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Quantifying the Economic Impact of Supply Voltage Magnitude on Consumers

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Abstract: Increasing penetration of distributed energy resources is manifesting as voltage regulation challenges in many LV networks. Appropriate regulation of supply voltage magnitude is essential to ensure efficacy and efficiency in the operation of electricity supply networks and consumer equipment. While the theoretical impacts of supply voltage magnitude on the performance of consumer equipment, which include additional energy consumption and decreased equipment lifespan as voltage magnitude increases, are relatively well known, this has not been translated into quantitative impacts. This paper applies the outcomes of previous impact of supply voltage magnitude studies by the authors, in conjunction with domestic load models, to develop algorithms to estimate the quantitative impacts of supply voltage magnitude on consumers. The paper then applies these algorithms to calculate quantitative economic impacts that can be associated with the magnitude of the supply voltage. The outcomes of this research suggest that the per-annum impact of supply voltage magnitude on consumer equipment loss of life is potentially an order of magnitude greater than the resultant increased energy consumption based on case studies using Australian data.

Keywords: voltage; economic impact; power quality; supply voltage magnitude

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1. Introduction

Magnitude of the supply voltage is the most fundamental power quality (PQ) parameter and perhaps the most overlooked in terms of assessment of impact. For optimal performance, voltage magnitudes must be maintained within a range suitable for the operation and resilience of equipment. Voltage magnitudes that are too low (undervoltage) or too high (overvoltage) may result in equipment not operating as intended, a reduction in equipment lifespan, or—in extreme cases—catastrophic failure. While there are many qualitative sources, e.g., [1,2], that describe the impact of supply voltage on consumer appliances, there is no comprehensive body of literature that provides a quantitative assessment of the impact of sustained steady-state voltage magnitudes on consumers. This may be due to voltage levels historically being kept close to the nominal voltage in many jurisdictions or because few extensive measurement campaigns have been undertaken in LV networks. However, in recent times, voltage regulation and the magnitude of supply voltage in LV networks have received particular attention due to the widespread installation of smart revenue meters and the proliferation of rooftop solar photovoltaic (PV) generators. Rooftop solar PV generators can lead to increases in LV voltage magnitudes, also known as 'voltage rise' [3,4]. In addition, due to connection requirements and for their own protection, solar PV inverters will generally disconnect from the network if the sustained voltage magnitude rises above a threshold. While disconnection of solar PV inverters is a highly visible consequence of voltage magnitude excursions (through alerts to owners), studies have shown that the actual economic impact from loss of solar PV generation is likely marginal for the average consumer [5]. However, the studies have not taken into account the cost of additional energy consumption when local generation has been curtailed. In all likelihood, the greater impact on consumers of sustained overvoltage manifests as the following:

(i) Increased electricity bills due to increased energy consumption;
(ii) Increased carbon emissions resulting from (i) given a significant portion of electricity generation is still dependent on fossil fuels (not considered in this study);
(iii) Accelerated aging and associated loss of life in consumer appliances; and
(iv) Accelerated aging and associated loss of life in electrical infrastructure (not considered in this study).

As detailed in (i) and (iii) above, in broad terms, the cost impacts on consumers related to supply voltage magnitude manifest through two mechanisms: costs related to additional energy consumption—which may be termed *direct costs*—and costs related to loss of lifespan—which may be termed *indirect costs*. Sustained supply voltages above the rated value will still have an impact even if the supply voltage magnitude remains within the allowable limit, as most equipment is designed to operate at the highest efficiency at the rated voltage, and the design (rated) lifespan is at the rated voltage.

This study focuses on supply voltage magnitudes in networks that have a nominal voltage of 230 V and uses the Australian National Electricity Market (NEM) as an example. Accordingly, for all calculations, the rated voltage for consumer appliances is 230 V. While the Australian 230 V LV network is used as an example, the data collection and analysis methodology presented in this study can be easily translated to different networks and nominal voltage configurations.

The subsections below provide a summary of the state-of-the-art with respect to the impact of supply voltage magnitude on both equipment energy consumption and equipment loss of life.

1.1. Impact of Supply Voltage Magnitude on Energy Consumption

There is a considerable volume of literature that evaluates the relationship between supply voltage magnitude and the electrical performance of consumer equipment. The concept of ZIP models, where devices can be categorized as either constant impedance (Z), constant current (I), or constant power (P), provides an indication of the likely behavior of equipment when supplied at any given supply voltage magnitude. The study presented in [6] investigates the impact of supply voltage variation on overall power consumption and energy cost for a domestic residence. The study examined the performance of more than 20 typical domestic appliances to investigate the impact of supply voltage magnitude on appliance power and energy consumption. One of the limitations of the study is its age. Undertaken in 2004, the study states that between 60 and 80% of domestic energy use may be considered to be resistive loads. Appliance design and performance have changed significantly over the past 15+ years, and the majority of modern devices are now much more likely to be electronics-based, i.e., supplied by switch mode power supplies (SMPS). The study also utilized an unregulated voltage source and low-precision measuring instrumentation, thus limiting the accuracy of results. The analysis presented in [7] is a more up-to-date study of the impact of supply voltage magnitude on domestic appliances. The study primarily investigates the impact of supply voltage on appliance energy consumption and functionality. The voltage range evaluated was 195.5 V–264.5 V. The study presented in [8] also examines the impact of variable supply voltage magnitudes on consumer loads. The study investigates the performance of equipment categorized into illumination, power electronics, and electrical drives with a total of 17 devices subjected to supply voltage magnitudes in the range 207 V–253 V. The study is mainly concerned with the calculation of ZIP coefficients as opposed to assessment of the impact of supply voltage variation on equipment performance, in particular, as it pertains to the operation of electricity networks. The studies presented in [9,10] provide a comprehensive and up-to-date evaluation of the relationship between supply voltage magnitude and active power and energy consumption for modern consumer appliances but do not extend to quantifying economic impacts.

The concept of conservation voltage reduction (CVR), which states that reduction in equipment active power and potentially energy consumption can be achieved through reduction in voltage levels, has been in existence for more than 30 years [11]. There is considerable evidence [12,13] that indicates that a reduction in supply voltage magnitudes will result in reduced electricity demand and, hence, reduced energy bills for customers. Both [9,10] provide CVR factors for modern consumer equipment. While the relationship between supply voltage magnitude and consumer equipment is relatively well understood, no comprehensive quantitative model that translates these understandings to calculate the direct and indirect cost impacts on consumers due to supply voltage magnitude has been described.

1.2. Impact of Supply Voltage Magnitude on Appliance Lifespan

1.2.1. Short Term Overvoltage

There are several studies that evaluate the impact of short-term overvoltages of various magnitudes on equipment life. These studies extend to destructive testing of equipment. The studies presented in [14,15] outline the results of laboratory testing of common household appliances under varying short-term overvoltage conditions. In the case of [14], 62 appliances were evaluated. These appliances included devices such as DVD players, personal computers (PCs), printers, televisions, and lighting. The appliances were exposed to voltage magnitudes between 230 V + 12% (258 V) and 230 V + 40% (322 V) for durations ranging between 100 ms and 100 s. These voltage levels exceed the Australian allowable range of 253 V + 10%, and the worst-case test of 230 V + 40% (322 V) for 100 s far exceeds voltage magnitudes likely to be present in LV networks during normal operation. The study presented in [15] expands on the work in [14]. In this case, 60 common household electrical appliances were tested at even higher voltages for longer durations, up to 230 V + 74% (400 V) for up to 30 min. Once again, these voltage magnitudes exceed likely sustained operating conditions.

