Master's Thesis

Assessing the Impact of Temporal Tariffs on Reshaping Household Prosumage: A Techno-Economic Modelling Approach

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Abstract

The operation of the electricity grid is changing due to simultaneous renewable energy integration occurring at the utility- and household-scales. Time-varying electricity tariffs provide an opportunity to mitigate the negative impacts from high solar photovoltaic (PV) penetration. They encourage households with a rooftop solar PV-system and a battery energy storage system (BESS) to strategically manage their electricity imports and exports in a grid-friendly manner.

In this work, a techno-economic optimisation model is used to evaluate the impact that flat and temporal tariff structures have on (i) rational household investment decisions in rooftop PV and/or BESS, as well as (ii) system operation in Australia and Germany. In both case studies, household behaviour is subjected to a temporal import and flat export tariff, as well as a temporal import and export tariff, and contrasted against a flat import and export tariff. For Case Study 1, a sensitivity analysis is performed, investigating the impact of electricity price developments (1.1) and BESS pricing (1.2) on rational investment decisions. In Case Study 2, system operation under different tariff structures is investigated for the installation of an average-sized PV-BESS.

The results of Case Study 1.1 reveal that an investment in BESS generally remains unprofitable for households during the financial horizon of 10 years, making a lower cost for batteries a prerequisite for an economically viable investment. When the BESS price is reduced in Case Study 1.2, the investment in PV-BESS becomes profitable for some households. However, system dimensions under temporal tariffs are generally optimised to respond to price signals of the import tariff, increasing self-consumption and reducing grid demand during peak price periods as much as possible. For increased system sizes, as investigated in Case Study 2, temporal export tariffs are able to incentivise households to reduce their daytime feed-in from PV generation and encourage evening feed-in from battery discharge. Furthermore, a minimum price spread is identified in the electricity tariff in order to trigger changes in system operation from households.

Overall, this work highlights the need for appropriate BESS pricing to fully leverage the potential of the interaction between tariff structures and household responses, and its potential to offer complementary system operation strategies.

Zusammenfassung

Durch die gleichzeitige Integration erneuerbarer Energien auf der Energieversorger- und der Haushaltsebene verändert sich die Betriebsweise des Stromnetzes. Zeitvariable Stromtarife bieten die Möglichkeit, die negativen Auswirkungen des starken Ausbaus der Photovoltaik (PV) abzumildern. Sie schaffen einen finanziellen Anreiz für Haushalte mit einer PV-Aufdachanlage und einem Batteriespeichersystem (BESS), ihre Stromimporte und -exporte gezielt und netzfreundlich zu steuern.

In dieser Arbeit wird ein techno-ökonomisches Optimierungsmodell verwendet, um die Auswirkungen von zeitinvarianten und zeitvariablen Tarifstrukturen auf (i) rationale Investitionsentscheidungen von Haushalten in PV und/oder BESS sowie (ii) deren Systembetrieb in Australien und Deutschland zu bewerten. In beiden Fallstudien wird das Verhalten der Haushalte mit einem zeitinvarianten Import- und Exporttarif, einem zeitvariablen Import- und einem zeitinvarianten Exporttarif, sowie einem zeitvariablen Import- und Exporttarif untersucht. Für Fallstudie 1 wird eine Sensitivitätsanalyse durchgeführt, in der die Auswirkungen der Strompreisentwicklung (1.1) und der BESS-Preise (1.2) auf wirtschaftlich rationale Investitionsentscheidungen betrachtet werden. In Fallstudie 2 wird der Einfluss verschiedener Tarifstrukturen auf den Systembetrieb eines durchschnittlich dimensionierten PV-BESS untersucht.

Die Ergebnisse der Fallstudie 1.1 zeigen, dass eine Investition in BESS für Haushalte während des Modellierungszeitraums von 10 Jahren in der Regel unrentabel bleibt, sodass niedrigere Batteriepreise Voraussetzung für eine wirtschaftlich rentable Investition sind. Wenn der BESS-Preis in Fallstudie 1.2 gesenkt wird, ist eine Investition in PV-BESS für einige Haushalte profitabel. Allerdings werden die Systemgrößen bei zeitvariablen Tarifen im Allgemeinen so optimiert, dass der Eigenverbrauch erhöht und die Netznachfrage während der Spitzenpreiszeiten möglichst reduziert wird. Für größere PV-BESS, wie sie in Fallstudie 2 untersucht werden, wird auch der Einfluss zeitariabler Exporttarife deutlich. Diese schaffen Anreize für Haushalte ihre PV-Einspeisung tagsüber zu reduzieren und die abendliche Einspeisung durch Batterieentladung zu fördern. Darüber hinaus wurde eine Mindestpreidifferenz im Stromtarif ermittelt, um Änderungen im Systembetrieb der Haushalte auszulösen.

Insgesamt unterstreicht die vorliegende Arbeit die Notwendigkeit einer angemessenen Preisgestaltung für Batteriesysteme, um das Potenzial, das Wechselwirkungen zwischen Tarifstrukturen und Systembetrieb für netzdienliche Betriebsstrategien bieten, voll ausschöpfen zu können.

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Nomenclature

Formula Symbols and Unit

Symbol	Meaning	Unit
B	Binary Variable	—
C_{Export}	Price of Exported Electricity	\$/kWh or €/kWh
C_{Import}	Price of Imported Electricity	\$/kWh or €/kWh
C_{new}	Cost of annual Electricity Bill after Optimisation	\$/a or €/a
C_{ref}	Reference Cost of annual Electricity Bill	\$/a or €/a
E	Electrical Flow	kWh
g	Solar Generation per kWp	kWh/kWp
P	Power	kW
r	Discount Rate	%
SOC	State of Charge	kWh
SOH	State of Health	kWh
T	Annual Time Steps	—
UC	Upfront Cost	\$ or €
Y	Financial Horizon	Years

Greek Formula Symbols

Symbol	Meaning	Unit
Δt	Time Step	sec
η_{charge}	Charging Efficiency	%
$\eta_{discharge}$	Discharging Efficiency	%

Indexes and Abbreviations

Symbol	Meaning
AEMO	Australian Energy Market Operator
ACT	Australian Capital Territory
ADRES	Autonome Dezentrale Erneuerbare Energie Systeme (Autonomous Decentralised Renewable Energy Systems)
BRT	Block Rate Tariff
BESS	Battery Energy Storage System
Cal.	Calendar
Cap.	Capacity
CGE	Computational General Equilibrium
C4NET	Centre for New Energy Technologies
Cyc.	Cyclic
DSO	Distribution System Operator
DER	Distributed Energy Resource
EEX	European Energy Exchange
EOL	End of Life
exo	Exogenous
FI-FE	Flat Import and Flat Export
GHG	Greenhouse Gas
HTW	Hochschule für Technik und Wirtschaft Berlin (Berlin University of Applied Sciences)
IRR	Internal Rate of Return
IZES	Institut für ZukunftsEnergieSysteme (Institute for Future Energy Systems)
LIB	Lithium-Ion Battery
MILP	Mixed-Integer Linear Programming
NEM	National Energy Market (Australia)
NREL	National Renewable Energy Laboratory
NSW	New South Wales
NT	Northern Territory
NPV	Net Present Value
OTC	Over-The-Counter
PV	Photovoltaic
PV-BESS	Photovoltaic and Battery Energy Storage System

Continued on the next page

Indexes and Abbreviations

Symbol	**Meaning**
QLD	Queensland
RE	Renewable Energy
ROI	Return on Investment
SA	South Australia
SoC	State of Charge
SoH	State of Health
TAS	Tasmania
TNSP	Transmission Network System Operator
TSO	Transmission System Operator
TI-FE	Temporal Import and Flat Export
TI-TE	Temporal Import and Temporal Export
TRY	Test Reference Year
VIC	Victoria
WA	Western Australia

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1 Introduction

In the context of climate change mitigation and the central role that emissions from the energy system play, transitions toward sustainable energy sources are realised around the globe, presenting both opportunities and challenges to system operation. However, the adoption of renewable energy is not limited to large-scale systems but is also taking place at the small-scale household level. In particular, rooftop solar photovoltaic (PV) and battery energy storage system (BESS) adoption is on the rise, as households aspire to reduce their expenses for electricity consumption, while increasing their independence from the grid and sustainability. Two countries that have amongst the highest PV penetration per capita are Australia and Germany [1]. However, their remarkable expansion of renewable energy sources also comes with issues concerning grid stability and efficient resource allocation that need to be addressed.

As the penetration of rooftop solar PV systems across all residential properties has exceeded 25 % in Australia, daytime grid feed-in levels have led the country to experience the "duck curve" [2, 3]. This phenomenon is characterised by a falling operational demand and wholesale prices during the midday, followed by a high demand and prices in the afternoon. As new minimum operational demand records are established each year, while peak demand during the evening remains persistently high, concerns about system security are being raised [4]. Although the duck curve phenomenon is not as pronounced in Germany as in Australia, the increasing incorporation of PV generation capacities also profoundly impacts electricity wholesale prices and the minimum net load experienced [1] [5, 6]. Potential problems associated with the strong expansion of solar PV in both countries include issues such as negative wholesale prices, grid instabilities, and curtailment challenges, as well as steep ramp-rates for conventional power generators, when solar generation decreases rapidly [3, 7]. Given the expectation of a continued surge in solar capacity expansion in the context of the energy transition and net-zero aspirations, these trends are likely to intensify.

Due to the challenges system operators and planners face, policy makers are developing mechanisms to moderate the interaction of behind-the-meter distributed energy resources (DER) with the power system. Technical methods include (dynamically) limiting grid feed-in, whereas the introduction of time-variable electricity tariffs provides economic incentives to mitigate negative effects on the grid. The new time-of-use tariff structures incorporate

[1] Difference between electricity demand and the power generated from renewable energy sources

off-peak pricing during midday and peak pricing after noon for grid imports, as well as time-of-export pricing that disincentivises grid feed-in during the midday [8, 9].

However, households that have only installed a PV system cannot store electricity generated in excess of their own consumption, resulting in any surplus being exported during the day. Once self-generation falls below consumption, electricity is imported from the grid again. Under the novel time-varying electricity import and export tariffs, these households are - if they do not make profound behavioural changes - likely to receive less revenue from daytime grid exports, while being exposed to high electricity costs in the afternoon and evening. Nevertheless, an emerging class of customers is opting for both PV and BESS, empowering them not only to generate and consume but also to utilise their energy storage to adapt the timing when they import and export electricity from and to the grid. Without requiring any behavioural changes, these households are therefore able to take advantage of their PV-BESS to minimise exposure to high import charges and shift their grid export to times of higher remuneration. This presents policymakers with the opportunity to design time-varying tariffs that encourage households with PV-BESS to mitigate the negative effects of solar PV on the grid. To the best of the authors' knowledge, given the relatively novel concept of temporal import and, in particular, of temporal export tariffs, there has been little to no investigation on the effect that temporal tariffs have on household investment decisions in PV-BESS, as well as subsequent system operation behaviour. [10–12]

Therefore, the present work aims to evaluate the impact that time-varying import and export tariffs have on an economically rational household's: (i) investment decision in PV and/or BESS; as well as (ii) system operation. In this context, household behaviour subject to a flat import and flat export tariff (FI-FE), a temporal import and flat export tariff (TI-FE), and a temporal import and temporal export tariff (TI-TE) is investigated.

In the following, Chapter 2 establishes the fundamentals of this work by elaborating the power system first, followed by an investigation of the Australian and German energy systems, a discussion of the principles of techno-economic modelling, and a literature review. In Chapter 3, the methodology is presented, focussing on the deployed techno-economic optimisation model. First, the structure of the model and its boundary conditions are explained along with the input and outcome of the model. In particular, the sensitivity parameters of electricity price development and BESS pricing are discussed for the investigation of rational investment decisions. Second, case studies (i) and (ii), as well as their parameterisation are presented. The results of both case studies for the Australian and German contexts are elaborated and critically discussed in Chapter 4. Finally, Chapter 5 concludes with a summary and discussion of the results, as well as future research possibilities.

2 Fundamentals

In the following sections, the theoretical and empirical foundations of this thesis will be explained. Chapter 2.1 focusses on the technical and economic principles of energy systems and markets. This section includes the basic structure, management and operation of the system, as well as price mechanisms, available trading possibilities, and implications for wholesale and retail markets. Second, Chapter 2.2 investigates the political, geographical, and technical boundary conditions of the Australian and German power systems in depth. In Chapter 2.3 the purpose and basic assumptions of techno-economic modelling are examined. The focus lies on available methodologies, as well as technical and economic fundamentals. Lastly, Chapter 2.4 examines the current state of literature, considering techno-economic modelling, the assessment of tariff structure impacts, and research gaps in those fields.

