Emissions Accounting for Rooftop PV

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Abstract

When considering investment in infrastructure assets such as photovoltaic panels, it is no longer sufficient to make solely financially based decisions. In order to follow sustainable best practice, assessing the carbon implications is also critical. The embedded emissions of PV panels from cradle to grave are assessed, using published life cycle inventories [1] to calculate the greenhouse gas (GHG) emissions per unit of generation. Multi-silicon panels were found to have lower GHG emissions compared to mono-silicon panels, predominately due to the lower energy requirements at ingot formation. To ascertain the substitution benefit of PV compared to the generation it offsets, typical calculations reference the country's average carbon emissions per unit of electricity. This necessitates forecasting a country's generation mix 25-30 years into the future. Considering New Zealand's goal of lowering the carbon footprint of electricity generation, this shows diminishing benefit (a self-defeating argument). Alternatively, small-scale distributed systems can be considered as offsetting marginal generation, the last and typically most expensive generation to be dispatched, i.e. gas peakers [2]. This alternative method of calculating carbon offsets, results in a vastly improved benefit and relatively short carbon payback period (circa 3-4 years), but will require industry agreement before it can be considered the most appropriate treatment.

To investigate a tangible example this paper considers the benefit of an installed PV system at the Trust Horizon office in Whakatane. The smaller PV systems were found to provide the most attractive Net Present Value using energy savings alone, however, if the associated carbon benefit was included, this shifted to more mid-size PV installations of 6 to 12 kWp which provide a balance between financial return and carbon emission offsets. This demonstrates the value of including both financial and non-financial estimates in considering the business case and sizing of a solar system.

1. Introduction

Trust Horizon is a charitable trust in the Bay of Plenty area and owner of Horizon Networks, the Eastern Bay of Plenty lines company. Part of their remit is to support local communities around energy-related projects. Reducing solar system costs and increasing climate change awareness has resulted in an increasing number of solar projects being brought to Trust Horizon for funding. To understand the environmental and financial benefits of investing in solar, the board decided to undertake due diligence to ascertain the benefit for NZ Inc.

2. Background

2.1 Approach

Solar PV installations have minimal emissions during operation, and in modelling treatments are often represented as having zero GHG emissions per unit of electricity generated [3], [4]. However, the upfront emissions from their manufacture are significant and ideally should be considered over the course of a solar system's lifetime. Large energy inputs are required, particularly to provide the high temperatures required to smelt the feedstock (silica sand) and for the formation of the silicon (either single crystalline or multi-crystalline) boules. A summary of the basic manufacturing processes for silicon panels are illustrated in Figure 1.

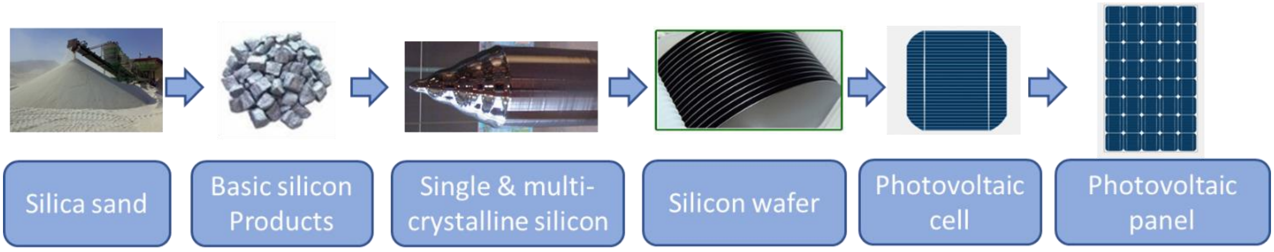

Figure 1 Basic process for silicon panel manufacture.

A variety of primary and secondary data sources were used with the primary data analysis based on process flows from ecoinvent's database, which was updated with more recently published inventories from IEA PVPS task 12 update of the Life Cycle Inventories (LCI) of PV supply chains [1].

2.2 Objectives

1) Evaluate the emissions for a standard rooftop solar system installed in New Zealand,
2) Assess the generation expected from the system at the location of interest over the system's lifetime to establish a per-unit emission value, with the desire for a simple tool to evaluate different locations as a function of local irradiance,
3) Investigate the per-unit emission values as a function of solar installation size for small to medium systems.
4) Assess the benefit of rooftop solar in the New Zealand electricity context from a carbon perspective.
5) Assess the financial benefits of rooftop solar.

