Quantifying The Environmental Implications Of Solar Thermal Technologies: A Comprehensive Examination Of Life Cycle Impacts And Payback Periods

Maria Zagorulko[1], Dr. Alexander Mellor[1], Dr. Adrian Murrell[1]

[1] Naked Energy Limited, Crawley (United Kingdom)

Abstract

This study evaluates the sustainability of solar technologies though life-cycle analysis (LCA). A comparison is made of the embedded carbon of solar thermal evacuated tubes and hybrid photovoltaic thermal (PVT) evacuated tubes and these are compared to photovoltaic (PV) panels. The solar thermal collector VirtuHOT is found to have the lowest embedded carbon (0.172 $kgCO_2eq$ /Wp), followed by the hybrid collector VirtuPVT (0.344 $kgCO_2eq$ /Wp), and both are significantly lower than published data for PV panels (0.81 $kgCO_2eq$ /Wp). VirtuHOT exhibits an average carbon payback period of 1.25 years, whereas VirtuPVT collectors require 3.25 years. While the hybrid PVT collector exhibits this longer carbon payback period due to the PV element and associated manufacturing and disposal intensities of silicon, its embedded carbon remains lower or comparable to that of PV modules utilizing the same carbon-intensive PERC silicon cells. This research addresses a gap in the existing literature on life cycle analysis of solar thermal technologies.

Keywords: solar thermal technology, sustainability, life cycle analysis, PVT collectors, evacuated collectors, embedded carbon

1. Introduction

With increasing governmental focus on environmental sustainability, there is an urgent need to assess the environmental impacts of technologies marketed as renewable and beneficial for the energy transition. Most comparisons of Renewable Energy products focus on quantifying the energy production (in J or kWh) and show how much CO2 each product therefore saves compared to burning fossil fuels. However, to make a more accurate assessment of total carbon displacement it is essential also to take account of the carbon budget for manufacturing the product (the Embedded Carbon) and other carbon generated throughout the whole life cycle of the product. Accurate comparisons therefore require product Life Cycle Analysis (LCA) studies that are holistic and transparent.

This research is becoming more and more relevant given the expansion in usage of green building certification systems such as LEED (Leadership in Energy and Environmental Design) or BREEAM (Building Research Establishment Environmental Assessment Method). These frameworks evaluate the full carbon footprint of buildings and require manufacturers of renewable products to calculate and declare their embedded carbon. Manufacturers who adhere to reporting standards inevitably broaden their market reach in an economy increasingly driven by sustainability.

In this study LCA analyses have been undertaken of both solar thermal and hybrid photovoltaic-thermal (PVT) collectors. This research represents one of the first commercial lifecycle evaluations of these technologies, offering valuable insights for consumers and real estate developers considering the integration of low-carbon solutions into their projects, for applications such as water and space heating. We examine the entire lifecycle of these technologies, from production through to disposal, with a particular focus on environmental impacts such as embedded carbon and greenhouse gas emissions.

10.18086/eurosun.2024.07.19 Available at http://proceedings.ises.org

Review of existing literature has revealed a significant gap in the life cycle assessments of solar thermal technologies. A notable exception is the work by Ardente et. al. (2005) [1] from the University of Palermo, who conducted an in-depth LCA of a flat plate solar thermal collector. Their research covered emissions and energy requirements throughout the lifecycle, including production, raw material delivery, installation, maintenance, disposal and transportation. The study also assessed the CO_2 and energy payback times, which were both under two years, demonstrating the significant environmental benefits of solar thermal technology given its typical service life of 25 to 30 years. Despite this important study, there remains a lack of available LCA data for major solar thermal manufacturers globally as well as comparative assessments of the environmental impacts of solar thermal collectors versus photovoltaic panels.