2.1 The Power System - Technical and Economic Principles

In order to assess the impact of temporal tariffs on reshaping household prosumage, the principles of energy markets need to be investigated. In the first step, the technical design and operation of the power grids are examined, including the structure of the grid, ancillary services, and power generation. Second, electricity markets are evaluated, analysing the different trading options, pricing mechanisms, and characteristics of the wholesale and retail market. Since this work investigates the Australian and the German contexts, this section focusses on fundamentals that are applicable for those countries but not necessarily transferable to other regions.

2.1.1 Design and Operation of Power Grids

Grid Design

As electricity is a network-bound product, its distribution inevitably requires an extensive grid infrastructure. However, due to the transmission of electricity being subject to ohmic losses that increase for lower voltage levels (given constant power and ohmic resistance), the grid is divided into several voltage levels. In the German and Australian grid, for example, the highest voltage levels (Germany: 380 kV/ 220 kV resp. Australia: 132 kV to 500 kV) are used for the transmission over long distances and the exchange of electricity between neighbouring countries or states, as well as for the connection of large power plants (e.g., coal or offshore wind) and very large industrial consumers to the grid. The high voltage level (110 kV resp. 132 kV/ 66 kV/ 33 kV) is mainly used for the interregional transport of electricity, with medium-sized power plants (e.g., wind farms) feeding in power and industrial consumers, rail-systems, or regional power utilities consuming power. Small power generators (e.g., combined heat and power plants) feed into the medium voltage level (20 kV resp. 22 kV/ 11 kV), which provides small industrial and agricultural consumers with electricity regionally. The lowest voltage level (both: 400 V/ 230 V) is used by households, commerce, or electromobility. Small generation units (e.g. rooftop photovoltaic) also feed into the grid at this voltage level. [13]

Historically, electricity transmission was performed only from high to low voltage levels. Due to the expansion of decentralised power generation, bidirectional power transmission is occurring increasingly. However, this change, as well as the increase in the connection of electric vehicles and heat pumps in private households, causes additional stress for low-voltage grids. Although the number of voltage levels and their magnitude may differ between different countries, the basic principle holds for most electricity systems. [13, 14]

Grid Operation

Concerning the responsibility for the secure operation of the grid, a distinction is made between transmission system operators (TSOs) and distribution system operators (DSOs). The specific division of the voltage levels for which each network operator is responsible varies from country to country. In any case, there is a need for close cooperation between grid operators on the same voltage level and between the different voltage levels. Each network operator is accountable to ensure the smooth system operation of its area. This responsibility includes providing adequate network security, carrying out maintenance, repair, and modernisation work, as well as handling power transmission, restoring the supply, and removing faults after an incident. [13]

Although the TSO in Germany coordinates electrical flows that occur when the network infrastructure is used by generators and end customers to transport electricity, this is already part of the security constrained economic dispatch in Australia. Quantities of energy transferred are balanced to ensure an equilibrium between the energy actually fed into the grid and the energy withdrawn from the grid. The power inflows of the market participants come from their own generation or from purchases on the electricity market. Outflows occur due to sales on the electricity market and forecasted delivery to end customers. [13]

In order to provide reliable and fault-free system operation, the grid operator makes use of several system services. In Germany, this job is performed by TSOs, while in Australia this is the responsibility of the Australian Energy Market Operator (AEMO). Due to the need for a stable frequency in the grid and only limited storage capacity of electrical energy, a constant balance between electricity generation and consumption is an important prerequisite for reliable grid operation. This is due to the fact that excess generation causes the frequency to increase, whereas lack causes it to drop. A fundamental system service for a secure grid operation is therefore reactive power control for frequency control measures. Depending on response time and available capacity, reactive power control is subdivided into primary, secondary, and minute/ tertiary reserve. In particular, the continuous expansion of volatile renewable energy sources and the avoidance of their curtailment make the principle of balanced generation and consumption increasingly difficult. To mitigate negative effects, several countermeasures are available. Pooling describes for example the possibility for a joint participation of small consumers and producers to reach the minimum market participation size and supply-security, whereas a reduction of the time period between auction and start of reserve provision enables renewable generators to take part in the reactive power control market more easily. Other grid services deployed by grid operators include congestion management, purchase of loss energy, reactive power for voltage control, and provision of black start capabilities. [13, 15]

2.1.2 Electricity Markets

Wholesale Electricity Markets

In Australia and Germany, there are two primary options for trading in electricity wholesale markets: trading on an energy exchange market and over-the-counter (OTC) trading. A schematic overview of the wholesale electricity market structure is shown in Figure 2.1. [16, 17]

In energy exchange markets, on the one hand, market participants can place asking or bidding orders that are matched through the trading platform. On the other hand, OTC-trading occurs between two market participants, which generally allows more customisation and longer time horizons in their agreements. [13, 16]

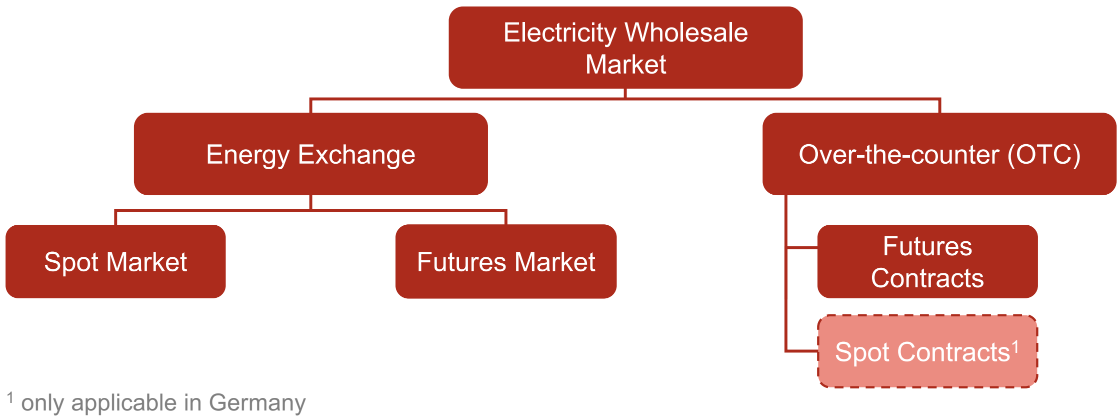

Figure 2.1: Schematic Structure of the Electricity Wholesale Market [16, 17]

Energy exchange markets are subdivided into futures and spot markets. Futures markets include medium- and long-term purchases or sales of electricity volumes. By trading future output at a certain price, participants in the forwards market protect themselves against price changes, which is also referred to as hedging. Furthermore, options (“caps” in Australia) can be negotiated that provide participants with the right, but not the obligation, to buy or sell electricity at a predetermined (capped) price and within a specified time frame in the future. On the spot market, electricity volumes for short-term use are purchased, enabling market participants to physically balance surplus quantities or shortfalls. These markets generally match supply and demand according to the merit order principle. This order is established by ranking the available power plants in ascending order of their ask bids, with the cheapest sources being dispatched first. The market operator also aggregates the demand bids into a descending demand curve, with the highest bids being realised first. The clearing price which is received by all generators and paid by all consumers is set at the intersection of the supply and demand curve. Therefore, high power generation and minor demand generally lead to a lower clearing price, whereas high demand and low generation capacities indicate higher wholesale electricity prices. This price is also an important indicator for trades that are not performed on exchange markets but over-the-counter. Auctions in the EPEX Spot, the largest European Spot Market, enable purchases for the following day in hourly and 15-minute intervals. After the auction of the intraday-market has passed, continuous trading, where bidding- and asking-orders are matched, is possible until 30 minutes before physical delivery. However, in the National Energy Market (NEM), the largest Australian energy market, electricity is dispatched every five minutes. [13, 16–19]

In addition to the exchange markets, *OTC-trading* enables buyers and sellers to enter into direct contracts with each other. Since there is no central authority as a contracting party, buyers and sellers are able to draught their own contracts, so that a greater variety of products can be traded than on the stock exchange. Brokers are often used to support contracting parties in their search for trading partners. In the German electricity system, OTC-trading includes spot contracts with a short time horizon as well as long-term contracts, whereas Australian agreements outside of the energy exchange only include long-term contracts. As with futures contracts on the spot market, long-term contracts in OTC-trading are used as a form of insurance against spiking spot prices. In this way, retailers can provide customers with fixed prices through long-term contracts, while also ensuring their profitability. [13, 16–18]

Retail Electricity Market

The retail electricity tariff sets the basis for the billing of end-consumer electricity consumption and is generally fixed over a longer period of time (for example, one year). As exemplified in Figure 2.2 for Australia and Germany, its magnitude and composition varies from country to country. Elements that are usually included are the price the retailer pays for electricity generation (wholesale price) and the network costs. As with all commodities, electricity is subject to many outer influences, causing fluctuations and changes in its price composition and magnitude over time. [13]

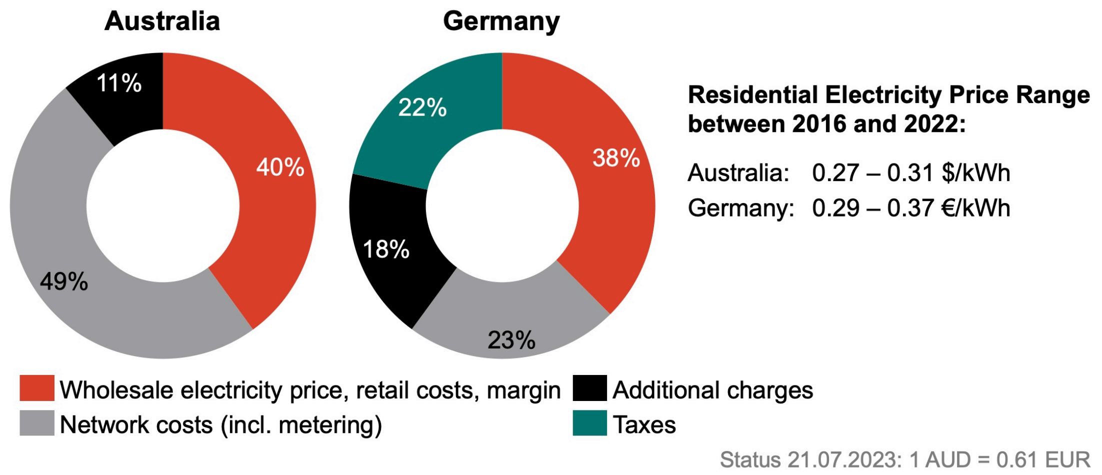

Figure 2.2: Average Composition of the Australian and German Electricity Retail Price in 2022 [20, 21]

In Australia, most of the average retail electricity price is made up of network costs (49 %) as well as the wholesale electricity price (28 %), retail costs (10 %) and the retail margin (2 %). Additional charges in Australia include environmental costs (10 %) that are caused by the expansion of renewable energy on the small and large scale. Additionally, it should be mentioned that Australia does not tax either the primary energy sources used for electricity production or electricity consumption itself [22]. [21]

The average German retail electricity price includes the same components with the addition of taxes. The wholesale electricity price (26 %) in combination with retail costs and the margin (12 %) represents the largest share, followed by network costs (23 %). The component taxes (22 %) can be subdivided further into the electricity tax (6 %) and the value-added tax (16 %). Additional charges (18 %) include a concession fee (5 %), an EEG-charge (10 %, abolished 01/01/2023) as well as several small charges. [20, 23] As more residential customers embrace rooftop photovoltaic (PV) installations, they transition to becoming 'prosumers', both consuming and generating electricity. The excess power is fed into the grid and is remunerated with a feed-in tariff. In Germany, the feed-in tariff is regulated through the government and depends on factors such as commissioning time, the chosen operation mode, or the size of the PV system. According to EEG-remuneration, a PV system commissioned at the beginning of 2023 and smaller than 10 kWp will receive 0.082 €/kWh for excess feed-in. This remuneration is guaranteed for 20 years. In Australia, the payment for solar feed-in depends on the type of solar system installed, the (minimum) amount that state/ territory government has set, and whether the retailer adds more to what the government has fixed. Although feed-in tariffs in Germany are flat, there are flat and time-dependent rates available in many regions of Australia [24]. [25, 26]