2.3 Goal & Scope Definition

The goal and scope of this study is the overall life cycle impact of small to medium rooftop silicon based solar systems between 3-24 kW_p. GHG emissions per kWh of generation are calculated over the recommended 30-year lifetime for the PV system [5] with material life expectancies as recommended in Table 1. The generation over the lifetime of the PV installation utilises hourly irradiance data from NIWA's Solarview tool [6], [7] which is then converted into electricity generation as described for the EECA Solar Calculator [8]. An updated panel degradation factor of 0.7% p.a. is used consistent with IEA treatment [5] to reflect the reduction in generation as solar panels age.

Table 1 Life expectancies used for materials in PV system [5].

Component	Life Expectancy	Comment
Modules	30 years	For mature technologies
Inverter	15 years	Residential based inverter
Structure & Cabling	30 years	Rooftop mounted systems

2.4 Framework

Life Cycle Assessments (LCAs) typically evaluate the full environmental impact of a product or service. This paper however, only considers the embedded greenhouse gas (GHG) emissions for a rooftop PV solar system; additional environmental impacts such as ozone depletion, impacts on water such as acidification or eutrophication, depletion of resources, toxic wastes are not assessed. Figure 2 illustrates the system boundary for a PV installation including raw material acquisition and processing, panel production, additional equipment such as the inverter, cabling and mounting system, transport of all materials, installation, operation and maintenance and finally treatment of materials at the end of life.

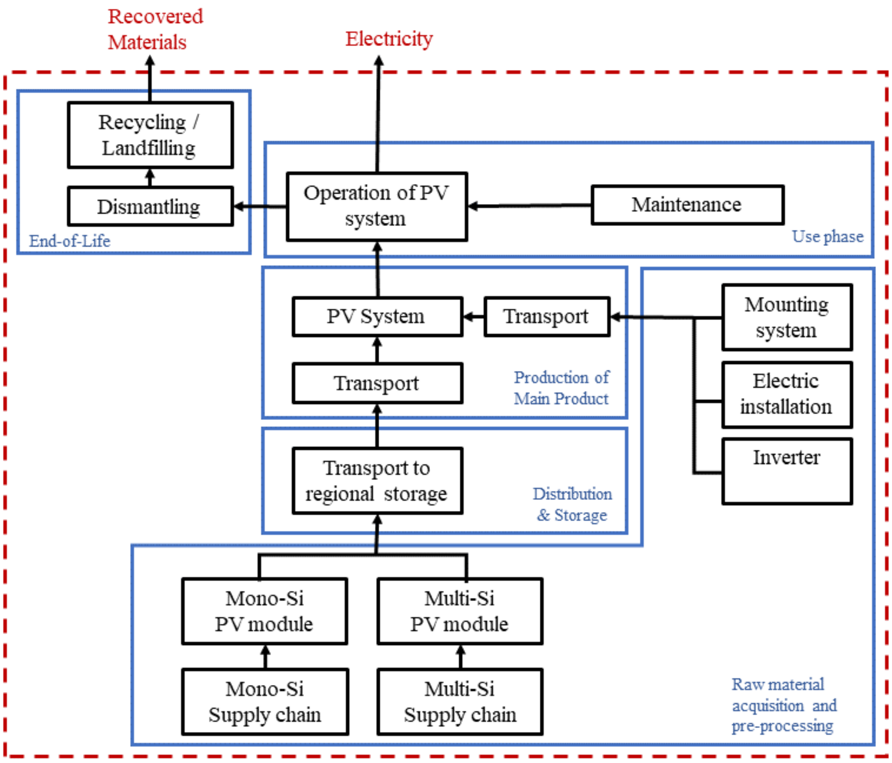

Figure 2 PV systems, showing the system boundary for considered activities, adapted from [1].

GHG estimates are based on the IEA PVPS task 12 update of LCI of PV supply chains [1]. These updates were imported into the UVEK LCI data DQRv2:2018 in ecoinvent, and assess emissions in terms of CO_2 equivalents (CO_2-e) as defined from IPCC's 5th Assessment Report (AR5) published in 2013 [9] according to the global warming potential (GWP) of GHGs based on a 100-year time horizon, see Table 2 and a cut-off database. Regionalised databases are available and this study utilises the APAC database which assumes 87.4% of photovoltaic panels are produced in APAC (predominately Korea, Indonesia, and Japan), while the remaining 12.6% panels are produced in China. As the APAC LCI references the solar panel being installed in Japan, the LCI was modified to include NZ electricity emissions for installation and additional shipping emissions to transport materials to New Zealand. Note that for some minor New Zealand adjustments, such as shipping, AR4 values from the MfE values are used where AR5 were not provided.