2. Methodology

2.1. System description

Thermal-only module: The solar thermal collector, VirtuHOT, is designed and manufactured by Naked Energy Ltd. It comprises an optimally designed aluminium absorber inside a vacuum-filled glass tube. It is used to generate heat in the range 40-120˚C and is usually installed on building roofs. With integrated reflectors, a low profile, and a modular design, it maximizes space efficiency and energy density. The product, tested by TUV Rheinland and certified under DIN CERTCO (EN 12975-1:2006, EN ISO 9806:2017), achieves peak power production of 400 Wp. An exemplar setup of the product is shown in Figure 1.

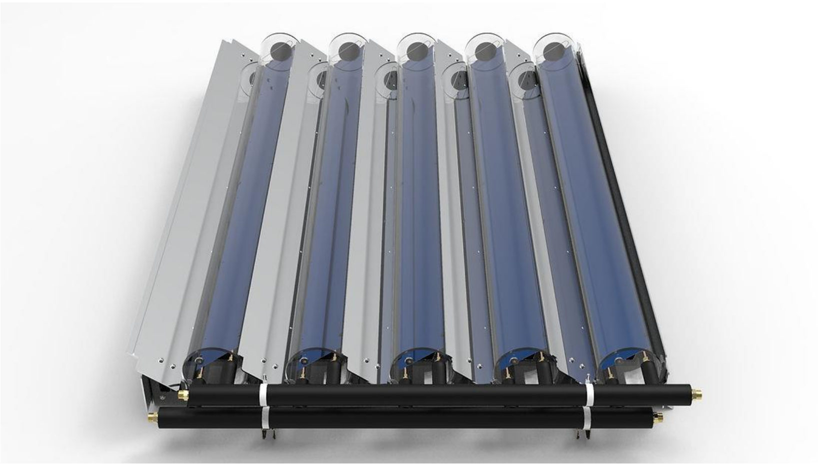

Figure 1. Fully kitted VirtuHOT array

Hybrid Module: The VirtuPVT module consists of photovoltaic cells laminated to a heat exchanger inside a vacuum-filled glass tube. It generates both heat and electricity and can be installed on building roofs, facades and the ground. It shares the same mounting frame and fluid connections as VirtuHOT, with the addition of electrical connectors. The VirtuPVT module integrates PERC-Si PV cells to achieve a thermal capacity of 275 Wp and an electrical capacity of 75 Wp. Both products are designed and manufactured by Naked Energy [2], a British design and engineering firm leading global innovation in solar thermal products and renewable heating systems. An exemplar setup of the hybrid product is shown in Figure 2.

Figure 2. Fully kitted VirtuPVT array

2.2. LCA scope

The lifecycle analysis (LCA) of both products was conducted in accordance with EN 15804+A2 and ISO 14025 / ISO 21930 standards, as outlined in the Whole Life-Cycle Carbon Assessments Guidance [3]. The method calculates the CO2 contribution from every component in the product, based on its weight, material type and production processes, including the manufacturing of raw materials, packaging and ancillary materials during the manufacturing and packaging stages (A1-A3 stages of LCA). Table 1. can be used for referencing different LCA stages. Fuel usage by machines, waste handling, material losses and electricity transmission losses are also considered. Key components of the solar thermal collectors, such as photovoltaic cells, absorber plates and glass tubes, are manufactured in different countries and assembled at two facilities, in the UK and the EU.