The structure, how electricity retailers decide to charge their customers changes from retailer to retailer and might be subject to various factors, like the existence of an energy meter or regulations imposed by the government for example. For residential customers, the final electricity price is usually a combination of a supply charge, meaning a fixed amount charged per time period and the usage charge, namely the price per kilowatt hour consumed. Currently, mainly tariff structures that only consider the amount of electricity consumed are applied to residential customers. However, due to the roll-out of smart meters that enable high metering granularity, the introduction of time-dependent tariffs is increasingly enabled. [27]

One of the simplest electricity import tariffs offered to residential customers is the *flat tariff*, which charges the same price per kilowatt hour regardless of the time and amount consumed. *Block rate tariffs* (BRT) charge a certain price until a predefined amount of electricity has been consumed. This tariff is also independent of the consumer's daily consumption pattern. As depicted in Figure 2.3 the price per kilowatt hour can either increase or decrease per block. The number of blocks and the consumption threshold are subject to the retailer and the tariff chosen. [27]

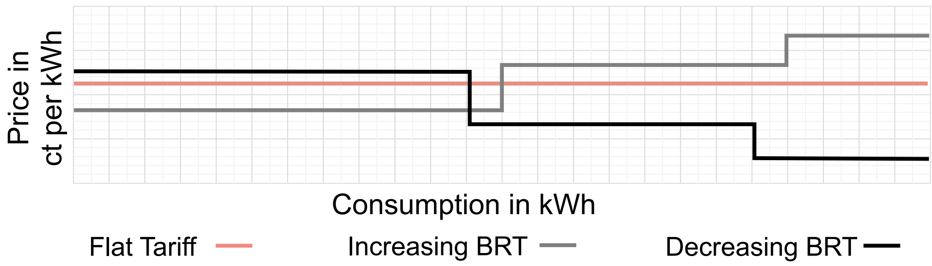

Figure 2.3: Schematic Structure of Flat, as well as Increasing and Decreasing Block Rate Tariffs (BRT) [27]

Temporal import tariffs (or time-of-use tariffs) also include several consumption rates. However, these rates are not subject to the amount but to the daytime that electricity is consumed. As exemplified in Figure 2.4, higher rates, called peak prices, are charged for time periods when there is a large demand in the electricity grid (e.g., late afternoon), while lower off peak charges apply when the grid generally experiences low usage (e.g., at night). In some cases, shoulder tariffs, which are set between peak- and off-peak times, are additionally introduced. The price for peak periods is generally higher for temporal than for flat tariffs, whereas off-peak rates are lower. Shoulder tariffs are less expensive than peak price but more expensive than off-peak pricing. [27, 28]

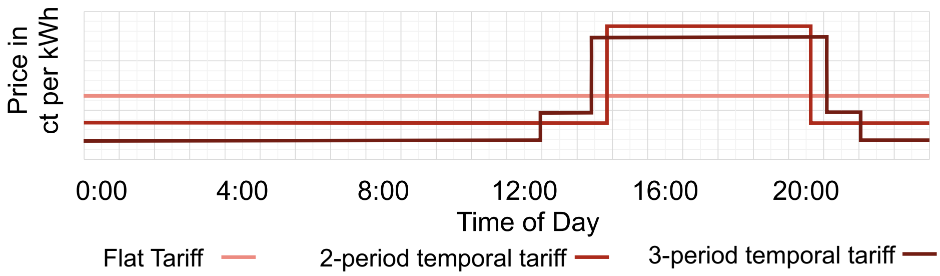

Figure 2.4: Schematic Structure of Flat, as well as 2- and 3-Period Temporal Tariffs [27]

Another tariff option available in most states of Australia is the *controlled load tariff*, which enables customers to nominate appliances that are metered separately and only charged during off-peak hours. These appliances, for example, hot water systems or pool pumps, receive a lower usage rate while the rest of the property is billed on one of the previously described tariffs. [29]

Relatively new to the residential market and not widely applied yet are *demand tariffs* and *dynamic electricity tariffs*. Demand tariffs charge electricity usage, as well as an additional fee for the highest occurring power demand (kW) in a specified time period. Dynamic electricity tariffs are subject to faster price changes over time, with the aim of reflecting at least a portion of fluctuations in wholesale prices. [27, 30]

Similarly to the previously described electricity import tariffs, electricity export tariffs can also be subdivided into flat and time-dependent tariffs. *Flat export tariffs* remunerate a prosumer's electricity feed-in with the same price per kilowatt hour throughout the day, while *temporal export tariffs* include several price levels. As the reasoning behind temporal export tariffs usually is to incentivise a decreased electricity feed-in for times with high power generation and low demand, remuneration is generally lower during the midday. Analogously, increasing electricity export is desired for times with high demand and less generation capacity, generally leading to a higher feed-in price in the afternoon and at night. As with temporal import tariffs, shoulder tariffs may also be introduced for export tariffs. Since feed-in tariffs and solar generation are often subject to government regulations and subsidies, there may also be different tariffs available depending on the region or retailer applicable. [31, 32]

2.1.3 Fundamentals of Distributed Energy Resources

Renewable energy sources are playing an increasingly important role in both the technical and the economic aspects of the energy system. Since this work focusses on behind-the-meter distributed energy resources (DER), the characteristics of rooftop PV systems and battery energy storage systems (BESS) are examined in detail. Although the term DER is generally defined for decentralised small-scale energy generation or storage systems, including various technologies, in the following it is primarily used in the context of PV and BESS.

Solar Photovoltaic (PV)

In the past decade, solar PV has become one of the lowest cost electricity generation technologies, whose average cost has decreased from roughly 4,800 USD/kW in 2010 to approximately 860 USD/kW in 2021. Price developments, as well as modular construction and scalability, have made PV systems an increasingly attractive technology, leading to an exponential increase in generation capacity from roughly 40 GW in 2010 to around 940 GW in 2021, making it the most significant source of new generation capacity. Figure 2.5 depicts the exponential behaviour that cumulative installed solar PV capacity and installation cost have shown over the last years globally. [33, 34]

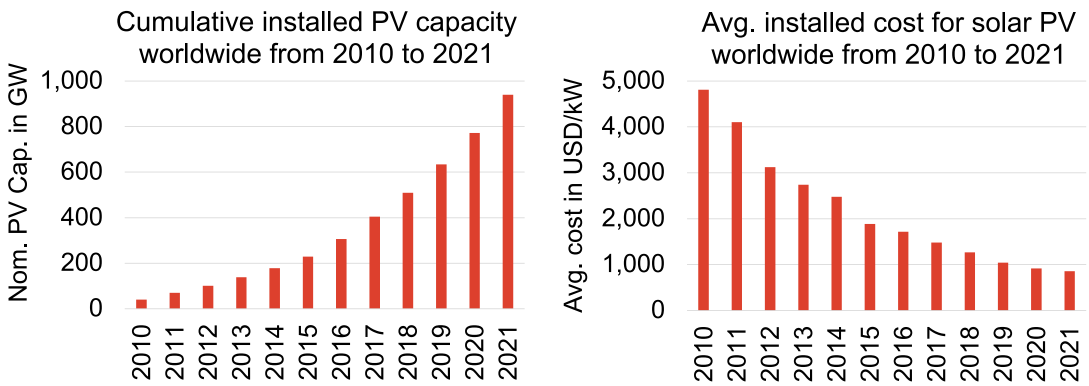

Figure 2.5: Global Cumulative Installed solar PV capacity and average installed cost for 2010 to 2021 [33, 34]

Concerning their basic physical principle, PV systems rely on solar radiation as a renewable energy source. By making use of the photovoltaic effect, PV cells generate a continuous flow of electrons, the electric current, from photons of a particular wavelength occurring in the sunlight. The solar radiation available for electricity generation depends on external influences including day-night cycles, weather conditions or seasonal variations, as well as the system's orientation (e.g., east or south) or incline (e.g., horizontal, 45° or perpendicular). Therefore, photovoltaic energy is considered a volatile resource that, unlike traditional gas-fired or biomass power plants, cannot be dispatched according to demand. [35]

The generation of electricity in a PV system also depends on other factors, including the specific type of technology utilised (e.g., thin film or crystalline silicon) or system size and age. In 2021, crystalline silicon technologies were applied in more than 95 % of manufactured PV-modules. Among crystalline technologies, single crystal silicon (sc-Si), featuring commercial efficiencies of 20 % to 25 %, was used in approximately 85 % of crystalline PV cells. Individual cells are assembled into larger modules, whose size is typically measured in kilowatt peak (kWp). This metric denotes the maximum power output of the module. By combining multiple modules, the available power output can be scaled to meet specific system requirements. While an average Australian household investing in a PV system installs approximately 8 kWp, utility-scale solar farms can operate in the megawatt range (e.g., 132 MW Glenrowan West Sun Farm or 200 MW Kiamal Solar Farm in Victoria) [36, 37]. Besides the system size, degradation effects affect the potential electrical generation capacity of a PV system. Lifespans are generally set to be around 20 to 25 years, with efficiency decreasing by about 20 % over time. Additional losses occur due to the connection of PV systems to the power grid via an inverter that converts the direct current (DC) generated by the PV modules to an alternating current (AC) used in the power grid. [35, 38]

Two important metrics that are often used in the context of small-scale PV systems are self-consumption and self-sufficiency. Self-consumption describes the share of self-consumed electricity from the PV system, either immediately or at a later point in time after storage, usually in a stationary or electric vehicle battery. Self-sufficiency indicates how much of the total electricity demand is met by self-generated electricity. [39]

In order to realise the energy transition, the general trend of increasing large- and small-scale installations of solar PV capacity is expected to continue.

Battery Energy Storage Systems (BESS)

As many renewable energy (RE) sources are volatile and cannot be dispatched according to demand (e.g., solar PV or wind energy), energy storage systems are a fundamental component of a sustainable energy system. As batteries have been widely applied in other sectors (e.g., consumer goods or electric vehicles) and count as an established, scalable and economically feasible technology, they are considered a viable option to store excess energy for time periods with a lack of electricity generation. [40, 41]

The underlying physical principle of battery energy storage systems (BESS) includes the conversion of electrical energy into chemical energy that can be stored and converted back into electrical energy as needed. Lithium-ion batteries (LIB) are currently the most widely used technology in BESS. This is because of their high energy densities, long cycle life, high efficiency, and comparatively low costs. The usual ranges for each characteristic are listed in Table 2.1. However, specific metrics are highly dependent on battery operation (e.g., depth of discharge) and environmental conditions (e.g., temperature). Other battery technologies used in storage systems include lead-acid, sodium-sulphur, and flow batteries, each with unique advantages and disadvantages, as well as respective properties and feasible applications. [42]

Table 2.1: Characteristics of Lithium-Ion Batteries (LIB) [43]

Characteristics	Unit	Lithium-Ion Battery
Energy density	Wh/kg	75 - 250
Round-trip Efficiency	%	75 - 97
Cycle Life	cycles	1,000 - 10,000
Calendar Life	years	5 - 20
Cost	AU$/kWh	137 - 2,000

During their lifetime, batteries lose their ability to store energy, reducing their overall capacity and efficiency due to degradation. Significant factors affecting battery storage system's performance and capacity are cyclic ageing and calendric ageing. Cyclic ageing refers to a capacity reduction resulting from repeated charge and discharge cycles, causing chemical reactions that lead to physical changes in the battery's components. Calendric ageing, on the other hand, refers to degradation processes over time, even when the battery is not in use (e.g., natural breakdown of components like the electrolyte or electrode materials). The period of time that a battery can be stored without losing a specific percentage of its capacity is known as the battery's calendar life. Both types of battery ageing affect the performance and lifespan of a battery simultaneously. The maximum lifespan of the battery is limited by the ageing process that meets the end-of-life condition defined by the manufacturer first. [42]

Due to the decreasing costs of the system and the political desire to expand renewable energy in the power grid, further expansions of PV and BESS are expected. However, since high PV penetration rates sometimes already cause bottlenecks in low-voltage grids that were not designed for a high electricity feed-in, there is a need for either grid reinforcements or curtailment. Storage systems have the potential to mitigate this problem by allowing PV systems to be reasonably integrated into existing grids and reducing the need for conventional backup power plant capacity. Decentralised storage solutions are forecasted to become a key component in solving the problem due to lower investment hurdles compared to centralised storage and a high potential economic value of stored energy for the prosumers. [41, 44, 45]

2.2 The Australian and the German Context

The energy sector in Australia, as well as in Germany, is transitioning from traditional fossil fuel-based sources to renewable energy sources. This transition is driven not only by the need to reduce greenhouse gas (GHG) emissions to mitigate the impacts of climate change and the declining cost of renewable energy technologies, but also by an increasing demand for clean energy from the people. Since this work focusses on the implications of temporal tariffs on household prosumage in Australia as well as in Germany, this section considers the energy policies, the DER installation behaviour, as well as the resulting effects on the energy system for both countries.