The results of [14,15] indicate that most household electrical appliances have good immunity, i.e., do not fail immediately or catastrophically, when exposed to overvoltages up to approximately 25% above the 230 V nominal voltage. As voltage magnitude increases above this level, more and more devices begin to fail. When devices are subject to 400 V, it becomes likely that they will fail. The study presented in [16] describes under- and overvoltage testing of consumer electronic equipment. As this study was conducted more than 30 years ago, it includes devices and internal device power supply techniques that are no longer widely deployed. The CBEMA curve, referenced to a North American 110 V nominal voltage, is used as the basis for determining test points. Overvoltage tests were performed at the following magnitudes and durations:

- 135 V (nominal + 12%) for 1000 cycles (60 Hz).
- 146 V (nominal + 22%) for 0.5, 1, 6, 30, and 120 cycles (60 Hz).

The outcome of the testing was that none of the devices tested showed any immediate adverse impact for the applied voltage levels. The study presented in [17] also subjects residential electrical equipment to short-term overvoltage testing. The testing was somewhat focused on assessing the performance of Metal Oxide Varistors (MOVs). In the case of this study, the devices tested included surge-protected power boards, PCs, programmable logic controllers (PLCs), and incandescent lighting. The results of the testing showed that no devices failed for the long-term overvoltage test.

While the aforementioned studies provide a good understanding of the immunity of equipment to catastrophic failure due to relatively short-term overvoltages, they do not investigate the longer-term impacts that sustained operation at the upper end of the allowable voltage range or sustained overvoltage may have on accelerated aging of the devices tested. The literature investigating accelerated aging due to sustained overvoltage is presented in the following sub-section.

1.2.2. Sustained Overvoltage

While short-term, high-magnitude overvoltage can have immediate, catastrophic effects on equipment, such as instantaneous failure of components, there is a clear distinction to be made between the relative effects of short-term, high-magnitude overvoltage (which may also be considered as transient phenomena) and sustained overvoltage, where the voltage magnitude is approaching or marginally above the upper limit of the nominal voltage range for extended periods of time. As such, the outcomes studies examining impacts of short-term high-magnitude voltages are not directly applicable in determining the impact on equipment of sustained supply voltage magnitudes in the range likely to be observed in electricity supply networks for extended periods. For the purposes of this review, sustained voltage magnitudes are those that persist for many hours and may be due to improper voltage regulation or voltage rise caused by renewable energy systems. In general, these voltage magnitudes would not be expected to exceed 1.15 per unit (or 264.5 V based on 230 V nominal voltage). A relatively small volume of literature has been identified that examine the impact of supply voltage, contained within likely sustained voltage magnitudes, on the performance of a range of specific domestic appliances. This literature is evaluated below.

Incandescent Lighting

Possibly the most obvious example of consumer appliance loss of life related to the operation at voltage magnitudes above the rated value is the premature failure of incandescent lamps. Noting that statutory policies in Australia (and elsewhere in the world) will see this type of load diminish in the future in favor of higher efficiency technologies, large numbers of this lighting technology remain in use. The effect of input voltage magnitude on incandescent lamp lifespan is very well understood, with supply voltage magnitude having a significant impact on both lamp output and lifespan. It has been stated in [18] that the impact of supply voltage magnitude V, near the rated voltage of the lamp, leads to:

- *Light* output that is approximately proportional to $V^{3.4}$.
- *Power* consumption that is approximately proportional to $V^{1.6}$.
- *Lifetime* that is approximately proportional to V^{-16}.
- *Color* temperature that is approximately proportional to $V^{0.42}$.

Applying the above, a 5% reduction in operating voltage will more than double the life of the lamp at the expense of reducing light output by about 16%. Conversely, a 5% increase in operating voltage above the rated value will halve the lifetime of the lamp, albeit with a higher light output as a trade-off. The study presented in [19] provides the following data with respect to supply voltage magnitude on the lifespan of halogen lamps:

- When supplied at 95% of the rated voltage, the lamp will last 168% of the rated lifespan, albeit with a 16% reduction in output.
- At 105% of the rated voltage, lifespan decreases to 62% of rated (output is 117% of rated).
- At 110% of the rated voltage, lifespan decreases to 36% of rated (output is 136% of rated).

Fluorescent Lighting

The data provided in [20] provide some data concerning the impact of supply voltage magnitude on the lifespan of tubular fluorescent lamps. This data is reproduced in Table 1, where it can be seen that supplying the lamp with a voltage magnitude 10% higher than the rated value leads to a 17% reduction in lifespan.

Table 1. Impact of Supply Voltage on Lifespan of Tubular Fluorescent Lamps (reproduced from [20]).

Supply Voltage (% of Rated)	Life (% of Rated)
90	95
95	102
100	100
105	92
110	83

Electronic Loads

The study presented in [21] examines the relationship between supply voltage magnitude and the lifespan of electrolytic capacitors similar to those used in SMPS. The study identified a strong relationship between supply voltage magnitude and capacitor life, with results aligning well with those presented in [22]. The outcomes indicate that a significant reduction in life occurs even if voltage magnitudes are kept within the allowable range. For example, the study identified that the lifespan of a capacitor is decreased by 25% if it is operated continuously at 253 V when compared to operation at 230 V.

The study presented in [23] states that the cost impacts of supplying equipment at voltages above the rated value are related to loss of equipment life. The study assumed that equipment lifespan reduces as the electric field increases, i.e., as supply voltage magnitude increases. This assumption is based on information from Toshiba, which indicates a linear loss of equipment life as supply voltage magnitude increases.

Similar to the case for the impact of supply voltage magnitude on direct consumer costs, while there is literature that can be cited that provides a relationship between supply voltage magnitude and consumer equipment loss of life, no model has been developed that attempts to quantify the cost impacts.

1.3. Purpose of This Paper

While the impacts of supply voltage magnitude on consumers are relatively well understood from a qualitative perspective, there are no comprehensive models or algorithms available to derive quantitative values. This paper addresses this knowledge gap, with the purpose of the paper being to provide algorithms and techniques that can be used to calculate the quantitative economic impacts (costs) to consumers as they relate to the magnitude of the voltage supplied to consumer devices (appliances). This paper is the culmination of research related to the impacts of supply voltage magnitude on consumers. The paper applies the outcomes of the studies presented in [9,21,24,25], which evaluate the relationship between supply voltage magnitude and the electrical performance of consumer appliances in terms of energy consumption and lifespan, to develop algorithms to calculate the economic impacts of supply voltage magnitude on consumers. The paper utilizes a range of readily available inputs, including consumer equipment stock, supply voltage magnitude data, equipment response to supply voltage magnitude, and energy costs. Algorithms have been designed to account for both direct (impact on electricity consumption and bills) and indirect (equipment loss of life) costs. While the algorithms are designed to evaluate costs for residential consumers, similar techniques can be applied to quantify costs for other consumer types, e.g., commercial and industrial or for electricity network supply equipment. The remainder of the paper is organized as follows:

- Section 2 provides a summary of the relevant supply voltage standards in force in Australia.
- Section 3 provides an overview of the values and trends for supply voltage magnitude in Australia.
- Section 4 details the algorithm that has been developed to quantify the direct costs related to the magnitude of the supply voltage.

- Section 5 details the algorithm that has been developed to quantify the indirect costs related to the magnitude of the supply voltage.
- Section 6 provides case studies that demonstrate how the developed algorithms are applied in practice and provide quantification of the costs related to supply voltage magnitude on consumers.
- Section 7 provides a discussion on algorithm refinement.
- Section 8 provides conclusions.

2. Supply Voltage Standards

There are two standards for supply voltage magnitude in LV networks that apply concurrently in Australia: AS IEC 60038-2022 [26] and AS 61000.3.100 [27]. AS 60038 specifies the voltage range that should be used by product developers when designing equipment. AS 60038 was updated from an Australian-specific version, AS 60038-2012 [28], to align with the IEC version in 2022. The principal difference between the two versions is the limit for the lower end of the allowable range. This was 230 V − 6% = 216 V in the 2012 edition, compared to 230 V − 10% = 207 V in the 2022 edition. However, as the change is relatively recent, at the time of writing, it is fair to assume that it has not matriculated into Australian electricity supply networks to any great degree. The limits specified in AS 61000.3.100 no longer align with AS IEC 60038-2022.

