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Deconstructing value in solar panel reuse with time-explicit life cycle assessment and costing

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ABSTRACT

Many solar panels are discarded before the end of their technical lifespan, wasting valuable energy generation potential. Reusing these panels in underserved communities expands clean energy access but incurs upfront processing costs and yields energy later, at diminishing capacity. To justify such value retention efforts, the temporal dimension is essential yet underexplored. This study uses Time-Explicit Life Cycle Assessment and Costing to investigate when, which values were retained, and at which cost, across three solar panel reuse cases in the Netherlands.

Results show life cycle Carbon Footprints savings of up to 231,700kg$CO_{2\text{-eq}}$ and financial savings up to €307,935. However, during reuse processing years, Carbon Footprints rise by 37 %, and upfront costs rise by up to 90 %. Cost bearers and beneficiaries differ. Nevertheless, these additional impacts balance out in 2–3 years. Reuse emerges as a promising circular strategy, provided financing and policy mechanisms will be in place to address upfront costs.

1. Introduction

Modern waste challenges often stem from a failure to preserve the value of products, leading to early retirement that accelerates environmental degradation and undermines sustainable resource use (van Ewijk and Stegemann, 2020). An example is solar panels, which are produced to serve 25 years but are currently discarded on average after only 7 years of service (Atasu et al., 2021; Duran et al., 2022). Despite their proven repairability and reusability, solar panels are rarely reused (Chhillar et al., 2025; Marinna et al., 2025; Nieto-Morone et al., 2024; Poulek et al., 2023; Tsanakas et al., 2020; Van Der Heide et al., 2022), even though reuse of solar panels have found a place in providing value to underserved, low-income communities (Stromberg, 2021, 2023). This results in losing residual electricity generation capacity and associated functional value due to suboptimal material recovery (Weckend et al., 2016).

"Functional value" refers to the *"objective measure of functions that materials, components, and products can potentially provide to humans"* (Vulsteke et al., 2024, p. 4), also termed as "functional utility" or "functionality" (André, 2024; Bocken et al., 2016; Campbell-Johnston et al., 2020; Da Silva et al., 2024; Hatzfeld et al., 2022). Conceptually, products have three nested functional values (Vulsteke et al., 2024): i) product functional value (PFV), e.g., the electricity generation of a functioning solar panel, ii) component functional value (CFV), e.g., the supporting function of the balance of systems (BOS) dismantled from a retired solar panel, and iii) material functional value (MFV), e.g., usage of the metal and mineral scraps that can be recovered through shredding a discarded solar panel. As the nested functional values change over the lifespan of a product, the concept functional value over time (FVOT) has been proposed to express the dynamic characteristics of the functional value (Hatzfeld et al., 2022). The retention of FVOT of products, components and materials is achievable through circular economy (CE) interventions. CE interventions are commonly conceptualized as 10 R's (Kirchherr et al., 2017; Reike et al., 2018): *Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover* and *Remine*, following a descending hierarchy regarding the potential for value retention. However, retaining value requires efforts such as labour, material, energy and financial inputs. The higher up the hierarchy the CE intervention is, the more efforts it may require, which explains why solar panel reuse is much rarer than panel recycling.

To justify the CE interventions, Life cycle assessment (LCA) and life cycle costing (LCC) have been used to assess the associated environmental gains and financial costs. Moraga and colleagues (2022) use LCA to quantify the environmental benefits of maintaining in-use occupation

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of materials in laptops and find a preference for higher tier CE interventions like *refurbish* and *reuse*. Salvi and colleagues (2023) use LCA and LCC to compare low-quality (downcycling) and advanced recycling of solar panels, and find that emissions reductions from downcycling are negligible compared to incineration and doesn't recover critical materials. Existing LCA and cost studies in solar panel reuse show the environmental and economic viability of reuse but fail to consider the variation of FVOT, showing how much value is retained and its environmental and economic impacts across time (Lunardi et al., 2018; Schünemann et al., 2021). These LCA and LCC studies lack nuance on a) incorporating the temporal dimension in the analysis and b) presenting the findings in an accessible way to engage stakeholders in CE interventions.

To bridge this gap, this study aims to address the functional value retention and the resulting environmental and economic impacts in a time explicit manner. Recent methodological development in LCA has made several attempts to incorporate the temporal dimension. In traditional LCA, the functional unit (e.g. 1 kWh of electricity production) is defined to be constant across the period of assessment (Beloin-Saint-Pierre et al., 2020; Kim et al., 2017; Weidema and Hansen, 2004), and the associated impacts are assumed 'simultaneous', i.e. not allocated explicitly over time. In dynamic LCA, the timing of processes and emissions is considered through dynamic characterisation factors (Levasseur et al., 2010), which is related to the *temporal distribution of activities*. In prospective LCA, not only changes in processes but also emissions in one future point in time are considered, which is related to the *temporal evolution of impacts* (Cardellini et al., 2025). When assessing the environmental impacts of a CE intervention, the processes within the supply chain to maintain FVOT occur in separate years over a long lifespan (e.g., 25 years for solar panels). Thus, both temporal evolution and temporal distribution must be considered. Moreover, both background and foreground activities change over the expected long lifespan, especially the electricity mix, due to future decarbonisation. As without a time-explicit approach, we won't know how much functional value is retained and when, and what are the life cycle impacts of doing so nor which end-use parties stand to gain or lose from these actions. This study will apply a time-explicit LCA and LCC approach (Cardellini et al., 2025; Theory—Bw_timex documentation 2025). To assess the environmental and economic impacts of the CE intervention case on solar panel reuse. Additionally, economic challenges such as high initial expenses, distributed future gains and not accounting for externalities prevent stakeholders investing in CE interventions (Khadim and Van Marrewijk, 2025).