Table 1. Life cycle stages utilised in environmental analysis

<table>
<tr><th colspan="3">Product stage</th><th colspan="2">Assembly stage</th><th colspan="7">Use stage</th><th colspan="4">End of life stage</th><th colspan="3">Beyond the system boundaries</th></tr>
<tr><td>A1</td><td>A2</td><td>A3</td><td>A4</td><td>A5</td><td>B1</td><td>B2</td><td>B3</td><td>B4</td><td>B5</td><td>B6</td><td>B7</td><td>C1</td><td>C2</td><td>C3</td><td>C4</td><td colspan="3">D</td></tr>
<tr><td>x</td><td>x</td><td>x</td><td>x</td><td>x</td><td>MND</td><td>MND</td><td>MND</td><td>MND</td><td>MND</td><td>MND</td><td>MND</td><td>x</td><td>x</td><td>x</td><td>x</td><td colspan="3">x</td></tr>
<tr><td>Raw materials</td><td>Transport</td><td>Manufacturing</td><td>Transport</td><td>Assembly</td><td>Use</td><td>Maintenance</td><td>Repair</td><td>Replacement</td><td>Refurbishment</td><td>Operational energy use</td><td>Operational water use</td><td>Deconstr./demol.</td><td>Transport</td><td>Waste processing</td><td>Disposal</td><td>Reuse</td><td>Recovery</td><td>Recycling</td></tr>
</table>

Modules not declared = MND. Modules not relevant = MNR.

The materials utilized include borosilicate glass, aluminium, high-density polyethylene and copper, with electricity being the primary energy source for manufacturing. Greenhouse gas emissions (GHG) are approximated from proper waste management practices, directing plastic waste to incineration, and recycling glass and metal waste streams. Transportation impacts (A4-A5 stages) from the production plant to the building site are evaluated, considering fuel exhaust emissions and related infrastructure impacts. The end-of-life stage (C1-C4, D) involves assessing energy consumption during de-construction, waste transportation to treatment centers and waste treatment processes such as recycling and incineration with energy recovery. Benefits from material and energy recovery, including the displacement of virgin material production and electricity and heat production, are accounted for.

The use phase (B1-B7) is not covered in this study as, once installation is complete, no additional energy or materials are required for maintenance. Our methodology adheres to strict cut-off criteria, ensuring the inclusion of all relevant modules and processes mandated by reference standards. Additionally, allocations are made according to reference standards and applied product category rules (PCR), ensuring accurate representation of data where separate measurement is not feasible.

2.3. Assessment method

The environmental analysis and impact calculation were performed using OneClickLCA software. OneClickLCA [4] is a comprehensive tool for lifecycle assessment, offering robust data analysis capabilities and alignment with international standards. It facilitates detailed environmental impact assessments across various phases of a product's lifecycle. Data for stages A2, A3, A4, A5, as well as for C1 and C2, were collected using presented values from the product supply chain. In contrast, data for stages A1, C3, and C4 were obtained through theoretical approximation.

2.4. Functional and declared units

The results of the lifecycle analysis are presented in $kgCO_2$ per declared unit (one vacuum tube collector), with the hybrid PVT collector at 19.99 kg and the solar-thermal collector at 18.19 kg per declared unit. The declared unit encompasses the total weight of the collector, including all auxiliary components such as the frame, reflector, and manifold. To facilitate the comparison of global warming potential (GWP) between solar thermal collectors and photovoltaic modules, the evaluated embedded carbon is converted to $kgCO_2$ per functional unit (Wp). For VirtuPVT, the functional unit is presented to be 1 Wp of combined thermal and electrical capacities while for VirtuHOT the functional unit is 1 Wp of thermal capacity.

This study includes a comparison that is based on work by Müller A. et.al. (2021) , [5] conducted at the Fraunhofer Institute, which focused on two single crystalline PV modules: one manufactured in China and one in the EU. For this study, we compare the environmental impact of the Virtu products to the glass-backsheet (G-BS) module manufactured in China. The G-BS module studied has similar peak performance values to the Virtu products and a comparable value chain, making it suitable for comparison. The declared unit of this study has been converted to a functional unit of Wp to align with the specimens studied by Müller A. et.al. (2021), ensuring an accurate and relevant comparison of environmental impacts.

