Research report on exploring the potential of re-using second-hand solar panels in the social housing sector of the Netherlands

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Contents

Special acknowledgement

This report presents the findings on solar panel reuse within the social housing sector. Special acknowledgment is given to Deyana Mineva, whose extensive knowledge in environmental science has been invaluable throughout this project. Her expertise significantly enhanced the depth and quality of the analysis.

This collaboration has led to critical insights and actionable recommendations for stakeholders, paving the way for a more sustainable energy landscape. It is hoped that this report serves as a valuable resource for decision-makers and inspires further discussions on the importance of solar panel reuse in achieving sustainability goals.

Objective

This report aims to inform the reader about the current practices in solar panel management within the Netherlands and the energy-related challenges facing the social housing sector. Additionally, it explores two potential future directions for energy management in the country. Through a combination of quantitative and qualitative research, the report seeks to determine whether the energy challenges in the social housing industry can be mitigated by reusing functional solar panels, as opposed to consistently purchasing new ones. This analysis includes a multi-perspective comparison of the benefits and drawbacks of reusing versus buying new solar panels and provides an overview of stakeholder attitudes toward each approach. The report concludes with a set of guidelines to address these challenges effectively.

Summary

This report provides a comprehensive analysis of solar panel adoption in the Dutch social housing sector, blending both empirical research and problem-solving approaches. It explores how solar panel implementation currently works within social housing, detailing the management of solar panel systems and the processes involved in their installation, maintenance, and end-of-life management.

On the empirical side, the report delves into how housing associations and residents navigate solar panel adoption, offering insights into the challenges and successes experienced by stakeholders. It explains how panels are managed across their lifecycle—from initial installation to recycling—and highlights key bottlenecks in the process, including financial barriers and resident reluctance.

On the problem-solving side, the report proposes solutions to address the mishaps in both the management of solar panel waste and the energy performance of social housing residents. It outlines strategies for improving solar panel waste management through reuse and recycling, and offers recommendations to housing associations on how to help residents achieve better energy performance, lower costs, and more sustainable energy consumption. Furthermore, the report provides a roadmap for the social housing industry to meet their energy targets and accelerate the transition to renewable energy sources.

By comparing new and reused solar panels under both innovative and conservative scenarios, the report also examines environmental and financial trade-offs, offering valuable insights for policymakers, housing associations, and residents alike.

Solar panel adoption in the Netherlands

The urgency to address climate change has rapidly accelerated the global shift toward renewable energy, with solar energy taking a leading role thanks to its affordability and significant technological advancements. These developments have resulted in the production of solar panels that are lighter, more efficient, and increasingly cost-effective, enabling a broader range of consumers to participate in the energy transition[1].

In the Netherlands, the drive towards renewable energy has been marked by a significant increase in solar capacity, which has reached nearly 24 million kW by 2023[2]. The sharp increase is presented in Figure 1.

This is largely driven by the residential sector, contributing to nearly half of the country's total solar capacity[3]. Such growth is critical for the national strategy to reduce dependency on fossil fuels and enhance energy security, aligning with broader European objectives to achieve carbon neutrality[4].

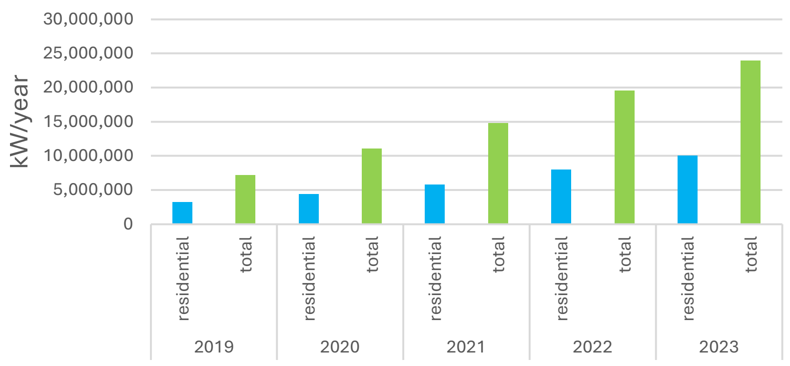

Figure 1: Total installed solar power in the Netherlands [2].

[1] International Renewable Energy Agency. (2023). World Energy Transitions Outlook 2023
[2] Bellini, E. (2024, March 25). Dutch PV additions hit 4.82 GW in 2023. pv magazine International https://www.pv-magazine.com/2024/03/25/dutch-pv-additions-hit-4-82-gw-in-2023/
[3] SolarPower Europe. (2022). Global market outlook for solar power 2023-2027.
[4] European Commission. (2019). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, and the Committee of the Regions: The European Green Deal https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640

End-of-life management for solar panels

According to the waste management hierarchy in Figure 2, prevention is the most favourable option to reduce waste. If a product is already manufactured, reuse is the most favourable approach to resource management[5]. In terms of solar panel management, guided by the EU's Waste Electrical and Electronic Equipment (WEEE) Directive, StichtingOPEN acts as the designated authority for collecting discarded solar panels[6]. They evaluate whether the panels can be reused or recycled and deal with the needed repairs.

The recycling process for solar panels involves a range of techniques aimed at recovering different components. According to the WEEE Directive, a minimum recycling requirement of 90% by weight is set for electronic products, including solar panels. As no specific recycling methods are mandated, producers often choose cost-effective but lower-value recycling options. In the Netherlands, the aluminium frame, junction box, and cabling are removed, and the remaining materials are shredded and used as fillers in asphalt and concrete production. This process does not prioritise the recovery of high-value materials such as silicon, silver, and copper, mainly because their retrieval is both technically complex and inefficient on an industrial scale[7].

Figure 2: Current solar panel management landscape in the Netherlands [5].

[5] European Parliament and Council of the European Union. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Official Journal of the European Union, L 312, 3–30. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0098
[6] European Parliament and Council of the European Union. (2012). Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). Official Journal of the European Union, L 197, 38–71. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32012L0019
[7] Korniejenko, K., Kozub, B., Bąk, A., Balamurugan, P., Uthayakumar, M., & Furtos, G. (2021). Tackling the circular economy challenges—Composites. Advances in Materials Science and Engineering. https://doi.org/10.1155/2021/6654831

Early decommissioning of solar panels

Typically, solar panels are designed to last approximately 25 years. Their lifespan is affected by unavoidable factors like the quality of materials and environmental conditions, which can reduce efficiency by 0.2 - 1% annually [8].

Despite these designed lifespans, a significant trend in the premature decommissioning of solar panels has been observed, often driven by economic reasons. For example, failures in components such as inverters, which usually last 10 - 15 years, lead installers to recommend a complete system replacement. This recommendation is often influenced by the advantages of newer, more efficient technologies and the economic benefits they offer, such as quicker returns on investments by selling back excess electricity to the grid [9].

As a result, many solar panels that are still functional and could continue to produce electricity are being decommissioned early. Projections show that the amount of these panels will grow exponentially in the coming years, as you can see in Figure 3[10].

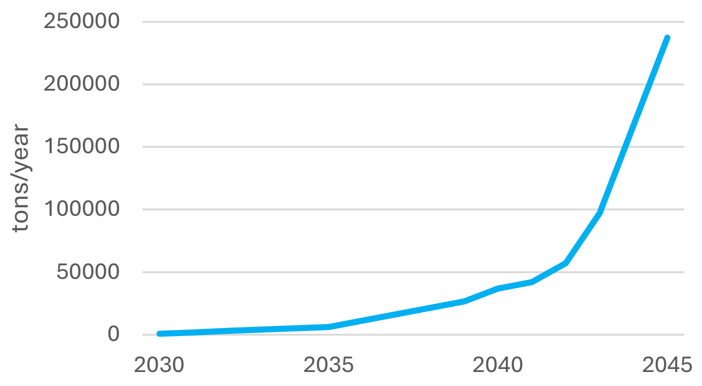

Figure 3: Projections of discarded solar panels until 2045[10].

[8] Blom, M., Scholten, T., & de Vries, J. (2020, September). Kosten zontoepassingen - methode om private en maatschappelijke kosten te vergelijken.

Supply and demand of early decommissioned solar panels

Figure 4 illustrates the potential supply and demand dynamics for second-hand solar panels within the social housing sector.