To generate accessible information for stakeholders, the Handprint (HP) concept is being introduced (Norris, 2015; Norris et al., 2021). LCA communicates negative environmental impacts. However, CE interventions by business actors are motivated by "doing good" (Norris, 2015). Therefore, a way to communicate positive perspective must be used. Thus, the comparative concept of Handprint is proposed. HPs serve as a lens to interpret benefits relative to a baseline. Moreover, HPs emphasise the agency of businesses in creating improvements to the business as usual, in this case, the reuse of solar panels. HPs highlight not only reduced harm to society but also created value (Vulsteke et al., 2024). However, taking a HP lens when exploring functional value retention is a recent concept which lack empirical analysis (Vulsteke et al., 2024). This study aims to link the retention of FVOT with its handprints and footprints.

We provide a comprehensive quantitative analysis of retaining the functional value of solar panels through its reuse in economically disadvantaged areas. First, we deconstruct the retention of FVOT for solar panel systems. Then we analyse its environmental and economic impacts using Time-Explicit Life Cycle Assessment (TE-LCA) and Life Cycle Costing (LCC). Finally, we interpret our results through a HP lens to show the comparative positive benefits brought out due to a change to the business as usual. This leads to our research question, How can we embed the concept of Functional Value over time with time-explicit LCA and LCC approaches to analyse the environmental and economic impacts of value retention by reuse?

2. Methods and data

2.1. Case study

Reuse of early-retired solar panels is a niche practice. Three solar panel reuse projects were realised during 2023 – 2024 to supply clean energy to underserved communities (Table 1 and Supplementary material 1, 1.1). The second-hand panels are installed in locations where users would otherwise be unable to afford new systems; for instance, energy poor households or community centres in lower income neighbourhoods. These communities would have continued with grid-based electricity without this intervention to provide second-hand panels. We take these cases as an example to examine the changes caused by a CE intervention in FVOT and environmental and financial impacts.

2.2. Functional value over time

The FVOT is divided into its product (PFV), component (CFV) and material (MFV) constituents (Vulsteke et al., 2024). In this study, the solar panel power output was used to measure PFV, the number of components in the system was used to measure CFV, and the mass of recoverable materials in the solar panel was used to measure MFV.

We attempted to combine the three functional values by creating a dimensionless value (between 0–1), assuming an equal weight for the three functional values Eq. (1).

$$FVOT_t = \frac{\frac{PFV_t}{PFV_{t(0)}} + \frac{CFV_t}{CFV_{t(0)}} + \frac{MFV_t}{MFV_{t(0)}}}{3} \tag{1}$$

Where,

- FVOTt: the functional value of the solar panel system of the solar panel at year t.
- PFVt(0): the theoretical maximum product functional value. It is measured by the electricity generation of the new solar panel at the first year of installation.
- PFV(t): electricity generation at year t
- $CFV_{t(0)}$: CFV at the first year measured by the number of original components
- CFV_t: CFV at year t measured by number of original components in use
- $MFV_{t(0)}$: MFV at the first year measured by the mass of materials in solar panels in use
- MFV_t: the total mass recoverable at year t

PFV follows a continuous function based on Eq. (2). PFV and hence, solar panel degradation, is denoted by parameters DR_1 and DR_2 in Eq. (2) based on (Frischknecht et al., 2020; Müller et al., 2021). This leads to the varying functionality with time. In the first year, the degradation rate is higher at about 3 % (DR_2) and the subsequent years, the solar panel is assumed to degrade linearly (DR_2) (Jordan and Kurtz, 2013).

$$V_i = (1 - DR_2)^{i-1} \times (1 - DR_1) \times I \times A \times \eta \times PR \tag{2}$$

Where:

- V_i = annual electricity generated (kWh/year)
- I = average annual irradiation on the installed location (kWh/m^2)
- A = surface area of solar panels (m^2)
- η = solar panel efficiency (%)
- DR_1 = Degradation rate at year 1 (%)
- DR_2 = Degradation rate of subsequent years (%)
- PR = performance ratio of solar panels (%)
- i = year

Table 1
Summary of case studies.

	Expected Lifetime extension	Age of panels at first retirement	Number of Panels	Starting year of panel reuse	Reuse of balance of system	Installation location of panel reuse, motivation of the case and funding
Case 1	15 years	7 years	6	2024	Yes, Inverter only	*Kazerne:* Temporary rooftop, creating awareness about clean electricity among the community Funder – Municipality Amsterdam
Case 2	8 years	5 years	24	2023	None	*Haarlemmermeer:* Energy poverty households, to save energy bills Funder – Municipality Haarlemmermeer
Case 3	22 years	3 years	220	2023	Yes, inverter and mounting system	*Projecthuis Madiba:* Community centre, to invest savings into the community Funder – Projecthuis Madiba

CFV is the fraction of the number of components reused after each use phase. At the end of the 2nd lifetime, materials functional value is recovered through recycling. MFV is the fraction of materials (kg) recovered through recycling compared to the total material mass in the solar panel. Material quality is an important characteristic when considering the functional value of materials (Moraga et al., 2019; Zink et al., 2016). Therefore, the functional value of recovered materials is reduced to reflect the loss of quality comparing to virgin material (see Table S3).

2.3. Time-explicit life cycle assessment

2.3.1. Goal and scope

The goal of this TE-LCA is to compare the environmental impacts of two options for managing early retired solar panels: the reuse of solar panels in underserved communities and advanced recycling, compared to the incumbent system of scrapping and recycling early retired solar panels. The environmental impact is simplified to one impact category as the Carbon Footprint. The temporal scopes are from 2017 to 2039 for Case 1, 2018–2031 for Case 2 and 2020–2045 for Case 3, a timeframe that allows solar panels reach their standard 25 years technical lifespan (Müller et al., 2021). The functional unit of this analysis is the provision of electricity to the end-users across the service-life of the solar panel system. The system boundaries of the study are shown in Fig. 1. In the baseline system, the panel is retired early and grid electricity supplies electricity to the underserved user, while in the reuse system, in the reuse system, the second-hand solar panels supply electricity.