2.2.1 Australia

Australia is comprised of six states, namely Victoria (VIC), New South Wales (NSW), Queensland (QLD), South Australia (SA), Western Australia (WA), and Tasmania (TAS), as well as several territories like the Northern Territory (NT) or the Australian Capital Territory (ACT). While every region must act according to national energy policies, it also has the flexibility to implement its own rules and regulations. [46, 47]

There are several energy markets that have been established in Australia, with the National Energy Market (NEM) being the largest among them. The NEM links QLD, NSW (including the Australian Capital Territory), VIC, SA, and TAS. Although it is one of the largest interconnected electricity systems in the world, it is linked by only six cross-border connections. This is due to the NEM rather emerging as a collection of coupled state-based power systems than as one integrated power system. Each of the state-based power systems has its own transmission network service provider (TNSP), which is operated by the Australian Market Operator (AEMO). The NEM covers around 76 % of Australian energy consumption (QLD 25.0 %, NSW 24.2 %, VIC 19.6 %, SA 5.4 %, TAS 1.8 %). The state of Western Australia accounts for approximately 21.5 % and the Northern Territory for 2.5 % of national energy demand. [48, 49]

Between 2015 and 2020, electricity demand increased steadily and remained stable in 2021 at approximately 240 TWh. The industry sector is the largest consumer, accounting for around 43 % of electricity consumption, followed by the service sector and households with 27 % each. The overarching target of the Australian energy transition is to reach climate neutrality by 2050. Furthermore, the government has formulated the plan to increase the share of renewable electricity in the national energy mix to 82 % by 2030. However, as shown in Table 2.2, the penetration of renewable energy as a proportion of consumption varies widely by state. [41, 49, 50]

Table 2.2: Penetration of Renewable Energy Sources as a Proportion of Consumption by State and in Australia [41]

	QLD	NSW	WA	VIC	SA	TAS	National
El. generation from RE sources	23.3 %	28.7 %	35.2 %	40.0 %	68.4 %	93.3 %	35.9 %

In 2022 renewable energy sources accounted for around 36 % of Australia's electricity generation. Wind energy was responsible for more than a third and rooftop solar for approximately a quarter of renewable generation.

To reach national and regional emission reduction and renewable energy deployment rates, several state/ territory policy incentives have been implemented [51]. For example, in Victoria a $1.6 billion energy package consisting of various incentives, grants, and supports target the up-scaling of renewable energy deployment in the commercial and private sectors. Subsidies include, among others, solar panel rebates with the option of an interest-free loan, solar battery rebates, and subsidies for zero emission vehicles, as well as discounts for energy saving products. [52]

As consumers are increasingly generating their own electricity through rooftop solar systems and the penetration of (utility-scale) renewable energy sources continues to expand, the minimum operational demand from the grid is successively decreasing. As illustrated in Figure 2.6, in particular the states of South Australia and Victoria are experiencing a strong decrease in minimum demand and low wholesale electricity prices during periods with high solar generation. At present, excess generation is usually exported to neighbouring regions (e.g., SA to VIC). However, especially these two states are increasingly facing negative wholesale electricity prices when generation exceeds demand [53]. With increasing renewable energy penetration rates and decreasing operational demand, the need for energy storage technologies is expected to increase. The Commonwealth Scientific and Industrial Research Organisation expects that between 10 to 14 times more storage might be necessary over the next decades to support the NEM. [54, 55]

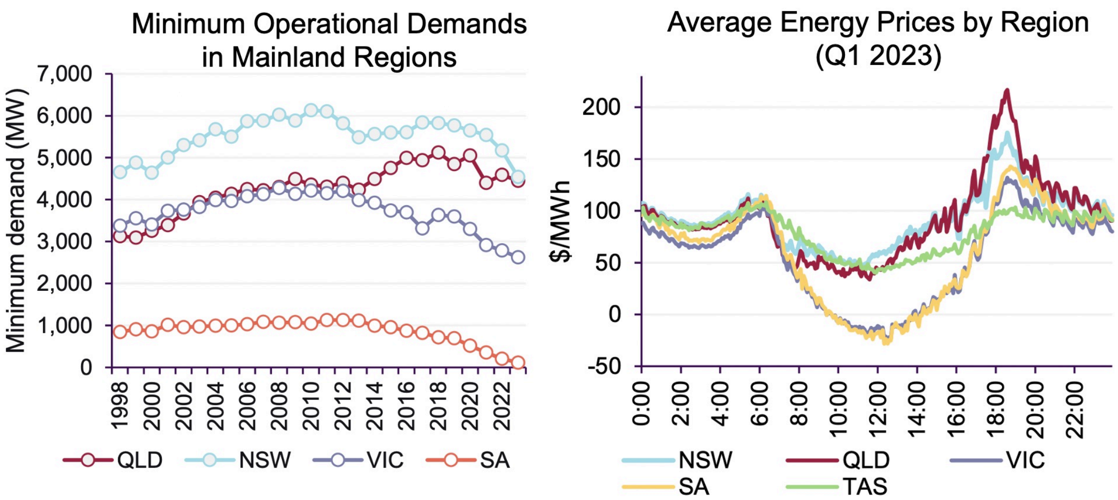

Figure 2.6: South Australia and Victoria are experiencing a strong Decrease in Minimum Operational Demand, as well as Low Wholesale Electricity Prices during Periods with high Solar Generation [54]

These findings are supported by the fact that Australia is currently the country with the highest solar power per capita [38]. Overall, more than 3.44 million PV installations have been realised until April 2023, adding up to a capacity of around 30.5 GW. The highest installation numbers are found in Victoria (18,000 installations/ 107 MW), Queensland (17,500 installations/98 MW), and Western Australia (17,700 installations/ 76 MW). In particular, rooftop solar contributed to the added renewable capacity, with approximately 2.7 GW in 2022 alone (total RE-capacity added: 5 GW). In the last decade, there has been a notable increase in the average size of installed solar systems. Before 2013, mainly smaller systems with sizes under 4.5 kWp were installed, while between 2013 and 2018, the average system sizes shifted toward ranges from 2.5 kWp to 6.5 kWp. However, since then, there has been a significant rise in the installation of larger systems with capacities exceeding 6.5 kWp leading to an overall average system size of 8.7 kWp in March 2023. [36, 41]

Despite the significant increase in residential battery installations within the last years, as depicted in Figure 2.7, PV-BESS uptake remains relatively slow, primarily attributed to the persistent long payback periods [56]. Currently, most state governments provide incentives for PV-BESS installations, indicating the continued need of the sector for additional funding to drive adoption rates [41]. However, by 2025, the payback period of a typical household is expected to be under eight years, a shorter period of time than the 10-year average battery life [57]. Findings from Australia's emissions projections 2020 suggest, that a strong increase in battery capacity will be needed until 2030, with the majority of 4.1 GW stemming from small-scale batteries behind the meter [58].

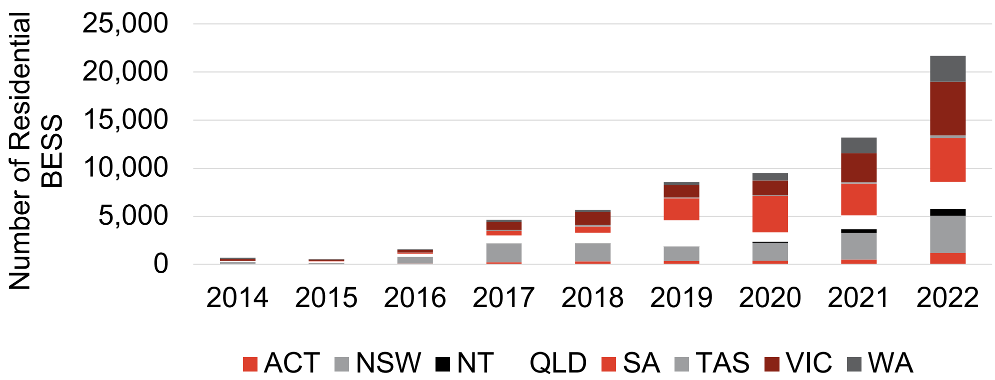

Figure 2.7: Number of PV-BESS systems by year and state or territory in Australia [59]

2.2.2 Germany

Germany consists of 16 states, which, similar to the regulation in Australia, have the flexibility to individually set goals and regulations, while being required to follow the legal framework provided by the national government [60].

The German electricity system is embedded in the European electricity system, whose largest wholesale market is the European Energy Exchange (EEX) [17]. Analogously to the interstate connections in the NEM in Australia, Germany has interconnectors with its neighbouring countries, enabling electricity flow between the different nations. In addition to international connections, there are interconnectors between several regions operated by the four transmission system operators (TSOs) within Germany. [61]

In the last decade, German electricity demand has continuously decreased and has returned to its 1990 value of 490 TWh in 2022. With approximately 40 %, the industry sector is the main electricity consumer, followed by the residential (28 %) and the services sector (25 %). [62]

Germany has legislated the target of reaching GHG emission neutrality by 2045, with an interim goal of -65 % GHG-reduction by 2030 (compared to 1990) [63]. Furthermore, the share of renewable energy in gross electricity consumption is set to increase from 42.2 % in 2022 to 80 % in 2030, while phasing out nuclear power (2023) and coal (legislated: 2038, aim: 2030) [64]. In 2022, wind energy provided the largest share of renewable generation with a contribution of almost 50 %, followed by solar PV (24 %) and biogas (12 %) [65].

This shift towards a greater proportion of renewable power generation has substantial implications for both the economic and technical aspects of the electricity system. As Figure 2.8 exemplifies for three days in June 2023, the integration of cost-effective renewable power generation has a strong influence on the formation of electricity wholesale prices.

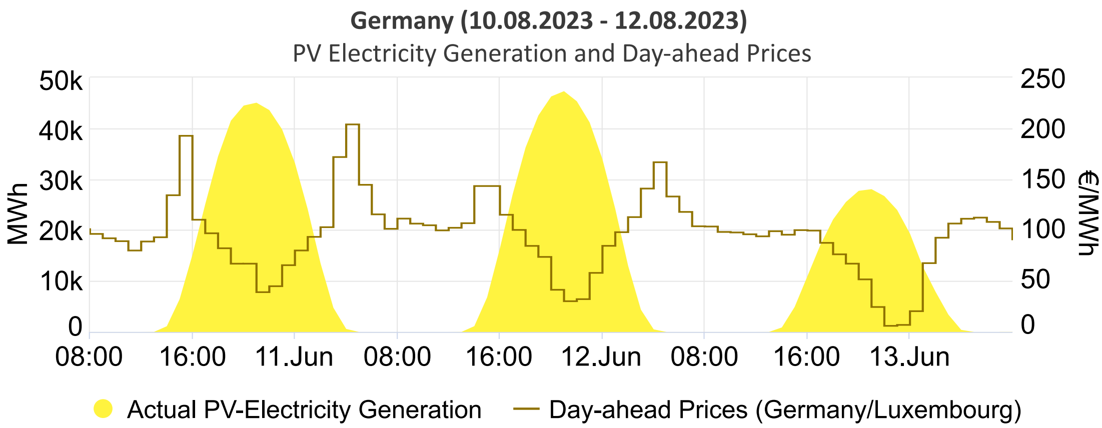

Figure 2.8: Day-ahead Electricity Price and PV Generation from 10/08/2023 to 12/08/2023 in Germany and Luxembourg [5]

On the technical side, the increased penetration of solar power, in particular, has led to a notable reduction in the minimum net load experienced in Germany [6]. This phenomenon will likely be reinforced, as more solar capacity is anticipated for the energy transition. Several states in Germany have already passed regulations that foresee an obligatory solar installation for several types of new construction and renovation projects. For example, Baden-Württemberg has legislated a mandatory PV system installation for newly built (non)residential buildings. This regulation was expanded in January 2023, making the installation of a solar PV system obligatory for roof renovations of residential buildings. [66]