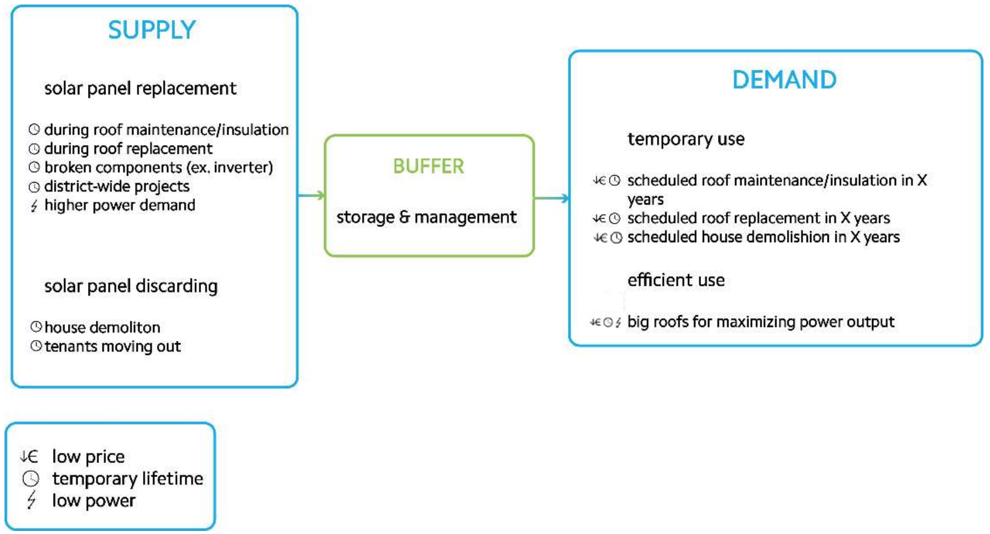

Figure 4: Schematic representation of the supply and demand of early decommissioned solar panels.

The legend in the lower-left corner clarifies the drivers behind the implementation of this system: the low price and temporary lifetime of second-hand panels coupled with their lower power output make them a viable option for specific, less permanent installations. This system aims to match the supply of available panels with the demand in a way that supports both economic and environmental sustainability within the social housing framework.

Currently, the majority of the supply of second-hand solar panels comes from companies that deal with disassembly of solar panel systems. Disassembly happens for various reasons, for example due to broken components within the system. In such situations, the common practice in the industry is to advise the client to replace the entire solar panel system with a more efficient. For the client, paying the investment costs is more advantageous that paying the repair costs.

[9] de Vilder, S. (2023, August). Changing environmental tides of Amsterdam's future PV systems - A multi-scenario projection for the environmental performance of residential PV systems in Amsterdam.
[10] Späth, M., et al. (2022, November). Balancing costs and revenues for recycling end-of-life PV panels in the Netherlands.

Simultaneously, an installation company generates more revenue by engaging in a complete replacement project compared to repair.

Another instance that creates supply of early decommissioned panels is replacement due to higher power demand of households. Some households, especially those with roofs sizes that cannot accommodate too many panels, are advised to opt for new, more efficient panels. This makes sense, as new technologies can produce more than double the watt-peak power of older technologies.

Moreover, panels get decommissioned prior to large residential projects of implementing new solar installations. Before engaging in district-wide projects of implementing solar energy, companies advise removing the solar panels from houses that already have panels.

After disassembly from roofs, these companies keep and store the used products. When houses get demolished, the companies also get to keep the solar panels. The same goes for panels left behind by residents of the rental sector who move out and don't want to take the panels with them, and the future tenants are also not interested in keeping the panels.

On the demand side, the use of these panels is categorized under temporary or efficient use. Temporary demand arises from scheduled roof maintenance, replacements, or demolitions, as early decommissioned solar panels have a limited life, so it makes sense to use them in housing situations with a limited life. Efficient use refers to their deployment on large roofs intended to maximize power output.

Social housing faces challenges in energy transition

In 2019, the EU committed to climate neutrality by 2050 through signing the Green Deal, aiming to reduce CO_2 emissions by 55% by 2030 as an intermediate goal. The state members are legally bound to reach the targets[11]. As a response, the Dutch government adopted a climate policy in accordance with the European plans, setting an internal goal of reducing greenhouse gas emissions to 49% by 2030. The 2019 National Climate Agreement outlines sector-specific actions to achieve the goals, including the built environment, responsible for 15% of the total CO_2 emissions[12]. A significant portion is attributed to house energy usage, primarily fuelled by fossil sources. The housing sector has been working towards reaching the set goals. However, it faces different challenges compared to the free rental and owner-occupied sectors. While they do not have a specific set of goals to achieve, in 2022, the social housing sector signed an agreement obliging it to withhold ambitious promises. The minister of Housing and Spatial planning signed the National Performance Agreements together with Aedes, VNG and Woonbond, which collectively represent all corporations, municipalities and tenants across the country. These agreements include supplementing the housing stock with 250,000 fully circular dwellings, making 450,000 existing homes gas-free, and supplying insulation free of charge to the residents of 675,000 existing units until 2030[13].

In the Netherlands, an estimated 400 thousand households struggled with energy poverty in 2023, 70 thousand more than in 2022. More than two-thirds of households with energy poverty live in social housing. Households with energy poverty have a low income in combination with high costs for gas and electricity or a home with a low energy quality. Low energy quality occurs if a home is difficult to heat (for example. due to inefficient insulation) and/or there are no possibilities to generate energy (for example, with solar panels)[14].

Regarding residents' perception, homeowners and private landlords have a stronger wish to be engaged in the energy transition and feel responsible. In contrast, social housing residents see the housing association as the responsible actor for adjusting their homes[15], and since they are a risk-averse social group, they often resist measures proposed by the associations[16]. Additionally, at the neighbourhood scale, they often slow down the pace of energy transition even more due to the lengthy process of meeting the 70% rule. This rule requires approval from 70% of tenants for renovations involving 10 or more dwellings[17].

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[11] European Commission. (2019, December 11). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee, and the Committee of the Regions - The European Green Deal.
[12] Ministerie van Economische Zaken en Klimaat. (2019, November). Integraal nationaal energie- en klimaatplan 2021-2030.
[13] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2022, June). Nationale prestatieafspraken woningcorporaties.
[14] TNO et al. (2024, July 2). Energiearmoede in Nederland 2019-2023: Een overzicht van 2019 tot en met 2023 en een verdieping op onderconsumptie (TNO 2024 R10801). TNO Publiek.
[15] Jansma, S. R., Gosselt, J. F., & de Jong, M. D. T. (2020). Kissing natural gas goodbye? Homeowner versus tenant perceptions of the transition towards sustainable heat in the Netherlands.
[16] R. van der Vlies, personal communication, March 2024
[17] van der Hagen, J. L. (2022). Dutch social housing associations' route towards 2050: establishing an assisting tool for the prioritization of dwelling complexes: "The factors influencing the pace of energy efficiency renovations and the prioritization and planning by Dutch social housing associations.

In consequence, social housing associations face challenges in reaching their goals. Therefore, experts have cast doubt on whether the targets will be achieved, as the transition is not going fast enough for the sector to become CO_2-neutral by 2050[18].

Social housing and solar panel adoption

The average household in the Netherlands only uses approximately 25% of the electricity generated by solar panels, which translates to a mere 12.5% of their total energy demand[19]. Consequently, a substantial portion of the energy savings potential remains unrealized, limiting the direct impact on reducing energy costs. Simultaneously, energy-storing technologies are still too expensive to penetrate the market[20]. However, to stimulate adoption, in the Netherlands, households are able to make use of the netting scheme. This policy allows users who generate their own electricity to offset their energy consumption against their solar production, allowing them to recoup energy costs. Especially in times of soaring energy prices, this has made solar panels an attractive choice for residents[21].

The netting scheme has significantly influenced solar adoption, but it will be abolished in 2027[22], meaning from then on, tenants will no longer be able to save on their energy bills as they do now. Projections indicate that by then, only 35% of the national social housing stock will be equipped with solar panels[23].

How are solar panels managed in social housing?

When it comes to solar panels, a district-oriented approach is currently followed, where solar panels are offered neighbourhood by neighbourhood. When a neighbourhood is selected, interested residents are visited by an advisor who assesses the feasibility of installation and provides necessary information, including potential savings, based on multiple factors[24]. Among these factors, one of the most impactful is the roof size of the dwelling, which translates to how many square meters of solar panels can be placed on the roof, and consequently, the maximum power output that the household can achieve[25]. Another crucial factor is electricity consumption, as it is equivalent with the household power demand. A common presumption is that tenants have acquired solar panels for the sole reason of taking advantage of the netting scheme, trying to keep their consumption to a minimum in order to be able to sell most of the energy they produce for the sake of profit[26].