Two foreground scenarios, representing the situations of avoiding early retirement and the reuse CE intervention, and two background scenarios, representing different future socio-economic development was modelled for time-explicit assessment. In the foreground, for each reuse case list in Table 1 a baseline scenario, representing early retirement of solar panels without reuse intervention was defined (Figs. S1–S3). This study assumed that advanced recycling will be available at the end of the solar panels' second life cycle (Lijzen et al., 2024).

In the background, two socio-economic scenarios were modelled, as future development can take different pathways tied to varying socio-economic trends. These trends are modelled in Shared-Socio-economic Pathways (SSPs) (Riahi et al., 2017). We wanted to assess two pathways of development which leads to below 2 °C of warming by 2100. Image SSP2-RCP26 was chosen as a representative of the 1.6–1.8 °C climate target (hereby SSP2) and remind SSP1-PkBudg500 as a representative of the 1.2–1.4 °C climate target (hereby SSP1). The SSP1 scenario is used as a sensitivity scenario to test the impact of a stricter climate goal (See S1.4).

The ecoinvent 3.9.1 cut-off system model was adopted in our TE-LCA. This model was chosen to characterise the direct, time-explicit impacts of reuse activities rather than to model broader market consequences. The system is multifunctional since it provides electricity and yields materials at the end-of-life (EoL) due to recycling. Allocation of multifunctionality is avoided through system expansion by including the additional functions of the system of producing co-products (Heijungs et al., 2021). In our case, the materials recovered through recycling need to be produced in the alternative system.

2.3.2. Life cycle inventory (LCI)

To embed the loss in product FVOT in the LCI, and hence the

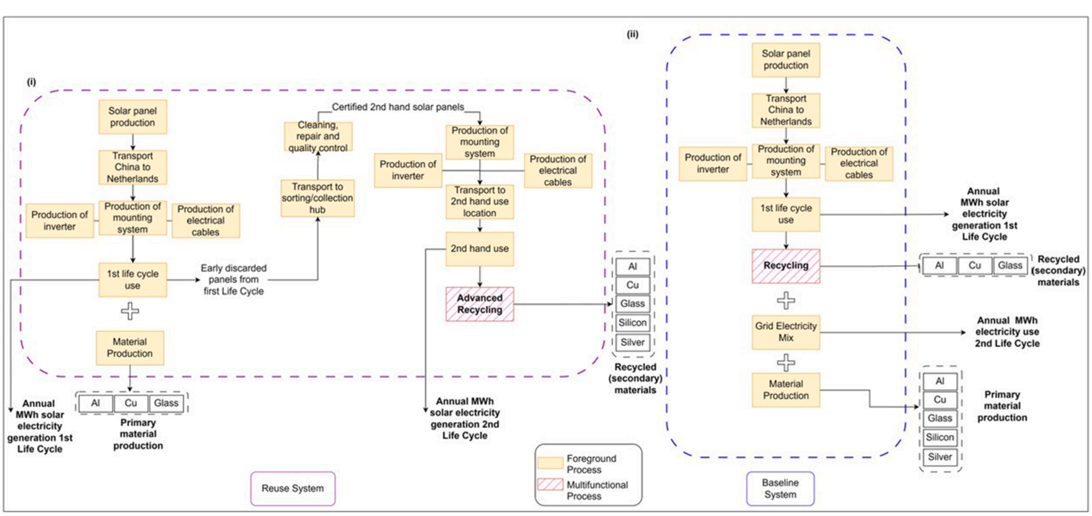

Fig. 1. (i) General system boundary of the reuse system where early retired panels are given a second life (ii) General system boundary of the baseline system where solar panels are retired early and sent to currently available commercial recycling facilities. The electricity production is divided across the first life and second life cycle. Primary material production of materials recovered from recycling at the end of life is added in both cases to represent co-products arising from the system.

temporal distribution and temporal evolution in the use phase, we considered the annual degradation of the solar panels in our system (Eq. (2)). For the end-of-life phase, the replacement of primary materials due to materials recovered from recycling (see Table S1–3). Therefore, the FVOT decline over time in the use and end of life phases is quantified and set in a time-explicit manner in the LCI.

First, the processes are created in *Activity Browser* software (Steubing et al., 2020) as outlined in supplementary materials Section 1.3.3. The ecoinvent 3.9.1 cut-off database is used to create the background processes. For all other processes, refer Section 1.3.3. in the Supplementary Materials 1. Then *Premise* is used to update the processes created, based on future changes to technology and environmental flows outlined by the SSP scenarios (Sacchi et al., 2022). The processes are updated to the specific year which the process occurs, thus including the temporal evolution and distribution for background processes. The TE-LCA is performed for each process using Activity Browser, the impacts on Climate Change category are calculated for the year it occurs e.g., production of inverter in 2035.The five stages in the reuse system modelled in this study are presented in Fig. 2.

2.3.3. *Impact assessment*

The life cycle impact is calculated using the ReCiPe midpoint (H) methodology. For simplicity, we present only the results on the impact category 'Climate Change'. We use global warming potential (GWP) to indicate Carbon FP in $kgCO_{2\text{-equivalent}}$. We first calculate the FP for both reuse and baseline systems, then subtract the baseline FP from reuse FP for each case to generate the HP of the CE intervention – reusing solar panels.