2.5. Payback on embedded carbon

The payback on embedded carbon is calculated using the following formula:

$$CP = \frac{Embedded\ carbon\ of\ 1\ declared\ unit\ in\ kgCO_2}{Abated\ carbon\ of\ 1\ declared\ unit\ in\ kgCO_2/year} \quad \text{(eq. 1)}$$

The abated carbon for thermal-only is determined using the equation:

$$Abated\ carbon = E_{th} \times I_{th} \quad \text{(eq. 2)}$$

where $\mathbf{E_{th}}$ is the geographically estimated thermal energy in kWh produced annually (values from the DIN CERTCO specification sheet), and $\mathbf{I_{th}}$ is the carbon intensity of the replaced heat source ($kgCO_2eq/kWh$). For this study, the heat source replaced is assumed to be natural gas with a carbon intensity of 0.210 $kgCO_2eq/kWh$.

The abated carbon for 1 declared unit of VirtuPVT is determined using the equation:

$$Abated\ carbon = E_{th} \times I_{th} + E_{el} \times I_{el} \quad \text{(eq. 3)}$$

where $\mathbf{E_{el}}$ refers to the geographically estimated electrical energy produced annually, expressed in kilowatt-hours (kWh), and $\mathbf{I_{el}}$ refers to the carbon intensity of the electricity source being replaced, measured in kilograms of CO2 equivalent per kilowatt-hour ($kgCO_2eq/kWh$).

Energy modelling considers four key locations that are used in the Solar Keymark certification (DIN CERTCO), including Athens, Greece; Davos, Switzerland; Stockholm, Sweden; and Wurzburg, Germany. For each location, two circulating fluid temperatures, 25°C and 50°C, are investigated. The results of this analysis are presented in subsection 3.3. An average value for Carbon Payback is then calculated for each product, based on the locations of VirtuHOT and VirtuPVT installations currently installed across Europe. These values are then compared to the Carbon Payback of a PV module manufactured in China, as analysed by Müller A. et.al., (2021).

3. Results and discussion

3.1. Global Warming Potential (GWP) of Virtu product line

The components level analysis of the PVT collector yielded a total embedded carbon value of 122 $kgCO_2$ per declared unit, while the thermal-only collector showed an embedded carbon of 69 $kgCO_2$ per declared unit. The pie charts depicting the GWP breakdown for solar thermal technologies provide a visual comparison. Figure 3. highlights the lower emissions associated with the thermal-only collector, particularly attributable to the absorber plate and other components. In contrast, Figure 4. showcases the hybrid PVT collector's higher emissions, primarily attributed to the inclusion of PERC Silicon Cells and associated components. These visual representations underscore the importance of selecting appropriate collector configurations to minimize environmental impacts effectively.

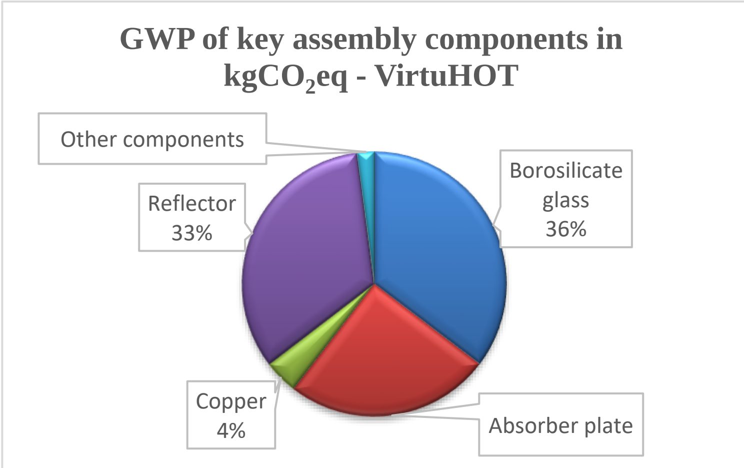

Figure 3. Global Warming Potential (GWP) in $kgCO_2$ of key components in VirtuHOT