Table 2 Global warming potential (GWP) values relative to CO_2.

GHGs	Scientific Formula	GWP (AR4)	GWP (AR5)
Nitrous oxide	N_2O	298	265
Methane	CH_4	25	28
Carbon Dioxide	CO_2	1	1

3. Silicon Roof-top PV GHG Life Cycle Analysis Results

This work utilises a $3kW_p$ PV slanted rooftop reference process and evaluates emissions for multi-silicon and mono-silicon, the most common panel materials in New Zealand. To estimate the carbon footprint for different PV installation sizes, it is assumed that the GHG emissions of the 3 kW_p system without the inverter are linearly scalable. Emissions for the 3, 6, 12 and 24 kW_p are calculated for multi and mono-silicon panels, in-conjunction with published inverter inventories [10] that are reproduced in Table 3. An Inverter Load Ratio (ILR) of 1.2 is assumed, consistent with the LCI based PV system analysed, (3 kW_p PV system, 2.5 kW inverter).

Table 3 Low power inverter emission values as a function of rating [10]

Inverter Rating (kW)	Inverter Weight (kg)	Per Unit Emissions (kg CO_2-e/unit)	Emissions per kW (kg CO_2-e/kW)
2.5	11.2	358	143.2
5	18	578	115.6
10	28.9	921	92.1
20	46.2	1471	73.6

The resultant estimated emissions for the PV systems are given in Table 4, assuming irradiance values consistent with the Trust Horizon's building location, for north facing panels, tilted at 15°. As the PV installation size increases, the overall emissions per kWh trend downwards, due to reductions in inverter emissions per kW and system weight for shipping.

Table 4 Embodied emissions for different sized PV Installations for the Trust Horizon site.

PV slanted Rooftop	Inverter Rating (kW)	Total Embodied Emissions ($kgCO_2$-e/unit)		Generation over Lifetime (kWh)	Emissions per unit Generation (gCO_2-e/kWh)	
		Multi-Si	**Mono-Si**		**Multi-Si**	**Mono-Si**
3 kW_p	2.5	5336	7943	111173	48.0	71.4
6 kW_p	5	10339	15555	222346	46.5	70
12 kW_p	10	20113	30544	444691	45.2	68.7
24 kW_p	20	39334	60195	889382	44.2	67.7

4. Offsetting Emissions in the NZ Grid

A standard approach when calculating the offset emissions for a distributed solar roof-top system, is to offset the average emissions of the electricity generation system. While this is certainly the simplest solution and avoids bias, it acts to disincentivise new renewable generation if high renewable electricity fractions are forecast. New Zealand has a high renewable composition, between 80-85% that is expected to increase to 95% by 2050 or potentially 100% according to current policy settings. If PV is offset against the average NZ electricity emission profile, any emission offset will be minimal or even negative if embodied emissions of PV are accounted for as current generation emissions quote operating emissions, such as combustion of coal or natural gas and fugitive geothermal emissions. Using an average emission value when offsetting PV emissions is also inaccurate, as it does not reflect the reality of which generation is offset by PV generation. PV generation is most likely to offset marginal generation, the last generation to be dispatched to meet load, which is typically also the most expensive generation. According to MBIE's Levelised Cost of Energy (LCOE) for new generation projects [11] this corresponds to gas or coal. PV generation is unlikely to displace cheap hydro-generation, or intermittent generation such as wind that is treated as a negative load. A reasonable assumption therefore, is to assume that solar will offset gas generation. A caveat to this approach, is that the electricity system is assumed to be configured so that spilling of energy is relatively rare. This paper presents the impact of considering emissions offset both against New Zealand's average emission profile and against natural gas generation.

4.1 NZ's Average Electricity Emissions

New Zealand's future electricity mix over the next 30 years was projected from the Times-NZ 2.0 modelling work [3]. Two scenarios are presented, Kea and Tūī which represent two different future pathways (Figure 3). The Kea scenario illustrates a future where climate change is prioritised and a low-emissions economy is pursued. Climate change is still addressed in the Tūī scenario however decisions are left up to individuals and market mechanisms. Interestingly, the Kea scenario requires lower overall electricity generation to meet lower demand, but has a higher overall electricity emission per kWh. The Tūī scenario has greater solar uptake and a slower reduction of geothermal generation compared to the Kea scenario, which has more generation from natural gas. Note that both scenarios have natural gas generation to maintain energy security through to 2060.