2.3.4. *Interpretation*

The environmental FP is dominated by material and energy inputs for primary production of the solar panels. In an absolute term, reuse chain activities and recycling processes do add FP. While comparing to the baseline situation, the HP of CE intervention, can largely balance the added FP since, when the reuse locations receive second hand solar panels, they avoid using electricity from the grid and MFV is also created

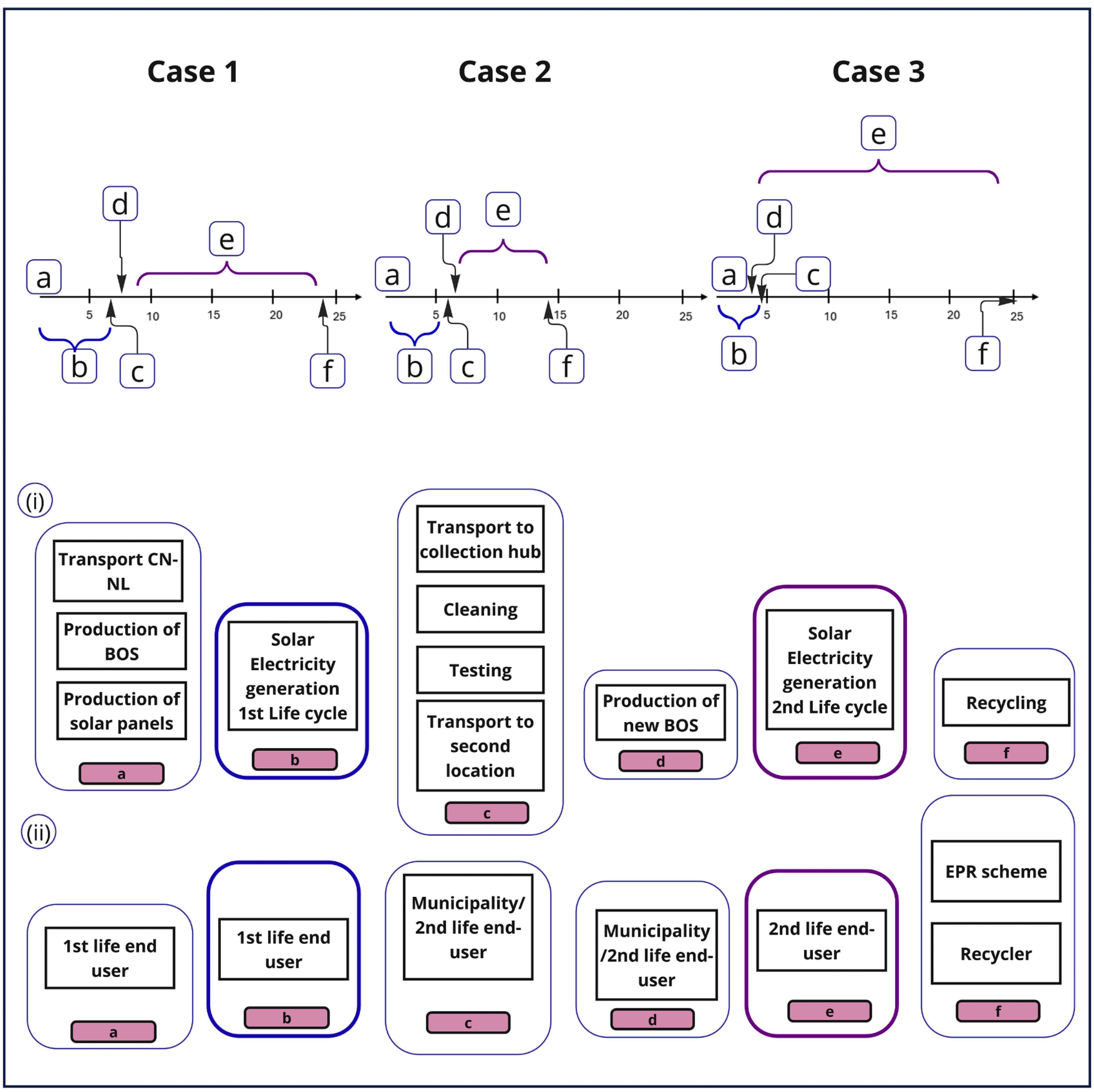

Fig. 2. Processes (i) and direct cost bearers (ii) in the 5 life cycle stages of the time-explicit life cycle inventory for the 3 case studies. They are: (a) Solar panel production stage, involving (i) process - transport, balance of systems (BOS) and panel production, (ii) cost bearer - 1st life end user of the panel; (b) 1st use stage, involving (i) solar electricity generation at 1st life cycle of the panel, (ii) 1st life end user; (c) preparation for reuse stage, involving (i) transport to collection hub, cleaning, testing, transport to secondhand use loction, (ii) reuse chain partner; (d) production of new BOS components stage, involving (i) production of new BOS, (ii) reuse chain partner; (e) 2nd use stage, involving (i) solar electricity generation at 2nd life cycle of the panel, (ii) 2nd life end user of the panel; and (f) Recycling stage, involving (i) recycling, (ii) recycler and material producer.

when recovering materials at the end-of-life.

2.4. Life cycle costing

2.4.1. Goal and scope

The goal of the LCC is to quantify the costs of reuse of solar panels in underserved communities and advanced recycling, compared to the incumbent system of scrapping and recycling early retired solar panels (Hunkeler et al., 2008). The LCC is performed across the same scope as the LCA. These costs are attributed to the relevant stakeholders in each stage of the life cycle. To account for the decline in the time value of money, discounting is performed for all future costs. The base year was 2023. The discount rate of 5 % was chosen based on (Hunkeler et al., 2008) as the lower end for public investments.

2.4.2. Inventory analysis

The costs of the second-hand solar panels and BOS components were based on consultation with stakeholders in the industry (WEEE NL and ZonNext, Personal Communication, 2024). The stakeholders affected by costs through the phases of the life cycle can be summarised in Fig. 2. For LCC cost calculations, see Supplementary materials 1,Section 2.1.

2.4.3. Impact assessment

Similar to the TE-LCA results, the life cycle costs were calculated annually. The net present-value (NPV) present value of the costs and revenues as each time-step (Zhang et al., 2019) was used to indicate the economic HP and FP. Based on the discount rate of 5 %, a NPV was calculated for each of the relevant future costs. The general equation for NPV is shown in Eq. (3):

$$NPV = \frac{FC}{(1+d)^{i}} \tag{3}$$

Where:

- *NPV = Net present-value (€)*
- *FC = Future Cost (€)*
- *d = discount rate (%)*
- *i = year*

We first calculate the costs and revenues occurring in both reuse and baseline systems at each time step. Then, the economic HP of the CE intervention is calculated by using Eq. (4). The HP consists of the cost savings from reuse of solar panels and revenue from material recovery.

$$Economic\ HP_t = (Costs)_{Reuse_t} - (Costs)_{Baseline_t} - (Revenues)_{Baseline_t} + (Revenues)_{Reuse_t} \tag{4}$$

2.4.4. Interpretation

As shown in Fig. 5, the economic FPs stem from acquisition of solar panels, BOS and recycling costs. The HP of the CE intervention is mainly created by saved grid electricity costs due to solar panel reuse.