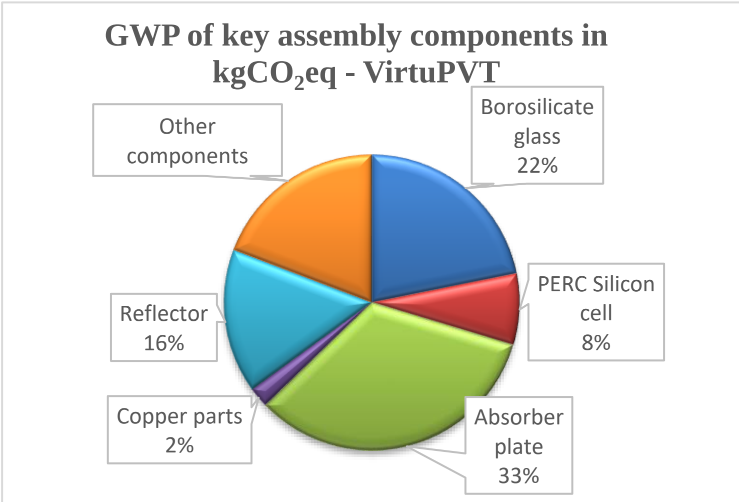

Figure 4. Global Warming Potential (GWP) in $kgCO_2$ of key components in VirtuPVT

Thermal-Only Collector (VirtuHOT)

For the thermal-only collector, the majority of the GWP is attributed to the borosilicate glass enclosure, which accounts for 36% of the total GWP. The integrated reflector also significantly contributes, comprising 33% of the total GWP. These high proportions are primarily due to the emissions from transportation of some components within the supply chain. The combined global warming potential of sea-freight and road freight from China to the United Kingdom has significantly increased the embedded carbon within the VirtuHOT product.

Additionally, the aluminium-copper absorber plate contributes 17.25 $kgCO_2$ to the embedded carbon within the VirtuHOT collector. The high intensity within this part is attributed to the energy-intensive process of aluminium sheet rolling. This highlights the importance of considering both transportation and manufacturing processes when evaluating the environmental impacts of solar thermal technologies.

Hybrid PVT Collector (VirtuPVT)

When examining the VirtuPVT data, the aluminium heat exchanger plate has a larger mass than the VirtuHOT absorber, since a thicker substrate is needed to support the PV cells and ensure temperature uniformity. Consequently, the embedded carbon for this part doubles to 40.25 $kgCO_2eq$. Similar to the VirtuHOT's carbon intensity, the borosilicate glass encapsulant and the reflector account for substantial portions of the total embedded GWP, at 22% and 16%, respectively. Given the commonality in the value chains, these results were expected.

Interestingly, the PERC-Si cells account for only 8% of the total GWP of VirtuPVT, which equates to 9.76 $kgCO_2eq$. Despite the fact that the sourcing and formation of silicon cells are highly carbon and energy-intensive processes, in this case, the proportional mass of silicon in the declared unit is under 1% of the total mass. This finding is significant as it indicates that the inclusion of PERC-Si cells in the PVT collector does not substantially increase the overall GWP.

In the sourcing and manufacturing stages (A1-A3) of the LCA, the VirtuPVT module requires approximately 557 kWh of energy, significantly higher than the 291 kWh needed for the VirtuHOT collector. The increased energy demand for the VirtuPVT module is largely due to the energy-intensive processes involved in producing the aluminium-copper heat plate, specifically the extrusion and rolling of aluminium, which contribute an additional 44% to the overall energy consumption. Additionally, the inclusion of PERC silicon PV cells in the VirtuPVT module raises the energy requirement by 25%. The production of these PV cells is energy-intensive, involving steps such as polysilicon ingot formation, Czochralski processing and subsequent wafer cutting and etching. These processes collectively account for the higher energy consumption associated with the VirtuPVT module compared to the VirtuHOT collector.

