Application of distributed solar photovoltaics and energy storage to mitigate bushfire risk in Victoria, Australia

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Application of Distributed Solar Photovoltaics and Energy Storage to Mitigate Bushfire Risk in Victoria, Australia

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Abstract

Recent catastrophic bushfires in Victoria, Australia have prompted examination of the risk of bushfire ignition from uninsulated powerlines. Policy and community debate has ensued over balancing electricity supply as an essential service with the risk of bushfires initiated by powerlines. The 2009 Black Saturday fires prompted debate and analysis resulting in public investments in undergrounding and insulating powerlines as well as deploying network protection devices that reduce ignition probability. This Study examines the technical and economic feasibility of deploying grid-interactive solar photovoltaic and energy storage systems on rural homes to allow powerlines to be disconnected on days of high fire risk to prevent bushfire ignition. Using studies of conditions during fire risk periods, solar photovoltaic yield models and bushfire ignition mechanisms, it concludes that PV systems coupled with energy storage can provide cost effective bushfire risk reduction benefits. Based on comparison with powerline undergrounding, it concludes that solar photovoltaics and storage could achieve the same risk reduction at 10% of the Net Present Cost. This approach is transferrable to other fire-prone regions such as New South Wales, South Australia and Southern California. The use of Bayesian belief networks is proposed as a decision support system for powerline risk management during high fire danger periods.

1. Introduction

1.1 Aims and Objectives

This study aims to evaluate the role of renewable energy and energy storage in rural Victoria in reducing bushfire risk, focusing on solar photovoltaics (PV) and lithium ion energy storage technology. The proposal examined in this Study is to deploy grid interactive PV arrays and storage systems to residential consumers on high risk rural powerlines that can provide an independent power supply during when a powerline is shut down during high fire risk days. The objectives of the Study are to:

i. Develop a comparative analysis of the technical, economic and social dimensions of utilising solar PV and energy storage on Single Wire Earth Return (SWER) lines to reduce bushfire risk in Victoria.

ii. Develop a conceptual model that inter-relates the variables driving PV electricity generation, powerline failures and bushfire risk. Investigate applying this model to a Bayesian network analysis to support the decision-making process on de-energising powerlines based on risk.

iii. Translate the technical analysis into an implementation model, identifying the potential roles of the network businesses, electricity retailers, Government and consumers; and the optimal allocation of asset ownership.

iv. Translate the analysis to other fire prone regions with uninsulated powerlines such as the peri-urban areas of Sydney and Adelaide, and Southern California to allow the results to be replicated by others.

1.2 Literature Review

The State of Victoria in south-eastern Australia is one of the most bushfire-prone regions in the world. Despite technological advances in firefighting, weather forecasting and communications, damages from the recent Black Saturday fires of 7 February 2009 were unprecedented in recorded history, causing the loss of 173 lives and over A$5.16 billion\(^1\) (US$3.77 billion) of economic losses. The principal cause of these fires was ignition of vegetation by wind-induced failure of uninsulated distribution powerlines\(^2\), accounting for some 90% of losses on the day. Extended drought, extreme fire weather conditions, the growth of peri-urban populations in bushfire prone areas near Melbourne and powerlines failures are all contributing factors to the scale of the 2009 disaster (Teague, 2010). Prior to Black Saturday, Victoria experienced another major catastrophic fire, the 1983 Ash Wednesday fires with 47 deaths\(^3\). The 2009 fires had the greatest impact of any recorded fire and 92% of deaths in this disaster were from fires initiated by powerlines (Teague, 2010). Ash Wednesday saw eight major fires of which 4 were caused by powerlines accounting for 17 deaths (Country Fire Authority, 2012) and economic losses of A$1.56 billion (Stephenson, 2012). The total losses calculated from bushfires include economic loss from deaths, homes burnt, ecosystem damage and emergency response costs. Social impacts such as mental health, erosion of social capital and irreplaceable property remain uncosted in these analyses. Excluding other sources of ignition in these two disasters, powerline-initiated bushfires in one generation in Victoria have led to A$5.5 billion

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1 Adjusted for inflation to 2015 dollars; all figures are in Australian dollars unless otherwise stated.
2 Typically through the structural failure of a line, pole or support element and subsequent contact of a live line with vegetation; or through conductors in a multiwire system clashing and releasing molten metal onto vegetation.
3 This figure is only for Victoria and does not include lives lost in South Australia.
in economic losses, including the deaths of 190 people. Given these costs and the potential for Victoria’s bushfire risk has to be exacerbated in the future by climate change (King, 2013) this is an important area for further analysis and research on preventing bushfire ignition from powerlines.

Following the role of powerlines in the 2009 disaster, debate has ensued over powerline bushfire safety in Victoria. It is estimated powerlines in Victoria have tens of millions of individual points of failure that could lead to ignition (Powerline Bushfire Safety Taskforce, 2011). There are 28,000 kilometres of uninsulated Single Wire Earth Return (SWER) lines and over 50,000 kilometres of multi-wire 22kV lines in rural areas of Victoria (Powerline Bushfire Safety Taskforce, 2011). Debate has ensured on the merits of switching off rural powerlines on days of high fire risk as a means of preventing bushfires. The impact of loss of electricity supply is high during fire danger weather when water pumping, air-conditioning and refrigeration are critical and life sustaining for vulnerable citizens (Broome & Smith, 2012). Telephone, internet, television and radio are electricity-based services relied on by the emergency management authorities to advise residents of bushfire danger and organise evacuations. Switching off powerlines potentially results in grave community impacts and this has not been accepted in Victoria4. The key stakeholders involved in powerline and bushfire safety include the Victorian Government, responsible for electricity supply and emergency management; the safety regulator Energy Safe Victoria; the Country Fire Authority; Powercor and Ausnet Services, the electricity distribution business servicing rural Victoria as well as the residents of fire prone areas.

A Royal Commission was established to investigate the Black Saturday disaster. Eight of the 67 recommendations in Commission’s report related to management of powerlines, particularly SWER and 22kV powerlines (Teague, 2010). The Victorian Government established a Powerline Bushfire Safety Taskforce to advise on the implementation of these recommendations and to enhance technical and economic understanding of powerline safety. The Taskforce’s 2011 recommendations outlined solutions such as new network safety devices to reduce the likelihood of powerline faults igniting vegetation, undergrounding powerlines in high risk areas, replacing uninsulated conductors with aerial bundled insulated cables and providing diesel backup power systems for aged care facilities. The Victorian Government has allocated A$250 million to these programs from 2012 to 2022 with a further $500 million to be invested by distribution network businesses (Department of Economic Development, Jobs, Transport and Resources, Victoria, 2011). The scale of the powerline safety challenge is immense. Some 12,000 kilometres of uninsulated powerlines are priority targets of the Government’s investment. The Government’s allocation of A$200 million for the powerline replacement fund over ten years will fund the replacement of about 1000 kilometres of this total, focusing on the higher risk assets. This leaves a substantial amount of infrastructure which needs to be made safe.