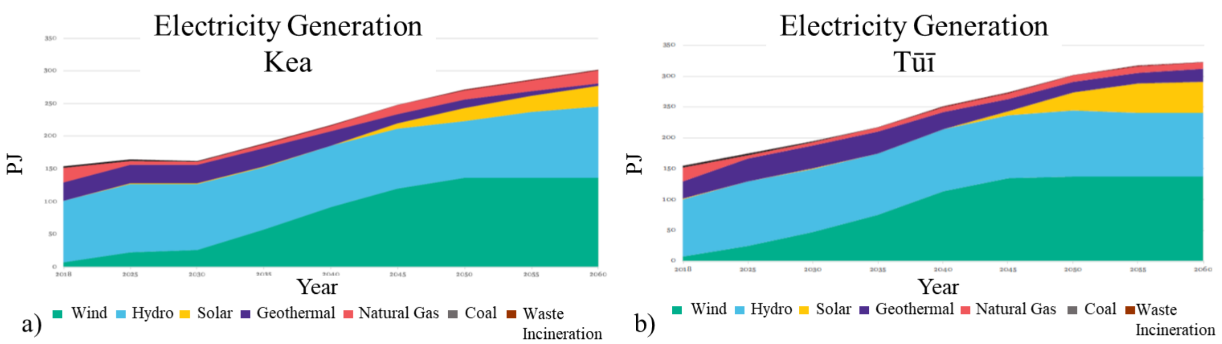

Figure 3 Electricity generation by fuel for TIMES-NZ 2.0 a) Kea, b) Tūī scenarios.

4.2 NZ's Natural Gas Power Plant Emissions

Natural gas operational emissions for electricity generation are modelled as 418.8 gCO_2-e/kWh [4] , [3]. This analysis uses a gas emission figure of 427.5 gCO_2-e/kWh, to include an additional 8.7 gCO_2-e/kWh attributed to emissions owing to losses within transmission and distribution

[12]. Note that carbon capture and storage (CCS) from natural gas generation is not considered due to the lack of projects operating or under consideration [13].

4.3 Emissions Offset Calculations for a Multi-Silicon PV installation

The graph in Figure 4 illustrates the contrast in offsetting the 3 kW_p multi-silicon PV system against the average NZ electricity emission profile, compared to natural gas generation. Note that 8.7 gCO_2-e/kWh of emissions representing transmission and distribution losses [12] are added to both the Kea and Tūī average emission scenarios to be consistent with the treatment of natural gas emissions. When the average emissions of New Zealand's electricity grid are offset, there is only a small offset of emissions for the first few years, then from 2027 the emission offset becomes negative, i.e. an additional source of GHGs. This is because only the operational emissions are considered for the NZ electricity system, compared to the full embedded-emissions considered for the rooftop PV system. The Kea scenario has a slightly higher overall emission factor compared to Tūī but the difference is negligible. It is a very different story however, if generation from the PV system is used to offset a natural gas power plant. For this case, the PV is offsetting over a tonne of GHGs per year, 1.56 tCO_2-e, down to 1.27 tCO_2-e. The declining emissions over the system lifetime reflect the reduced generation of the PV panels, owing to panel degradation. The mono-silicon PV system offsets are just under 100kgCO_2-e/year less than the multi-silicon system, due to the higher embedded carbon footprint. Larger PV systems roughly multiply the emissions offset by the multiplier of the system size.

