof surface provides effective water retention, resulting in less wastewater and therefore savings in runoff. Secondly, green roofs allow a noticeable cooling of the room below by around 4 degrees, which in turn leads to a reduction in the energy consumption of air conditioning systems. Lastly, the longer life span of green roofs is an advantage, as they are less sensitive from pebbles, for example.

Krings: How often do the roofs need to be checked or maintained? Do you know how many workers are needed and for how long and what this would cost the installer per m^2?

Formanek: There is now a standard in Austria that specifies roof maintenance at least once a year. This means that with our own intensively utilized roof of $100m^2$, for example, we need 3 - 4 people for approx. 4 hours to take care of the maintenance each year. With an extensively used roof, on the other hand, the maintenance is significantly less intensive and is reduced to approx. 30 minutes twice a year for 100 m^2. However, if you also consider the technology, you must of course check it and see whether there is a leak somewhere and whether the protective layer is still functional. The check is carried out in various ways, usually using water and electrical sensors to check whether the system is still working. Therefore, the system is slightly flooded, and an electrical tape is placed over it to see if this electrical tape might be interrupted. If this is the case, you know that there is a small crack somewhere.

Krings: Can it be said that vegetation zones could be installed on all roofs on which solar systems could potentially be installed as well?

Formanek: Theoretically, this is possible, but similar to solar systems, the technical factors must also be taken into account. For example, some buildings are protected as historical monuments and others have inadequate statics. However, an extensive green roof is possible for any roof on which solar systems could be installed. Only intensive greening may not always be feasible due to the additional load.

Krings: Is there a specific time when the system must be replaced or is a renewal of some components necessary after some years? How is this even possible for intensive and extensive roofs?

Formanek: In principle, it can be said that under optimal conditions, green roofs can live forever and there is no expiration time. Only the different layers used to protect the roof have a limited lifespan which varies between 30 and 50 years depending on the type and location. Currently, some green roofs are even up to 80 years old.

Krings: How many employees are needed to install the system and for how long? Is it possible to refer this amount to the installation per m^2?

Formanek: Usually 1 to 3 people are necessary to implement a vegetation zone on top of a roof. However, it heavily depends on the rooftop and which construction is requested. For example, some layers can be installed by one person alone and others must be installed by 3 people. Sometimes it only takes a few hours while especially for extensive rooftops it can take longer. Another problem is that it is not possible to calculate the needed employees per square meter because the necessary labor force is required per rooftop independent of the size, the floor, and the system.

Krings: Is the added value mainly domestic or international?

Formanek: We have 3 large manufacturers just for the implementation of green roofs and then there exist manufacturers for fleece and insulating materials which are also located in Austria. Generally, however I can say that the substrate often comes from Germany, the drainage from Austria and the plants mostly come from Austria as well.

This means that the economic revenue is mainly generated domestically and in Europe.

Krings: Can there be innovative or better solutions or exist any research to improve the system?

Formanek: Definitely! Currently there is ongoing research which focuses on refining technologies that impact the subsoil or AI functionalities to optimize the plant yield. Additionally, there are efforts to identify innovative plant species, including leaves with a subtle silvery shimmer to enhance the albedo reflection or trees with minimal water requirements to reduce resource consumption and the use of grey water.

Krings: Does the construction of the vegetation involve toxic substances or are there any risks to humans?

Formanek: Yes unfortunately, biocides and PVC is rarely used, but thanks to more innovative materials, these substances are hardly used any more. Therefore, there is also no danger to humans.

Krings: What does this mean for the End of Life? Are the resources recycled?

Formanek: At the moment, the majority of the construction can be recycled, and it is already taking place with the existing roof systems in Austria. The recycling process is also constantly being expanded and improved which helps to reduce the amount of unnecessary waste and is beneficial for the environment.

Ulrike Pitha

Ulrike Pitha is specialized in the fields of structural greening, sustainable construction and vegetation technology and regularly publishes on these subjects. Furthermore, she is also head of the Vegetation Technology and Green Infrastructure working group at the Institute of Soil Bioengineering and Landscape Construction while she lectures about these topics at the BOKU University in Vienna.
The interview has been conducted on the 18th of March 2024.

Catalogue of questions:

Krings: Do you know how many green roof cadasters are in the 9 federal states?

Pitha: Overall, each province and each city regulate this question for itself and there is no collective register in which you can find out the roof area potential for the whole of Austria. In Vienna, for example, there is currently a potential register that depends on the slope of the roof. Generally, I cannot say exactly how many roof areas and how many municipalities provide such an analysis.