The use of solar PV and energy storage technology as stand-alone power systems for powerline safety was not recommended by the Taskforce which concluded that the capital costs were high, estimated at $60,000 per household (Powerline Bushfire Safety Taskforce, 2011 p. 76). The assumptions and the conceptual model underpinning this conclusion can be debated. Stand-alone power systems must operate 365 days per year, designed to manage low winter solar radiation compared to summer-optimised systems for use in fire danger periods. Hence the PV array size and storage capacity will not be comparable, nor will be the capital costs to a grid-tie storage system which can operate in stand-alone mode during fire danger periods. Furthermore, unlike the powerline investments considered by the Taskforce, a grid-tie PV system provides an income stream from supplying electricity to the household and exporting to the grid, which has to be considered in addition to the capital cost when undertaking comparison.

Understanding powerline bushfires requires recognition of wind as the key driver in powerline failure bushfire ignition and propagation of large, difficult to control bushfires. High fire risk days in Victoria typically involve strong winds arising by mid-morning. Wind provides the failure mechanism for powerlines, support elements or poles, with aerodynamic load proportional to the square of the wind speed. Wind causes contact between trees and lines as well as inducing contact between the phases of 22kV lines, igniting vegetation through direct contact or ejecting molten metal into dry vegetation (Mitchell, 2013).

As these ignitions occur at a high wind speed, fires are supplied with oxygen and embers are transported, hence the propagation of these bushfires can be rapid and uncontrollable which increases their destructive capacity.

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4 However the literature does not consider that the highest risk powerlines serve only a small number of people, but a catastrophic bushfire impacts a much larger group. This presents a markedly different cost-benefit analysis. Predicting which powerlines to switch off and when, given the stochastic component of powerline failure is the more challenging conceptual exercise.
This phenomenon explains the deadly impact of the Kilmore and Murrindindi fires on the same day in 2009, where fires moved quickly, resisted suppression and overwhelmed residents. Research from California (Mitchell, 2013) examined 11 years of outage data from San Diego Gas and Electric Company and correlated this with wind speed to indicate that the probability of an outage (a powerline failure, which is a proxy for ignition) increases by a factor of 10 with every 25 km/hr increase in gust speed. Based on Mitchell’s analysis of the California data, at wind speeds of 97km/hr, outages are observed at a rate 10,000 higher than the background rate when wind gusts are below 8 km/hr (Mitchell, 2013). Some researchers have considered that high wind speeds will also prevent any ignition of fuels from electrical arcs or ejection of molten metal from powerlines through dispersing the pyrolysis gases and cooling the combusting material (Coldham, 2011). However empirical evidence shows that fires have started this way during gale force winds such as on 7 February 20095.

Wind is also a driver of overall bushfire risk for the reasons identified and the fire danger index used by authorities increases exponentially with wind speed. Hence the interaction of wind and powerlines in a bushfire context presents risks for consideration: increasing wind speed will drive powerline failures at an exponential rate, increasing 10 fold with every 25 km/hr increase in wind speed; high wind will elevate the bushfire risk in the landscape; and wind-induced powerline failures may occur at multiple points within a short timeframe as winds increase (Mitchell, 2013) Fires which start under high wind conditions will move rapidly, they may not be manageable by suppression efforts and there may insufficient time to warn affected populations. The prominence of wind as a driver of these three aspects of bushfire risk provides a basis for the development of a decision support system with wind as a key input for powerline management, including the identifying the thresholds for changing safety settings of protection devices and de-energisation of powerlines in response to fire risk. This is discussed in Section 4.3, including a proposed Bayesian Network that can be used as a decision support system for distribution network safety management.

The use of solar PV and energy storage in combination with the existing grid offers several advantages. Firstly, PV and storage technology are advancing rapidly in performance and cost effectiveness. Lithium ion storage technology is reducing rapidly in cost, with breakthroughs in anode technologies and lithium processing (Wood, 2015). Energy storage is a growth area in the Australian residential PV market6 (Frischknech, 2015). Two Australian energy retailers are offering lithium ion storage products with their solar PV installations and distributions are developing energy storage as a network solution (Parkinson, 2015). A number of companies are developing software compatible with energy storage products to enable PV owners to export electricity to the grid when prices are high to maximise revenue. These technology improvements, increased energy prices and interest from networks in managing peak loads have led to interest in energy storage in the Australian market7.

Secondly during the fire risk scenario, when the PV/storage system is the primary energy source for the consumer, solar radiation is statistically very high. This allows smaller system sizes compared to stand-alone systems. Thirdly, the existing grid, which has high sunk investment, can be utilised for the remainder of its service life. Outside of the fire danger period the PV/storage system continues to deliver public and private value, such as supplying electricity, providing electricity price arbitrage, lowering greenhouse gas emissions and reducing network peaks. Other stand-alone power technologies exist such as small wind turbines and diesel generation. However solar PV offers some advantages over these – it has a high level of availability during fire danger weather, it is an evenly distributed resource across Victoria, it does not require detailed investigation of geography or terrain for its feasibility and it does not rely on stored flammable fuel.

The Victorian Government is implementing the Taskforce recommendations to reduce the bushfire risk of rural SWER and multi-wire 22kV powerlines. Appendix 1 summarises the Government’s implementation of the funded measures along with details of the safety characteristics of each powerline type and the statistics and configuration of these assets in Victoria. Measures include replacing the highest risk SWER and privately owned overhead lines with underground lines or aerial bundled cable, installing Rapid Earth Fault Current Limiting8 (REFCL) devices on 22kV lines and Auto Circuit Reclosers (ACRs) on both SWER and 22kV lines to reduce the risk of a fault igniting vegetation (Powerline Bushfire Safety Taskforce, 2011). These approaches have varied costs, benefits and risk reduction. REFCLs are estimated to reduce ignition risk by 70% and ACRs by 50%, while

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5 Alternative explanations include lulls in wind speed during which ignition occurs (Coldham, 2011) (less likely as the failure mechanism is driven by high wind) or that the ignition occurs in long grass, where wind speed is low.

6 Energy storage is attractive in many Australian states because of high peak tariffs and low export rates for PV electricity.

7 Ergon Energy has announced a Queensland trial in 2015 of solar PV and energy storage systems in homes which will use software to dispatch energy to the network at critical times to reduce exposure to high energy prices and reduce network peaks.

8 The technology was developed to manage faults on underground lines but has been adapted in Victoria for fire safety with a variant using Ground Fault Neutraliser technology.
undergrounding offers close to 100% risk reduction (Powerline Bushfire Safety Taskforce, 2011). Undergrounding is the most expensive treatment costing approximately A$300,000 per kilometre (Powerline Bushfire Safety Taskforce, 2011).

2. Methodology
2.1 Overview
Figure 1 summarises the analysis process utilised to develop the technical analysis and business case. The methodology draws on public data, such as meteorological data, records of historical TFBs, load data from zone substations, electricity tariffs, PV market data, household demographic data and studies of household energy consumption.