3. Results

3.1. Retention of functional value over time

In theory, solar panels can serve 25 years until its technical end of life and retain its MFV through advanced recycling methods. Due to early retirement, 70 % of the FV is lost in the baseline system including valuable materials like silicon, silver and solar glass. Solar panel reuse can retain between 35–70 % of the FVOT, depending on how much components are reused. For example, in case 3, both inverter and mounting system are reused and in case 1, the inverter is reused. PFV of 26 MWh (case 1), 62 MWh (case 2) and 1485 MWh (case 3) is retained serving the second hand users. The MFV recovery is 29 % for the baseline system due to downcycling and 30 % for the reuse system due to advanced recycling. The difference is low but critical and more expensive materials, silicon and silver, are recovered by advanced recycling Fig. 3.

3.2. Time-explicit life cycle assessment

We assessed the environmental HPs and FPs of solar panel reuse in three real-world cases, under two socio-economic scenarios (SSP1 and SSP2). Fig. 5 presents time-explicit results, for the baseline and reuse systems with HP shown on the negative y-axis and FP on the positive.

The time-explicit perspective allows us to see when pulses of FP occur across the life time of our systems. As shown in Fig. 4, the majority of the Carbon FP occurs in the first year due to the primary production of the solar panels and BOS. Additional FP from reuse activities in cases 1–3 are modest, comprising just 20 %, 35 % and 37 % on top of existing emissions from the production year, respectively. It is largely dependent on whether BOS components are replaced or reused. Between 45–75 % of this added FP stems from producing new BOS components; the remainder arises from cleaning, testing, and transporting the panels and material production needed to offset the recovered materials from the baseline system. Case 1 reuses the inverter, while Case 3 retains both the inverter and mounting system, leading to substantially lower additional impacts than Case 2, where all BOS components are newly produced.

HPs are positive in the first two to three years of reuse in all cases since the baseline system has a lower FP for two reasons. Firstly, in the baseline system, the solar panels are recycled early, recovering glass, aluminium and copper. Due to system expansion, this creates a demand for virgin materials in the reuse system which has to be produced. Secondly, the additional production of balance of systems creates more emissions than the grid electricity emissions in the baseline system. The cumulative HPs show when the emissions saved through reuse balances out the additional FP from the reuse processing. These HPs decline over time due to panel degradation and its associated functional value loss. Moreover, in the baseline system, the electricity grid becomes cleaner also contributing to a decline in HPs. Additional HPs are also generated from recovering MFV at end-of-life, since these materials have to be produced by the baseline system. Due to only recovering MFV rather than PFV, the HPs are visibly smaller. In all cases, the cumulative HPs outweigh the additional reuse-related FPs within two-to-three years, confirming the environmental soundness of reuse.

HPs are notably higher under SSP2, reaching 4500–232,700 kg CO_2-eq, compared to 1300–71,400 kg CO_2-eq in SSP1 (see Fig. S5). This difference reflects the slower decarbonisation of the electricity grid in SSP2, where displaced grid electricity has a higher carbon intensity, making solar reuse more impactful. In SSP1, where the grid decarbonises more rapidly, longer reuse durations are needed to achieve comparable HPs.

Overall, maintaining FVOT through reuse in underserved end-user segments generates clear environmental gains, especially when large-scale installations, BOS reuse and longer second-life periods are achieved. Results also highlight that if panels are not successfully reused after incurring the additional FP from preparation, emissions are added without delivering any corresponding value.

3.3. Life cycle costing

Successful implementation of reuse involves a financial investment. As illustrated in, across all three reuse cases, most of the cost-related FP, occur in the first year. Additional costs arise when panels are prepared for reuse, including procurement of second-hand modules and BOS. These add 76 %, 90 %, and 56 % in costs compared to the initial year in the three cases, respectively. 25–64 % of these additional costs come from the BOS rather than the panels themselves. These costs are borne by reuse chain actors and are passed down to the stakeholders purchasing the solar panels: Municipalities in case 1 and 2 and the end user

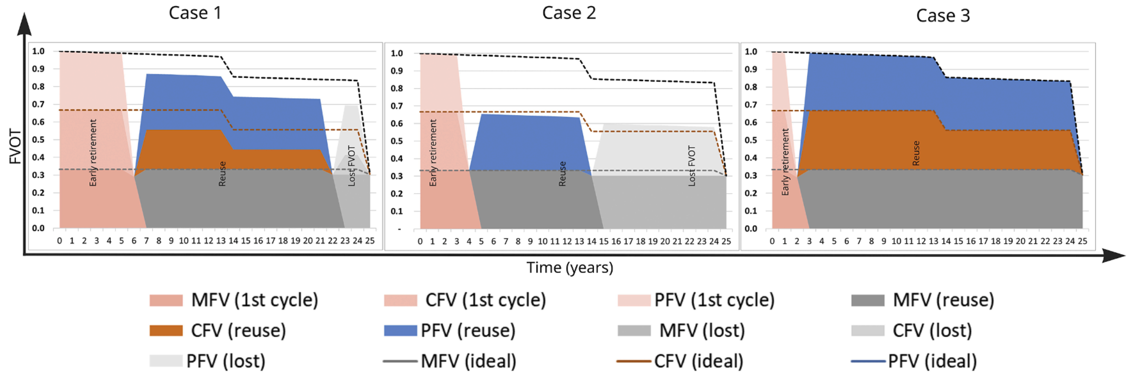

Fig. 3. The deconstruction of solar panels system's functional value over time (FVOT) for the three cases in baseline, reuse scenarios. The red shaded area shows the baseline system is where the solar panels are retired early. The blue, orange and dark grey shows the FVOT retained due to reuse. The light grey area shows the FVOT lost due to not extending the lifetime until the maximum serviceable lifespan of 25 years. The dashed lines show the theoretical FVOT, is when a solar panel system is designed for its full 25 year service at the first use location.