AS 61000.3.100 is more akin to a power quality standard and specifies allowable magnitudes as well as the measurement/assessment methodology that should be used to determine compliance. In most jurisdictions, the nominal LV voltage is 230 V, and the allowable magnitudes for voltage range are as follows:

- 99th percentile voltage: 253 V (230 V nominal + 10%).
- 1st percentile voltage: 216 V (230 V nominal − 6%).

In accordance with [29], a further 5% voltage drop is allowed in installation wiring, reducing the lowest allowable voltage to 230 V − 15% V = 195.5 V. When considering the upper end of the allowable range, the Australian Standard for connection of inverter energy systems, AS/NZS 4777.2 [30], along with other service and installation rules, e.g., [31], allows a maximum of 2% voltage rise within an installation. Consequently, the maximum voltage within an installation may reach 230 V + 12% = 258 V. The voltage of 258 V is also the limit for sustained inverter operation prescribed in AS 4777.2.

To summarize, the combination of Australian Standards and other regulations effectively allows a utilization voltage range of 195.5 V–258 V at the terminals of consumer equipment.

3. Trend of Supply Voltage Magnitude

Before attempting to quantify the impact of supply voltage magnitude on consumers, it is illustrative to examine present and historical trends for supply voltage magnitudes in Australia. The study presented in [32] is an analysis of power quality data collected throughout Australian LV networks. Published in 2010, the impact of small-scale solar PV generation on the reported data is likely to be minimal. The study reports that 25–30% of LV sites record 95th percentile steady state voltage magnitudes above the allowable upper voltage magnitude limit (230 V + 10%). Given that the study was published before significant volumes of solar PV generation were connected to LV networks, the high voltage magnitudes cannot be attributed to small-scale solar PV generation. The study presented in [33] also suggests that voltage levels in Australian distribution networks are not well managed in relation to compliance with limits, albeit based on results from only four locations.

Published in 2020, the study presented in [5] presents a more recent analysis of voltage magnitudes in Australian LV networks. The data in this study were sourced from monitoring devices installed as part of small-scale solar PV generation systems. While these devices do not measure voltage using standardized methods (i.e., the methods prescribed in AS 61000.3.100), the data provide an indication of network performance. The study indicated that voltage magnitudes above 253 V are prevalent in all Australian LV networks.

The study presented in [24] evaluates the impact of small-scale solar PV generation on supply voltage magnitudes. The study indicates that there is a trend toward higher voltage magnitudes overall across a day as solar generation is creating a second 'peak' in voltage magnitudes during daylight hours (compared to the pre-solar single peak, which generally occurred during the very early morning where the load was light).

Figure 1 provides an example of field measurements (data collected at 5 min intervals across 1 year) of supply voltage magnitude data. The data were collected from a relatively poor-performing low-voltage site. It can clearly be seen that there are significant periods where the voltage magnitude exceeds the prescribed upper limit of 253 V (as indicated by the dashed red line on the graph) and that there are many instances where the supply voltage magnitude exceeds 270 V.

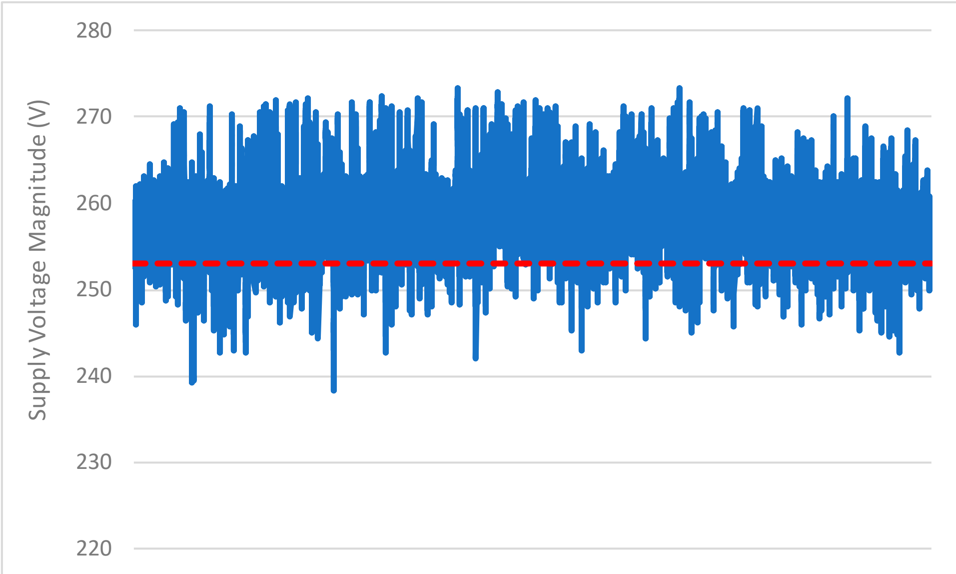

Figure 1. One-Year Trend of 5 min Supply Voltage Magnitude Measurements from an Example LV Site (dashed red line indicates upper limit).

4. Algorithm for Calculation of Direct Costs

This section describes the algorithm that has been developed to calculate the direct costs of supply voltage magnitude on consumers, i.e., those associated with increased energy consumption and, in turn, increased electricity bills. The algorithm is predicated on supply at 230 V being the reference case, i.e., supply at 230 V results in no additional direct costs. The algorithm calculates the additional energy usage on a per-device basis. This information can then be applied on a dwelling-by-dwelling basis, considering the device mix in each dwelling. The input data required for the algorithm are as follows:

- A breakdown of device energy consumption
- The price of electricity
- CVR factors for energy consumption (CVR_E values) for each device
- The number of dwellings

Data for the energy consumption by device type for Australia are available in the Residential Baseline Study (RBS), a study commissioned by the Australian Federal Department of Industry, Science, Energy, and Resources into energy use in the Australian and New Zealand Residential Sectors in 2020 [34]. The RBS contains data for each year from 2000 to 2019, as well as projections out to 2030.

The RBS data separate residential equipment stock as well as energy consumption into seven equipment categories as follows:

- Appliances, further separated into sub-categories:
    - White goods
    - IT&HE (information technology and home entertainment)
    - Other equipment
- Cooking
- Lighting
- Space conditioning
- Water heating
- PV (solar photovoltaic generation)
- Transport (electric vehicles)

Each of the above categories is further divided into constituent device types. For example, the lighting category is divided into the following:

- CFL
- ELV halogen
- LED
- Linear fluorescent
- Medium voltage (MV—in this case, 230 V) halogen
- MV incandescent

Using the device energy consumption data, which is expressed in PJ per annum, and the total number of dwellings, it is possible to calculate the daily energy consumption for each device in each dwelling in kWh using Equation (1) (for the purposes of this study, 1 PJ = 2.778×10^8 kWh).

$$\text{Daily Energy Consumption} = \frac{\text{Annual Energy Consumption}}{365 \times \text{Number of Dwellings}} \times 2.778 \times 10^8 \text{ kWh} \quad (1)$$

Using 230 V as the reference, i.e., consumption at the rated voltage of 230 V is considered to be the '0' point, the additional energy usage at each voltage level for each device is calculated by applying the relevant conservation voltage reduction (CVR_E) factor to calculate the voltage-dependent daily device consumption as follows in Equation (2):

$$\text{Voltage} - \text{Dependent Consumption} = \frac{\Delta V}{230} \times CVR_E \times \text{Daily Energy Consumption} \quad (2)$$

where $\Delta V = \text{supply voltage magnitude (V)} - 230 \text{ V}$

5. Algorithm for Calculation of Indirect Costs

This section describes the algorithms that have been developed to calculate the indirect costs of supply voltage magnitude on consumers, i.e., those associated with equipment loss of life, which is also termed accelerated depreciation. Two algorithms have been developed, one for incandescent lamps and one for electronic equipment. Each algorithm is again predicated on supply at 230 V being the reference case, i.e., supply at 230 V results in no additional costs. The input data required for this algorithm are as follows:

- The total device numbers and the total number of dwellings (to derive the number of each device in each dwelling)
- The rated lifespan of each device
- The purchase price of each device
- A relationship between supply voltage magnitude and device lifespan

Using the above data, the rated depreciation for each device is calculated as follows:

$$\text{Rated Depreciation} = \frac{\text{Number of Devices} \times \text{Purchase Price Per Device}}{\text{Rated Lifespan}} \quad (3)$$

The rated depreciation from (3) can then be compared to a re-rated depreciation (as described in the following sections) based on loss of life calculations. The cost impact is then calculated as:

$$\text{Loss of Life Cost} = \text{Rerated Depreciation} - \text{Rated Depreciation} \quad (4)$$

5.1. Incandescent Lighting Accelerated Depreciation Algorithm

This algorithm calculates the voltage-dependent lifespan for incandescent lighting equipment. The relationship between supply voltage magnitude and incandescent lighting lifespan is relatively well-known and is expressed by Equation (5) from [18]:

$$\text{Voltage} - \text{Dependent Lifespan} = \left(\frac{V_a}{V_d}\right)^{-12\text{ to}-16} \times \text{Rated Lifespan} \quad (5)$$

where

- V_a is the supply voltage magnitude.
- V_d is the design (rated) voltage magnitude (assumed to be 230 V).

For traditional incandescent lamps, the exponent in the above equation is −16, while for halogen lamps, the exponent is −14.

5.2. Electronic Device Accelerated Depreciation Model

For electronic devices, the internal front-end capacitor of the rectifier, or SMPS, is assumed to be the most susceptible component to variations in supply voltage magnitude. Accordingly, the accelerated depreciation model for electronic loads in this study is based on experimental results for electrolytic capacitors published in [21]. The relationship between supply voltage magnitude and accelerated aging of electrolytic capacitors is given by the blue trace in Figure 2.

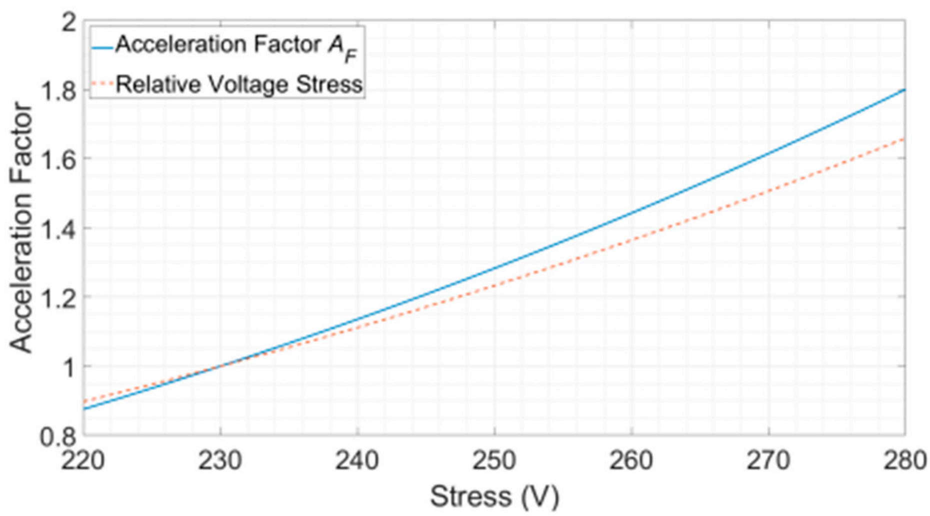

Figure 2. Relationship between Supply Voltage Magnitude and Loss of Life Acceleration Factor [21].

The linearized equation for the blue trace in Figure 2 is given by (6):

$$\text{Acceleration Factor} = 0.0125 \times \text{voltage} - 1.875 \quad (6)$$

Using the above relationship between supply voltage magnitude and acceleration factor, an accelerated depreciation value can be obtained using the same methodology as was applied for incandescent lighting devices.

6. Case Studies

The below case studies are based on data from a single Australian state. All data applied in these case studies are for data for the year 2021. As described above, the number of dwellings is required for all models. Data from the Australian Bureau of Statistics give the number of dwellings in the case study state in 2021 as 3,357,785 [35].

6.1. Direct Costs

6.1.1. Input Data

The direct costs model requires the following input data:

- Annual energy consumption for each device
- CVR_E factors for each device
- The price of electricity (which has been assumed to be USD 0.30/kWh)

The Residential Baseline Study (RBS) data provide annual energy consumption data for each device [34]. CVR_E factors have been adapted from the data given in [9]. Based on these inputs, the data that were used for the case studies are shown in Table 2.

Table 2. Energy Consumption and CVR_E Factors for Direct Cost Model (adapted from [9,34]).

Device	Annual Energy Consumption (PJ)	Daily Consumption (at 230 V) (kWh)	*CVRE*
Clothes dryers	0.45	0.10	2.55
Clothes washers	1.29	0.29	1.38
Dishwashers	1.18	0.27	0.00 [1]
Freezers	1.67	0.38	0.21
Refrigerators [2]			
Inverter (30%)	2.16	0.49	0.00
Motor (70%)	5.04	1.14	0.21
Computers—desktop	0.25	0.06	0.10
Computers—laptop	0.21	0.05	2.40
Game consoles	0.42	0.09	0.00
Home entertainment—other (mostly audio equipment)	0.27	0.06	0.04
Miscellaneous IT equipment	0.26	0.06	0.00
Monitors (used with desktop computers)	0.22	0.05	0.00
Set-top box—free-to-air	0.00	0.00	0.04
Set-top box—subscription	0.26	0.06	0.04
Television—composite average	3.26	0.74	0.01
Video players and media recorders	0.13	0.03	0.04
Wireless/Wired networked device	1.97	0.45	0.00
Battery chargers	0.74	0.17	0.00
Class 2 Common Areas [3]	2.09	0.47	0.00
Miscellaneous [2]			
Motor (20%)	1.01	0.23	2.26
Electronic (80%)	4.05	0.92	0.01

Table 2. *Cont.*

Device	Annual Energy Consumption (PJ)	Daily Consumption (at 230 V) (kWh)	*CVRE*
Pool Equipment—Elec	2.99	0.68	0.00
Pumps	0.38	0.09	0.31
Cooktops (Electric)	0.97	0.22	0.00
Microwave	1.21	0.27	2.52
Ovens	1.22	0.28	0.00
Uprights	1.62	0.37	0.00
CFL	0.65	0.15	0.99
ELV halogen	0.75	0.17	2.40
LED	0.76	0.17	−0.04
Linear fluorescent	0.82	0.19	3.82
MV halogen	1.07	0.24	2.40
MV incandescent	0.67	0.15	2.40
AC ducted	3.97	0.90	−0.06
AC non-ducted (split and WW)	4.72	1.07	−0.06
Electric resistive	4.26	0.96	0.00
Evaporative (mostly central)	0.36	0.08	0.35
Fans	0.17	0.04	1.65
Electric water heater—Med/Large	11.99	2.72	0.00
Electric water heater—Small	1.31	0.30	0.00
Heat pump	0.17	0.04	0.00
Solar electric water heater	0.48	0.11	0.00

[1] No CVR_E value was available for dishwashers. As such, it has been set to 0. [2] Some devices may fall into more than one classification for applicable CVR_E values. For example, refrigerators may be either inverter type (an electronic load) or direct-on-line motor type (a motor load). The RBS data do not provide a breakdown of the number of devices that fall into different categories. As such, assumptions for the percentages of devices in each classification have been made. The devices for which assumptions were required were refrigerators and the miscellaneous category of other equipment under appliances. [3] Class 2 Common Areas equipment consists of devices such as hot water heating, space conditioning, and lighting. To simplify the model, a CVR_E factor of 0 has been applied. Given the strong relationship that exists between lighting and supply voltage magnitude, the outcome of this action is that the model likely underestimates additional energy consumption.