The sizing and costing of grid-tie residential PV and storage systems for customers on rural powerlines as a means of reducing bushfire risk requires detailed analysis of the interlinked variables that drive fire danger weather, solar PV generation, electricity demand and powerline ignition risk. These include temperature, wind speed, humidity and solar radiation. To support the analysis developed in this Study a conceptual model has been developed which illustrates and inter-relates these factors. This is provided at Appendix 2.

Understanding this conceptual model assists in the evaluation of the PV/storage solution. For example increasing wind speed increased the fire danger index\(^9\) and it also causes powerline structural failures that ignite fires. Solar radiation increases both temperature and PV yield, while temperature increases the fire danger index. Examining the historical record of Total Fire Ban Days (TFBs) in Victoria provides insights into the statistical distributions and combinations of these variables during fire danger conditions. Some of these relationships are exponential (wind speed and temperature with fire danger) while others are linear (solar radiation with PV yield). Evaluating the history of major bushfires in Victoria and the role of powerlines provides contextual data for understanding the significance of powerlines in bushfire losses. The historical records of TFBs combined with data from the Bureau of Meteorology provide an evidence base for the combinations of environmental variables experienced and their contribution to fire risk, PV yield and electricity demand. Lastly, data from a project undertaken in 2014-15 to underground 17 SWER lines in the fire-prone Otways region of southern Victoria was used to provide a basis for comparison with PV/storage technology. This data includes the costs to retire existing overhead line and avoided maintenance costs from undergrounding.

2.2. Total Fire Ban Days in Victoria
The Study uses Total Fire Ban days, or TFBs as a means of identifying days of high fire risk. TFBs are an instrument employed by the authorities to reduce the probability of bushfire ignition on days of high fire risk. A further description of TFBs and the history of TFBs from 1945 to 2015 is summarised in Appendix 3\(^10\). TFBs in a sequence present the critical design case for a PV/storage system as it requires system autonomy from the grid (assuming that the fire danger conditions do not drop below a danger threshold at night). Single TFB days are less critical as the system will have additional support from a fully charged battery. The PV/storage systems can be sized on the requirement to supply adequate energy over these five days of outages. Since 2004 from when accurate load profile data is available, the critical combination of PV yield and electricity demand occurred from 14 to 17 January 2014.

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\(^9\) The fire danger index, calculated from a modified version of the McArthur Fire Danger Index is used by authorities in Australia to estimate overall fire risk and declare Total Fire Ban Days at an index of 50. It is based on wind speed, temperature, humidity, and antecedent dryness (drought index). The index increases exponentially with wind speed, temperature and humidity and linearly with the drought index.

\(^10\) After 1986 the State was divided into 9 fire regions. Data from 1945-1986 reflects the whole state of Victoria; post 1986 reflects the Central Fire Region located around Melbourne.
3. Results, Analysis and Discussion

3.1 Household Power Consumption and Load Profile on Total Fire Ban Days

Household electricity consumption is a complex phenomenon, which is driven by consumer behaviour, weather, pricing and energy efficiency. Household power consumption in Victoria is now decreasing. Data from analysis of household electricity consumption in 2015 was used (ACIL Allen Consulting, 2015), combined with household size distribution from the 2011 Australian Census to estimate the distribution of household power consumption along a typical rural powerline\textsuperscript{11}. For the purposes of the analysis, it was assumed that 50% of the houses use bottled or main gas and 50% have no gas connected. Homes without gas consume more electricity. Victoria has adopted a digital metering technology known as Advanced Metering Infrastructure, or Smart Meters, which collect half hourly information on electricity consumption and provide the data remotely. As this is not publicly accessible, residential load profiles have been synthesised using load profiles from rural zone substations. A suitable zone substation from Powercor’s network near Melbourne was selected (Winchelsea) having minimal data gaps and servicing a rural residential customer base, with data from 2004 to 2014. The ratio of the area under the zone substation load curve for any chosen year to household consumption over the same period, gives a scaling factor to generate a load profile. The zone substation data averages the demand variation of several thousand customers, hence giving a ‘smoothed’ approximate curve for an individual household. Appendix 5 provides a sample load profile estimated this way. Load profiles impact the optimisation of energy storage.

3.2 Estimating PV Yield on Total Fire Ban Days

Understanding the levels of PV energy available during TFBs underpins the analysis. Half hourly time series data of weather variables (GHI, DNI, temperature and wind speed) at Melbourne Airport were used. Appendix 3 maps the distribution of annual GHI across Victoria highlighting the resource around Melbourne. There is a band of relatively uniform GHI within a 50 to 100 kilometre radius of Melbourne, including Melbourne Airport, of about 4.2 to 4.4 kWh/day averaged over the year. Daily GHI is a good fit to a Weibull distribution ($R^2 = 98.6\%$ for the 15 year daily record). A cumulative Weibull distribution of daily GHI provides insight into PV yield on TFBs, as GHI is the primary driver of PV yield. Figure 2 shows the cumulative Weibull distribution for three datasets - all of the days from 2000 to 2014, the TFBs only and the consecutive TFBs in this period. This confirms that TFB days experience significantly higher levels of irradiance than the average. However the dataset indicated that consecutive TFB days experience higher irradiation TFBs generally. The 90th percentile GHI of the consecutive TFB dataset is equivalent to the 40th percentile of the annual GHI. By contrast, stand alone power systems need to be designed with PV and storage that can cope with the 5th percentile GHI. This confirms the intuitive concept that fire weather is concurrent with abundant solar radiation. Detailed PV simulation was then performed using inputs of environmental variables – spectral and diffuse radiation, wind speed and air temperature from Melbourne Airport. Victoria, although the southern part of Australia has excellent solar resources, at par with Bangkok, Athens and Valencia. This Study used two simulation packages – NREL’s System Advisor Model (SAM) and PVSYST to model PV yield. SAM offers suitable features including user-defined time bound meteorological data rather than TMY or long-term averages, allowing simulation of PV yield during specific periods, such as TFBs. PVSYST offers a module to design stand alone systems with storage. Simulations with SAM using inputs of GHI, DNI, temperature and wind speed in 30 min time steps were undertaken using Melbourne Airport data for the period 2000-2014. Output data parsed to examine the total fire ban days. A

\textsuperscript{11} The average household size in Victoria is 2.543 persons (ID, 2012).
simulation was done for a typical monocrystalline\textsuperscript{12} PV system of 4.6kW peak capacity with results converted into normalised as kWh per kW peak output. Orientation assumptions were due North azimuth and roof slope of 20 degrees, typical of Victorian house construction styles. This is representative of systems in rural Victoria based on a survey undertaken of 41 randomly sampled rural PV systems\textsuperscript{13}. This sample indicated that the average elevation of systems was 19 degrees, 68% of systems were oriented due north and 98% of systems were oriented within 45 degrees of due north.