3.2. Environmental impacts per Wp of nominal power

When evaluated on the basis of CO_2 per Wp of nominal power, the results of the embedded carbon assessments reveal interesting contrasts between the various solar collector technologies. Specifically, the hybrid PVT collector and the thermal-only collector exhibited significantly lower embodied carbon values when compared to a generic PV module. The hybrid PVT collector demonstrated an embedded carbon of 0.344 $kgCO_2$ equivalent per Wp, while the thermal-only collector exhibited an even lower value at 0.172 $kgCO_2$ equivalent per Wp. In contrast, the generic PV module registered a higher embedded carbon of 0.81 $kgCO_2$ equivalent per Wp,.

Table 2. Embodied Carbon Comparison of Solar Collector Technologies

Collector Type	Embodied Carbon ($kgCO_2eq/Wp$)
Hybrid PVT Collector	0.344
Thermal-Only Collector	0.172
PV Module	0.81

Table 2 summarizes these results and highlights the superior environmental performance of solar thermal technologies. While the PVT collector and the thermal-only collector may exhibit differences in their specific embedded carbon values, both significantly outperform the generic PV module. These findings hold substantial implications, particularly within the context of the imperative to mitigate carbon footprints in energy systems. The lower embodied carbon of solar thermal collectors underscores their promising role as sustainable energy solutions.

A comparison of the presented LCA results with the Global Warming Potential (GWP) of PV panels, utilizing the IPCC 2013 100-year method for two distinct types of solar modules (Müller A. et.al., 2021) accentuates the superiority of solar thermal technologies. One module is a glass-backsheet sc-Si PERC module with specifications of P = 366 Wp and η = 19.79%, produced in China. The other module is a glass-glass sc-Si PERC module with specifications of P = 359 Wp and η = 19.40%, produced in the EU. The aforementioned table only considers the PV module made in China, which is representative of the PVT's geographical value chain.

Particularly noteworthy is the significantly lower embedded carbon per Wp exhibited by the hybrid PVT collector, rendering it an especially attractive alternative to PV. These findings underscore the potential of solar thermal technologies to significantly contribute to sustainable energy transition.

3.3. Payback on embedded carbon

Considering carbon payback periods across various geographical locations, including Athens, Davos, Stockholm and Wurzburg, reveals insightful data as presented in Table 3.

Table 3. Payback on embedded carbon for VirtuHOT

	Athens		Davos		Stockholm		Wurzburg	
Fluid Temperature (˚C)	25	50	25	50	25	50	25	50
Thermal Yield, E_{th} (kWh/year)	567	474	439	355	314	244	353	277
Carbon Abatement ($kgCO_2$/year)	119	99.5	92.2	74.6	65.9	51.2	74.1	58.2
Carbon Payback (years)	0.69	0.82	0.89	1.10	1.24	1.60	1.11	1.41

Athens has the shortest carbon payback period due to its high solar irradiance and warmer climate, resulting in higher thermal yields and greater carbon abatement. In contrast, Stockholm, with its cooler climate and lower solar irradiance, exhibits the longest payback period due to reduced thermal yields and less carbon abatement.

Higher fluid temperatures (50°C) consistently decrease thermal yield and carbon abatement, extending the payback periods across all locations. Davos, characterized by a cooler alpine climate, and Würzburg, with a moderate climate, show intermediate payback periods, reflecting the impact of regional climate conditions.

For VirtuPVT, in Table 4., the analysis has taken into account the carbon intensity of the grid in the equivalent geographical locations.

Table 4. Payback on embedded carbon for VirtuPVT

	Athens		**Davos**		**Stockholm**		**Wurzburg**	
Fluid Temperature (˚C)	25	50	25	50	25	50	25	50
Thermal Yield, E_{th} (kWh/year)	362	217	238	132	177	92	203	107
Electrical Yield, E_{el} (kWh/year)	103	94	91	83	63	58	70	64
Carbon intensity of the grid ($kgCO_2/kWh$)	0.448	0.448	0.357	0.357	0.012	0.012	0.314	0.314
Carbon Abatement ($kgCO_2/year$)	122	87.5	82.5	57.4	37.9	20.0	64.6	42.6
Carbon Payback (years)	1.07	1.49	1.59	2.28	3.46	6.55	2.03	3.08

The VirtuPVT system's carbon payback period is shorter in locations with higher grid carbon intensity and better solar conditions, such as Athens, and longer in areas with lower grid carbon intensity and less favorable conditions, like Stockholm.