6.1.2. Single Device

This example illustrates how the additional energy usage for MV halogen lamps is calculated. From Table 2, MV halogen lamps accounted for 1.07 PJ of energy consumption. Given the 3,357,785 dwellings in the state, utilizing Equation (1), the daily consumption per dwelling (in kWh) for MV halogen lamps is as follows:

$$\text{Daily energy consumption} = \frac{1.07 \times 2.778 \times 10^8}{365 \times 3,357,785} = 0.24 \text{ kWh} \quad (7)$$

The above value is considered to be the value consumed at 230 V and is the ‘zero’ point for further calculations. The CVR_E for MV halogen lighting is 2.4. Using these values, the additional daily energy consumption per volt increase in supply voltage is calculated using (2) as follows:

$$\text{Additional daily energy consumption} = \frac{1}{230} \times 0.24 \times 2.4 = 0.0025 \text{ kWh} \quad (8)$$

The additional energy consumption per annum for each 1 V increase can be calculated by multiplying this value by 365, i.e.,

$$\text{Additional annual energy consumption} = 365 \times 0.0025 = 0.91 \text{ kWh/year} \tag{9}$$

Assuming an electricity cost of AUD 0.30/kWh, the cost of additional energy per annum for each volt increase above the reference 230 V is as follows:

$$\text{Additional annual energy } \cos t = 0.91 \times 0.30 = \text{AUD } 0.28 \tag{10}$$

If the device is supplied at 250 V, the additional energy usage each day is calculated as follows:

$$\text{Additional daily energy consumption @ 250 V} = \frac{20}{230} \times 0.24 \times 2.4 = 0.05 \text{ kWh} \tag{11}$$

The additional energy consumption per annum is as follows:

$$\text{Additional annual energy consumption} = 365 \times 0.05 = 18.28 \text{ kWh/year} \tag{12}$$

The cost of additional energy per annum is:

$$\text{Additional annual energy } \cos t = 18.28 \times 0.3 = \text{AUD } 5.48 \tag{13}$$

Using the above calculations, the relationship between supply voltage magnitude and additional energy costs for MV halogen lamps is shown in Figure 3.

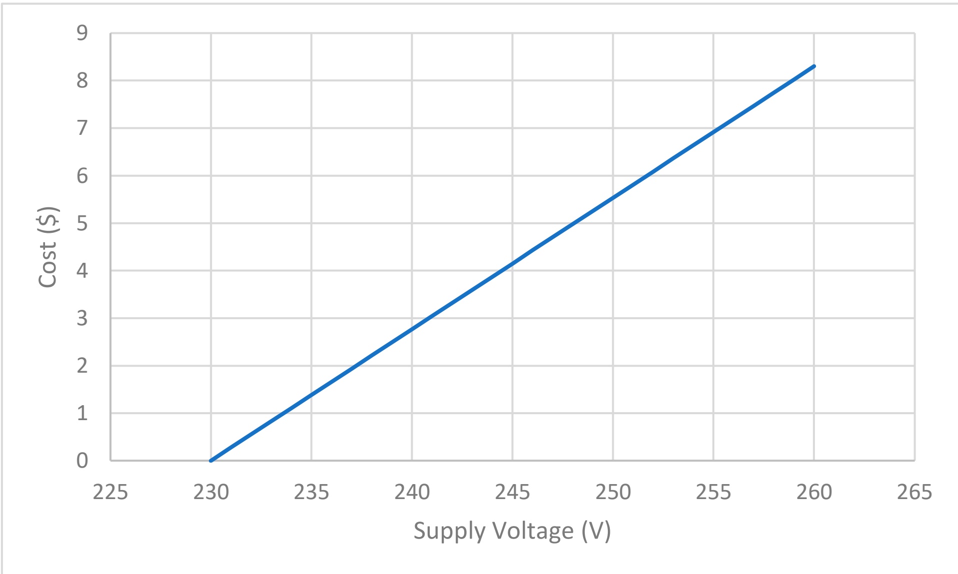

Figure 3. Relationship between Supply Voltage Magnitude and Additional Energy Consumption Cost for an MV Halogen Lamp.

The approach described in Equations (7)–(13) can be applied to all of the appliances shown in Table 2 in order to calculate the additional energy consumption and, in turn, the additional costs for each item of consumer equipment. Figure 4 provides additional examples of the outcomes of these calculations for a range of appliance types. The figure demonstrates the variation in additional energy consumption and, hence, cost across various appliance types. In the case of the hot water heater, while these devices have a large CVR for active power, the CVR for energy is zero as a finite quantum of energy is required to heat the water regardless of the magnitude of the supply voltage. In the case of the television, this device has constant power and, as such, constant energy. The linear fluorescent lamp has the highest CVR_E, resulting in a significant increase in energy consumption and cost per annum. In the case of the LED lamp, the negative value of CVR_E for this device means that energy consumption and cost decrease as the supply voltage magnitude increases.

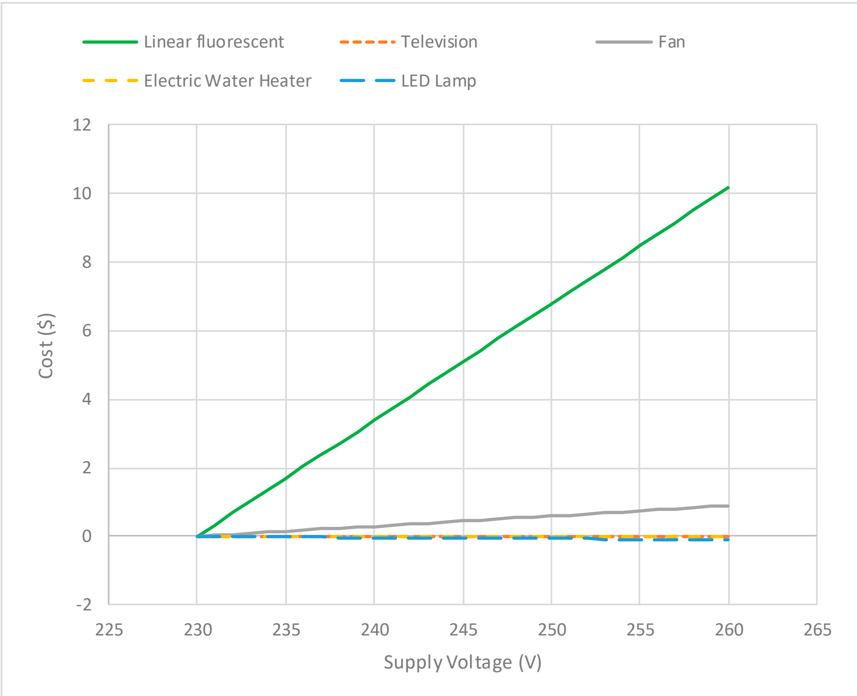

Figure 4. Relationship between Supply Voltage Magnitude and Additional Energy Consumption Cost for Linear Fluorescent Lamps, Television, Fan, Electric Hot Water Heater, and LED Lamp.

6.1.3. Single Dwelling Total

The data shown in Table 2 have been applied to calculate the additional energy costs for a single dwelling by summating the additional energy costs for all devices. The outcomes of this calculation are shown in Figures 5 and 6, which show the percentage change in energy consumption and annual additional energy costs based on supply voltage magnitude, respectively.