in case 3. In Cases 1 and 3, additional maintenance costs occur in Year 15 due to inverter replacements. These additional costs form the key barrier for not implementing high tier CE interventions such as reuse

In contrast, HPs, are realised by end users through savings on grid electricity costs, and by recyclers through minor material recovery revenues. Without discounting, 2nd end-user savings are €3200, €10,200, and €308,000; when accounting for the time value of money, these drop to €2050, €7800, and €174,000. In contrast, material recovery benefits are modest, with non-discounted values of €90, €434, and €3980 while discounted values are just €43, €294, and €1430. In all cases, the HPs outweigh the additional reuse-related costs within two-to-three years, confirming the economic soundness of reuse.

Most costs, except for recycling after reuse and inverter replacement, occur upfront. Moreover, in case 1 &2, these are born by people who do not benefit from future benefits i.e., Municipalities. Discounting reduces future benefits by 24–44 %. This reflects the upfront nature of reuse costs and the delayed nature of the low-income end user's savings. The results reveal a structural mismatch: those who pay to retain value are not always those who benefit. Overall, reuse delivers much greater long-term gains than recycling, especially for low-income users, if the financial barriers can be overcome.

4. Discussion

This study demonstrated that higher level CE interventions – reusing solar panels – can effectively retain all three types of functional value while generating clear environmental and economic benefits. However, although upfront environmental footprints are quickly balanced out and large economic benefits are possible by reusing solar panels and its BOS, the upfront reuse processes costs and BOS costs act as barriers to the rapid implementation of reuse of solar panels.

4.1. From material recovery to functional value retention

Echoing studies like André (2024), André and Nilsson (2024) Hatzfeld (2022) and Vulsteke et al. (2024), we expressed the decline of functionality in a solar panel system over time by deconstructing value into PFV, CFV and MFV. Deconstructing functional value into its 3 components allows us to see how much functionality is left at all three levels of FVOT. This creates opportunities for harnessing PFV. We showed that reuse retains high FVOT by harnessing the residual electricity generation potential of solar panels, reusing components and recovering valuable materials. Thus, by extending the lifetime though reuse, we prioritise retaining high FVOT for a longer time (Vulsteke et al., 2024) while also saving solar panels from being shredded in low-value recycling methods.

Although the WEEE Directive's criteria of recovering 85 % of material is achievable with current recycling methods (EU, 2024), it overlooks the residual PFV in solar panels that can be harnessed before recovering MFV. In our FVOT graph, we gave equal weights for all functional value types. However, our results also reveal that retaining PFV results in larger environmental and economic benefits compared to retaining MFV. Thus, for CE interventions, it is important to view waste as having nested functional value rather than only materials to be recovered while giving an appropriate weighting for different functional value types. Given the high costs of recycling and high fluctuations in silver prices (Weckend et al., 2016) retaining PFV and CFV through reuse could help to create a stockpile of solar panels while technologies for advanced recycling mature. This enables higher value material recovery of solar-grade silicon, silver and copper (Späth et al., 2022). Moreover, as demonstrated in our cases, underserved communities can be provided with an entry point into the energy transition, echoing findings by Stromberg (2021, 2023).

Realising the benefits of reuse depends on actual second-life deployment, making successful implementation essential for the reuse chain to generate meaningful impact. Clear benefits of reuse of solar panels are shown in previous studies (Lunardi et al., 2018; Poulek et al., 2023; Schünemann et al., 2021; Van Der Heide et al., 2022). However, there are barriers to this CE intervention implementation and a TE perspective can help explain this.

4.2. The value of a time-explicit perspective

A time-explicit perspective on FVOT shows how the nested functional value of a product system varies over time and how much of it can be retained. The time-explicit perspective in LCA provides a year-by-year outlook of when emissions occur and how these change over time. We also breakdown the costs and revenues per year and define who are the cost bearers and beneficiaries. Integrating the time-explicit results with a HP lens showed that upfront environmental impact (up to 37 %) and especially upfront economic costs (up to 90 %) hinders the large scale adoption of reuse. Moreover, the benefits bear fruit gradually, illustrating that sustainable value creation is time-dependant. The time-explicit perspective allows to aid in decision making because, 1) the actors know how much FVOT is retained when they opt for different functional value retention, 2) how much and when upfront costs and emissions occur, and 3) the accrual of the benefits and when they offset the costs are known. Stakeholders can opt for early MFV retention, at the cost of losing PFV and losing valuable materials.

This TE-LCA and LCC, modelled the consequences of actions due to a change in the way the EoL market is handled through a reuse CE intervention. Reuse was modelled as a decision that alters the existing