Literature has shown that residents who find sustainability important are more likely to be open to solar panels than the ones who don't[27]. Research indicates that social housing tenants are often willing to engage in sustainability initiatives and are knowledgeable about relevant issues. However, they may experience barriers, such as a lack of confidence in their knowledge or self-interest[28].

Installing a solar panel system and ensuring its optimal functionality over time is often considered a complicated process. Common concerns include the need for ongoing maintenance and potential malfunctioning of the system[29]. Social housing residents are reluctant towards measures proposed by corporations due to concerns about the inconvenience of maintenance[30]. However, if tenants approve the project, housing associations handle the installation and maintenance of solar panels, by cooperating with solar energy equipment suppliers.

In exchange, tenants currently pay a monthly fee set by their own corporation, depending on the number of panels acquired. This fee ranges from zero to 24 euros per month, based on a study checking the fees of all social housing associations in North Brabant. However, tenants often resist measures proposed by corporations due to the unwillingness to incur additional costs, regardless of their magnitude[31].

Parties forming the national government are occupied with tackling the concerns of tenants. A measure they are considering is a 'purchasing law', stating that every tenant of a social rental home is given the legal right to purchase their rental home. This way, more people can reap the benefits of homeownership, including the energy-efficiency measures taken by their corporation[32]. In addition, as

[18] Conijn, J. (2022, January 27). Afdwingbare prestatieafspraken – een slag in de lucht. PropertyNL. https://propertynl.com/Nieuws/Column-Johan-Conijn-Afdwingbare-prestatieafspraken-een-slag-in-de-lucht
[19] gridX. (2023). The Netherlands conundrum: Low grid capacity, high feed-in. https://www.gridx.ai/blog/the-netherlands-conundrum-low-grid-capacity-high-feed-in
20 International Energy Agency. (2024). Technology Roadmap Energy storage. www.iea.org
[21] CBS. (2023). The Netherlands largest importer of Chinese solar panels. https://www.cbs.nl/en-gb/news/2023/36/the-netherlands-largest-importer-of-chinese-solar-panels
[22] Bellini, E. (2024). Netherlands to phase out net-metering scheme in 2027.
[23] Aedes datacentrum. (2024). Forecast of the percentage of installed solar panel in social housing for 2027.
[24] Personal communication (2024)
[25] Personal communication (2024)
[26] Personal communication (2024)

[27] Ebrahimigharehbaghi, S., Qian, Q. K., Meijer, F. M., & Visscher, H. J. (2019). Unravelling Dutch homeowners' behaviour towards energy efficiency renovations: What drives and hinders their decision-making? Energy Policy, 129(June 2018), 546–561. https://doi.org/10.1016/j.enpol.2019.02.046
[28] Bal, M., Stok, F. M., Van Hemel, C., & De Wit, J. B. F. (2021). Including Social Housing Residents in the Energy Transition: A Mixed-Method Case Study on Residents' Beliefs, Attitudes, and Motivation Toward Sustainable Energy Use in a Zero-Energy Building Renovation in the Netherlands. Frontiers in Sustainable Cities, 3. https://doi.org/10.3389/frsc.2021.656781
[29] Energy theory. (2023). Solar panels are not reducing the bill. https://energytheory.com/solar-panels-not-reducing-bill/
[30] [31] Jansma, S. R., Gosselt, J. F., & de Jong, M. D. T. (2020). Kissing natural gas goodbye? Homeowner versus tenant perceptions of the transition towards sustainable heat in the Netherlands. Energy Research and Social Science, 69. https://doi.org/10.1016/j.erss.2020.101694

[32] NSC. (2023). Verkiezingsprogramma 2023.

corporations' operating funds often come from equity from unit sales[33], such a law may work in their benefit as well.

Projections on the energy transition in the Netherlands: Innovative and conservative scenarios

Based on the political ambitions of the parties of the 2024 government coalition, their common agenda and various opinions of experts from the fields of energy and housing, two scenarios have been drawn. These scenarios give an idea about the two possible directions in which the Netherlands can head in the future. The most important difference between the two scenarios is that in the innovative one, a larger part of the energy mix will consist out of locally sourced solar energy. These scenarios will serve as basis for investigating whether life extension of solar panels through re-use can represent a possibility in the future of the Netherlands.

The innovative scenario

The innovative scenario envisions a proactive transition to renewable energy sources, with a strong emphasis on achieving climate neutrality through technological innovation and decentralized production of energy. Solar power will take a bigger portion of the energy mix, and smarter, circular solar technologies will penetrate the market, together with affordable energy storage solutions. On the residential level, the government will take a holistic approach on the measures they take, making efforts towards abolishing energy poverty, while also striving to reach the climate goals set for 2030 and 2050.

The scenario prioritises flexibility in energy distribution and storage, recommending both the expansion of the electricity grid and promoting energy holons through encouraging data-driven, hybrid, local production of energy[34], as can be seen in Figure 5. Under this framework, social housing associations are envisioned to have significant governing authority, enabling decision-making that aligns closely with local energy needs and capabilities. However, they will be supported by instruments that encourage cooperation with the industry of smart energy technology.

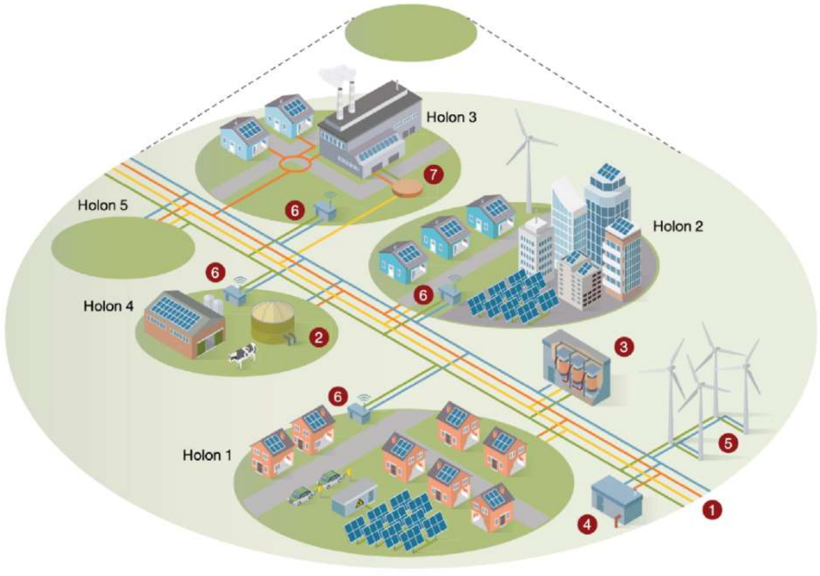

Figure 5: Schematic example of an energy holon.[35]

To what concerns solar panels, this scenario envisions clean recycling technologies reaching the market with the help of government subsidies, slowly replacing the current traditional method, shredding. Moreover, the supply of early decommissioned solar panels that are still usable will grow, thanks to a more informed, conscious approach from parties that handle solar panels.

The conservative scenario

Contrasting sharply with the innovative approach, the conservative scenario places less emphasis on climate-related measures, prioritising them only when they align with overall affordability for citizens. The primary focus here is a national shift to nuclear energy, sticking to a more traditional energy mix. On a residential level, there will be no motivation to switch to gas-free housing in the timeframe set in 2022. Although this scenario supports the expansion of the energy grid, it advocates for stricter regulations on the distribution of solar energy. Here, the government retains control over the social housing associations, suggesting a centralised approach to managing energy transitions in social housing.

[33] Deursen, van. (2023). The People's Housing: Woningcorporaties and the Dutch Social Housing System Part 2: The Mechanics. www.jchs.harvard.edu.
[34] [35] Topsector Energie. (2022, September 8). Naar een holarchisch energiesysteem? Energy.nl. https://energy.nl/publications/holarchisch-energiesysteem/

What is the attitude of the stakeholders?

The attitudes of various stakeholders toward solar panel adoption in the Dutch social housing sector have been gathered through a combination of means. These consist of literature review, qualitative research based on document data and interviews with representatives from different stakeholder categories, including housing associations, policymakers, solar panel installers, energy experts and residents. This comprehensive approach provides insights into the different perspectives and motivations that shape decision-making regarding solar panel implementation and management. This chapter will unravel a summary of each stakeholder's perspective on the topic. An overview of interviewees, document data and literature review can be accessed upon request.