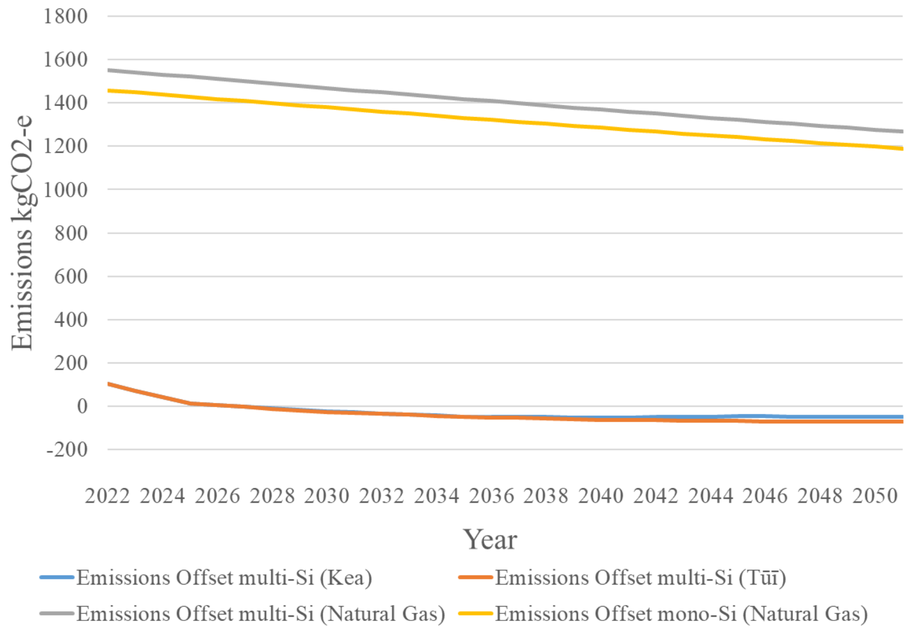

Figure 4 Emission offsets using NZ's average electricity emissions compared to offsetting natural gas emissions for a 3 kW_p multi-Si PV system located at the Trust Horizon building in Whakatane. An additional offset curve (yellow) represents the offsets for natural gas, assuming a 3 kW_p mono-Si PV system.

Alternatively, a simplified viewpoint, and perhaps less controversial, is to consider the PV installation decoupled from the NZ electricity grid. The embedded PV emissions could be offset by way of a carbon-offset scheme up-front, and thereafter, your PV generation can be considered emissions free.

If the embedded emissions for the PV installations are considered upfront, we can see how the emission offsets accumulate as PV offsets natural gas generation. Figure 5 shows that it takes 3-4 years to offset the embedded emissions for the PV installations to provide a positive emission offset. The multi-Si systems offset their embedded emissions a year earlier than mono-Si systems. PV installations show the potential to offset between 13 tonnes of CO_2-e/kW_p for mono-Si and 14 tonnes of CO_2-e/kW_p for multi-Si over their thirty-year lifetime. The largest multi-Si system analysed, 24 kW_p, offsets an estimated 340 tonnes of CO_2-e.

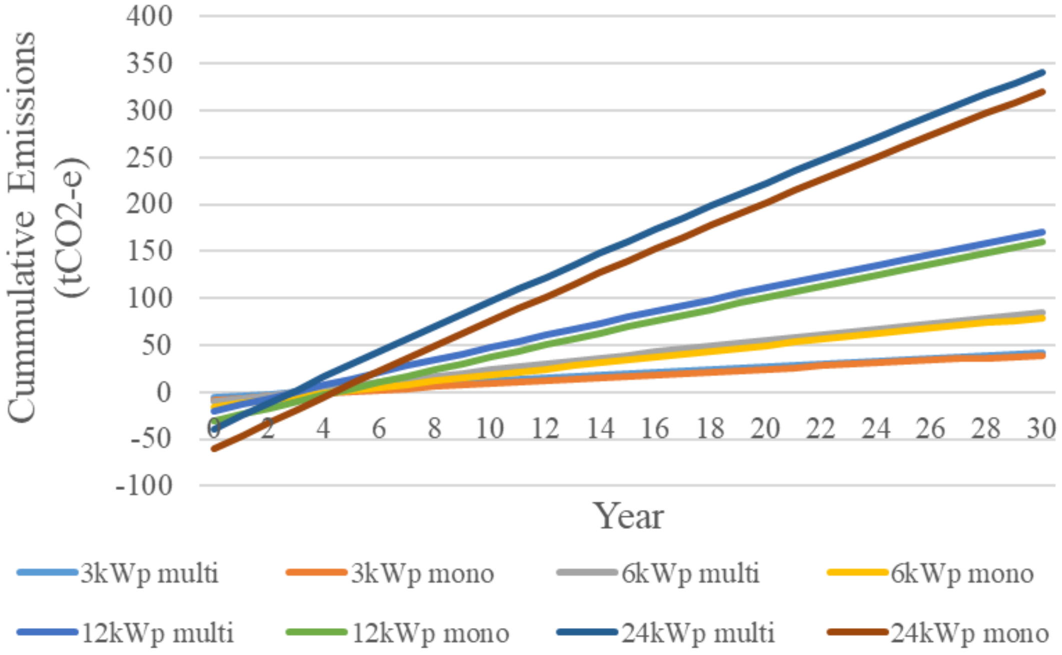

Figure 5 Accumulation of emission credits as PV generation offsets natural gas for different installation sizes and panel types. The x-axis intercept represents the embedded offsets of the PV installation.