The result is a time series of PV outputs with a 30 minute time step for each 30 minutes from 2000 to 2014. Figure 3 shows an output from the simulation during a fire danger period of January 2014, along with a comparison with four randomly selected PV systems\textsuperscript{14} in the Melbourne area from www.pvoutput.org. This was a period of four consecutive TFBs with extreme high temperatures. The PV output is a fairly uniform bell shape with some interruption by afternoon cloud visible in the yield curve. The simulated daily yield is consistent with the actual generation recorded by operating PV systems on these days.

Figure 3 - Typical PV Yield Output from SAM (daily profile and daily outputs compared to other Melbourne PV systems)

3.3 Sizing and Optimisation of PV and Storage Systems for Autonomy
The sizing of PV and storage systems is usually done for stand-alone power systems. The design criteria of the grid-tie PV/storage system for the purposes of this Study is for autonomous operation on fire danger days with particular solar and load characteristics, a different design requirement to stand-alone systems. The software PVSYST has a module that performs analysis and optimisation of stand-alone systems. PVSYST allows the user to specify location, weather and load inputs, acceptable unserved energy probability and minimum days of battery autonomy to derive an appropriate array and battery bank size. PVSYST was used to model a representative two person household over the period 2000 to 2015, allowing critical periods of consecutive TFBs to be identified from the PV yield and load analysis in January 2009, February 2009 and January 2014. The inputs were modified to give a low but non zero load outside of fire season to allow the algorithm to solve for the times of high fire danger. One compromise in this approach is that PVSYST by default has a minimum one day of battery storage as part of its design solution. This will tend to give an overestimate of the required battery capacity.

To optimise battery size, a half hourly energy balance model was run in Excel to analyse of PV generation, consumption and storage. By iteration, the battery capacity required on the critical time periods could be determined. The constraints of the model were that the charge and discharge rate should not exceed the battery’s capacity and the state of charge should not fall below 20%. A second Excel model based on half hourly energy balance and battery capacity was run to estimate the export rate to the grid. This is required for the financial model as Victoria has a solar feed-in tariff less than the retail rate. For a two person household, the PVSYST optimises a 4.6 kW PV array and the energy balance model suggests a 14kWh lithium ion storage system (2 x 7kWh units) is sufficient to meet demand and maintain the depth of discharge above 20%. The modular nature of the energy storage units results in a variation of the levels of redundancy of some household sizes. Appendix 5 illustrates the profiles for PV yield, load and battery storage for the critical January 2014

\textsuperscript{12} Monocrystalline and polycrystalline have near identical performance, but monocrystalline has a slightly lower temperature co-efficient. Analysis with SAM simulation predicts monocrystalline has 1.5% greater output over the heatwave period 14-17 January 2014. A module from a large-scale manufacturer was chosen with typical performance characteristics.

\textsuperscript{13} The data was drawn from www.pvoutput.org, a website that compiles PV performance data through crowdsourcing.

\textsuperscript{14} Systems were selected having an azimuth plus or minus 45 degrees from North
heatwave. The representative solution for the two person household was expanded to other household categories by linear scaling based on daily consumption\textsuperscript{15} and the results checked with the energy balance model to ensure that loads are met and the battery state of charge is adequate.

3.4 SWER Undergrounding Data
In 2014 and 2015 Powercor undertook works to underground 17 SWER lines measuring 104 kilometres serving an estimated 204 homes\textsuperscript{16} in forested areas of the Otway Ranges near Melbourne at a total cost of $31 million (Powercor Australia, 2014). Further undergrounding works are planned for the Dandenong Ranges, Whittlesea and Warburton. These costs provide a benchmark for comparison with the PV/storage solution by calculating the cost for a PV/storage system for each of these houses. The Powercor undergrounding project costs were adjusted for any avoided replacement and maintenance costs and converted to 20-year costs in line with the life of the PV/storage system.

3.5 Cost Benefit Analysis
A discounted cash flow analysis was undertaken based on the technical design and assumptions of technology costs, energy pricing and future pricing changes escalation. The Net Present Cost is calculated within the household boundary of implementing the PV/storage system. Hence purchase and installation costs are included as costs, while avoided electricity purchases and revenue from exports to the grid are counted as the benefits. The externalities of bushfire safety, increased security of supply, avoided or added network costs and emissions reductions are not included at this stage of the analysis. Table 1 below summarises the PV and storage configurations, capital cost and Net Present Cost for different household sizes. The capital cost ranges from $16,000 for a 1 person household to $33,000 for a 5 person household. The PV cost scales linearly with household power demand, but the storage cost increase in discrete steps owing to the use of 7kwh storage modules. Generally 65% of the system CAPEX is accounted for by storage costs\textsuperscript{17}.

<table>
<thead>
<tr>
<th>Household Size (persons)</th>
<th>Summer Consumption (kWh / day)</th>
<th>% of Victorian Households</th>
<th>PV Array (kW)</th>
<th>Energy Storage (kWh)</th>
<th>Capital Cost PV/inverter</th>
<th>Capital Cost Storage</th>
<th>Total Capital Cost</th>
<th>Net Present Cost (over 20 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.3</td>
<td>27.9%</td>
<td>2.96</td>
<td>10</td>
<td>$5,565</td>
<td>$10,560</td>
<td>$16,125</td>
<td>$7,025</td>
</tr>
<tr>
<td>2</td>
<td>12.9</td>
<td>36.3%</td>
<td>4.6</td>
<td>14</td>
<td>$7,820</td>
<td>$14,784</td>
<td>$22,604</td>
<td>$8,946</td>
</tr>
<tr>
<td>3</td>
<td>13.6</td>
<td>13.9%</td>
<td>4.86</td>
<td>14</td>
<td>$8,262</td>
<td>$14,784</td>
<td>$23,046</td>
<td>$8,439</td>
</tr>
<tr>
<td>4</td>
<td>12.7</td>
<td>13.1%</td>
<td>4.53</td>
<td>14</td>
<td>$7,701</td>
<td>$14,784</td>
<td>$22,485</td>
<td>$9,082</td>
</tr>
<tr>
<td>5 plus</td>
<td>18.3</td>
<td>8.8%</td>
<td>6.55</td>
<td>21</td>
<td>$11,135</td>
<td>$22,176</td>
<td>$33,311</td>
<td>$14,101</td>
</tr>
</tbody>
</table>

Table 1 – Design Configuration of PV/Storage Systems

The discounted cashflow model and its supporting assumptions are summarised in Appendix 6. The PV/storage solution can be compared with other powerline safety enhancements which are currently being implemented or planned in Victoria. Comparisons must be done with caution, as all of these vary in terms of cost, service life and levels of risk reduction. Some can be used in combination with PV and storage while others are mutually exclusive. For example the enhanced protection devices on SWER lines and the new generation ACRs are a low cost measure and can be deployed in tandem with PV and storage. The ACR offers risk reduction of approximately 50% but the addition of PV and storage reduces this residual risk to practically zero while offsetting the drawback of time off supply when the devise does not reclose. The ACR is remotely controllable and may enhance the ability of the network operator to isolate parts of the network in line with its bushfire safety plan. Given the distributors in Victoria are already installing these devices across the high risk sections of their networks it is appropriate to combine the two solutions. Table 2 overleaf provides a summary of powerline treatment options and costs. Options A to G are excerpted from the Taskforce Report (Table 28 p.159, Powerline Bushfire Safety Taskforce, 2011), while Options H to K are calculated from the analysis in this Study.