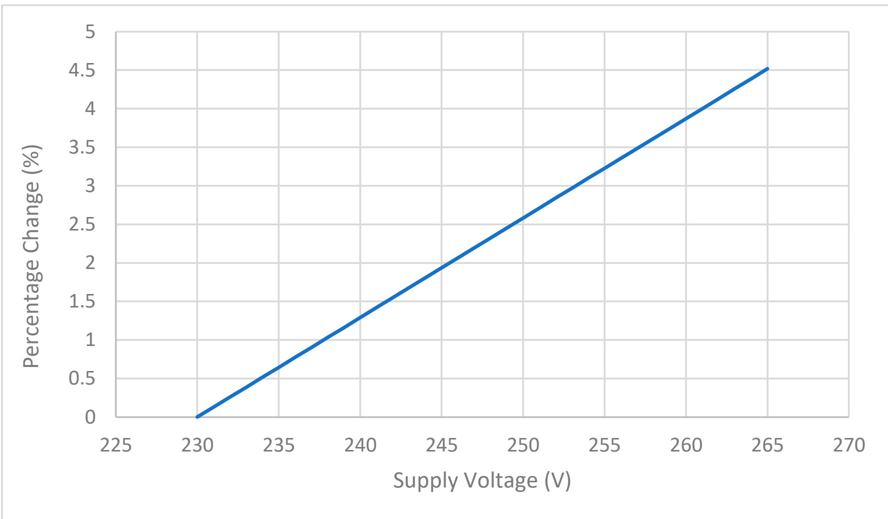

Figure 5. Single Dwelling Percentage Change in Energy Consumption based on Supply Voltage Magnitude.

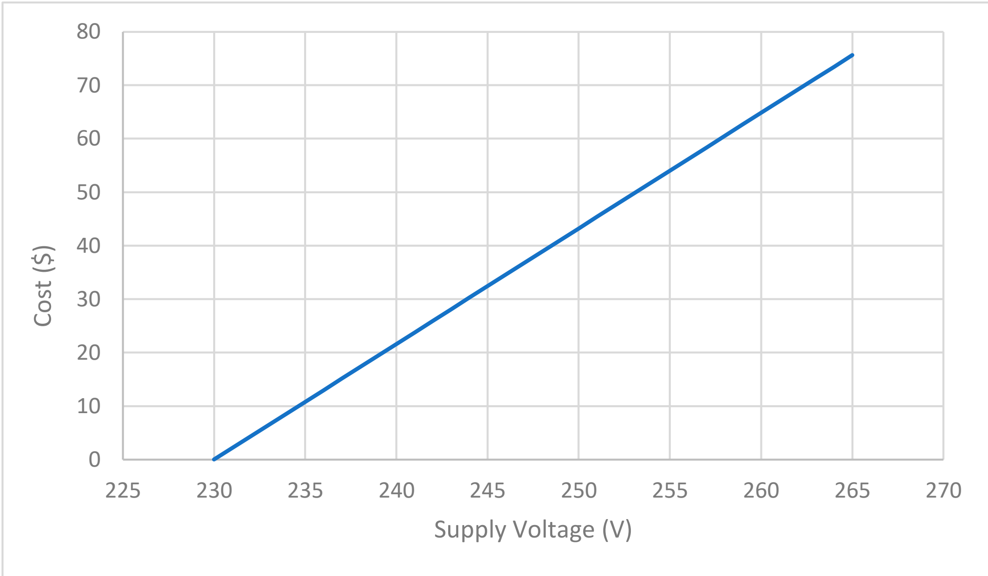

Figure 6. Single Dwelling Additional Energy Cost based on Supply Voltage Magnitude.

6.2. Indirect Costs

The below case studies are again based on data from an Australian state. All data applied in these case studies are for 2021. The indirect costs algorithm requires the following input data:

- The number of dwellings
- The number of each device in each dwelling
- The purchase price for each device
- The rated lifespan of each device

6.2.1. Incandescent Lighting Model

Table 3 provides the input data for the incandescent lighting loss of life model. The rated lifespan is based on manufacturer data. The purchase price is an estimate.

Table 3. Input Data for Incandescent Lighting Model (including data from [34]).

Device	Total Stock	Number per Dwelling	Purchase Price (AUD)	Rated Lifespan (Hours)
ELV halogen	10,644,387	3.2	2	2000
MV halogen	11,284,094	3.4	2	2000
MV incandescent	5,730,302	1.7	2	1000

Single Device

This example calculates the accelerated depreciation costs for MV halogen lamps. The 2021 RBS data, as shown in Table 3, indicate that there are 11,284,094 MV halogen lamps in the case study state. This equates to:

$$\frac{11,284,094}{3,357,785} = 3.4 \text{ lamps per dwelling} \tag{14}$$

The purchase price of each lamp is assumed to be AUD 2.00. The rated lifespan of the lamp is 2000 h. Assuming that the lamp is used for 15% of the day or 3.6 h per day, the lamp is used for 1314 h per annum. As such, the rated life of the lamp is 1.52 years.

Rated depreciation cost per annum can be calculated using Equation (3). For MV halogen lamps, this gives:

$$\text{Rated Depreciation} = \frac{3.4 \times 2}{1.52} = \text{AUD 4.47 per annum} \tag{15}$$

Using the relationship between supply voltage and lamp life and assuming a supply voltage of 245 V, the rerated lamp lifespan using Equation (5) is as follows:

$$\text{Re} - \text{rated Lifespan} = \left(\frac{245}{230}\right)^{-16} \times 1.52 = 0.63 \text{ years} \tag{16}$$

The re-rated depreciation (measure of accelerated depreciation) is as follows:

$$\text{Re} - \text{rated Depreciation} = \frac{3.4 \times 2}{0.63} = \text{AUD 10.79 per annum} \tag{17}$$

Thus, the additional cost per annum is AUD 10.79 − AUD 4.47 = AUD 6.32 per annum ongoing for each dwelling.

Figure 7 shows the outcome when Equations (14)–(17) are applied to all of the incandescent lighting types shown in Table 3 across all considered supply voltage magnitudes.

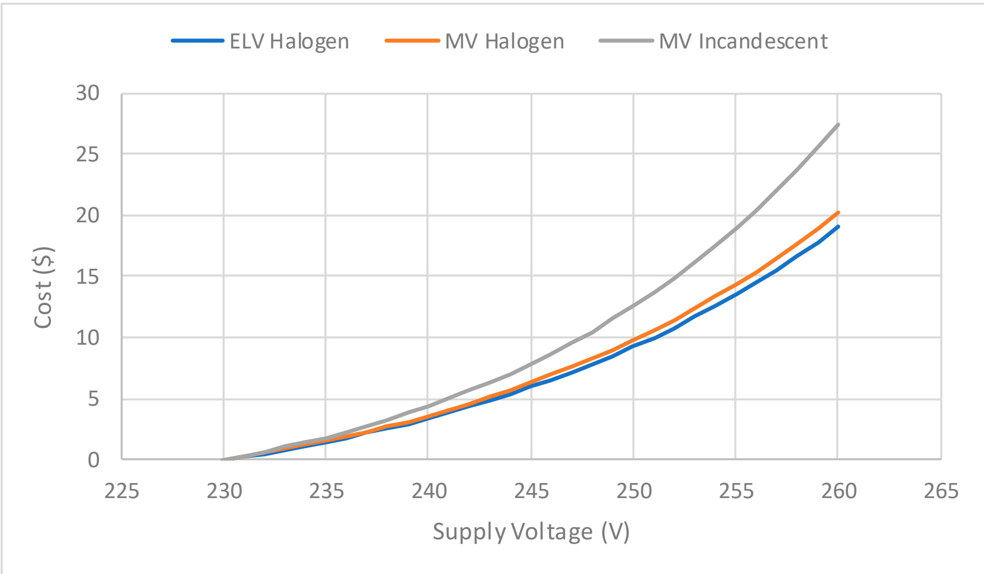

Figure 7. Additional Cost Due to Loss of Life for Incandescent Lighting Technologies.