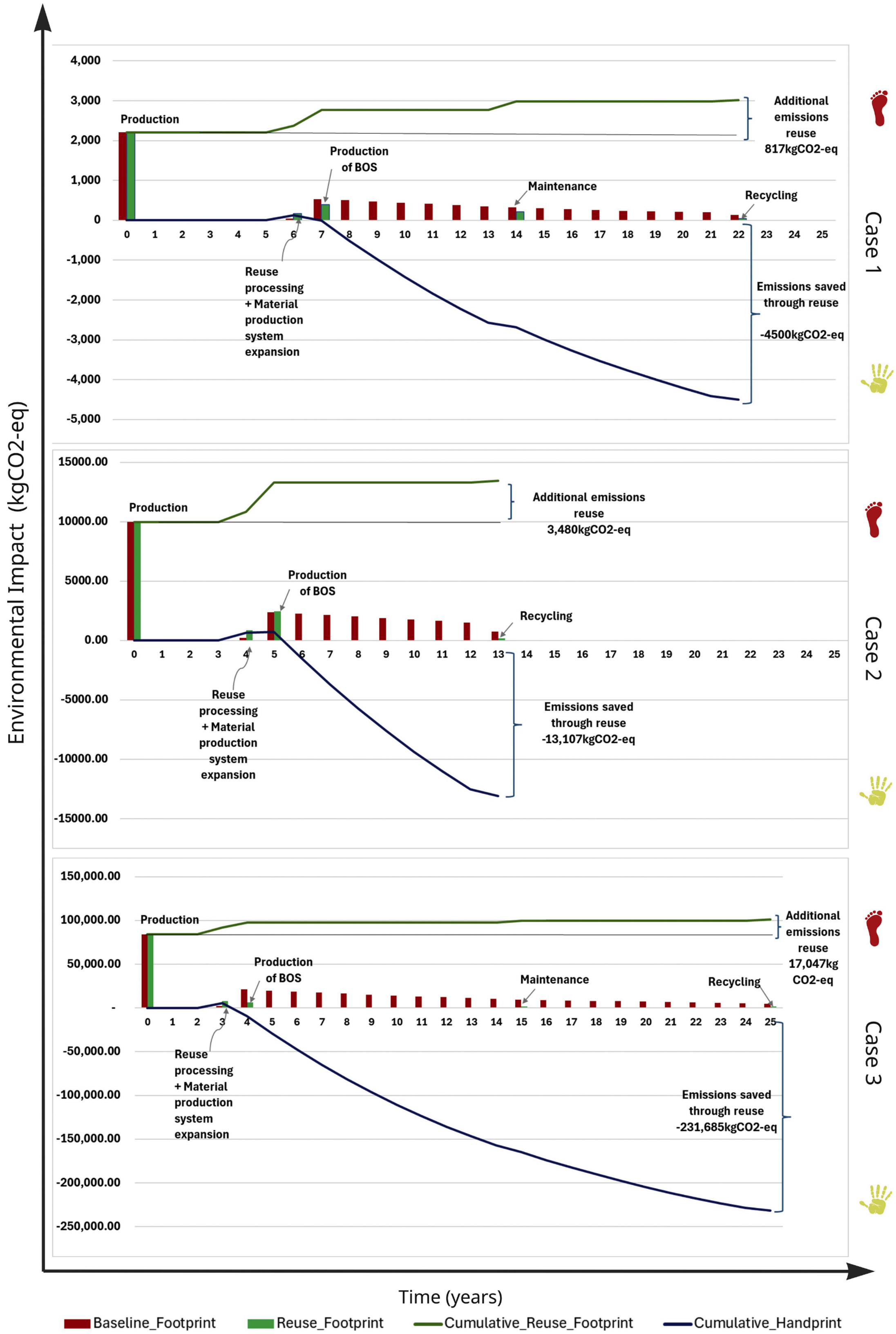

Fig. 4. Annual carbon footprints (FP) for baseline and reuse systems and the cumulative handprint (HP) and FP of reuse system for the SSP2 scenario. The hand and foot symbols represent what counts as the handprint and footprint on the graphs. For the reuse system, the FPs are provided per process. The HP is the comparative improvement brought out by change to the baseline.

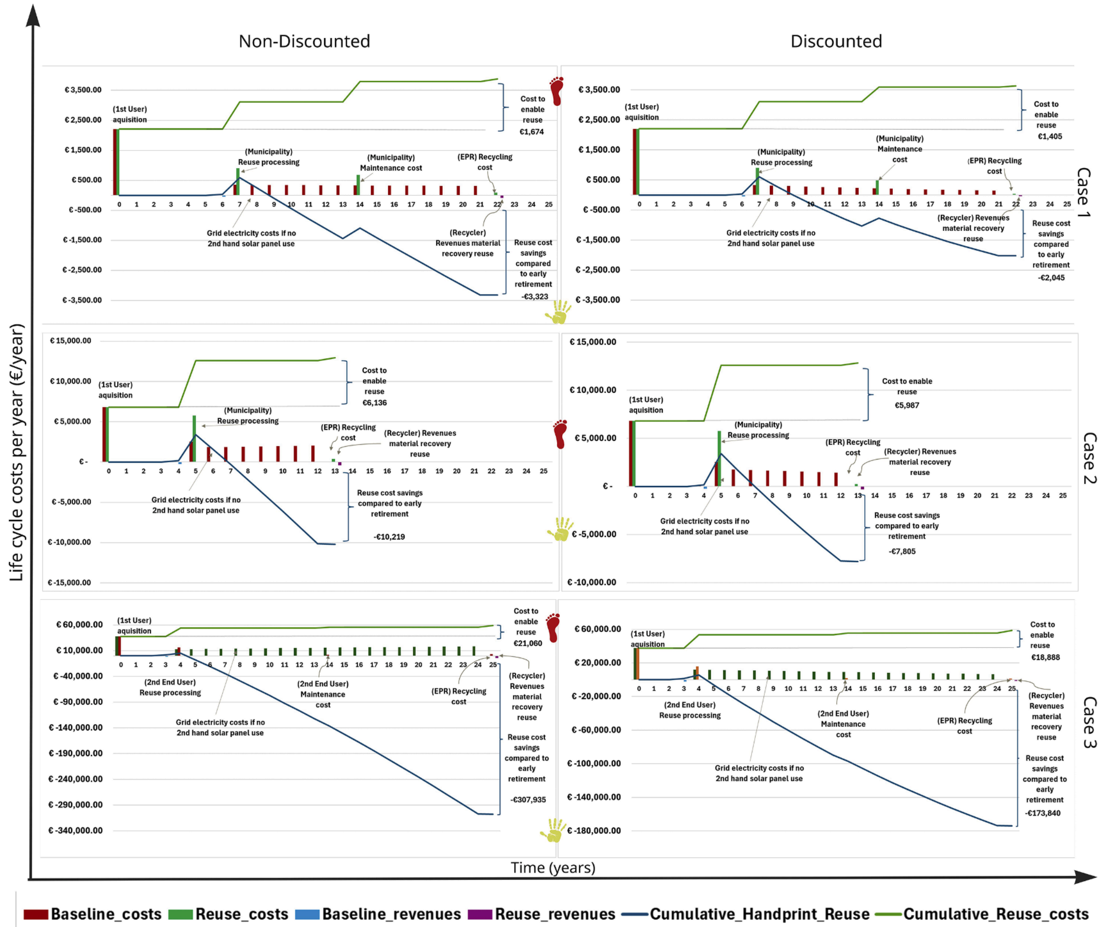

Fig. 5. Annual costs for baseline and reuse systems across the lifetime of the solar panel for cases 1–3. The hand and foot symbols represent what counts as the handprint and footprint on the graphs. For the reuse system, the Footprints are provided per stakeholder as annotated. The Handprint is the comparative improvement brought out by change to the baseline.