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\textsuperscript{15} This assumes all household sizes have the same load profile shape.

\textsuperscript{16} Based on an assumption that each kiosk substation serves one home.

\textsuperscript{17} Costs are based on the Tesla Powerwall design which incorporates the charge controller.
<table>
<thead>
<tr>
<th>Technology Option</th>
<th>Mean Customer Density/ km</th>
<th>NPC (Incremental $/km) Lifetime</th>
<th>Risk Reduction</th>
<th>Lifespan (years)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) New generation SWER ACRs</td>
<td>2.4</td>
<td>$1,229</td>
<td>50%</td>
<td>38</td>
<td>deployed under existing measures</td>
</tr>
<tr>
<td>B) REFCLs on multi-wire</td>
<td>13.9</td>
<td>$8,798</td>
<td>70%</td>
<td>38</td>
<td>deployed under existing measures</td>
</tr>
<tr>
<td>C) Convert SWER to multi-wire (REFCL)</td>
<td>2.4</td>
<td>$163,897</td>
<td>63%</td>
<td>70</td>
<td>not implemented</td>
</tr>
<tr>
<td>D) SWER – insulated wire</td>
<td>2.4</td>
<td>$284,253</td>
<td>90%</td>
<td>30</td>
<td>not implemented</td>
</tr>
<tr>
<td>E) SWER – underground</td>
<td>2.4</td>
<td>$366,998</td>
<td>99%</td>
<td>45</td>
<td>deployed for high risk powerlines</td>
</tr>
<tr>
<td>F) Multi-wire – insulated wire</td>
<td>13.9</td>
<td>$341,887</td>
<td>90%</td>
<td>30</td>
<td>not implemented</td>
</tr>
<tr>
<td>G) Multi-wire – underground</td>
<td>13.9</td>
<td>$567,468</td>
<td>99%</td>
<td>45</td>
<td>no information on implementation</td>
</tr>
<tr>
<td>H) PV/Storage on SWER</td>
<td>2.4</td>
<td>$22,302</td>
<td>99%</td>
<td>20</td>
<td>no planned implementation</td>
</tr>
<tr>
<td>I) PV/Storage on multi-wire</td>
<td>13.9</td>
<td>$129,167</td>
<td>99%</td>
<td>20</td>
<td>feasibility doubtful</td>
</tr>
<tr>
<td>J) SWER ACR plus PV/Storage</td>
<td>2.4</td>
<td>$23,531</td>
<td>99%</td>
<td>20 to 45</td>
<td>no planned implementation</td>
</tr>
<tr>
<td>K) Stand alone PV/storage - remove SWER line</td>
<td>2.4</td>
<td>$137,964</td>
<td>99%</td>
<td>20</td>
<td>not implemented</td>
</tr>
</tbody>
</table>

Table 2 – Powerline Treatment Options

Undertaking an appropriate comparison between PV and storage and other technologies requires several steps. Firstly, the comparison technologies need to achieve a similar level of risk reduction (90-100%). Secondly, the incremental costs - the capital costs net of savings from avoided future replacement or reduced maintenance, (published by the Taskforce) were utilised. Thirdly, to align with the lifetime of the PV/storage system, incremental costs were truncated to 20 year time horizons by subtracting the net present residual value of the powerline asset at 20 years life. This results in a series of comparable costs expressed in $ per kilometre of powerline length and the analysis is presented in Figure 4.

Figure 4 – Net Present Incremental Cost of Powerline Safety Options with 90–100% Risk Reduction ($ per km over 20 years)

3.6 Sensitivity Analysis

A sensitivity analysis of the key variables in the cashflow model was undertaken using Monte Carlo analysis to run the cashflow model with variations (normal and skewed triangular distributions) to PV cost, energy storage cost, escalation of electricity tariff and degradation of PV performance. The results are summarised in a Tornado chart in Figure 5 expressed as 25th and 75th percentile values of the resulting distribution. Strong dependencies were evident for the retail electricity rate, storage cost and the PV cost. Decrease in storage costs is a key opportunity to make the solution more cost-effective.

Figure 5 – Sensitivity Analysis Using Monte Carlo Analysis – 25th and 75th Percentile Net Present Cost Results
4. Discussion

4.1 Key Results

The analysis demonstrates that the use of solar PV and energy storage is an economically and technically feasible means of preventing powerline initiated bushfires in Victoria. PV and energy storage can meet electricity demand for rural homes during days of high fire risk, allowing powerlines to be taken off line. The approach is principally applicable on SWER lines which connect rural residential dwellings, where it is cost effective in avoiding undergrounding of powerlines but also can be used on other SWER lines which will be fitted with ACRs to remove the 50% residual risk post-installation of these devices. The Net Present Cost of the solution is less than 10% of the cost of conductor insulation or undergrounding, based on State average customer densities of 2.4 per kilometre\(^{18}\).

Typical two to three person households will require PV arrays of 4.6 to 4.9 kW capacity and energy storage system of 14kWh capacity, noting that these are based on State averages across Victoria and there will be some outlying high energy consuming households. The sizes of these PV arrays are typical of installations in Australia, which averaged 5 kW in 2015\(^{19}\). The analysis has utilised some conservative assumptions: that energy conservation steps are not undertaken by the householder when on stand-alone power; and that power shutoff persists overnight on TFBs. It is highly likely that there are discretionary or deferrable components that can reduce the customer loads at these times. A household energy efficiency package using LED lights, insulation, efficient air-conditioners and solar water heaters may have economic justification in their own right as well as reduce the capital cost of the PV/storage system (Sustainability Victoria, 2014). The fire danger index may drop in the evenings during multiple TFB events. Monitoring of the fire danger index may allow power to be restored in the evenings and reduce the load on the PV/storage system. A deeper analytical view of powerline bushfire risk as opposed to conventional bushfire risk is needed to guide these decisions. This is discussed further in Section 5.3 in the context of Bayesian networks. A significant impact is that the energy flowing through the SWER line reduces considerably with bidirectional power flow. Based on analysis of 2014 solar and load data for a representative two person household, it would export power for 12% of the time and import for 20% of the time, with no line loading for 68% of time.