This continuous increase in volatile renewable energy sources requires the expansion of energy storage systems. The largest stationary storage market in Germany is the home storage segment. This sector has seen significant growth during the last two decades and added up to around 5.5 GWh in 2022. More than two thirds of newly installed solar power systems on private properties in Germany are installed in combination with a home storage system [67]. Industrial and large-scale storage have a cumulative capacity of 0.27 GWh respectively 1.4 GWh. However, several studies that examine the energy transition and the demand for energy storage indicate the need to expand the battery storage capacity by several hundred GWh until 2045 [68]. [69]

2.3 Techno-Economic Modelling

Modelling is an essential tool for the analysis and evaluation of possible future scenarios, outcomes, or strategies in a wide range of fields, including engineering, economics, environmental science, and many others. It is used to simplify complex relationships and helps answer specific research questions. Since there are a variety of techniques and approaches that are used to address different issues, the specific question to be answered must always be considered when selecting or constructing a suitable model. [70]

Techno-economic modelling in particular is used to understand the interactions between technology and the economy. This type of modelling typically involves analysing data on the expected economic performance of a technology and predicts potential future economic and technological developments. The results of the modelling can be used to guide investment strategies, make informed policy decisions and support other types of decision making that require an understanding of the relationship between technology and the economy [71]. [72]

Regarding the energy sector, techno-economic modelling is generally used to analyse and evaluate the viability, performance, and costs of various energy technologies and systems. It offers a broad understanding of the interaction between technology, economics, and policies, with the aim of generating a detailed analysis of the benefits, costs, and compromises of different energy options. [71, 72]

The results of techno-economic models are used for a variety of purposes that include:

- Comparing the costs and benefits of various energy system alternatives (e.g., [73, 74])
- Planning and optimizing energy systems (e.g., [75, 76])
- Assessing the technical and economic viability of novel energy technologies and systems (e.g., [77, 78])
- Analysing the impacts of energy policies and regulations (e.g., [79, 80])

Techno-economic models can range from simple spreadsheets to complex computer models that include a variety of inputs, such as data on technology costs, energy demand, fuel prices, and policy regulations. To generate reliable results, uncertainties and risks related to different energy options such as price changes or technological breakthroughs must be considered. [72]

2.3.1 Optimization, Simulation, and Equilibrium Models

Within the realm of (techno-economic) modelling, further subdivision of the methodology into optimisation, simulation, and equilibrium model is possible.,[70]

Optimisation Model

Optimisation models aim at maximising or minimising a given quantity (e.g., maximising welfare). They are composed of an objective function and a set of boundary conditions that represent requirements that need to be fulfilled, like serving an electric load, for example. Since these models are driven by cost assumptions and decisions for or against an option are based on its associated expense, optimisations are identified as hard-line and inflexible. To mitigate this effect, mechanisms that encourage distribution may be used, promoting diversity among possible solutions or options. Instead of selecting only the cheapest solution, for example, a range of different options is ensured which can lead to more robust and flexible results, taking into account different scenarios, risk factors, or preferences. [70]

Simulation Model

The objective of a simulation model is to represent the mechanisms and logic of a real system following a set of rules defined by the modeler. Usually, statistical descriptions of the individual events considered are implemented, and the associated process is then developed incrementally over time, starting with a given initial condition. In a simulation model, there are entities (e.g., a solar system or a battery) and activities (e.g., generating or storing electricity) that follow the logic of the model. Afterward, results, such as bottlenecks or inefficiencies, can be extracted. Although simulation models have the ability to imitate complex systems, their construction can be expensive and their results must be carefully examined due to their statistical nature. While two runs of an optimisation model will produce the same results, a simulation model may give different ones. Therefore, an appropriate number of model runs must be performed to properly evaluate the expected performance of a system. [70, 81]

Computational General Equilibrium Model

Computational general equilibrium models (CGE models) aim to represent the whole economy by balancing the flows of goods and services. This type of model enables an economic analysis by efficiently allocating resources among the stakeholders of an economy (e.g., households, firms, and government). By using the pricing mechanism, which consists of prices decreasing for a lack of demand and prices increasing for an excess demand, the model calculates an equilibrium price that balances demand and supply. While households increase their utility depending on their budget limitations, firms maximise their profits according to production limits. CGE models are therefore a possibility to quantitatively investigate market economies. [82]

2.3.2 Financial Metrics

As techno-economic models not only consider technological boundary conditions as described in Section 2.1, but also take into account economic characteristics, the following section presents several of the most commonly used financial metrics used to compare and evaluate investment opportunities. Metrics like the net present value, the internal rate of return, the payback period or the return on investment are commonly applied to guide decision-makers. The choice of metric depends on a variety of factors such as investment objectives, available resources, or risk tolerance.

Net Present Value

The Net Present Value (NPV) is a popular financial metric that is applied to calculate the current value of an investments expected cash flows, taking into account the time value of money by discounting future cash flows accordingly. The NPV of an investment is determined by applying Equation 2.1, which involves discounting each cash flow CF_t at a specific time t back to its present value using the discount rate r, and summing up all discounted values. Applicable discount rates for the private sector include, for example, the rate of return on a risk-free investment, the cost of debt, the cost of equity, or a combination of the metrics. An investment is considered more beneficial as the NPV increases, while investments with a negative NPV are typically not realised. [83]

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} \tag{2.1}$$

Internal Rate of Return

The Internal Rate of Return (IRR) is another financial metric that takes into account the time-value of money. As seen in Equation 2.2, it expresses the rate of return that an investment is predicted to generate over its lifetime by calculating the discount rate at which the NPV equals zero. An investment is considered beneficial if the calculated IRR is greater than a predefined discount rate, which is chosen analogously to the discount rates applicable for NPV calculations. [83]

$$0 = \sum_{t=0}^{n} \frac{CF_t}{(1 + IRR)^t} \tag{2.2}$$

Return on Investment and Payback Period

While the Return on Investment (ROI) measures the profit (return) that an investment yields in comparison to the original investment, the Payback Period expresses the amount of time that an investment needs to recover the initial investment. As Equation 2.3 shows, the ROI is calculated by dividing the net profit generated by the initial investment and multiplying that value by 100 % to obtain the value as a percentage. Table 2.3 gives an example of how to calculate the Payback Period. For each time period, the cumulative cash flow is calculated by summing up the cash in- and outflows of an investment. The Payback Period is the point in time when the amount of cash inflows equals the amount of money spent. In contrast to NPV and IRR, ROI and payback period generally do not consider the time value of money, which enables to determine the present value of future cash flows. [83]

$$ROI = \frac{\text{Net Profit}}{\text{Initial Investment}} \times 100\,\% \tag{2.3}$$

Table 2.3: Process to Calculate the Payback Period

Time-period	0	1	2	3
Investment ($)	-7,000	0	0	0
Cash-Flow ($)	0	2,750	2,000	2,250
Cumulative Cash Flow ($)	-7,000	-4,250	-2,250	0
Payback Period (years)	-	-	-	3

In comparison to the other metrics, it is particularly advantageous to use the NPV when a clear indication of the net benefits or losses of an investment in monetary terms is needed or the most profitable investment option has to be chosen from a set of alternatives. However, the discount rate for the NPV must be carefully determined, as small changes in this value can sometimes lead to different investment decisions.

Although there is no need to determine a discount rate for the calculation of the IRR in advance, the decision-maker needs to set a certain threshold discount rate to evaluate whether an investment is beneficial. Given that all future cash flows are positive, meaning no further investment is needed, and the same discount rate, respectively, threshold is chosen, NPV and IRR yield the same result and can be used to easily compare investment opportunities. However, the estimation of the IRR may be difficult for complex investment opportunities, and since it is a value captured in percentages, the magnitude of the investment or the size of the cash flows is not considered when comparing the final outcomes.

The main advantages of the financial metrics ROI and the payback period are that both values are easy to calculate and understand. The ROI provides a simple estimate of profitability; however, it ignores the time-value of money as well as scale and magnitude of an investment. On the other hand, by calculating the payback period, the decision maker is able to estimate the duration needed to recover the initial investment and gain insight into short-term cash flow needs. Nevertheless, it ignores the time-value of money as well as cash flows beyond the payback period. As the Payback Period does not consider the entire lifespan of the investment, it is not possible to identify overall profitability. [83]

2.4 Literature Review

As assessed in Chapter 2.2, the adoption of DER is on a steady rise. This trend not only affects the technical operation of the power grid but also has significant implications for its economic dynamics. Given the projected further expansion of DER and the lack of monitoring and control of power flows at the household level, the operation of the power grid remains largely reactive and vulnerable to aggregate changes in household grid-utilization [84]. Without adequate management, the growing adoption of rooftop solar PV poses significant challenges to grid management. In particular, the surge of solar PV installations can lead to the "duck curve" phenomenon, which is characterised by low residual demand and high feed-in during the midday, as well as a steep rise in demand in the afternoon. As investigated by Wilkinson et al. and Hou et al., this phenomenon can result in potential issues such as negative wholesale prices, grid instabilities, curtailment challenges, and steep ramp-rates for conventional power generators [3, 7]. Say et al. argue that, especially with declining feed-in tariffs and PV-BESS costs, there is a demand-side pressure on the energy market to evolve and develop innovative strategies [86]. [9]

A strategy to mitigate the negative impacts of the duck curve on the grid is to take advantage of the continuously growing potential of customers equipped with PV-BESS systems by introducing temporal electricity tariffs. As these customers have the ability to become active participants in the energy system and react to price signals, they can be economically incentivised to interact with the grid in a way that is beneficial for its technical operation. [87]

In order to assess those potentials, energy system modelling becomes a vital tool. As shown by Ringkjøb et al., there is a wide range of models available. Most of the models investigated by the authors are optimisation models with the goal of providing guidance for investment and/or operation decisions. The models included in their review range from the small-scale, like isolated energy systems to global analysis tools, focussing on international energy flow assessments. According to their specific purpose, such as investigating a cost-optimal national net-zero strategy, the different models cover time horizons of only seconds to decades. [88]

Nousdilis et al. investigate the impact that different incentive policy schemes and BESS operation strategies have on the economic viability of PV-BESS systems. The authors deploy a techno-economic optimisation model to obtain the ideal system size, maximising the NPV of an individual household for the region of Thessaloniki, Greece. Model inputs include the incentive scheme (e.g., battery price or feed-in-tariff), PV generation and load consumption profiles, PV and BESS investment costs, as well as electricity charges (including temporal tariffs). The authors conclude that an investment in an integrated PV-BESS systems is not as profitable as an investment in a PV-only system under current market conditions. However, it is suggested that price signals could be used by market operators and policy makers to encourage additional adoption of PV-BESS and affect the operation of PV-BESS systems. [89]

Similarly, Say et al. have also implemented a techno-economic optimisation model to obtain the ideal dimensions of a PV-BESS system for a set of households, maximising NPV. However, the authors focus on the impact that different levels of (flat) feed-in tariffs have on PV-BESS adoption rates and the consequences that might arise for the grid operation in Australia. The cumulative effects on the demand for the network and the retail revenues are analysed across all households. Furthermore, projections for the distribution network on expected grid imports and exports, installed PV and BESS capacities, retailer revenues, and feed-in tariff policy are provided. The authors point out that future research is needed to understand the impact that different retail tariff structures might have on the adoption of PV and BESS, as well as the subsequent effects on system integration. [85]

Another approach was chosen by Duman et al., who modelled a home energy management system that aims to minimise daily electricity costs under temporal import and flat export tariffs in Turkey. They use mixed-integer linear programming to schedule the operation of controllable power loads, such as BESS or electric vehicles, as well as thermostatically controlled appliances. The day-ahead optimisation is applied to different system configurations that always include thermostatically controlled and time-shiftable appliances. The system may additionally contain a solar PV system, BESS and/or an electric vehicle. The authors find that significant cost reductions can be achieved in the presence of time-of-use pricing. However, they acknowledge that the chosen metric of daily cost reductions can be misleading, as the reduction might not compensate for the initial investment. However, they concluded that temporal pricing provides advantages not only for the demand side but also for the grid side, as it helps smooth out peak demand, reducing the need for additional generation capacity and operational expenses. [90]

Also focussing on system operation, Shaw-Williams et al. assess the overall profitability of predefined residential PV-only and PV-BESS systems for 700 households in Australia, evaluating economic impacts on the investigated customers and the network operator. By implementing a simulation model and incorporating temporal import and flat export tariffs, their research concludes in agreement with the findings of Nousdilis et al. that PV-only systems are generally the most profitable choice for individual households. However, when accounting for savings in network operation costs as well, residential PV-BESS systems emerge as the more advantageous option. [91]

Although the necessity for novel approaches to manage the growing penetration of PV and BESS in the electricity system is widely acknowledged, there remains a gap in the literature on various issues. In accordance with established approaches, the current work uses a techno-economic optimisation model to investigate economically ideal PV and BESS dimensioning and operation in the residential sector. However, by analysing the rational investment decision of households under current market conditions first, followed by an exploration of necessary additional investment incentives, and finally investigating operational strategies for the installation of an average-sized system, a more holistic research approach is pursued. Additionally, in contrast to predominant proceedings in the literature due to a lack of available data, the current analysis is performed for 400 real household load profiles in Australia and 72 profiles in Germany, providing a more representative portrayal of individual grid interactions. Furthermore, the optimisation model not only includes the concepts of flat and temporal import tariffs, but is also extended with the implementation of temporal export tariffs. To the best of the authors' knowledge, given the relatively novel nature of temporal export tariffs, there have been little to no investigations on the economic and technical implications of time-varying feed-in tariffs for prosumers as well as the grid.