The European Union

EU directives and policies

The Netherlands, as a proactive member of the European Union, is deeply committed to environmental sustainability, taking significant steps to reduce carbon emissions[36] . Within the EU's environmental framework, the Renewable Energy Directive plays a crucial role in driving the adoption of renewable energy sources. Its most recent revision in 2023 introduced measures aimed at boosting the use of renewables in buildings, setting a target of 49% renewable energy use in this sector by 2030[37]. Simultaneously, the Energy Efficiency Directive focuses on improving energy efficiency through system-wide strategies and cost-effective solutions[38]. The European Green Deal encapsulates the overarching goal of achieving carbon neutrality by 2050, emphasizing cost-efficient renovation methods and encouraging the repair and reuse of materials[39]. These regulations are key for shaping the Netherlands' sustainability efforts, guiding the development of various national and regional initiatives. However, the research highlights that the implementation of EU legislation in the Netherlands has faced hurdles, with the national government often setting climate goals that are either overly ambitious or too conservative. Despite several attempts by successive governments to meet their targets, challenges have persisted, resulting in two infringement cases initiated by the EU[40].

StichtingOPEN & the Right to Repair law

In addition to the overarching EU directives and policies, key non-governmental stakeholders like StichtingOPEN play a vital role in the implementation of solar panel waste management under the EU's WEEE Directive which mandates the collection and recycling of at least 85% of end-of-life (EoL) solar panels. As a producer responsibility organization (PRO), StichtingOPEN ensures compliance with the EU's recycling and collection targets for solar panels, resulting in an almost exclusive focus on recycling instead of re-using. This leads to the fact that StichtingOPEN does not direct significant efforts towards improving the logistics or consolidating partnerships necessary to ensure that solar panels remain fit for re-use, such as through repair or refurbishment, which is another reason most panels that are decommissioned early are only suitable for recycling, not re-use[41]. This gap in their strategy leads to missed opportunities in extending the lifespan of solar panels. Moreover, there is a lack of clear guidance for consumers and businesses on how to handle solar panel waste in ways that make panels viable for re-use, further limiting the potential of circularity in this sector[42] [43].

The Right to Repair law, introduced by the EU in 2024, aims to promote sustainable consumption by ensuring that manufacturers provide access to spare parts and repair services, extending the lifecycle of products, including electronics and renewable energy systems like solar panels[44].The law encourages repair over replacement and requires that companies make repair services more accessible and affordable to consumers, fostering a circular economy. The EU also supports businesses in implementing the Right to Repair through various mechanisms, such as offering financial incentives, setting up repair platforms, and providing regulatory guidance. These initiatives aim to make the repair of products like solar panels a more viable option for businesses and consumers[45].

For solar panels, applying the Right to Repair would mean encouraging repair and refurbishment, ensuring that panels can be reused rather than prematurely

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[36] Government of the Netherlands. (2024). Dutch goals within the EU. Retrieved from https://www.government.nl/topics/climate-change/eu-policy.
[37] European Parliament and Council of the European Union. (2023). Directive (EU) 2023/2413 amending Directive (EU) 2018/2001 and Regulation (EU) 2018/1999 on renewable energy promotion. Official Journal of the European Union, L 317/1. October 31, 2023
[38] European Parliament and Council of the European Union. (2023). Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955. Official Journal of the European Union, L 229/1. September 20, 2023.
[39] European Commission. (2023). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal. COM(2023) 540 final.
[40] European Parliament and Council of the European Union. (2018). Regulation (EU) 2018/1999 on the governance of the Energy Union and Climate Action. Official Journal of the European Union, L 328/1. December 21, 2018.
[41] Personal communication (2024)
[42] Circulaire Kennis. (2022). Balancing costs and revenues for recycling end-of-life PV panels. https://circulairekennis.nl
[43] Personal communication (March 2024)
[44] European Commission. (2024). Directive on common rules promoting the repair of goods. Official Journal of the European Union, L 1799/3. https://eur-lex.europa.eu
[45] Inside Energy & Environment. (2023). The Right to Repair gains momentum in the EU. Covington & Burling LLP. https://www.insideenergyandenvironment.com

recycled. StichtingOPEN, currently focused primarily on recycling, could leverage this framework to overcome the two main challenges: lack of logistics and partnerships for re-use and insufficient guidance on handling solar panel waste for repair. With the support mechanisms offered by the Right to Repair directive—such as financial incentives and access to repair platforms—StichtingOPEN could shift its strategy to include re-use and refurbishment as viable alternatives, thereby extending the lifespan of solar panels and contributing more effectively to the circular economy.

The National government

At the national level, the Netherlands focuses its energy and circular economy strategies across various sectors. The National Energy and Climate Plan outlines the country's approach to expanding renewable energy use and improving energy efficiency[46]. In support of this, the National Performance Agreements, established by the Minister of Housing and Spatial Planning in collaboration with key organizations (Aedes, VNG, and Woonbond), aim to speed up construction, enhance home insulation, and transition buildings to gas-free heating[47]. Additionally, the National Programme Circular Economy outlines measures to minimize primary resource use, substitute sustainable materials, extend the lifespan of products, and improve recycling processes[48]. The research suggests that as more responsibilities shift towards local governance, regional collaboration becomes increasingly critical. However, this transition has also impacted the actions of the national government, with a greater focus on stabilizing existing practices over promoting new innovations[49].

The province of North Brabant

In the North Brabant province, efforts are underway to achieve 100% sustainable energy by 2050 and reduce CO_2 emissions by 90% from 1990 levels. The province employs three main strategies to meet these goals: societal mobilization, technological innovation, and cross-sector collaboration. Societal engagement is driven by local energy cooperatives that work to enhance sustainable local energy supplies. These cooperatives encourage community involvement and raise awareness of energy conservation practices[50]. The Brabant Development Company (BOM) supports technological innovation, particularly in high-tech systems and sustainable energy, through partnerships with both local and international stakeholders[51]. Cross-sector collaboration is facilitated through public-private partnerships, which involve cooperation between public and private entities to pool resources and expertise[52]. Central to this approach are the Regional Energy Strategies (RES), which coordinate efforts across 30 energy regions—four of which are in North Brabant—to generate sustainable electricity, reduce fossil fuel use, and save energy. These strategies bring together various stakeholders, including provincial and municipal governments, water boards, businesses, and local residents[53].

The municipalities

The Dutch strategy for transitioning to a low-CO_2 economy relies heavily on a regionally driven approach, with municipalities at the forefront. In this system, the district-oriented renovation approach focuses on transforming each neighborhood individually. Municipalities are responsible for leading these efforts, guided by Heat Transition Visions. These visions outline how each municipality plans to phase out natural gas by 2050, often through methods such as enhancing district heating systems, deploying heat pumps, and incorporating renewable energy sources like solar and wind[54]. Municipalities also collaborate with local industries to implement energy-saving measures and promote the adoption of renewable energy. This collaboration typically includes providing guidance to industries on improving energy efficiency and sustainability. Furthermore, municipalities, in conjunction with provincial authorities, help establish local energy cooperatives to engage communities in the transition to sustainable energy practices. To encourage broader participation, municipalities run information campaigns, offer subsidies, and hold consultations with citizens and businesses to create a supportive environment for these initiatives[55]. Despite these efforts, research has highlighted that municipalities often face significant pressure from provincial and national governments. As a result, they tend to rely on soft enforcement mechanisms, which are generally insufficient to ensure strong compliance and often lead to less effective implementation of these ambitious plans.

[46] Ministerie van Economische Zaken en Klimaat. (2019). Integraal nationaal energie- en klimaatplan 2021-2030. November 2019.
[47] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2022). Nationale prestatieafspraken woningcorporaties. June 2022.
[48] Rijksoverheid. (2023). Nationaal Programma Circulaire Economie 2023 - 2030. February 2, 2023.
[49] van Dokkum, H. P., Loeber, A. M. C., & Grin, J. (2023). Understanding the role of government in sustainability transitions: A conceptual lens to analyse the Dutch gas quake case. September 2023.
[50] A. M. Schwencke, O. Stolwijk and J. de Graaff, "Lokale energie monitor 2023" March 19, 2024.
[51] Brabantse Ontwikkelings Maatschappij, (2022). "Jaarverslag 2022".
[52] Ooster van 't, S. (2021). Symbiotisch samenwerken: Een onderzoek naar de factoren voor succesvolle publiek-private samenwerking in het kader van de Noord-Brabantse uitdagingen rondom klimaatverandering. Radboud University.
[53] R. Nationaal Programma, (2022) "Jaarplan 2023".
[54] Netherlands Enterprise Agency. (2020). Long-term renovation strategy – En route to a low-CO2 built environment. March 6, 2020.
[55] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2022). Beleidsprogramma versnelling verduurzaming gebouwde omgeving. June 2022.