4.2 Implementation Issues

The challenges to implement the solution will be to ensure that all of the customers on a given line adopt the PV/storage technology. The safety benefits of the scheme rely on the networks’ ability to shut down powerlines, with the assurance that all customers have an alternative supply. This will require community engagement and an incentive scheme to ensure scheduled adoption. There may be dwellings on a SWER line with excessive shading that means the solution cannot be implemented.

Prioritisation of powerlines can be supported by a survey of each distributor’s network to develop a priority list of SWER lines to be generated. Some high energy consuming households may have insufficient roof space, but split east-west arrays, ground mounted systems, carports or sheds can be used. Smart Meter data for each customer provides individual half hourly consumption during fire danger periods, which can provide a rapid customised design for the array and energy storage.

Modified software control of the battery state of charge will be required during bushfire season to hold the battery at 100% charge prior to a TFB being declared. This will provide the system with maximum autonomous capability in the face of a series of TFBs. For the remainder of the year it can be programed to maximise revenue or reduce network peaks. There are technologies in the market which perform this type of control to maximise system revenue through energy trading and arbitrage. For example some hybrid inverters can process weather forecasts over will and optimise its storage accordingly and an Australian start-up company offers software to remotely manage PV/storage systems to export at high spot market prices (Reposit Power, 2015). The weather forecast input could be modified to include a notification of TFB which would change the system protocol to hold the battery at a full state of charge until the grid is lost. Detailed analysis of TFBs indicates that afternoon cloud cover is frequent. Based on examination of simulated PV yield on14 critical TFBs from 2009-14, the pre-solar noon yield is on average 36% higher than post-solar noon. Hence east facing arrays are preferable to west facing arrays if the roof orientation prevents arrays facing due north. The existing distribution networks in high risk areas where this solution is deployed will have lighter loading, voltage rise and reverse power flows as part of their

\(^{18}\) The break even customer density for cost parity with undergrounding is 38 customers per kilometre – well above Victorian rural SWER densities.

operation, so the operation of the network will need to manage these, with possible hardware changes required. Depending on the energy storage algorithms adopted there may not be significant reductions in peak loads. The zone substation at Winchelsea utilised for load profiles in this Study experiences winter peak loadings in July and August around midnight owing to concurrence of space and water heating loads. This period corresponds to low levels of solar radiation. The energy storage could be programmed to reduce network peaks if this benefit could be monetised.

4.3 Use of Bayesian Belief Networks to Guide Powerline Shutdown Decisions

Bayesian networks are a very powerful tool for modelling complex systems and guiding decision making, even if some input data are incomplete (Uusitalo, 2007). This technique is useful in managing the complex decisions on powerline management during bushfire weather, which must balance the low probability of a high consequence event (a bushfire) against a high probability of loss of supply to customers and its impacts. The environmental variables affecting the balance between these two decisions—temperature, wind speed, humidity and fuel load - will vary continuously in space and time. The decisions taken by authorities could be to shut down a powerline or to remotely enact a fire safe setting on a protection device. Section 3.1 introduced a conceptual model that linked bushfire risk, PV yield and household load (Appendix 2). This model has been modified to produce a Bayesian network that represents the causal relationships between variables that lead to powerline risk. This is shown in Figure 6. The application of this model with accurate meteorological data could provide sophisticated daily or hourly estimates of powerline risk which currently use the fire danger index. As noted, the fire danger index may not be an accurate proxy for powerline bushfire risk. It may not reflect as precisely the role of wind or wind gusts in powerline failure and it does not consider factors endogenous to the powerline, or the local fire risks along its route. As noted, the occurrence of potential bushfire ignitions increases by a factor of 10 with each 25 km/hr increase in wind speed. The fire danger index exhibits a weaker relationship with wind speed, doubling with each 30 km/hr increase in wind speed. The fire danger index may underestimate the role of wind in powerline failure and ignition. The proposed Bayesian network in Figure 6 can reflect the risk relationship with wind more appropriately and utilise other inputs such as the condition of the powerline, the vegetation density on the route and the modelled bushfire consequence of the location based on the PHOENIX model. This could assist decisions on disconnecting powerlines and on enacting fire safety protocols on devices such as REFCLs and ACRs which deliver value to distributors and consumers, while reducing fire risk.

4.4 Implementation Model

While the costs of this model are significantly lower than many powerline upgrades, implementation may be more complex. Firstly it involves placing infrastructure on customers’ properties. Secondly, an implementation model must be designed which distributes costs and benefits amongst the actors involved in the implementation – the Victorian Government, the distributors, the householders, the electricity retailers and the wider community. An investment model is provided in Appendix 7. This model proposes a Government-sponsored procurement process for the PV/storage equipment for householders connected to high risk powerlines. Installation is undertaken by a system integrator which may be an electricity retailer, with ownership resting with the Government. The system energy is metered through the Smart Meter (including self-consumption, time of use and export components). The retailer then bills the home owner for the energy produced at a discount to the prevailing rates, including accounting for peak and off-peak rates. This model may help in mobilising support

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20 In practice a day of moderate fire risk and gale force winds may present greater powerline bushfire risk than a day of extreme fire danger and moderate winds.

among home owners for the scheme. Alternatively the system ownership can be transferred to the home owner in return for annual payment collected through the electricity bill in a manner that is cost neutral.

4.5 Translation to SA, NSW and California

The conditions in Victoria with regard to solar radiation and fire danger are by no means unique. While Victoria is one of the most fire prone regions of the world, the issues with powerlines and fires are also relevant for other jurisdictions. An analysis of the fire seasons in NSW, South Australia and Southern California was undertaken and summarised in Figure 7. The fire season in each locality is also concurrent with higher levels of solar radiation, even to a greater extent than Victoria. Hence the solution in Victoria could be broadly replicable in these other regions, subject to other variables such as level of bushfire risk, powerline configurations and electricity rates. It could also be applied for regions subject to other natural disasters which cause supply interruptions such as floods, and storms.

5. Conclusions

Bushfires will continue to be a major public policy challenge in Victoria and efforts to reduce bushfire risk from all sources will need to continue into the future, while balancing these with economic, social and environmental constraints. The impacts of climate change in the future will introduce another source of uncertainty into the challenge of balancing cost and risk mitigation.

The Study has concluded that PV and energy storage systems have an important role to play in reducing bushfire risk from powerlines in fire-prone regions of Victoria. When deployed on individual homes which are connected to SWER lines in high bushfire risk areas, PV/storage systems can provide a reliable source of stand alone electricity during times of high fire danger, allowing SWER lines to be de-energised and reducing the bushfire ignition risk from these lines to zero. When compared to alternatives such as undergrounding powerlines or replacement with aerial bundled cable, this technology can be deployed at an average of 10% of the net present cost per kilometre of network, but will vary according to the number of customers per kilometre of powerline. The sizes of the PV arrays required are consistent with the average system sizes currently being deployed in Victoria. The costs of this approach are highly sensitive to the cost of lithium ion storage technology which was elected as the basis for the Study, and this cost is projected to decrease in the next several years. The lifecycle costs of the PV/storage system is calculated over 20 years, following which the replacement by more cost effective technologies may offer some future cost savings and performance enhancements. This is in contrast to powerline upgrades which have service lives of 30 to 45 years, over which time the costs and performance are locked in. Data from Smart Meters can have benefits from better understanding customer demand and fire weather load profiles to allow rapid tailoring of PV/storage systems to individual homes. It may be feasible to use PV and storage on 22kV multi wire lines in future with improvements in the costs of the technology, or a greater emphasis on bushfire safety, if the private benefits of adopting these technologies are such that universal coverage for individual 22kV powerlines is achieved. The key challenge is implementation and developing a business model that will capture the value offered to multiple stakeholders, to adequately apportion the costs and benefits and enable an orderly deployment on the highest risk powerlines. To this end the implementation model proposed in the study provides a starting point to develop alternative models.