5. Financial Benefit

The financial benefit of the PV system is evaluated using a Net Present Value (NPV) analysis, calculated according to the equation below, where *r* is the discount rate.

$$NPV = \sum_{year=0}^{29} \frac{Savings(year)}{(1+r)^{year}} - \frac{Costs(year)}{(1+r)^{year}}$$

Savings are calculated from generation calculations utilising hourly irradiance data from NIWA's Solarview [6] in the approach used by the EECA Solar Calculator [8]. Savings are acquired from self-use of electricity generated and export of excess electricity using the Trust Horizon's building load profile from in 2020/2021 (~26,000 kWh). Dates were selected to avoid Covid-19 lockdowns and a fixed load profile is assumed over the 30-year lifetime. Costs for the project include the installation of the system and a replacement inverter after 15 years. Note that as a registered charity Trust Horizon is tax exempt.

5.1 NPV Sensitivity Analysis for Different PV System Sizes

A sensitivity analysis is presented for the four PV system sizes, due to uncertainty of some financial parameters. The results are presented in mirror bar charts in Figure 6. The independent variables analysed were the price of electricity, system cost, discount rate, electricity retail tariff adjustment rate p.a. and buyback rate adjustment rate p.a. (adjustment of the export price).

All four systems show a positive NPV for the 5% discount rate base case considered. The 3 kW_p system has the highest simple payback and NPV relative to the initial investment and lowest payback times. This reflects the improved economics from having a larger proportion of electricity generated, consumed by Trust Horizon as opposed to exporting excess generation at low rates per kWh. The 3 kW_p system has over 96% self-consumption, with generation in the first year ~ 16% of Trust Horizon building's yearly load.

The 12 kW_p system returns the largest absolute NPV, which is ~ 30% of the initial system cost, while the 3 kW_p system's NPV translates to ~ 56% of the initial system cost and the 24 kW_p system just under 5% of the initial system cost.