Single Dwelling Total

The overall costs for a single dwelling for any given supply voltage magnitude are calculated by applying Equations (14)–(17) to all incandescent lighting types shown in Table 3 individually and then summing the outputs, i.e., summing the curves shown in Figure 7. The outcome of this calculation is shown in Figure 8.

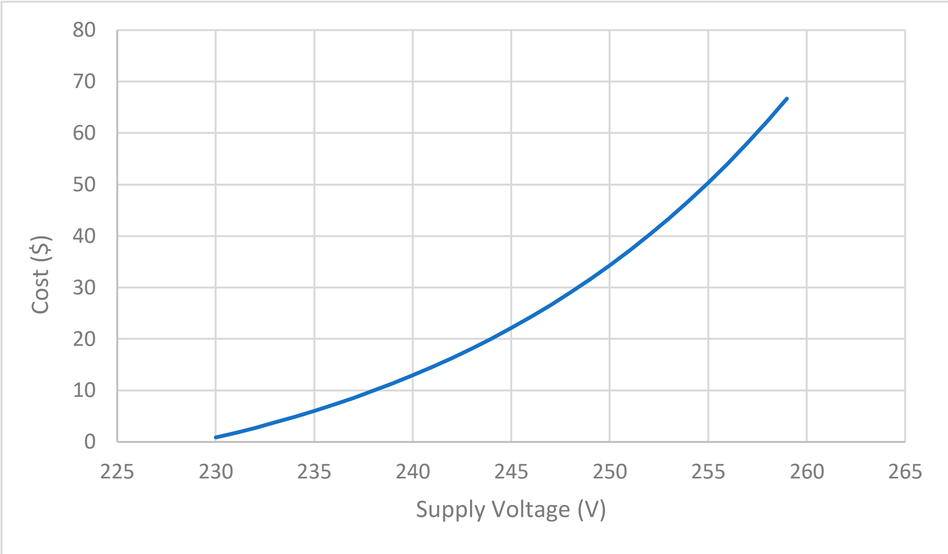

Figure 8. Single Dwelling Additional Cost Due to Loss of Life for Incandescent Lighting.

6.2.2. Electronic Load Model

Table 4 provides the input data for the electronic load loss of life model. Rated lifespan and purchase price are estimates based on a combination of warranty periods and times to obsolescence (e.g., for computers, while the device may last longer than the estimated 3 years, the replacement cycle is generally this value). As this model is for electronic equipment, any device not considered to be electronic has been omitted from the model. In the case of devices, which may be either electronic (inverter) or motor type loads, e.g., refrigerators, assumptions have been made with respect to the percentage of appliance stock that falls into each classification. The assumptions that have been made (as reflected in Table 2) are as follows:

- Freezers—30% of total stock is electronic.
- Refrigerators—30% of total stock is electronic.
- Miscellaneous equipment—80% of total stock is electronic.

Table 4. Input Data for Electronic Load Model (including data from [34]).

Device	Total Stock	Number per Dwelling	Purchase Price (AUD)	Rated Lifespan (Years)	Rated Depreciation (USD/Year)
Freezers	380,188	0.1	1000	10	11.32
Refrigerators	1,479,724	0.4	2000	10	88.14
Computers—desktop	1,122,436	0.3	1000	3	111.43
Computers—laptop	2,991,138	0.9	1000	3	296.94
Game consoles	1,691,757	0.5	500	5	50.38
Home entertainment—other (mostly audio equipment)	2,717,251	0.8	500	10	40.46
Miscellaneous IT equipment	3,316,632	1.0	200	3	65.85
Monitors (used with desktop computers)	1,525,177	0.5	250	5	22.71
Set-top box—free-to-air	24,219	0.0	100	5	0.14
Set-top box—subscription	753,861	0.2	100	5	4.49
Television—composite average	5,360,195	1.6	1000	5	319.27
Video players and media recorders	2,499,609	0.7	100	5	14.89
Wireless/Wired networked device	6,298,240	1.9	100	5	37.51
Battery chargers	24,762,470	7.4	20	5	29.50
Miscellaneous	42,600,086	12.7	50	5	126.87
Microwave	3,261,333	1.0	300	10	29.14

Table 4. *Cont.*

Device	Total Stock	Number per Dwelling	Purchase Price (AUD)	Rated Lifespan (Years)	Rated Depreciation (USD/Year)
CFL	29,692,826	8.8	5	7.6	5.82
LED	73,629,002	21.9	10	38	5.77
AC ducted	615,433	0.2	10,000	20	91.64
AC non-ducted (split and WW)	274,7634	0.8	2000	10	163.66
Heat pump	56,198	0.0	2000	10	3.35
Generation	752,982	0.2	1000	10	22.42

All air conditioning has been assumed to be inverter-type. For generation devices, costs have been calculated for the inverter.

Single Device

This example shows the calculation for determining the costs associated with accelerated depreciation for televisions. The 2021 RBS data indicates that there are 5,360,195 televisions in the case study state. Given that there are 3,357,785 dwellings in the case study state, this equates to:

$$\frac{5,360,195}{3,357,785} = 1.6 \text{ televisions per dwelling} \quad (18)$$

Assuming that the purchase price of each television is AUD 1000 (based on a review of pricing) and the rated lifespan is 5 years, the rated depreciation can be calculated using (3). For televisions

$$\text{Rated Depreciation} = \frac{1.6 \times 1000}{5} = \text{AUD 320 per annum} \quad (19)$$

Assuming that the televisions are supplied at 245 V. The acceleration factor is as follows:

$$\text{Acceleration Factor} = 0.0125 \times 245 - 1.875 = 1.19 \quad (20)$$

The accelerated depreciation is then:

$$1.19 \times \text{AUD } 320 = \text{AUD } 381 \quad (21)$$

Thus, the additional cost per annum is:

$$\text{Additional annual Cost} = \text{Accelerated Depreciation} - \text{Rated Depreciation} = \text{AUD } 381 - \text{AUD } 320 = \text{AUD } 61 \quad (22)$$

As an example of the outcome when Equations (14)–(17) are applied across all considered supply voltage magnitudes, Figure 9 shows the calculated values for several devices selected from Table 4.

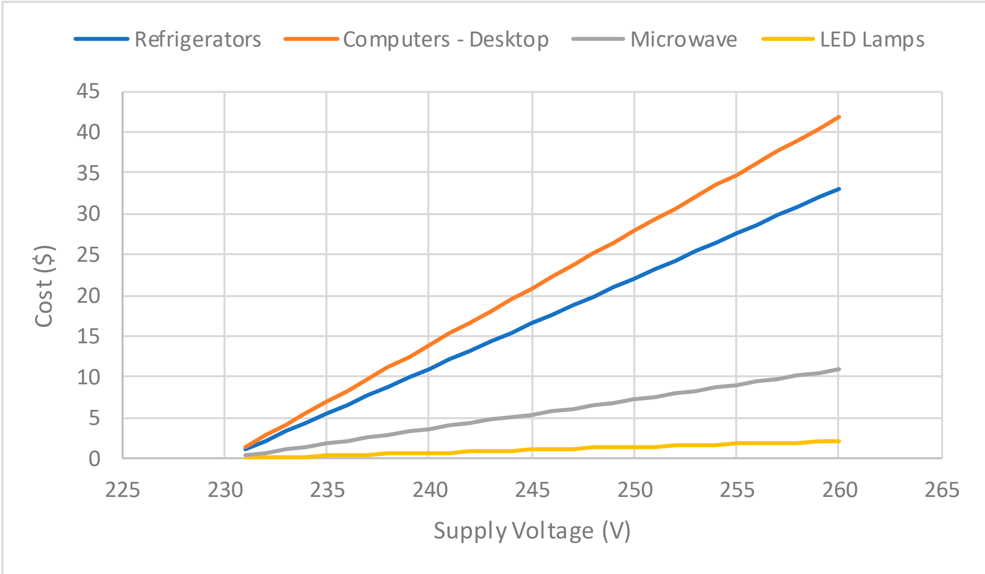

Figure 9. Example—Additional Cost due to Loss of Life for Selected Electronic Devices.