The Study also examined alternative approaches to evaluating powerline bushfire risks by using Bayesian networks and proposed a candidate Bayesian network that could be used to predict powerline risk and guide the management of protection devices and powerlines de-energisation based on a deeper understanding of wind related powerline failure and bushfire ignition. This tool, if developed could enhance bushfire safety while improving supply reliability for customers. Based on a preliminary analysis of solar availability in other regions, the results of the Study are readily applicable beyond Victoria to other fire prone regions such as New South Wales, South Australia and Southern California.
Acknowledgements

I am grateful to many people who assisted me with this project and were generous with their time and expertise. Firstly, my supervisor Dr Paul Rowley, for his enthusiasm and interest in this project and for challenging me to take the analysis in directions I would not otherwise have. Dr Ian Muirhead and his colleagues at the Bureau of Meteorology provided insights into bushfire weather and excellent data support. To Glenne Drover from the Victorian Government for his feedback and sharing his extensive knowledge of the energy system. I owe great thanks to Dr Joe Mitchell from M-Bar Technologies in California for his advice and encyclopaedic knowledge on bushfires and powerlines. Dr Paul Gilman from NREL assisted greatly with using the SAM software. Lastly, my thanks to my wife and son, for their support and forbearance in allowing me to spend many hours on this project away from them.

Works Cited

Appendix 1 – Powerline Safety for SWER and 22kV Lines in Victoria

The key features of SWER and 22kV distribution lines in Victoria are summarised in Table A1.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>SWER line</th>
<th>22 kV line</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Voltage</td>
<td>12.7 kV</td>
<td>22 kV</td>
</tr>
<tr>
<td>Density of Customers</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>2.4 per kilometer (state average)</td>
<td></td>
<td>13.9 per kilometer (state average)</td>
</tr>
<tr>
<td>Typical Length</td>
<td>Short, 2 – 30 km</td>
<td>Long, 10 – 1100 km</td>
</tr>
<tr>
<td>Indicative No. Customers per Feeder</td>
<td>50</td>
<td>2200</td>
</tr>
<tr>
<td>Bushfire Ignition Mechanism</td>
<td>Line to vegetation, line to ground contact</td>
<td>Line slap, line to vegetation, line to ground contact</td>
</tr>
</tbody>
</table>

Table A1 – SWER and 22kV Distribution Lines in Victoria

Sources: Powerline Bushfire Safety Taskforce Report

The proposed application of Auto Circuit Reclosers – ACRs – on SWER lines allows remote control of the reclose settings. This allows the network operator to allow the circuit to remain tripped following a fault that does not clear itself during high fire danger periods. It reduces fire starts from multiple reclose operations but still leaves some 50% residual risk of ignition. The proposed measure of - REFCLs on 22kV lines may provide a higher level of risk mitigation. The program of installing REFCLs has already begun in Victoria. REFCLs can rapidly reduce the energy supplied to a fault, reducing the probability of the fault current providing sufficient energy to ignite vegetation. During fire risk periods the REFCLs can be remotely adjusted by the network operator to increase their sensitivity to faults and offer higher risk reduction (Marxen Consulting, 2014). The ACRs are similarly remotely controlled and can be programmed to limit reclose attempts to one fast operation during high fire risk periods. This will reduce the probability of vegetation ignition if the line has come in contact with a tree, fence or the ground. The application of both the REFCLs and the ACRs in this manner imply greater supply interruptions during fire risk periods, as linesmen must visually clear any fault before the device is manually reset. During fire danger days the number of faults may increase and access by crews may be difficult. The Victorian Government is addressing this increased probability of sustained outages by funding a program to provide backup diesel generation to facilities housing vulnerable people such as nursing and old age homes. Investigation into the configuration of rural power networks indicates that the SWER networks represent the greatest opportunity for the solar PV/storage solution. SWER line customers are typically homes or small farms. It is less likely to find energy intensive users such as dairy farms, poultry sheds or industries connected to the single phase SWER lines. For SWER lines, the lower number of customers per kilometre makes the use of undergrounding, aerial bundled cables or other conductor treatments expensive on a per customer basis. Figure A1 below illustrates the customer density on distribution feeders across Victoria.

Figure A1 – Electricity Customers per Feeder Length in Victoria (image courtesy Powerline Bushfire Safety Taskforce)

The setting is enacted when the fire danger index reaches 30, lower than the threshold of for declaring a TFB which is 50.
Appendix 2 – Conceptual Model of Fire Risk and PV Generation
TFBs are declared the previous day based on the modelled fire danger index by the Bureau of Meteorology to be forecasted at greater than 50. Open fires and certain types of machinery that may ignite fires are banned on these days. From 2000 – 2014, an average of 13.4 TFBs were declared per year. TFBs are announced the previous day and are called when the fire danger index is projected to exceed 50. The ban commences from midnight and extends for 24 hours. Figure A3 illustrates the history of TFBs since 1945. The variation of annual TFBs with the el nino cycle is evident. It can be seen that TFBs can occur as isolated days, but also in a multi-day continuous sequence.

Figure A3 – Total Fire Ban History in Victoria

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23 Based on advice from the Bureau of Meteorology, which forecasts the fire danger index for the following day.
Appendix 4 – Distribution of GHI across Victoria and the Melbourne Region
Appendix 5 – Modelling Outputs of PV/Storage

January 2014 Heatwave Demand - 2 Person Household

Energy Storage Jan 2014 Heatwave (2 person HH, 4.6 kw PV, 14 kwh Storage)
## Appendix 6 – Discounted Cash Flow Analysis and Supporting Assumptions

### Cash Flow Model PV and Storage

<table>
<thead>
<tr>
<th>Source</th>
<th>Tariffs – flat rate, Powercor Rural</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Size</td>
<td>4.6 kw</td>
</tr>
<tr>
<td>Storage</td>
<td>14 kWh daily cycling, maximise self consumption</td>
</tr>
<tr>
<td>No of People per household</td>
<td>2 user input</td>
</tr>
<tr>
<td>Input Data</td>
<td>Red Energy</td>
</tr>
<tr>
<td>PV size</td>
<td>4.6 kw</td>
</tr>
<tr>
<td>No of People per household</td>
<td>2</td>
</tr>
<tr>
<td>Annual Consumption</td>
<td>4658 kWh</td>
</tr>
<tr>
<td>PV cost per Watt</td>
<td>$0.75</td>
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<tr>
<td>Storage cost per kWh</td>
<td>$1.05</td>
</tr>
<tr>
<td>Total cost (PV and storage)</td>
<td>$22,660</td>
</tr>
</tbody>
</table>