Social Housing Associations

As of January 1, 2023, a major legislative shift significantly impacted housing associations in the Netherlands. This change involved the elimination of the landlord levy, freeing up 1.7 billion euros annually for social housing associations[56]. While this policy aimed to strengthen the social housing sector, it came with increased expectations. Housing associations were required to adopt more ambitious targets for both construction and renovation of homes. However, interviews with stakeholders revealed that this financial boost has placed considerable strain on housing associations. Although additional funds were allocated, stakeholders voiced concerns that the elevated construction and renovation goals could potentially threaten the financial stability of some associations, with a risk of bankruptcy. Tension has emerged between the influx of funding and the pressures to meet these heightened goals. As a result, some associations have been hesitant to invest in new initiatives like the one discussed in this project, fearing the financial risks. On the other hand, larger associations that are financially stable expressed interest, recognizing future financial incentives[57].

Solar Panel Installers

During interviews with solar panel installer company representatives, it became evident that installers are generally knowledgeable about both the advantages and challenges of using second-hand solar panels. This awareness comes from their frequent involvement in the collection of panels that are decommissioned prematurely. Despite this, installers expressed a need for stronger incentives and assurances regarding the safety of second-hand panels in order to adopt them on a larger scale. They emphasized that clear regulatory frameworks and financial incentives would be crucial in making the use of second-hand panels both safe and economically viable. One of the reasons second-hand solar panels pose risks in installations is that they may not always meet the safety standards required by inspections in the Netherlands. These inspections, performed by certified professionals following standards such as NEN-EN-IEC 62446 and NEN 1010, are designed to ensure that solar systems meet strict safety guidelines. Installers worry that second-hand panels could fail to meet these standards, especially if their history or performance is uncertain. Thus, installers are often a key factor to the early decommissioning of solar panels. Based on interviews conducted for this project, as well as research from the city of Amsterdam, it was found that installers tend to favour a more "secure" option by recommending either the installation of new panels or the complete replacement of systems at the first sign of an issue. This approach is generally taken over exploring options like repair or prolonged use of the existing systems.

Residents

The attitudes of social housing residents represent a unique case, as their perspective was studied in-depth through an empirical quantitative research project. The study, based on a sample of 2408 social housing tenants in the Netherlands, used both survey data from the Dutch housing survey (WoON 2018) and interviews to uncover the factors that influence residents' willingness to adopt solar panels during their tenancy. The research aimed to explore the relationship between residents' energy usage, financial concerns, and sustainability beliefs, in order to provide decision-makers with actionable insights into how tenant attitudes can support or hinder the energy transition.

The research findings indicate that financial concerns are the primary motivators for social housing residents when it comes to adopting solar panels. Tenants tend to be supportive of solar panel installations as long as they are guaranteed upfront that it will result in tangible savings on electricity bills. According to the study, in 2018, social housing residents of the Netherlands who were living in houses powered by solar energy were saving, on average, 60 euros/year in energy costs compared to residents who had no solar panels on their roofs.

Sustainability beliefs—while present among tenants—did not always translate into higher adoption rates of solar panels. The research found that residents who strongly agree with sustainability goals are not necessarily more willing to adopt solar panels. This suggests that, while tenants may hold pro-environmental values, practical considerations such as costs, maintenance, and potential disruptions during installation play a more decisive role in their decision-making process.

In conclusion, addressing the financial concerns of tenants and clearly communicating upfront the energy savings potential are key strategies for housing associations aiming to increase solar panel adoption in the sector.

[56] Ministerie van Volkshuisvesting en Ruimtelijke Ordening. (2022). Intrekking van de Wet maatregelen woningmarkt 2014 II (afschaffing verhuurderheffing). October 6, 2022.

[57] Personal communication (March 2024)

New panels vs. Old panels

Based on the two scenarios that were set in the beginning of this report, calculations have been performed in order to establish the financial and environmental implications of installing new solar panels or panels that have already been used for a part of their lifetime. More details regarding the assumptions made regarding old solar panels and the numbers behind the calculations can be found in Appendix 2.

What is the difference for the investor?

The investment cost difference between an installation of 8 old and new solar panels has been calculated. The costs include hardware costs and installation costs. The costs of installation were established based on a quotation provided by a Dutch solar panel installer company, which does not differentiate between the age of panels in its pricing. However, other companies that deal with installation are often hesitant to handle second-hand solar panels as complications may arise in the installation process and they might be held accountable during system inspections. More than that, some companies charge different amounts based on the slope of the roof, as a flat roof requires additional equipment, care, and a more complex installation process. That is not the case in our situation.

Both systems are envisioned using a new inverter, as experts believe that the high malfunction risk of using second-hand inverter makes the ongoing investment not viable[58]. Furthermore, the typical lifespan of an inverter is a maximum of 10 years. Utilizing an inverter that has already been in service for 8 to 10 years, which is the typical amount for second-hand inverters, would result in an insignificant remaining lifetime.

As indicated in Table 1, the total investment cost for installing 8 new solar panels is €6,100. This includes the cost of new hardware components such as the inverter and mounting system, along with the installation costs. In contrast, the total investment cost for installing 8 old solar panels, as shown in Table 2, is significantly lower at €1,580. This reduction is largely due to the lower hardware costs associated with using second-hand components, though the installation costs remain the same. From a purely financial standpoint, the use of old solar panels presents a more cost-effective solution for investors, especially in scenarios where initial capital expenditure is a concern, such as social housing corporations. The lower upfront costs could make this option particularly appealing for small-scale investors or for projects where budget constraints are a critical factor. However, good planning around the lifetime of solar panels and the other components is crucial for maintaining the costs at the estimated level.

Table 1: Investment costs of an installation of 8 new solar panels.

Panels		Inverter		Mounting system		Hardware costs	Installation costs	Total investment cost
New	x	New	x	New	x	€5,320.00	€780.00	€6,100.00
Old		Old		Old				

Table 2: Investment costs of an installation of 8 old solar panels.

Panels		Inverter		Mounting system		Hardware costs	Installation costs	Total investment cost
New		New	x	New		€800.00	€780.00	€1,580.00
Old	x	Old		Old	x			

What is the difference for the user?

The difference for the user between installing new and reused solar panels, across both the innovative and conservative scenarios, lies in energy production, costs, and savings over time. In order to create approximate calculation of the energy production and financial implications of the different scenarios, data has been used. For the Innovative Scenario, synthetic data has been created based on trends and statistics representing hourly consumption of a gas-free typical household in Eindhoven (family with children). For the Conservative Scenario, real data has been used to represent daily consumption of a typical two-person household from Eindhoven, with a combination of fossil fuels, solar energy and grid electricity in their dwelling. For more details about how the data has been sources, please consult Appendix 1.

Energy production and consumption

The analysis of energy production and cost savings from solar panels reveals important insights across different months, not just during peak summer months. In the innovative scenario, illustrated in Figure 6, new solar panels consistently

[58] Personal communication (2024)

generate more electricity compared to reused panels throughout the year. For instance, while new panels reach significant outputs during peak months like May (approximately 151.22 kWh), the production from reused panels remains notably lower at about 65.94 kWh. It's essential to consider that during the winter months, such as January and December, both types of panels produce almost no energy due to shorter daylight hours and lower sunlight intensity, as production may drop to less than 100 kWh during these months, impacting the overall energy supply to households, failing to match the high demand during those months. In the conservative scenario shown in Figure 7, the performance of new panels still outstrips reused panels, although the overall electricity consumption is lower due to the assumed fossil supply of energy. While the contribution of reused panels is consistent, with about 65.94 kWh during peak months (offsetting max. 31.4% of consumption), the energy output during the winter months is significantly reduced to a maximum of 5%. This affects the overall reliance on the grid, highlighting that users opting for reused panels may still face challenges in meeting their energy needs during less favourable seasons. For instance, during the winter months, the output might drop below 50 kWh, leading to almost full reliance on grid energy.