In summary, regions with higher solar irradiance and warmer climates, like Athens, have shorter carbon payback periods, while cooler, less sunny regions, like Stockholm, have longer periods. The efficiency of solar energy conversion and the operating fluid temperature are key factors in these variations.

Overall, the payback periods for the VirtuPVT and VirtuHOT systems are short compared to the their service lifetime. While thermal-only collectors demonstrate an average payback period of approximately 1.25 years, PVT collectors require an average of about 3.25 years to offset their embedded carbon. This indicates that, despite regional variations in payback periods, the long-term environmental benefits of PVT collectors generally outweigh their initial carbon costs.

4. Conclusions

The life cycle analysis of the VirtuHOT and VirtuPVT collectors demonstrates an interesting and environmentally important benefit of solar thermal technologies compared to generic PV modules. The thermal-only collector, VirtuHOT, and the hybrid VirtuPVT collector both exhibit significantly lower embedded carbon per Wp than standard PV modules (manufactured in China), highlighting their potential for reducing carbon footprints in energy systems. Notably, the thermal-only collector demonstrates the lowest embedded carbon, particularly due to the optimized design and lower material use. In contrast, the hybrid PVT collector, while offering both thermal and electrical outputs, shows a slightly higher embedded carbon due to the additional PV components, yet still remains significantly more environmentally favorable compared to typical PV technologies.

The results emphasize the importance of careful material selection and design optimization in minimizing environmental impacts. The detailed component level analysis reveals that the borosilicate glass enclosure and integrated reflector contribute substantially to the embedded carbon total, particularly due to the transportation emissions involved in the supply chain. For the PVT collector, the energy-intensive processes associated with the aluminium heat exchanger and the PV cell silicon components are also significant contributors and would be targets for future improvement.

In terms of payback on embedded carbon, both products show favorable results, with VirtuHOT offering a shorter payback period than VirtuPVT, due in large part to its lower initial carbon footprint. However, the benefits of

VirtuPVT, which include electrical generation capabilities, provide a broader scope of carbon offset opportunities, particularly in regions with high grid carbon intensity.

The study also identifies key areas for future research. Specifically, more detailed investigation into the use phase (operation and maintenance) of solar thermal technologies is necessary to fully understand their long-term environmental impacts. Additionally, obtaining supplier specific data on the sourcing and manufacturing processes of constituent parts will enhance the accuracy of the analysis. This will not only refine the understanding of the environmental impacts but also inform strategies for further reducing the carbon footprint of these renewable technologies. The ongoing development of solar thermal technology, along with improved data transparency and material efficiency throughout the product life cycle, offers significant potential for future technology applications.

5. References

[1] B. G. C. M. L. B. V. Ardente F, “Life cycle assessment of a solar thermal collector,” *Renewable Energy,* pp. 1031-54, 2005. Available from: https://doi.org/10.1016/j.renene.2004.09.009

[2] “Naked Energy,” 30 7 2024. [Online]. Available: https://nakedenergy.com/ .

[3] “Whole Life-Cycle Carbon Assessments guidance,” 8 03 2024. [Online]. Available: https://www.london.gov.uk/publications/whole-life-cycle-carbon-assessments-guidance.

[4] “Product carbon footprint,” 31 7 2024. [Online]. Available: https://oneclicklca.com/en-gb/software/manufacturing/product-carbon-footprint

[5] F. L. R. C. H. S. M. M. N. D. Müller A, “A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory,” *Solar Energy Materials and Solar Cells,* 2021. Available from: https://doi.org/10.1016/j.solmat.2021.111277