3 Methodology

This chapter describes the methodology used to investigate the impacts that different tariff structures have on household prosumage. In Section 3.1, the techno-economic optimisation model is explained in detail. Section 3.2 focusses on the data, parameters and assumptions that have been applied to the model for the Australian and the German scenarios.

3.1 Techno-Economic Model

In the following the framework of the utilised techno-economic optimisation model is described, including the model structure, the objective function, applicable boundary conditions and the model outputs. It is a mixed-integer linear programming (MILP) model that uses both linear correlations and binary variables. The model is an adaptation of the Electroscape Model, that Say and John deployed to investigate transitional pressures from household PV-BESS adoption under flat tariff structures [86].

Figure 3.1 gives a schematic overview of the model's input parameters, optimisation goal, and the results obtained.

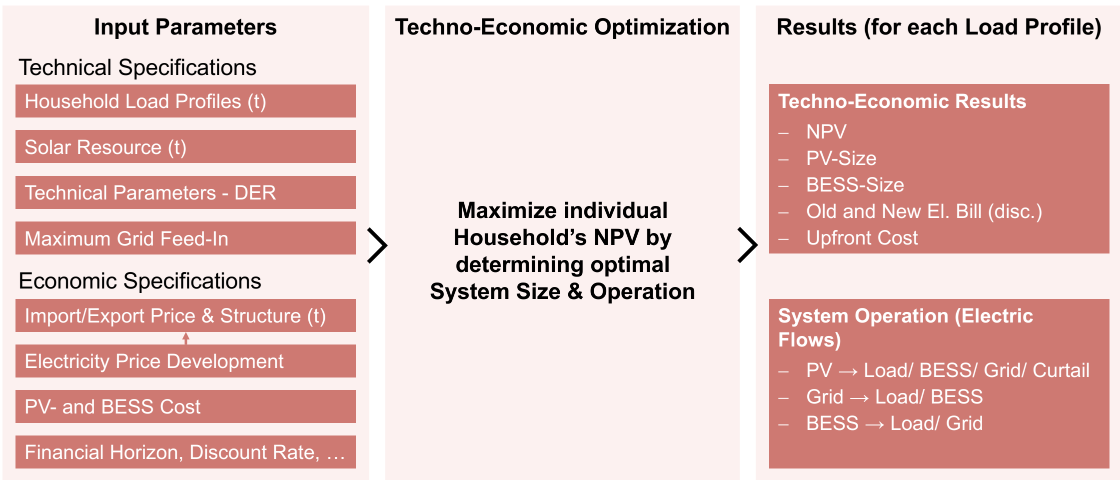

Figure 3.1: Schematic Overview of the Techno-Economic Optimization Model

3.1.1 Objective Function and Model Structure

The overarching goal of the optimisation model is to maximise the NPV as seen in Equation 3.1 over a set time period for every given household load profile.

$$max(NPV) \tag{3.1}$$

The rationale behind the selection of the NPV as the optimisation metric is its consideration of the time-value of money and its ability to quantitatively evaluate the financial performance of an investment opportunity (see Section 2.3.2). As economic incentives drive DER adoption, and a fixed financial modelling horizon determines the maximum accepted recovery time for the investment, the NPV proves to be a suitable measure for assessing the investment's monetary viability.

As shown in Equation 3.2, the NPV of the model is comprised of the upfront investment cost UC and the discounted annual cash-flows that are represented using expected electricity bill savings. Each household has the opportunity to either not invest or to purchase a PV system, a BESS or a PV-BESS. The annual electricity bill savings are calculated by subtracting the electricity bill after investment C_{new}, from the reference one C_{ref} without any investment. The reference and the new electricity bill are explained in detail below. The discount rate r and the financial horizon Y are fixed parameters.

$$NPV = -UC + \sum_{y=0}^{Y-1} \frac{(C_{ref}(y) - C_{new}(y))}{(1+r)^y} \tag{3.2}$$

The annual reference electricity bill $C_{ref}(y)$ before a potential installation is calculated by multiplying the exogenously given net load of the household with the applicable electricity tariff, which is represented by Equation 3.3. Positive values of the net load profile represent household electricity demand, whereas negative values indicate a generation surplus. As the model does not exclude households that may have previously installed a PV system, existing electricity feed-in $E^{exo}_{Ex.\to Grid}$ is remunerated with the electricity feed-in tariff C^{exo}_{Import}. The existing electricity demand $E^{exo}_{Ex.\to Load}$ is priced according to the import tariff C^{exo}_{Export}. The annual electricity bill is computed, considering the modelling time steps t per year y, where T is the overall number of annual time steps.

$$C_{ref}(y) = \sum_{t=0}^{T-1} (C^{exo}_{Import}(t) * E^{exo}_{Ex.\to Load}(t) + C^{exo}_{Export}(t) * E^{exo}_{Ex.\to Grid}(t)) \tag{3.3}$$

$$\forall\ t \in n \text{ with } n := \{0,\, t_1,\, t_2,\, ...,T-1\} \text{ x } y \text{ and}$$
$$y \in\ z\ with\ z := \{0,\, y_1,\, y_2,\, ...,Y-1\}$$

The approach for the new electricity bill is shown in Equation 3.4. It is subject to the net load after a potential investment, which in turn is dependent on the optimisation. Equation 3.5 illustrates that electricity imported from the grid can be used to satisfy the household load $E_{Grid \to Load}$ or to charge the BESS $E_{Grid \to BESS}$. The remunerated electricity feed-in is represented by Equation 3.6, which may come from the solar system $E_{PV \to Grid}$, the BESS $E_{BESS \to Grid}$ or a previously existing electricity export $E_{Ex. \to Grid}$.

$$C_{new}(y) = \sum_{t=0}^{T-1} (C_{Import}^{exo}(t) * E_{Import}(t) + C_{Export}^{exo}(t) * E_{Export}(t)) \tag{3.4}$$

$$E_{Import}(t) = E_{Grid \to Load}(t) + E_{Grid \to BESS}(t) \tag{3.5}$$

$$E_{Export}(t) = E_{PV \to Grid}(t) + E_{BESS \to Grid}(t) + E_{Ex. \to Grid}(t) \tag{3.6}$$

As the new bill is subject to optimisation and depends on the interaction of the household with the grid, the logic of the optimisation model follows the electricity flows which are schematically depicted in Figure 3.2. If an investment in a technical component is not realised, electrical flows from and to that device are not possible.

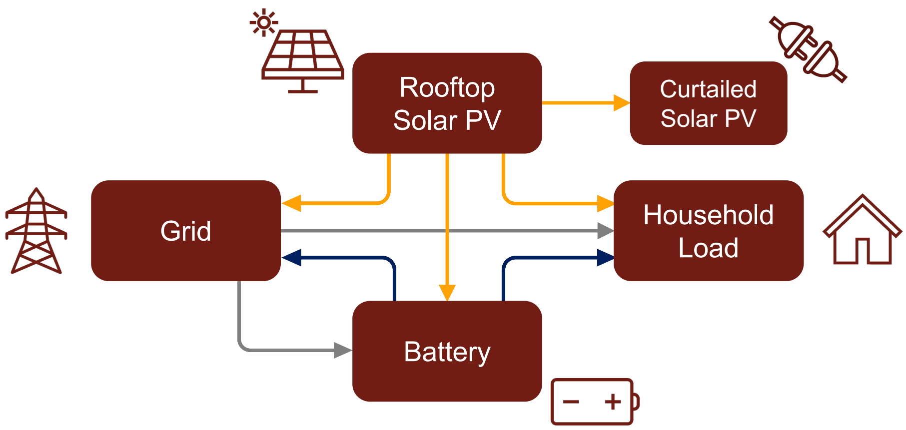

Figure 3.2: Schematic Overview of possible electrical Flows in the Optimisation Model

Since the given electrical load of the household must be met, the optimisation model has to evaluate what savings can be realised through an investment in a PV and/or BESS system. First, there is the option to not invest at all, resulting in a NPV of zero and no changes to the net-load of the household. Second, the three possible solution spaces are modelled: the most profitable PV system without a BESS, the most profitable BESS without a PV system and the most profitable PV-BESS. In any case, the model optimises for the dimension and operation of the system that achieves the highest NPV under given constraints. The maximum NPVs of all solution spaces and the case of no investment are compared, and the overall maximum NPV is chosen as the most profitable option for the household.

It is also possible to set a PV-BESS system size in advance, allowing the optimiser to skip the other solution spaces and only optimise for the system's operation. However, the highest NPV achievable might be negative, and an economically rational decision maker would not make an investment.

3.1.2 Boundary Conditions

As the optimisation model aims to determine the economically optimal size and operation of the technical system, the economic and technical boundary conditions must be met. In the following, the underlying rationale behind the equations is described. The implemented calculations can roughly be subdivided into energy balances, PV- and BESS-, as well as grid interaction equations.

Energy Balance Equations

The energy balance equations ensure that the physical principles of electricity conservation and continuity are met for every time step of the modelling, as well as that the electrical household load is satisfied. These equations represent the electrical flows depicted in Figure 3.2. Equation 3.7 exemplifies the boundary condition that ensures that the exogenously given household load $E^{exo}_{Ex.\rightarrow Load}$ is met by the electricity generated by the rooftop solar PV system $E_{PV\rightarrow Load}$, the grid $E_{Grid\rightarrow Load}$ and/or BESS $E_{BESS\rightarrow Load}$ for all modelled time steps t. Additional balance equations, including energy flows regarding PV-generation or load satisfaction, are listed in the Appendix (Equations A.1 - A.3).

$$E^{exo}_{Ex.\rightarrow Load}(t) = E_{PV\rightarrow Load}(t) + E_{Grid\rightarrow Load}(t) + E_{BESS\rightarrow Load}(t) \tag{3.7}$$

PV Equations

The PV system is specified by Equations 3.8 and 3.9. Equation 3.8 describes how much solar generation is available to a household if a system with the nominal power capacity of $P_{PV\text{-}nom.cap}$ is installed. The exogenously given solar power generation per kWp $g^{exo}(t)$ already includes the solar system's (linear) calendric degradation processes. Equation 3.9 ensures that the generated electricity is used primarily to meet the household load and that the surplus may then be directed towards grid feed-in, BESS storage, or curtailment.

$$E_{PV\text{-}Gen}(t) = g^{exo}(t) * P_{PV\text{-}nom.cap} \tag{3.8}$$

$$E_{PV\rightarrow Load}(t) = min(\,E^{exo}_{Ex.\rightarrow Load}(t)\,,\,E_{PV\text{-}Gen}(t)\,) \tag{3.9}$$

BESS Equations

The equations that define the BESS behaviour consider the state of charge (SoC), ageing mechanisms, and charging and discharging constraints.