system. The HP lens shifts the framing from avoided burdens to created value (Ndzibah et al., 2022; Vulsteke et al., 2024) and emphasises the agency of business actors in designing interventions (Norris, 2015). Our use of the HP lens aligns with Consequential LCA thinking, as both approaches assess the consequences of diverting products into alternative pathways (Weidema, 2003). In this case, reusing solar panels rather than discarding them. System expansion in CLCA ensures that avoided electricity generation or material production is captured, which parallels how HPs are defined as positive contributions arising from avoided FPs (Norris, 2015; Norris et al., 2021).

Additionally, our scenario analysis shows that HPs are larger under slower grid decarbonisation in SSP2 where solar electricity offsets more carbon-intensive grid supply. In rapidly decarbonising systems in SSP1, panels must be used for longer periods to yield similar benefits. This has implications for where the redeployment of 2nd hand panels has the potential to harness the greatest HPs.

Building on prior studies of solar panel reuse and recycling (Lunardi et al., 2018; Schünemann et al., 2021), this work extends the scope to include the full system, including BOS, and temporal differentiation. Our approach illustrates when additional FPs occur and when they are balanced out by HPs. We highlight how high upfront costs hinder scaling reuse. Unlike earlier models, it also integrates future changes in background systems such as grid decarbonisation.

We argue that CE intervention adoption is slowed down because of upfront FPs. Focusing only on these early FPs leads to short-term decision making. Our combined time-explicit perspective with a HP lens show that while impacts are immediate, long-term value creation are delayed but cumulative. This approach can support long-term, value-based decision making and is adaptable for studying other CE interventions along the R-ladder (Reike et al., 2018).

4.3. Mismatch between the stakeholders at different moments in time

The insights from the time-explicit analysis highlight not only the potential of reuse, but also the temporal misalignment that hinders its widespread implementation. Despite the clear environmental, economic and social benefits of solar panel reuse, a persistent imbalance exists between those who benefit and those who bear costs. Extending the lifetime of panels generates significant environmental and economic HPs which accrue gradually over time. Extra Carbon FP are relatively modest (37 %) but significant upfront investment costs, up to 90 %, are required in the present for reuse to occur. Moreover, HPs occur in the future to end-users and recyclers, with discounting further reducing the perceived value by 24–44 %. This temporal misalignment creates split incentives across the reuse chain, particularly between installers, recyclers, and end users, reinforcing the importance of financing mechanisms that reflect the time-distributed nature of returns (Khadim and Van Marrewijk, 2025). Similar mismatches are noted in other CE interventions where high upfront investments are required to unlock long-term benefits (Luthin et al., 2023). Our approach helps reveal and deconstruct these imbalances. We call for making temporal sustainability impacts transparent and supporting policy mechanisms which bridge the temporal gap between investments and benefits.

4.4. Limitations and future research

While this study provides a comprehensive assessment of solar panel reuse using a time-explicit HP approach, several aspects warrant further exploration. A detailed breakdown of all sub-costs within the reuse chain, such as disassembly and reinstallation, could refine the understanding of the distribution of costs and benefits across stakeholders. Additionally, sensitivity analysis related to solar electricity output, material recovery rates and revenues, and discounting effects would strengthen the robustness of the results. This study only focused on trade-offs in global warming potential rather than other LCIA categories. Nevertheless, the approach presented here offer a solid foundation for future research on the uncertainties and trade-offs involved in circular economy interventions.

While the environmental and economic impacts were addressed quantitatively, the social aspects dimension of reuse remain underexplored. However, to fully operationalize a holistic sustainability assessment, future research should integrate social life cycle assessment and stakeholder-based evaluation to quantify these outcomes and align reuse practices with broader sustainability goals.

5. Conclusion

This study assessed three cases of solar panel reuse by underserved communities, demonstrating how FVOT can be retained when panels are retired early. The combined FVOT and TE-LCA-LCC approach reveals which values, when and to whom benefits accrue, highlighting the importance of time-explicit analysis for understanding circular economy interventions.

Our results reveal that reuse retains product, component and material functional value over the extended lifetime. Solar panel reuse has low environmental impacts and provides high cost savings for underserved communities. Yet there is a temporal and stakeholder mismatch. Economic Handprints primarily benefit users in the long term, while environmental Handprints accrue gradually to society. However, large upfront investments are required to unlock these benefits, but their additional Footprints are outweighed by the cumulative environmental and economic Handprints, particularly when lifetimes are extended and BOS components reused.

Our findings highlight the need for supportive financing mechanisms and policy frameworks to bridge early investment gaps and enable businesses to act as agents of Handprint creation. Future work should add a social dimension, capturing distributional equity and financing mechanisms, to complete the sustainability perspective.

Declaration of generative AI in scientific writing

The authors declare that ChatGPT was used to improve the readability of the text. the authors reviewed and edited the text and take full responsibility of the contents of this publication.

CRediT authorship contribution statement

Droovi Beven Keanu de Zilva: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Tomer Fishman:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Arnold Tukker:** Writing – review & editing, Supervision. **Mingming Hu:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108699.

Data availability

The model and datasets can be found on the Zenodo repository: 10.5281/zenodo.15535704

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