**PV Array**
- PV array and storage
- PV/storage Capex: $16,125
- Origin rate freeze: $0.260

**Storage**
- 14 kWh, daily cycling, maximise self consumption
- 10 days, maximise self consumption
- 1

**Export rate**
- 36%

**Feed-in rate**
- $0.062

**Retail rate**
- $0.263

**Energy Generation**
- 6092 kWh per annum (modified for 92% loss on 39% of generation cycled through battery)

**PVSYST Simulation from Melbourne Airport solar data**
- Average energy yield: 6092 kWh per annum

**Total Cost PV and Storage**
- $22,660

**Specific PV yield**
- 1324 kWh per kw

**PV/battery performance loss per annum**
- 0.5%

### Cost and Benefit Analysis

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<tbody>
<tr>
<td>Energy Generation</td>
<td>6092</td>
<td>6062</td>
<td>6031</td>
<td>6001</td>
<td>5971</td>
<td>5941</td>
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<td>5708</td>
<td>5679</td>
<td>5651</td>
<td>5623</td>
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<td>Cost $22,660</td>
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<tr>
<td>Total $22,660</td>
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</table>

### Benefit - Export
- $136
- $135
- $135
- $134
- $133
- $133
- $132
- $131
- $131
- $130
- $129
- $129
- $128
- $127
- $127
- $126
- $125
- $125
- $124

### Benefit - Self consumption
- $1,025
- $1,051
- $1,077
- $1,104
- $1,132
- $1,160
- $1,189
- $1,219
- $1,249
- $1,281
- $1,313
- $1,345
- $1,379
- $1,414
- $1,449
- $1,485
- $1,522
- $1,559
- $1,596

### Cashflow
- $-21,499
- $1,186
- $1,212
- $1,238
- $1,265
- $1,293
- $1,321
- $1,350
- $1,380
- $1,411
- $1,474
- $1,507
- $1,541
- $1,576
- $1,611
- $1,648
- $1,685
- $1,724
- $1,763

### Net Present Cost
- $9,456

### LCOE
- $0.42 per kWh incl. storage
- $0.11 per kWh PV cost only

### Household size

<table>
<thead>
<tr>
<th>Household size</th>
<th>NPC</th>
</tr>
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<tbody>
<tr>
<td>base case 2 pers hh</td>
<td>$9,456</td>
</tr>
<tr>
<td>% of homes 2011 census</td>
<td>27.5%</td>
</tr>
</tbody>
</table>

| 1 | $2,363 |
| 2 | $4,976 |
| 3 | $8,584 |
| 4 | $14,097 |

| 5 | $23,407 | 80.0% | $1,244 |

<table>
<thead>
<tr>
<th>Type</th>
<th>Cost per kWh incl. storage</th>
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</thead>
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<td>PV</td>
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<tr>
<td>Storage</td>
<td>$1.06</td>
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<tr>
<td>Total</td>
<td>$2.76</td>
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<tr>
<td>Weighted average NPC per hh</td>
<td>$9,456</td>
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<tr>
<td>2</td>
<td>$3,442</td>
</tr>
<tr>
<td>3</td>
<td>$1,239</td>
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<tr>
<td>4</td>
<td>$1,244</td>
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<tr>
<td>5</td>
<td>$1,305</td>
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### Supporting Financial Model Assumptions

<table>
<thead>
<tr>
<th>Financial Model Input</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household size (persons)</td>
<td>User defined, 1 to 5 persons</td>
</tr>
<tr>
<td>Power consumption</td>
<td>ACIL Tasman Bill Benchmarking Study</td>
</tr>
<tr>
<td>PV array size (kW peak)</td>
<td>PVSYST analysis based on critical multi-day TFB loads and solar radiation</td>
</tr>
<tr>
<td>PV yield - lifetime</td>
<td>Long term analysis of TMY by PVSYST&lt;br&gt;Output reduced to account for battery charging losses based on 30 min simulation of 2014 load and weather&lt;sup&gt;24&lt;/sup&gt;</td>
</tr>
<tr>
<td>PV grid export</td>
<td>30 minute energy balance model run for 2104</td>
</tr>
<tr>
<td>Storage Capacity</td>
<td>Energy balance analysis run for critical fire danger period</td>
</tr>
<tr>
<td>PV CAPEX ($ per Watt)</td>
<td>Australian PV Price Index for Victoria (&lt;a href=&quot;https://www.solarchoice.net.au&quot;&gt;www.solarchoice.net.au&lt;/a&gt;) for Q2 2015</td>
</tr>
<tr>
<td>Storage CAPEX ($ per Watt Hour)</td>
<td>SolarCity pricing&lt;sup&gt;25&lt;/sup&gt; for Tesla Powerwall, consistent with LG Chem RESU 6.4 kWh battery priced in August 2015</td>
</tr>
<tr>
<td>Discount rate</td>
<td>Long term bond rate, Australia</td>
</tr>
<tr>
<td>Solar Feed-in tariff</td>
<td>Regulated rate by Essential Services Commission Victoria</td>
</tr>
<tr>
<td>Electricity tariff</td>
<td>Average from survey of standing offers on Powercor network in rural Victoria</td>
</tr>
<tr>
<td>Escalation of retail tariff</td>
<td>Assumption of 3%</td>
</tr>
<tr>
<td>Degradation of PV/ energy storage&lt;sup&gt;26&lt;/sup&gt;</td>
<td>Assumption 0.5% from published literature&lt;sup&gt;27&lt;/sup&gt;&lt;br&gt;&lt;a href=&quot;http://www.nrel.gov/docs/fy12osti/51664.pdf&quot;&gt;<a href="http://www.nrel.gov/docs/fy12osti/51664.pdf">http://www.nrel.gov/docs/fy12osti/51664.pdf</a>&lt;/a&gt;</td>
</tr>
</tbody>
</table>

<sup>24</sup> Actual cycling losses will depend on the charging algorithm.


<sup>26</sup> Degradation of energy storage capacity will have a limited effect on the NPC model as it influences export rates rather than energy generation. It may impact the efficacy of backup supply on TFBs. The model assumes battery replacement at year 10 which would limit the impact of any degradation.

<sup>27</sup> NREL’s study reports a median of 0.29% per annum for monocrystalline panels installed after 2000.
Appendix 7 – Proposed Business Model to Deploy PV/storage Solution for Bushfire Risk Mitigation

[Diagram showing the proposed business model with details on payments and benefits flow for each stakeholder group]