Concerning the SoC, it is defined that the model starts and ends with an empty battery. For the time steps in between, Equation 3.10 holds. The SoC at time t is based on the SoC of the time step before (t - 1), and may increase when the BESS is charged or decrease when power is drawn from the battery. As the process is subject to efficiency losses, both terms are multiplied by the applicable (dis-)charging efficiency $\eta_{(dis\text{-})charge}$.

$$\begin{aligned} SOC_{BESS}(t) = {} & SOC_{BESS}(t-1) \\ & + \eta_{charge} * (E_{PV\rightarrow BESS}(t) + E_{Grid\rightarrow BESS}(t) + E_{Ex.\rightarrow BESS}(t)) \\ & - \eta_{discharge} * (E_{BESS\rightarrow Load}(t) + E_{BESS\rightarrow Grid}(t)) \end{aligned} \tag{3.10}$$

In Equation 3.11 (in combination with Equations 3.12 and 3.13), the binary variables $B_{BESS\text{-}charge}$ and $B_{BESS\text{-}discharge}$ ensure that the BESS can only charge or discharge and not do both at the same time.

$$B_{BESS\text{-}charge}(t) + B_{BESS\text{-}discharge}(t) \leq 1,001 \tag{3.11}$$

Equations 3.12 and 3.13 ensure that the maximum allowed power flow must be greater than or equal to the power fed into or drawn from the BESS. The maximum power flow of the battery is defined in Equation 3.14. It is calculated by dividing the nominal BESS capacity by the exogenously defined $\mathit{(Energy\text{-}to\text{-}Power\text{-}Ratio)}_{BESS}$. The actual power flow to or from the battery is computed by converting the energy flow in the time step t, defined in Equations 3.15 and 3.16, into a power flow and multiplying it by the efficiency of the battery.

$$B_{BESS\text{-}charge}(t) * P_{BESS\text{-}nom.cap} \geq \eta_{charge} \frac{E_{BESS\text{-}in}(t)}{\Delta\, t} \tag{3.12}$$

$$B_{BESS\text{-}discharge}(t) * P_{BESS\text{-}nom.cap} \geq \frac{1}{\eta_{discharge}} * \frac{E_{BESS\text{-}out}(t)}{\Delta\, t} \tag{3.13}$$

$$P_{BESS\text{-}nom.cap} = \frac{E_{BESS\text{-}nom.cap}}{(Energy\text{-}to\text{-}Power\text{-}Ratio)_{BESS}} \tag{3.14}$$

$$E_{BESS\text{-}in}(t) = E_{PV \to BESS}(t) + E_{Grid \to BESS}(t) + E_{Ex. \to BESS}(t) \tag{3.15}$$

$$E_{BESS\text{-}out}(t) = E_{BESS \to Load}(t) + E_{BESS \to Grid}(t) \tag{3.16}$$

Furthermore, in this model, the state of health of the battery (SoH) is considered. It is calculated in kilowatt hours and represents the storage capacity available at time t, which decreases over time due to calendric and cyclic degradation mechanisms. Its initial value at $t = 0$ equals the installed nominal capacity $E_{BESS\text{-}nom.cap}$. In order to calculate the SoH over time, several auxiliary variables are introduced first.

Equation 3.23 calculates the maximum capacity loss in kilowatt hours until the exogenously defined capacity EOL criterion (i.e., 70 %) is reached. By definition, the capacity EOL criterion is reached either after the calendric EOL (i.e., 10 years) or the cyclic EOL (i.e., 10,000 cycles). However, both processes occur simultaneously.

$$\Delta\, Cap_{max} = (1 - EOL\text{-}cap.) * E_{BESS\text{-}nom.cap} \tag{3.17}$$

Calendric ageing is assumed to be linear over the modelled time horizon. To calculate the capacity loss due to calendric ageing per time step, the duration of each time step in seconds $\Delta\, t_{sec}$ is multiplied by the number of seconds a year has and the exogenously defined EOL in years $EOL\text{-}Years^{exo}_{BESS}$. This means that the value of $Ageing^{exo}_{Cal.}$, when multiplied by the number of time steps until the calendric EOL is reached, results in one.

$$Ageing^{exo}_{Cal.} = EOL\text{-}Years^{exo}_{BESS} * \Delta\, t_{sec} * Const._{sec\text{-}per\text{-}year} \tag{3.18}$$

Cyclic ageing is subject to battery operation. In Equation 3.19, the absolute amount of electrical energy that is fed into or drawn from the BESS at time t is calculated.

$$E_{abs,BESS}(t) = B_{BESS\text{-}charge}(t) * \eta_{charge} * E_{BESS\text{-}in}(t) + \frac{B_{BESS\text{-}discharge}(t)}{\eta_{discharge}} * E_{BESS\text{-}out}(t) \tag{3.19}$$

With Equation 3.21 the cyclic degradation is calculated for each time step. This ageing mechanism is represented by the fraction that the total energy flow of time step t contributes to the overall possible energy flow in the battery's cyclic life span shown in Equation 3.20.

$$E_{BESS,overall} = 2 * EOL\text{-}cycles_{BESS} * E_{BESS\text{-}nom.cap} \tag{3.20}$$

$$Ageing_{Cyc.}(t) = \frac{E_{abs,BESS}(t)}{E_{BESS,overall}} \tag{3.21}$$

Finally, as shown in 3.22, the SoH in time step t is based on its value of the time step before in combination with the ageing processes mentioned above.

$$SOH_{BESS}(t) = SOH_{BESS}(t\text{-}1) - \Delta\, Cap._{max} * (Ageing_{Cal.}^{exo} + Ageing_{Cyc.}t)) \tag{3.22}$$

Lastly, Equation 3.23 demonstrates the constraint that the available BESS capacity must be smaller than or equal to its current SoH.

$$SOH_{BESS}(t) \geq SOC_{BESS}(t) \tag{3.23}$$

Grid Interaction Equations

The last Equation group focusses on grid interactions. Equation 3.24 ensures that the maximum feed-in power $P_{max,feed-in}$ is not exceeded by the electrical energy $E_{Export}(t)$ fed into the grid over time $\Delta\, t_{sec}$.

$$E_{Export}(t) \leq P_{max,feed-in} * \Delta\, t_{sec} \tag{3.24}$$

Equations 3.25 and 3.26 ensure that electricity can only be drawn or fed into the grid at any time step t. When the binary variable B_{Grid} is equal to one, the right term of Equation 3.25 becomes zero, preventing any grid exports and only allowing for grid imports. If electricity is fed into the grid, the binary variable B_{Grid} is equal to zero and forbids drawing electricity from the grid in Equation 3.26.

$$E_{Import}(t) \leq M * B_{Grid}(t) \tag{3.25}$$

$$E_{Export}(t) \leq M * (1 - B_{Grid}(t)) \tag{3.26}$$

$$\text{where } M \gg E_{Import}(t)$$

3.2 Model Inputs

In the subsequent section, the inputs for the optimisation model presented in Chapter 3.1 are explained in detail, including the underlying data, the chosen parameters, and the key assumptions.

3.2.1 Data

An integral part of the deployed model is the underlying data on the load profiles. Due to privacy regulations, real household load profiles generally remain anonymous, and data availability is usually scarce. For this work, 400 Australian and 72 German household load profiles were investigated.

Australian Household Load Profiles

The Australian household load profiles were provided by the Centre for New Energy Technologies (C4NET), which conducts data-driven research in the energy sector [92]. C4NET has access to smart metres utility data in Victoria and has supplied data from the JEMENA Electricity Network, which covers the north-west metropolitan Melbourne [93].

The data is from 2019 (April-December) and 2020 (January-March) and has an hourly resolution. In this work, load profiles that lack many data points and those that have a controlled load tariff (see Section 2.1.2) were ignored. The final data-set contains 400 anonymous household net-load profiles, meaning that it is unknown how many people live in the household or how air and water are heated (electrical or gas). As negative values indicate an electricity feed-in from the household and none are to be found in the data-set, it can be assumed that no household has installed a (large) rooftop PV system. Figure 3.3 shows a box plot diagram of the annual electricity consumption of the Australian households regarded. While the average consumption is approx. 4,000 kWh/a, the median lies around 3,500 kWh/a.

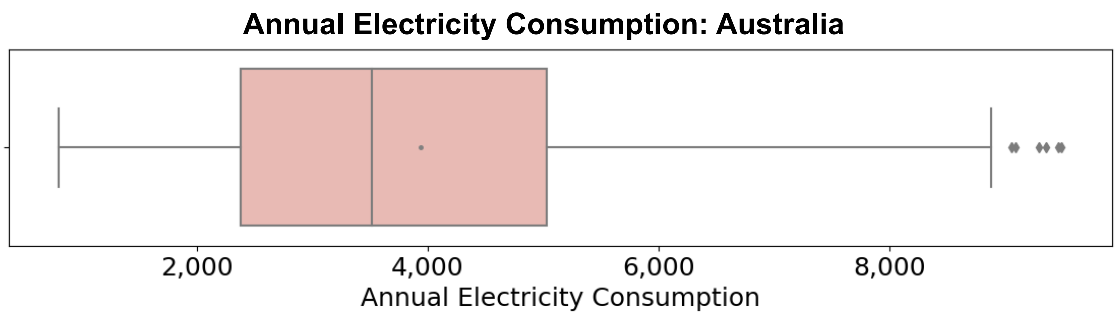

Figure 3.3: Statistical Distribution of annual Electricity Consumption of 400 Australian Households from the C4NET Data-set

As mentioned earlier, there is no electricity feed-in and minimum power demand is 0 kW. The average power drawn from the grid is around 0.45 kW. Although the maximum recorded power value is 14.8 kW, only around 1 % of the power drawn from the grid exceeds 3 kW.

German Household Load Profiles

The data used for the German context have been published by Tjaden et al. (HTW data-set). The authors have synthesised household load profiles and subsequently demonstrated their ability to represent single-family houses in Germany. The data-set consists of phase-resolving annual load profiles of active and reactive power from German single-family households and has a secondary resolution. It is based on the IZES data-set that was measured in 15 minute time steps for 497 households between 2008 and 2011 [95]. In order to increase the resolution of the load profiles, the ADRES data-set was incorporated, which includes 30 Austrian households with a second resolution [96]. The final data-set of the load profiles is extended by a time-stamp file, covering every second for the year 2010. Additional information on the synthesis of household load profiles can be found in Tjaden et al., 2015. [94]

In this work, 72 German household load profiles were used. They were generated on the basis of the HTW data-set by summing up the three phases of the active power profiles, given in Watt. The data was subsequently converted to kilowatt hours.

As depicted in Figure 3.4, the average and median annual electricity consumption of the German household profiles are 4,750 kWh/a and 4,600 kWh/a, respectively, and therefore generally higher than for the Australian data-set. Although household consumption in the German data-set generally tends to be higher, it ranges in a similar order of magnitude as the Australian profiles.

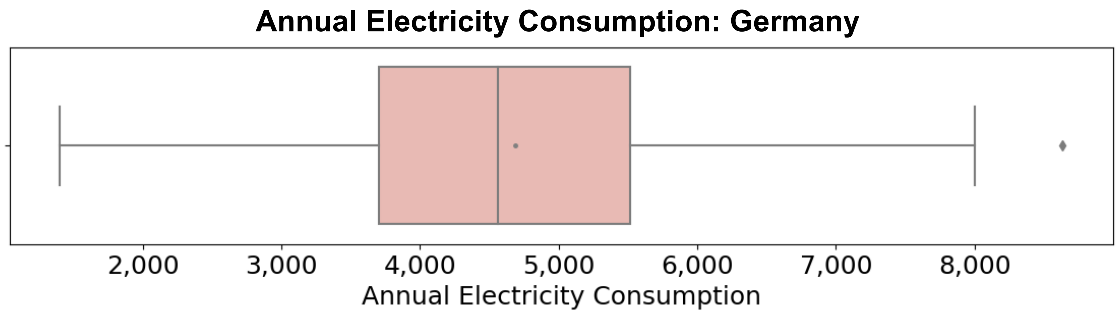

Figure 3.4: Statistical Distribution of the annual Electricity Consumption of 72 German Households from the HTW Data-set

Concerning power usage, the German data-set does not include any power feed-in either. The average power drawn from the grid is around 0.5 kW. Although the maximum recorded power value is 8.7 kW, only about 0.5 % of the power drawn from the grid exceeds 3 kW.

Solar Resource

In addition to the hourly household load profiles, the solar resource is indispensable for the modelling of a PV system's economic viability. The solar resource profile for Australia and Germany has an hourly resolution. They are scaled so that when multiplying by the nominal size of a PV system, the annual electricity generated is computed (kWh/kWp).

The Australian solar profile was derived from the National Renewable Energy Laboratory (NREL) for the location of Tullamarine, Melbourne. It represents a north-facing PV system with a nominal capacity of 1 kWp. The data suggest that approximately 1,400 kWh of electricity is generated per 1 kWp of solar capacity. [97]

The German solar profile is based on data published by the German Meteorological Office (Deutscher Wetterdienst) in 2017. The Meteorological Office provides extensive data on several meteorological parameters and has published test reference year (TRY) data for many of its weather stations. TRYs are defined so that their monthly and seasonal data match the long-term mean values of the 17-year base period (1995-2012) as closely as possible. In this work, global radiation measured for the city of Kassel was sourced, which is roughly situated in the centre of Germany. Subsequently, the data was scaled so that its sum equals the average energy generated in Germany per kWp installed, which is 990 kWh/kWp [99]. [98]

3.2.2 Parameters

In the following, the most important techno-economic modelling parameters for the investigated research question are described in more detail.