Krings: Why is the slope on one hand and the insulation on the other hand responsible for the greening of a roof?

Pitha: The slope is necessary to take into account for the installation of a green roof because certain additional substructures have to be considered so that the structure and the plants do not slip. The insulation is important because every building has a different type of construction. On the one hand, there is the inverted roof, where the insulation lies above the roof waterproofing. With these roofs, the insulation is always a little more humid. On the other hand, there are also roofs where the roof waterproofing is above the insulation and therefore the plants and the substructures do not have to take additional moisture factors into account.

Krings: What does the value chain of the individual components for a vegetation zone on the roof look like? Is the production mainly located in Austria or abroad?

Pitha: Overall, I would say that the production is increasingly taking place domestically. This is mainly because it often only makes sense to use plants from Europe and Austria. Firstly, because it avoids the high transport costs, and secondly because the regional plants are best adapted to the local climate. Some components of the substructure are imported, but I am not quite sure how many. Overall, however, I can say that the value chain is mainly located in Austria.

Krings: How many workers are needed on average to install a green roof?

Pitha: Unfortunately, there are very different figures for this, as the installation depends very much on the roof area and its structure. On average, however, I would say that around 3 - 4 people are needed.

Krings: Do you know the margin of the companies and whether the costs for the producers have increased or decreased recently?

Pitha: Unfortunately, I don't know the margins of the companies, but I have noticed that the boom during the pandemic has levelled off recently. In addition, labor costs have risen, which in principle tends to have a negative impact on manufacturers and should lead to higher costs. However, I don't know how this will affect the final price and the demand because there are also still a lot of subsidies and new ones are also being offered.

Krings: What does the maintenance of green roofs look like?

Pitha: The ÖNORM dictates that green roofs must be inspected at least once a year. This means that it exists an obligation in contrast to solar systems because solar system manufacturer usually only gives a recommendation how often the system should be checked. During the maintenance of green roofs, any unwanted sprouts are removed, the water shaft is checked, and the system is checked overall for proper functioning.

Krings: Due to the fact that extensively utilized roof areas contain less greenery, I would like to know to what extent they still contribute to increase the biodiversity?

Pitha: In general, intensive and extensive roof areas help to promote biodiversity but extensive roof areas inherit fewer plant types. This does not have to be to be a disadvantage. It mainly depends on which plants and how many different plant species are planted. Therefore, extensive green roofs can also have a positive effect on biodiversity if the focus is set on it.

Krings: Do the substructures of the roofs contain toxic materials or do rare earth elements have to be used for the construction of a green roof?

Pitha: A big issue regarding toxic materials is the use of redecides in the waterproofing membrane. Redecides prevent the plants from growing through the root resistant layer, and those layers are usually made out of plastic or are mineral oil based. Currently, producers are increasingly trying to use mechanically active alternatives, but this is not an easy task. In general, it can be said that they could be washed out in the worst case, however, usually this does not happen. Compared to solar systems, the use of toxic materials therefore is very low. Studies are even currently being carried out to determine the extent to which these redecides could become problematic, especially considering the mobility of the substances. Overall, it can be said that those hazardous chemicals are only getting a problem if there are any major damages, and they are barely a risk to humans.

Krings: To what extent is the End of Life of the construction already taken into account during production? Are individual parts recycled?

Pitha: Overall, the manufacturers are very keen to ensure that the components can be recycled. For example, the individual layers of plastic can be fed back into the circular economy and the repair of any damage that occurs can also be done very locally. This means that if, for example, the waterproofing of a roof is no longer properly guaranteed, the damage can be localized fairly precisely. The location is then limited to an approx. $4m^2$ section which can then be cut out individually and only repaired where necessary. This of course prevents unnecessary replacement or additional damage to materials and reduces waste.

Krings: Some studies say that if the greening only takes place on the roof, the effect on thermal comfort for people at the street level is very low? What do you think about this and what should be done in order to achieve an effect on the thermal well-being of city dwellers?

Pitha: That's true. There is not a noticeable effect of a temperature reduction at the street level, but an interplay of different types of greenery on different levels makes perfect sense. A mix of street trees, façade greening, and roof greening is an excellent combination that influences the air flows and provides additionally more shade. This means that green roofs alone hardly have a noticeable effect at street level but are an important part of the overall green infrastructure and then potentiate the positive effect.