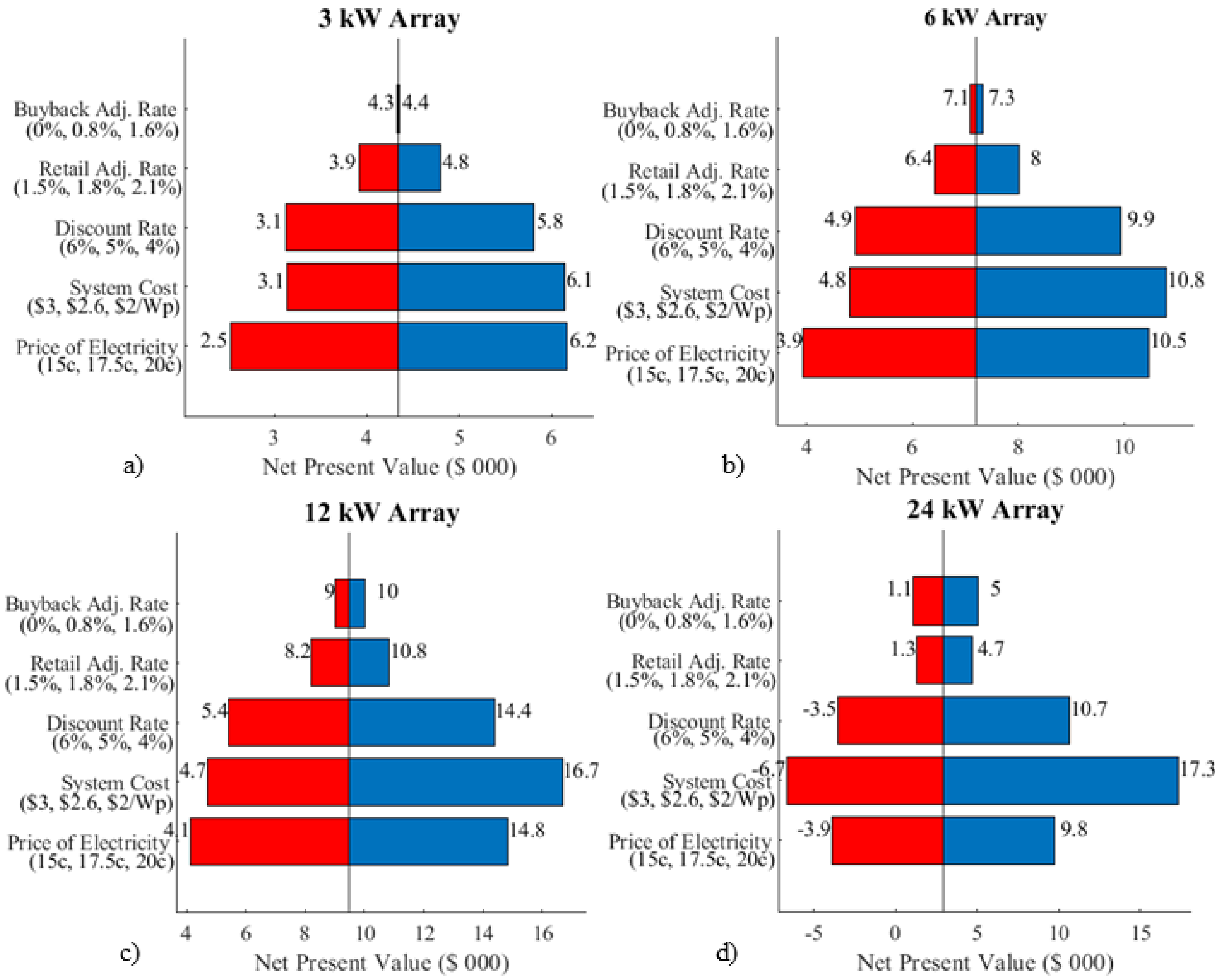

Figure 6 NPV sensitivity analysis varying the price of electricity, system cost, discount rate, retail adjustment rate, buyback adjustment rate p.a. for PV system sizes a) 3kW, b) 6kW, c) 12 kW, d) 24 kW.

5.2 Modified NPV Incorporating Carbon Accounting

The Net Present Value (NPV) reflects the value of the project over its lifetime considering all financial inflows and outflows but does not account for the value of carbon emissions. While New Zealand does have an operational Energy Certificate System where renewable energy certificates can be traded, participation costs are prohibitive for the scale of PV generation systems considered here (< $25kW_p$). In this section, the impact of carbon offsets by the solar PV system are factored in to a ‘carbon-modified’ NPV. The carbon-offset benefit is not a physical financial inflow and no costs are considered for participating in such a renewable energy-trading scheme as these would outweigh any benefit. The carbon-modified NPV represents the carbon offset as an inflow and monetized based on the carbon price used in the Times-NZ 2.0 scenarios. Interpolated carbon prices for the Kea and Tūī scenarios are presented in Figure 7. The Kea scenario, models significantly higher carbon prices than the Tūī scenario, underlining that fact that future carbon prices are highly uncertain. The carbon-modified NPV is provided for interest only as it is not a recognised methodology.

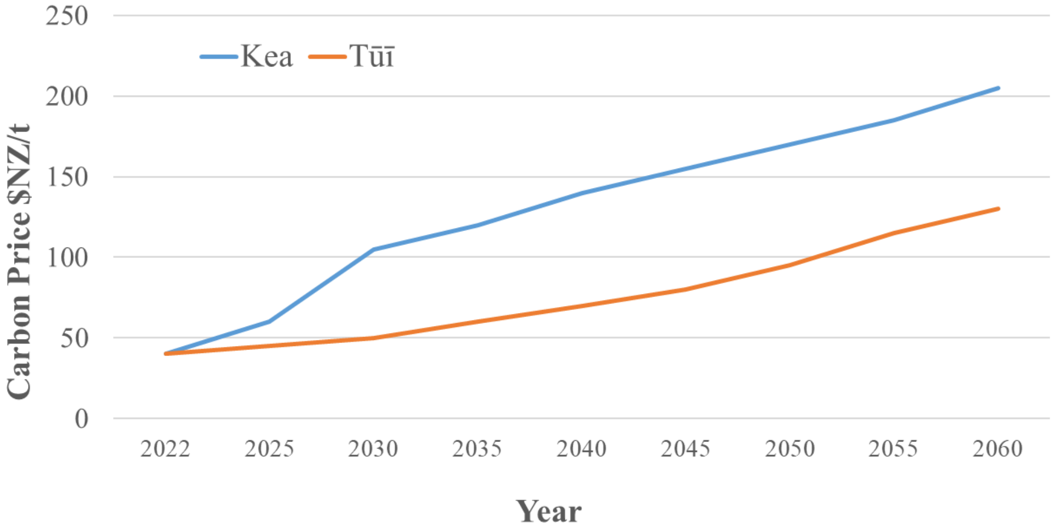

Figure 7 Carbon price as modelled by Times-NZ 2.0 the Kea and Tūī scenarios [3].