Cost savings

When examining cost savings, Figure 8 and Figure 9 illustrate a similar pattern as the energy production and consumption graphs, the financial benefits of solar panels being substantially more pronounced during the summer months. With an average price per kilowatt, in June, for example, users with 8 new panels see a drop in electricity costs from €216.24 to €177.18, yielding notable savings of €39.06. Reused panels, while still providing savings show a smaller financial benefit of €17.04 compared to new panels. This demonstrates that although reused panels can provide some relief from energy costs, the savings are not as substantial. In the conservative scenario, new panels can lead to savings of €-31.43 in May, indicating surplus energy generation that offsets overall bills. In contrast, users with reused panels experience reduced costs of €26.56. This reflects that while reused panels do contribute to savings, the economic advantages of new panels are more substantial, particularly in scenarios where surplus energy can be sold back to the grid and the household can make use of energy storage.

The analysis shows that while reused panels can offer some relatively low financial advantages, new solar panels provide significantly higher energy production and cost savings, in both innovative and conservative scenarios.

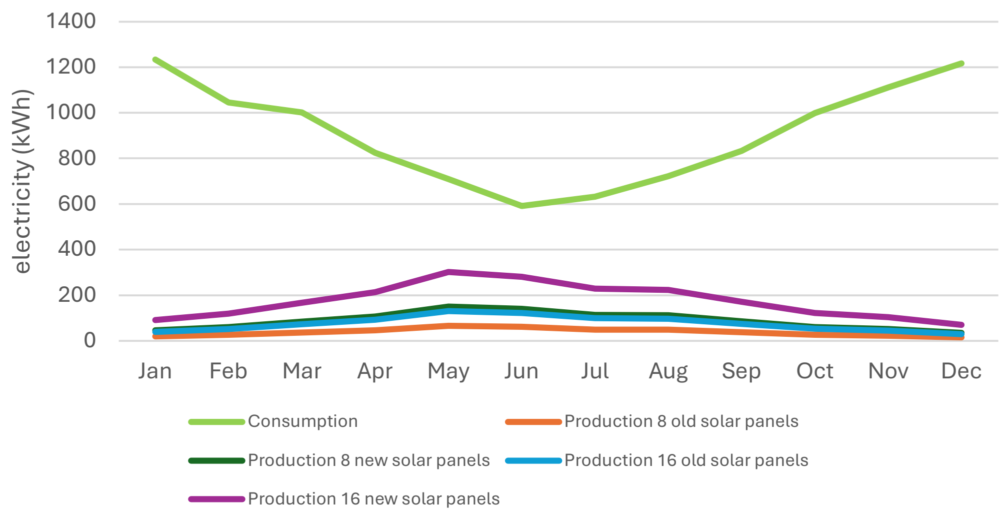

Figure 6: Consumption and production of electricity (innovative scenario) .

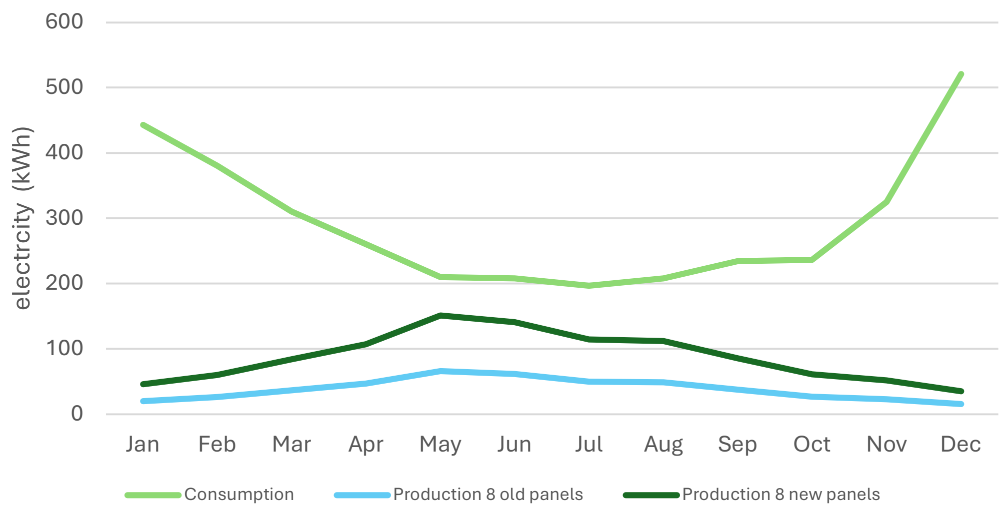

Figure 7: Consumption and production of electricity (conservative scenario).

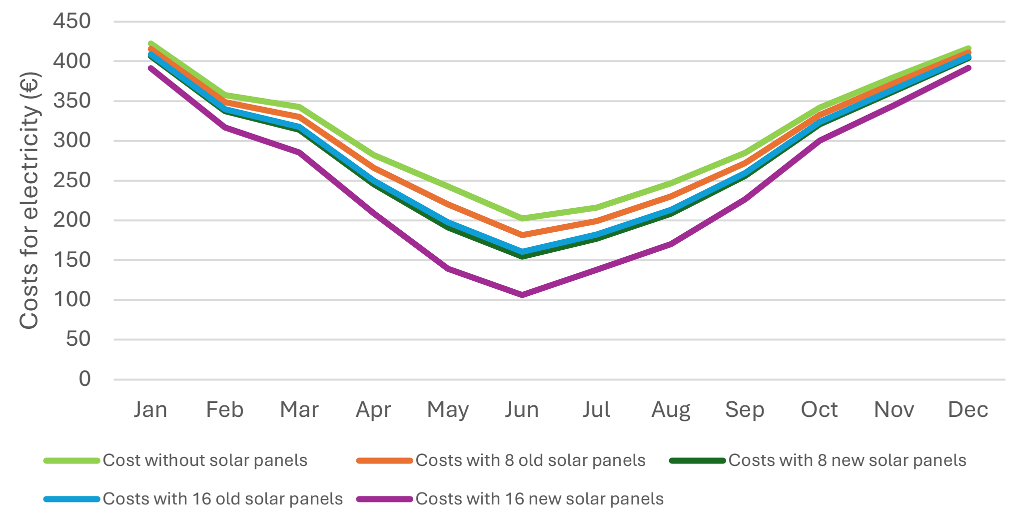

Figure 8: Comparison of costs (Innovative scenario).

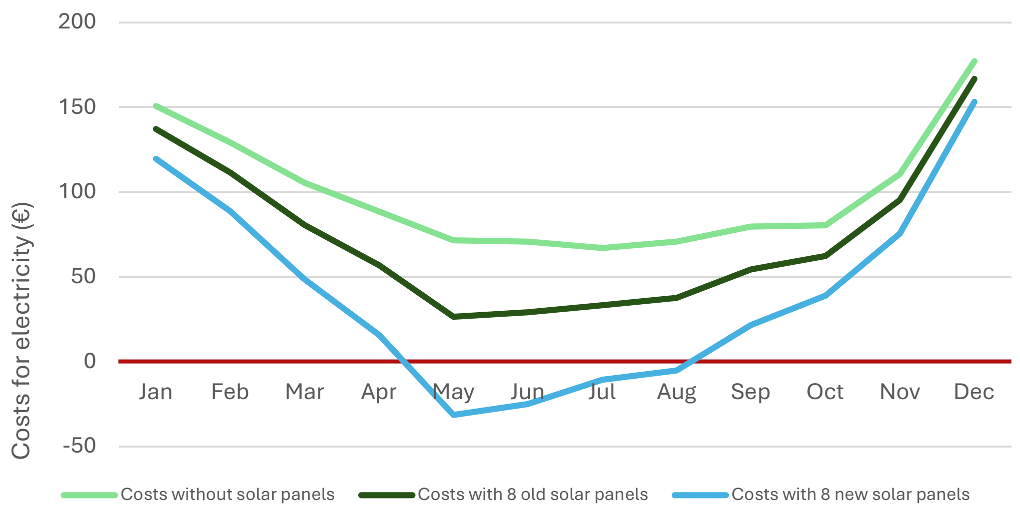

Figure 9: Comparison of costs (conservative scenario).

What is the difference for the environment?

As this report distinguishes between two possible scenarios, it outlines the environmental impact of installing 8 solar panels—comparing new and reused panels—over their respective lifetimes. More explanation about the calculation of each figure can be found in Appendix 2.

CO_2 Emissions in Production and Transport

For both scenarios, the production and transportation of 8 new solar panels results in approximately 1760 kg of CO_2 equivalent (Table 3). This covers the energy-intensive extraction of raw materials like silicon, silver, and aluminum, as well as the manufacturing and transport processes, typically from China[59]. The production emissions are the same across both scenarios, as they rely on the same manufacturing infrastructure and supply chains.