Single Dwelling Total

The overall costs for a single dwelling are calculated by applying Equations (18)–(22) to all of the electronic devices shown in Table 4 individually for each supply voltage magnitude and then summing the outputs. The outcome of this calculation is shown in Figure 10.

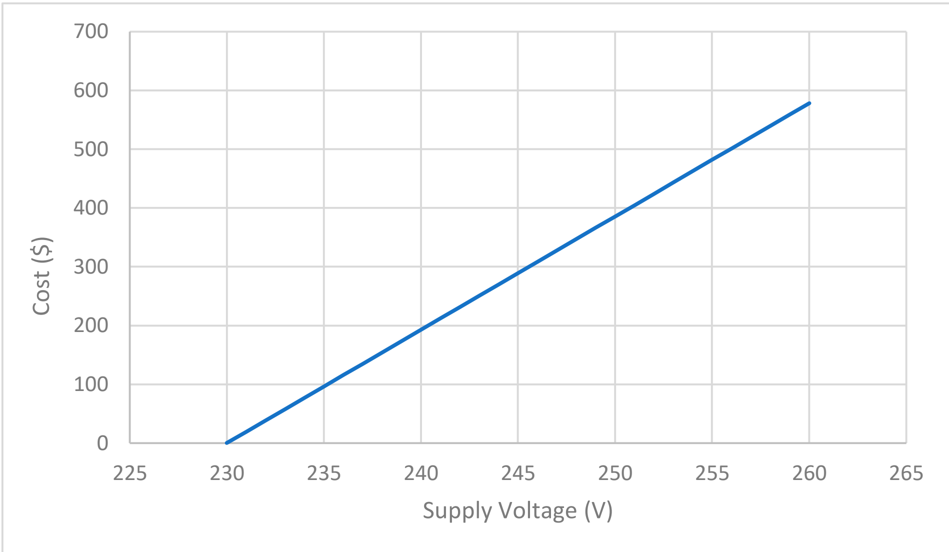

Figure 10. Single Dwelling Additional Cost Due to Loss of Life for Electronic Loads.

6.3. Single Dwelling Total Costs (Direct and Indirect)

The overall total economic impact of supply voltage magnitude on a single dwelling can be derived by summing the costs produced by each algorithm. Figure 11 shows the outcome of this calculation for a single dwelling for a fixed supply voltage magnitude. It can be seen that the economic impacts are dominated by the loss of life for electronic equipment in spite of the fact that both curtailments of DER and increased energy bills are likely to be much more visible to consumers.

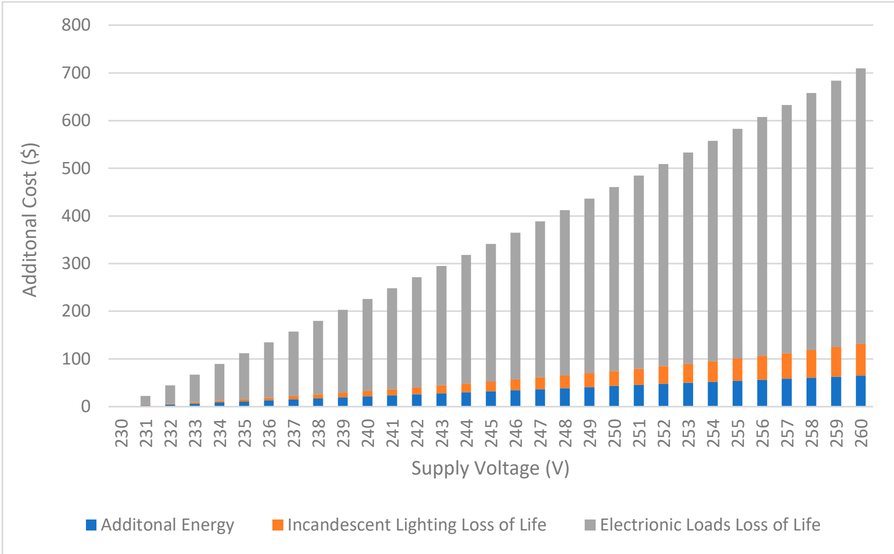

Figure 11. Total Additional Costs per Dwelling Based on Supply Voltage Magnitude.

7. Algorithm Refinement

It is noted that one of the limitations of the additional energy consumption algorithm is that it assumes both supply at a constant voltage magnitude and consistent energy consumption across the day, both of which will not be the case in practice. In practice, it is likely that maximum consumption will correlate with reduced voltage magnitude (due to voltage drop under heavy load). As such, the unrefined algorithm may overestimate impacts. These limitations can be overcome if measured voltage data are available (likely given the increasing penetration of smart metering devices) as well as periodic energy consumption data by appliance type (which may be more difficult to achieve). However, this approach adds considerable complexity and data requirements to the algorithm.

A further limitation of the work presented in this paper is that it does not consider loss of life for equipment that is of the motor type due to the fact that a well-accepted relationship between supply voltage magnitude and loss of life in motors is not available. As such, the loss of life algorithm may underestimate the overall impacts due to the omission of the impacts on motor-type loads.

8. Conclusions

This paper proposes algorithms that can be used to quantify the economic impact of supply voltage magnitude on consumers. These algorithms utilize recent studies that evaluate the impact of supply voltage magnitude on consumer equipment energy consumption and lifespan. The novelty of this paper is that it applies relationships between supply voltage magnitude and appliance energy consumption and lifespan to address an identified lack of literature with respect to the determination of the quantitative as opposed to qualitative impacts of sustained steady-state voltage magnitudes on consumers in terms of real costs. Two algorithms are proposed; one calculates direct costs due to increased energy consumption, while the other calculates indirect costs due to decreased equipment lifespan for incandescent lighting and electronics. Both the direct and indirect costs are borne by consumers. The proposed algorithms are relatively simple to apply, provided that data related to appliance stock and the relationship between appliance energy consumption.

Based on a case study using Australian data, the outcomes of the study suggest that the impact of supply voltage magnitude on increased energy consumption across the range of devices that constitute a domestic load is in the tens of dollars per annum, while the impact on consumer equipment loss of life-based on assessment of incandescent lighting and electronic devices is potentially in the hundreds of dollars per annum. It is noteworthy that the economic impacts are dominated by the loss of life for electronic equipment, although both curtailment of DER and increased energy bills are likely to be much more visible to consumers. While it is not possible to operate electricity supply networks such that the rated voltage is seen at all dwellings, the case study indicates that there are significant benefits that may accrue to consumers through better management of supply voltage magnitudes.

While this paper utilizes a supply voltage magnitude of 230 V as the reference for all calculations, it should be recognized that it is not practicable to supply all consumers at the nominal voltage. It must also be recognized that DNSPs are operating networks that may have been built many years ago and may have significant legacy challenges. In addition, present regulation in Australia does not include a framework that allows for the estimation of the consumer impact of supply voltage magnitude on consumers (beyond value estimates related to DER capacity). As such, DNSPs remain financially constrained with regard to the level of investment that they can make in better management of supply voltage magnitude. While this paper provides an assessment of the cost impacts of supply voltage magnitude on domestic (residential consumers), similar techniques can be applied to other load types, such as commercial and industrial, provided that the relationships between supply voltage magnitude and energy consumption and device lifespan are known or can be derived.

Author Contributions: S.E. was responsible for the development and implementation of the research methodology. He was also responsible for drafting the manuscript. J.C.K. was responsible for drafting and verification of the manuscript along with research conceptualization. G.D. assisted with data analysis and verification. T.L. assisted with the conceptualization of the research as well as the drafting and verification of the manuscript. D.A.R. was responsible for overall project supervision as well as review and editing. All authors have read and agreed to the published version of the manuscript.

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