Carbon-modified NPV’s are graphed in Figure 8 for multi-Silicon PV systems using embedded carbon figures from Table 4 for the various installations. The low export price paid by electricity retailers for excess generation flattens the NPV for larger system sizes as the component of self-consumption decreases. This is not the case for the carbon modified NPV however which factors in a return for carbon offsets. Larger installations look a lot more attractive with the inclusion of carbon price, with the 24 kW_p system showing a 60% improvement in NPV using the Tūī scenario, while for the Kea scenario, the carbon-modified NPV is more than double the standard NPV.

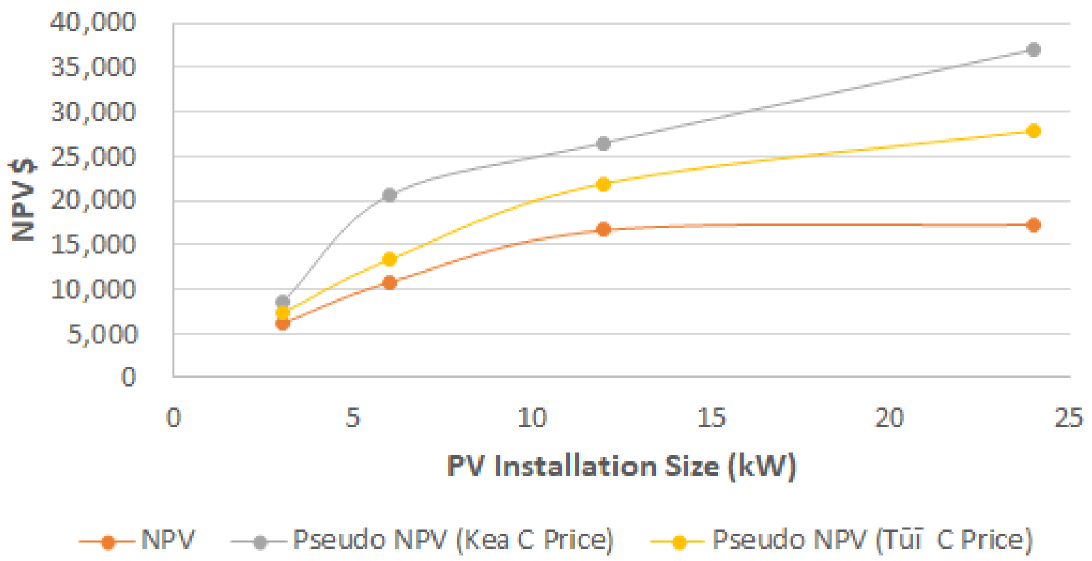

Figure 8 NPV and "carbon-modified" NPV results that include carbon price inflows based on Times-NZ 2.0 scenarios for Kea and Tūī assuming a \$2/W_p PV installation cost for different installation sizes.

6. Conclusions

The embedded emissions for rooftop PV systems installed in New Zealand were assessed using published database inventories and adjusted for New Zealand's location and electricity mix. PV systems using multi-silicon panels were found to have emissions in the order of 48 gCO_2-e/kWh over the system's lifetime. This is approximately a third smaller embedded emissions compared to mono-silicon panels (71 gCO_2-e/kWh) for the 3 kW_p reference system. Lower embedded emissions for multi-silicon panels are due to lower energy requirements largely at the ingot formation stage. As PV installation size increases, a gradual decrease in embedded emissions per kW is expected. In the future, PV embedded emissions are expected to decrease as cleaner energy is used in their manufacture. New solar technology such as perovskite-based solar cells would significantly lower embedded emissions.

PV's ability to offset carbon emissions in New Zealand with an already high renewable proportion is open to debate, especially where the full embedded emissions for alternative generation are not available. Offsetting PV generation against marginal generation, the last and typically most expensive generation to be despatched is justifiable. Natural gas generators meet this criteria and are anticipated to be required to balance the electricity mix for decades to come. Lifecycle PV emissions are an order of magnitude lower than the operational emissions of natural gas ~ 427 gCO_2-e/kWh. Roof-top PV installations were able to offset their embedded emissions in three to five years and had the potential to offset 13-14 tonnes of CO_2-e/kW_p over their thirty-year lifetime.

Financially the small commercial PV systems are expected to provide a positive Net Present Value, assuming an estimated system cost of NZ\$2.6/W_p, and application of the Treasury prescribed discount rate of 5%. The solar generation profile matches Trust Horizon's load profile well, providing high self-consumption, the best route to profitability with low buy-back rates for excess generation. The smallest PV system had the shortest payback times and highest rate of return. Given that the larger PV installations are more attractive from an emissions offset point of view, a more mid-size PV installation in the 6 to 12 kW_p range may provide a balance between financial return and offsetting carbon emissions.

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