Reused Solar Panels: In traditional analyses, CO_2 emissions from production are not factored into reuse scenarios, since these panels have already been manufactured. However, to provide a full lifecycle analysis, we include them here for comparison. Even so, reused panels generate 0 kg of CO_2 equivalent from production in both the innovative and conservative scenarios, since they bypass the need for new material extraction and manufacturing. This represents a major advantage in terms of minimizing environmental impact, as can be observed in Table 3.

CO_2 Savings During Use

Over their assumed full 25-year lifespan, 8 new panels in the innovative scenario save approximately 1280 kg of CO_2 equivalent. The savings come from the high amount of energy they produce, superior to the reused ones, which replaces electricity that would otherwise be generated using fossil fuels. In the conservative scenario, where energy policies are slower to adapt, new panels still save 1152 kg of CO_2 equivalent during their 25-year lifespan. The savings are slightly lower due to fewer advancements in energy storage and grid optimization, but still significant.

For reused panels, with a remaining lifespan of around 13 years, the CO_2 savings are approximately 768 kg of CO_2 equivalent in the innovative scenario. Even though they have a shorter remaining lifespan, the reused panels still provide meaningful reductions in emissions. In the conservative scenario, reused panels save around 785 kg of CO_2 equivalent over their remaining lifespan. It is interesting that in a

[59] International Energy Agency (IEA). (2015). Life cycle inventories and life cycle assessments of photovoltaic systems. IEA-PVPS Task 12. https://iea-pvps.org

scenario which reflects less integration of smart energy systems, the contribution of re-used solar panels is slightly higher than in the innovative scenario.

Although it seems counterintuitive, In the innovative scenario, smart energy systems (e.g., energy storage, grid efficiency) may optimize energy use from multiple sources, reducing the relative contribution of reused solar panels in terms of CO_2 savings. Essentially, the system is already optimized for efficiency, so adding reused panels doesn't drastically change the overall savings. In the conservative scenario, without advanced systems, the reused panels might play a more central role, leading to slightly higher savings because there's less optimization elsewhere, making their contribution more noticeable.

Shadow Cost Savings

The shadow cost represents the monetary value of the environmental and societal damage avoided by reducing CO_2 emissions [60]. Shadow costs reflect the economic value of environmental and societal damage avoided by reducing CO_2 emissions, making them essential for decision makers. By incorporating shadow costs, policymakers can more accurately assess the societal value of investments. For instance, the municipality of Amsterdam has integrated shadow costs into its decision-making processes to evaluate renewable energy projects. This method highlights long-term savings from reduced emissions and encourages investments in technologies like reused solar panels, which minimize environmental harm. Understanding shadow costs allows for better resource allocation, enhances public engagement, and supports policies that align economic growth with ecological sustainability[61].

In the innovative scenario, the shadow cost savings for new panels are €228.80 over the full 25-year lifespan. This is based on the reduction of 1280 kg of CO_2 emissions, calculated using a shadow price of €0.13 per kg of CO_2. The shadow cost savings for reused panels in the innovative scenario amount to €169.72, reflecting 537.6 kg of CO_2 savings over their 13-year remaining lifespan. These savings are lower than those of new panels, but they provide a more immediate benefit, especially when considered in light of their lower upfront cost and reduced environmental impact during production.

Table 3: Comparison of environmental impact of the different scenarios.

	old panels		**new panels**	
scenario	Innovative	Conservative	Innovative	Conservative
production year	2012		2024	
installation year	2024		2024	
used lifetime (years)	12		0	
remaining lifetime (years)	13		25	
induced CO_2 (kg CO_2 - eq.) production & transport	0	0	1760	1760
CO_2 savings (kg CO_2 - eq.) use phase	768	785	1280	1152
CO_2 savings (kg CO_2 - eq.) re-use phase	537.6	-1152	0	0
Shadow costs (€)	0	0	228.8	228.8
Shadow cost savings (€)	169.728	-47.71	-62.4	-79.04

[60] de Bruyn, S., et al. (2010). Shadow prices handbook: Valuation and weighting of emissions and environmental impacts. Delft.

[61] de Vilder, S., van Driel, J., Cucurachi, S., & Vogt, M. (2024). The impact of solar panels in cities: Advice for a future-proof and circular energy transition for municipalities. AMS Institute, Leiden University, Delft University of Technology.

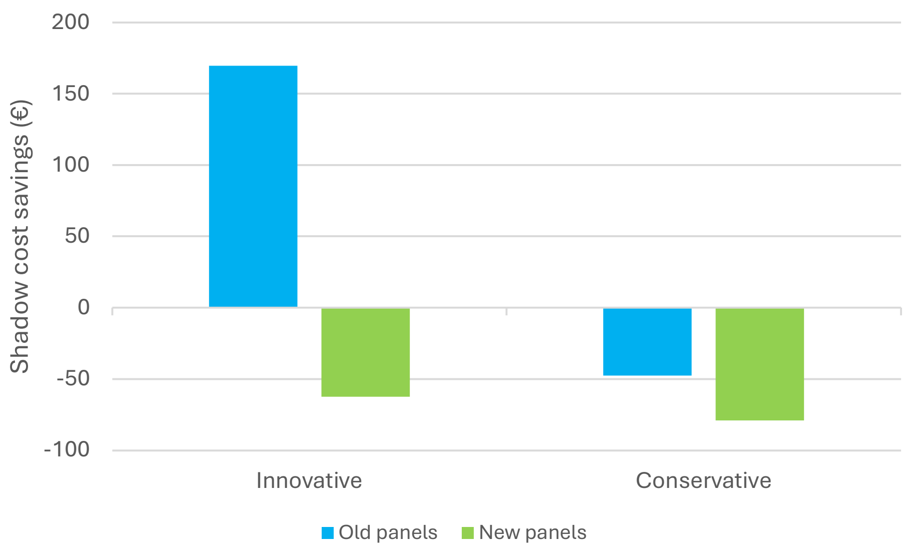

Figure 10: Shadow cost savings for the `different scenarios in euros.

When comparing an installation of 8 solar panels, both the innovative and conservative scenarios, reused solar panels offer significant shadow cost savings, primarily by avoiding the need for new material extraction and production. While new solar panels provide greater efficiency and longer-term CO_2 savings, the environmental costs associated with their production and transport are substantial. Reused panels, with their shorter remaining lifespan, still contribute meaningfully to CO_2 reductions and shadow cost savings, making them a highly sustainable option for shorter-term applications. Overall, the reuse of solar panels aligns well with circular economy principles, minimizing waste and maximizing the lifecycle value of existing resources. In the context of reducing environmental impact, reused panels emerge as a practical and efficient choice, particularly when immediate sustainability goals are prioritized.

Future perspectives

The role of this chapter is to outline future perspectives which could enable solar panel reuse, focusing on the importance of increasing public awareness, implementing supportive legislation, and establishing pilot-scale projects. By addressing these key areas, stakeholders can enhance the adoption of reusable panels and promote sustainable practices within the social housing sector. These recommendations are derived from previous findings and serve as actionable steps for decision-makers to foster a more sustainable energy landscape in the social housing industry of the Netherlands.

Public awareness

Most attention needs to be drawn to an increase in public awareness. The project uncovered that this is the most important measure to ensure a successful implementation since currently, there is almost no discussion about the topic, and many potential stakeholders are not aware that there is a surplus of reusable solar panels and a possibility of reusing them. Campaigns, both online and on-site, can be organised to shift public perception and increase knowledge about the benefits of solar panel reuse. They should provide clear information about the differences between choosing new panels and highlight personal stories from people who have already adopted reusable panels. Various educational programs for residents and businesses can expand public awareness about the benefits and feasibility of solar panel reuse. These can be done either online or organised through workshops, and certifications can be offered to boost awareness further. Additionally, quick educational segments can be implemented online in the form of calculators that provide information about the configuration of an installation and the associated financial savings.

Legislation

On a governmental level, several aspects should be targeted. Policy support is vital for creating a supportive environment for better management of solar panels. The development of financial incentives such as tax rebates, subsidies, or reduced tariffs for using solar energy plays a crucial role, as the project confirmed that financial incentives are usually the biggest driver for all stakeholder levels. Other research also states that making financial support more accessible and appealing can encourage both social housing residents and housing associations to opt for reuse rather than new solar panels.

Standardising a certification program for refurbished panels is another logical step that not only ensures that they meet safety and performance standards but also provides potential users with confidence in their reliability. Other research also confirms that this measure is crucial to ensure better management of solar panels. In addition to that, there could be a development of a national registry for certified panels. This registry could list all panels that have passed rigorous testing, providing consumers with an easy way to verify the quality and history of second-hand panels they are considering purchasing.

Pilot-scale project

A better connection needs to be established between stakeholders interested in reusing solar panels in social housing. This would allow for the launch of a pilot-scale project for a social housing neighbourhood in the province that would showcase the implications of reusing panels. Consequently, the results imply whether this should be tested on a bigger scale. Additionally, as the plans for abolishing the netting scheme have become known to the public, a financial analysis needs to be done on reusing solar panels to prove how financially viable it is to undertake such an initiative. This would serve as proof to residents whether reusing panels still offers benefits and ultimately decide whether they will be adopted by most.

Conclusion

This report has explored the potential of using both new and reused solar panels within the social housing sector in the Netherlands, comparing their environmental and financial impacts across innovative and conservative scenarios. Through the analysis of energy production, cost savings, CO_2 emissions, and shadow cost savings, we have identified key advantages and trade-offs for users, policymakers, and housing associations in the energy transition.

In both scenarios, new solar panels provide higher energy efficiency and longer-term financial benefits, particularly in contexts where smart energy systems and policies favour renewable energy adoption. However, they come with significant upfront environmental costs due to raw material extraction, production, and transport. These long-term investments are most suitable for users seeking to maximize energy output and reduce energy bills over the full lifespan of the panels.

On the other hand, reused solar panels offer a compelling short-term solution, especially for users with budget constraints or in situations where temporary installations are needed. Although they have a shorter remaining lifespan and lower energy output, reused panels help minimize CO_2 emissions from production, reduce waste, and lower initial installation costs. This makes them a viable option for meeting immediate sustainability goals and contributing to the circular economy by extending the useful life of existing resources.

Additionally, the choice between new and reused panels must be viewed through the lens of broader societal goals, including reducing CO_2 emissions, promoting sustainability, and enhancing resource efficiency. While the innovative scenario highlights the benefits of rapid energy transition and technological advancements, the conservative scenario emphasizes a slower but still meaningful path toward sustainability, where both new and reused solar panels play critical roles.

Overall, this report underscores the importance of flexibility in solar panel adoption strategies. Policymakers and housing associations should consider both options—new and reused panels—depending on the specific needs of residents, financial constraints, and long-term sustainability objectives. As the energy transition accelerates, the integration of reused solar panels can complement the deployment of new technologies, helping to balance cost, efficiency, and environmental impact.

Disclaimer

The data and figures presented in this report are based on a combination of synthetic and real datasets, with the purpose of offering a comprehensive comparison between new and reused solar panels under innovative and conservative scenarios. For the Innovative Scenario, synthetic data was created to represent the hourly consumption of a gas-free typical household in Eindhoven, while the Conservative Scenario uses real data representing the daily consumption of a typical Dutch two-person household with a fossil-based dwelling.

It is important to note that:

- All personal data has been anonymized, and no individual household or personal information was used in the creation of these datasets. Ethical guidelines were strictly adhered to in order to maintain privacy and confidentiality.
- The number of 8 solar panels used in this report has been arbitrarily chosen for modeling purposes, as it reflects a common installation size for households in the Netherlands, where roof space frequently allows for this configuration.
- The numbers used for energy production, consumption, and cost savings are based on industry-standard assumptions and statistical models. While every effort has been made to ensure the accuracy of the figures, they should be considered approximate and may not precisely reflect actual future outcomes in all cases.

- The shadow cost savings and CO_2 emissions calculations are based on current market conditions and environmental data, which may change over time as new technologies and policies are introduced.

Users and readers are encouraged to use these figures as illustrative examples for understanding general trends and differences between new and reused solar panels, rather than as exact predictions for any specific application. For more detailed information on data sourcing, assumptions, and methodology, please refer to the appendix.

Appendix

Appendix 1: Data sourcing

- The average daily energy consumption for a household in the Netherlands was set at 30 kWh[62].
- A seasonal variation of ±10 kWh, to account for significant changes in energy use between summer and winter. This reflects increased consumption during winter due to heating and reduced consumption during summer. The variation was modelled using a cosine function, ensuring a smooth transition between seasons and capturing the expected higher energy demand in colder months[63].
- Hourly mean irradiance for the city of Eindhoven was derived from the KNMI database. The horizontal irradiance was used, taking into account the effect of the 35 degree slope of solar panels[64].
- The consumption data is adjusted with an hourly breakdown of energy consumption based on a distribution of hourly fractions retrieved from the European Commission PVGIS tool, which reflects typical household usage patterns. Higher consumption is modelled during peak hours (morning and evening), while lower consumption is assumed during off-peak hours (late night and early morning)[65].

[62] CBS. (2020, March 4). Energy bill 170 euros lower this year. CBS. https://www.cbs.nl/en-gb/news/2020/10/energy-bill-170-euros-lower-this-year

[63] Stolwijk, A. M., Straatman, H., & Zielhuis, G. A. (1999). Studying seasonality by using sine and cosine functions in regression analysis. Journal of Epidemiology & Community Health, 53(3), 235-238. https://doi.org/10.1136/jech.53.3.235

[64] Royal Netherlands Meteorological Institute (KNMI). (n.d.). Sunshine and radiation datasets. KNMI Data Platform. Retrieved July 3, 2024, from https://dataplatform.knmi.nl/dataset/?groups=sunshine-and-radiation&tags=Radiation

[65] PVGIS. (n.d.). Photovoltaic Geographical Information System (PVGIS). Retrieved July 3, 2024, from https://pvgis.com/

[66] Lazaroiu, A. C., Osman, M. G., Strejoiu, C. V., & Lazaroiu, G. (2023). A comprehensive overview of photovoltaic technologies and their efficiency for climate neutrality. Sustainability, 15(23), 16297. https://doi.org/10.3390/su152316297

- The datasets cover a full calendar year from January 1, 2023 to December 31, 2023.

Appendix 2: assumptions and rules of thumb

- 1.6 m^2 monocrystalline solar panel was used in the calculations, as it is the most wide-spread size and technology of solar panels[66].
- Based on literature, older solar panels for residential purposes have an efficiency of approximatively 15%, and new panels 20% efficiency[67].
- The price per kWh for electricity was set by calculating the mean price per kWh from the three biggest energy providers in the Netherlands in 2024, paying €0.342 per kWh.
- The solar panels are assumed to be installed at the ideal slope (35) for the Netherlands and 0o azimuth (facing south).
- There are no shading or obstructions that would reduce the sunlight reaching the panels.
- Loss due to inefficiencies in the system (e.g., inverter losses, wiring losses) were considered 15% for both old and new panels. The performance degradation of solar panels over time was not factored into the calculations[68].
- The solar panels are assumed to produce the maximum electrical power that can be supplied by a photovoltaic panel under standard temperature and sunlight conditions (0.25 kWh for old panels produced in 2012 and 0.43 kWh for new panels produced in 2024) minus losses due to inefficiencies in the system[69].
- Shadow cost is set at €0.13/kg CO_2-eq, based on the Shadow prices Handbook[i] [70].
- Total lifetime of solar panels is assumed 25 years.
- In the environmental impact calculations, the difference in numbers between the innovative and conservative scenarios is based on the scenarios' 'fossil-free by 2035' and 'fossil-free by 2045' from de Vilder (2024) report, figure 10 and 11[71].

[67] Franco, M. A., & Groesser, S. N. (2021). A systematic literature review of the solar photovoltaic value chain for a circular economy. Sustainability, 13(17), 9615. https://doi.org/10.3390/su13179615

[68] Alqaed, S., Mustafa, J., Almehmadi, F. A., & Jamil, B. (2023). Estimation of ideal tilt angle for solar-PV panel surfaces facing south: A case study for Najran City, Saudi Arabia. Journal of Thermal Analysis and Calorimetry, 148, 8641–8654. https://doi.org/10.1007/s10973-022-11753-5

[69] de Vilder, S. (2023). Changing environmental tides of Amsterdam's future PV systems - A multi-scenario projection for the environmental performance of residential PV systems in Amsterdam.

[70] de Bruyn, S., et al. (2010). Shadow prices handbook: Valuation and weighting of emissions and environmental impacts. Delft.

[71] de Vilder, S., van Driel, J., Cucurachi, S., & Vogt, M. (2024). The impact of solar panels in cities: Advice for a future-proof and circular energy transition for municipalities. AMS Institute, Leiden University, Delft University of Technology.