Tariff Structure

As the goal of this work is to assess the impact that temporal tariffs have on reshaping household prosumage, three different tariff structures are investigated. The most common tariff currently is the flat import and flat export (FI-FE) tariff. Second, a temporal import and flat export tariff (TI-FE) is introduced. Lastly, the relatively new concept of temporal export tariffs in combination with temporal import pricing (TI-TE) is considered.

Values for the modelling of Australia are derived from the government's "Victorian Default Offer" and "Minimum Feed-In Tariff", applicable from 1 July 2022 to 30 June 2023 [28, 32]. As the default offer depends on the applicable distribution zone, an average price was calculated. Supply charges ($/day) are independent of the tariff structure chosen and therefore disregarded. The minimum feed-in tariff is set uniformly for all energy companies. As weekday and weekend pricing is distinguished in the export tariff, this is also considered in the optimisation model. Tariff prices and time periods for the Australian context are listed in Table 3.1.

Table 3.1: Import and Export Tariffs in Victoria, Australia

Pricing Type	Price in $/kWh	Time
Flat Import	0.243	*Always*
Temporal Import	0.184	$9\,pm - 3\,pm$
	0.332	$3\,pm - 9\,pm$
Flat Export	0.052	*Always*
Temporal Export	0.069	$3\,pm - 9\,pm$ (*only weekdays*)
	0.071	$10\,pm - 7\,am$
	0.050	*all other times*

Figure 3.5 additionally illustrates the tariffs graphically. It should be noted that the price spread between peak and off-peak import prices (14.8 ct) is significantly higher than the maximum feed-in price spread (2.1 ct).

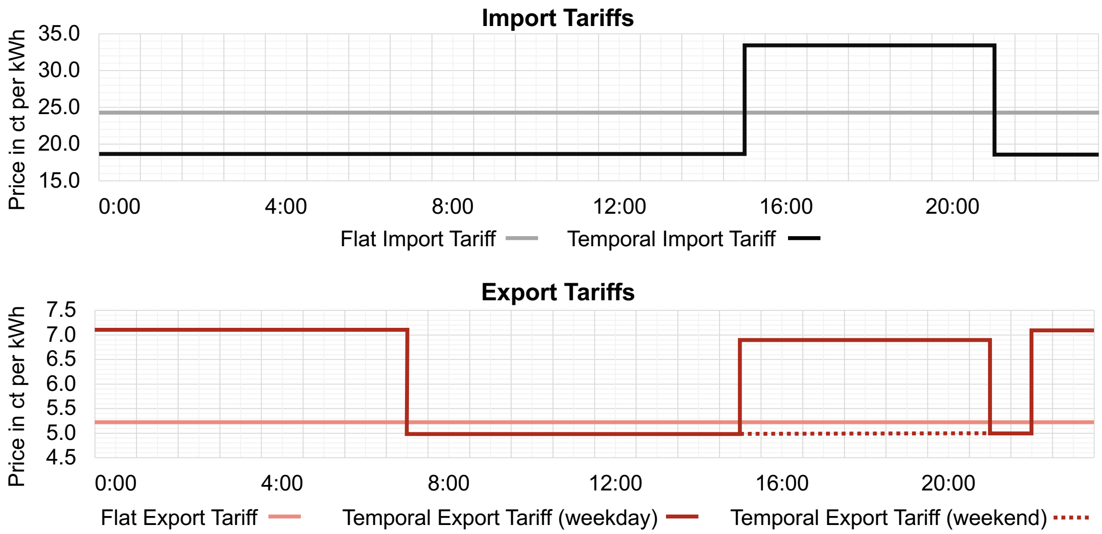

Figure 3.5: Structure of the Flat and Temporal Export Tariff in Australia

As temporal tariffs are still rather rare in Germany, and in particular temporal feed-in tariffs have not been introduced, the temporal tariff structures for the German context are computed based on the price spreads and time periods of the Australian offer. The level of the flat import tariff (35.7 ct/kWh) is based on the retail electricity price of the basic electricity provider, published by the Bundesnetzagentur and Bundeskartellamt [20]. The flat feed-in tariff (8.2 ct/kWh) is specified according to the feed-in price set by the government for

January 2023 [25]. Although this remuneration is only applicable for systems smaller than 10 kWp, and a feed-in of additionally installed capacity is remunerated at a lower rate, this value is applied to all PV systems regarded in this work.

Table 3.2: Import and Export Tariffs in Germany

Pricing Type	Price in €/kWh	Time
Flat Import	0.357	*Always*
Temporal Import	0.271	$9\,pm - 3\,pm$
	0.487	$3\,pm - 9\,pm$
Flat Export	0.082	*Always*
Temporal Export	0.109	$3\,pm - 9\,pm$ (*only weekdays*)
	0.112	$10\,pm - 7\,am$
	0.079	*all other times*

Electricity Price Development

As the investment decision in this work is based on the expected NPV over a time horizon of 10 years and the electricity price is subject to fluctuations, it is important to consider (perceived) electricity price developments. As future developments cannot be foreseen, the potential developments considered in this work are based on price trends observed over the past ten years. In order to assess an average annual price change, electricity prices published by respective national statistical agencies are adjusted for inflation and a linear regression analysis is performed. Calculations for the Australian context show that the real price changes in the past 10 years are close to zero [98, 100]. The same approach has been used to determine the development of the German electricity price, resulting in an increase in the average price of +2 %/a in recent years (excluding 2022 due to the Ukraine war) [20, 101].

PV and BESS Pricing

Lastly, one of the main obstacles for many households in investing in DER is the high upfront costs. Since the cost to install PV as well as BESS differ between Australia and Germany, common prices in both areas were investigated.

The cost of the PV system is determined through a linear regression of market-data. It is assumed that the installation of a PV system has a set fixed cost (i.e., inverter and installation) and a variable cost (price per kW). The cost of the BESS in Australia is also based on a linear regression analysis that indicates that there are no fixed but only variable costs. This assumption is justified, by determining a minimum battery size of 3 kWh, impeding unreasonably cheap BESS-installations. In accordance with this postulation, the variable price of home storage determined by Hecht et al. (2022) was used in the German context [102]. DER cost assumptions are listed in Table 3.3.

Table 3.3: PV and BESS Pricing in Australia and Germany

Component	Fixed Price	Variable Price
Australia		
PV	3,000 $	630 $/kW
BESS	–	1,300 $/kWh
Germany		
PV	2,650 €	1,300 €/kW
BESS	–	1,200 €/kWh

3.2.3 Assumptions

As modelling always includes a simplification of reality, key assumptions of the optimisation are addressed in the following.

One of the most important premises is the concept of perfect foresight, which refers to the idealised ability to accurately predict future events or outcomes without any uncertainty. While this assumption enables an optimal system dimensioning and operation, it should be noted that future electricity demand, as well as solar radiation, are not entirely predictable.

Furthermore, it is assumed that the household is an economically rational decision maker. This assumption is insofar adequate as economic incentives are key drivers for the adoption of DER. However, other not financially quantifiable factors, such as sustainability or self-sufficiency, may also significantly influence investment decisions.

Lastly, it is assumed that the underlying demand profiles for each household are not subject to change over time and are repeated for each year of the simulation. The same holds for the solar resource. It is expected that the solar system degrades linearly over time and that BESS degradation is only subject to the calendric and cyclic ageing mechanisms described in Section 3.1. Additionally, battery charge and discharge efficiency, as well as operational performance remain constant throughout the operational lifespan of the battery.

3.3 Model Outputs

In the following, the outputs resulting from the previously described model, its input data, and inherent assumptions are presented. First, the techno-economic outcome values are described. Subsequently, the hourly operation results of the system are outlined.

3.3.1 Techno-economic Outcome

The techno-economic outcomes consist of each household's optimal NPV, nominal PV- and BESS-capacity, the reference and the new discounted overall electricity bill, as well as the upfront cost.

As described in Section 3.1, if no fixed PV-BESS size is preset, there are three optimisation steps (reference, PV-only, BESS-only, PV-BESS), each with a resulting NPV. However, the final result represents only the system that demonstrates the highest value among the four alternatives. As the NPV consists of the sum of the initial cost and the difference between the reference (no investment) and the new discounted bill (see Equation 3.2), it is the direct result of the other techno-economic output values. The upfront cost is calculated on the basis of the optimal dimensions of the rooftop solar PV system and the BESS. Although the overview of the final outcomes lists only the specifications for every household's optimal NPV, ancillary output files provide further insights into the techno-economic results of each solution space.

3.3.2 System Operation

The techno-economic optimisation not only yields the previously described output values, but also provides the hourly system electricity flows and, if applicable, the state of health as well as the state of charge of PV and/or BESS for each household over the entire time horizon.

All possible electrical flows in the system (see Figure 3.2 for reference) are computed and saved after optimisation. They include flows from the PV system to the household load, grid, BESS or curtailment; from the grid to the load or BESS; from the BESS to the load or grid; as well as previously existing surplus generation to the grid, BESS or curtailment. Additionally, the state of health of the PV and BESS, as well as the battery's state of charge, are given for every time step. The entries in the time series equal zero if the technical component that is the source or destination of the electricity flow is not installed. All electricity flows and performance parameters considered are listed in Tables A.1 and A.2 in the Appendix.

3.4 Case Studies

In order to assess the overarching research question on the impact that temporal tariffs have on household prosumage, several case studies are investigated for the Australian as well as for the German context. The first part of the case studies investigates rational investment decisions, whereas in the second step operational implications under different tariff structures are focused. The case studies and the associated variables are explained in the following. Tables A.3 and A.4 in the appendix summarise the parameters that are analysed in each step.

Within every case study, flat import and flat export (FI-FE), temporal import and flat export (TI-FE), as well as temporal import and temporal export (TI-TE) tariffs are investigated.

3.4.1 Case Study 1: Rational Investment Decision

Firstly, rational investment decisions are analysed. As this work assumes economically rational decision-making, the main influences on whether to invest or not are the development of the electricity price and the upfront costs.

Case Study 1.1: Electricity Price Development

Firstly, the effect of different electricity price developments on DER-adoption is examined. Recent developments, such as Russia's invasion of Ukraine, which resulted in a significant surge in electricity prices worldwide, have increased consumer awareness of changes in electricity prices [103].

As explained in Section 3.2, the Australian electricity price (adjusted for inflation) has not undergone greater changes over the past decade. Therefore, a price development of ±0 %/a is set as the base-case in this work. Additionally, the effects of a strong annual price increase of +5 %/a as well as a strong decrease of -5 %/a are investigated. [98, 100]

Similarly, the German investigation of the impacts of electricity prices includes the base-case of a +2 %/a electricity price development, as well as a significantly stronger annual price increase of +7 %/a and a price decrease of -3 %/a. However, only the import tariff is subject to change in the German model, since the feed-in remuneration in Germany is fixed over a 20-year time period. [20, 101]

Case Study 1.2: Cost of BESS

In the second step, the impact of BESS price levels is studied in order to find a tipping point, at which the installation behaviour of households changes. As a starting point for the investigation, the NPV values of the base-case scenario in Case Study 1.1 are referenced and the gap to profitability is identified. Subsequently, three battery price levels are investigated.

In Australia, BESS prices of 300 $/kWh, 400 $/kWh and 500 $/kWh are studied.

For the German model, prices of 400 €/kWh, 500 €/kWh and 600 €/kWh are analysed.

3.4.2 Case Study 2: Impacts of Tariffs on System Operation

In the second step of the case studies, the operation of the technical system is investigated for the three electricity tariff structures presented, as well as the different price spreads thereof. It is assumed that every household installs the average PV and BESS size of the respective nation. For Australia, the installation of an 8 kWp solar PV system as well as a 12 kWh BESS is assumed [36, 36]. The German model includes a PV system of 9 kWp and a 9 kWh BESS [102, 104].

First, the implications of the FI-FE, TI-FE, and TI-TE tariffs explained in Section 3.2 are presented. These tariffs are also referred to as base tariffs in Case Study 2. Second, additional tariffs "between" flat and temporal structures are introduced in order to find a tipping point, where behavioural changes occur. As indicated in Figure 3.6, the additional tariffs are created through a linear interpolation between the flat and temporal tariff structures.

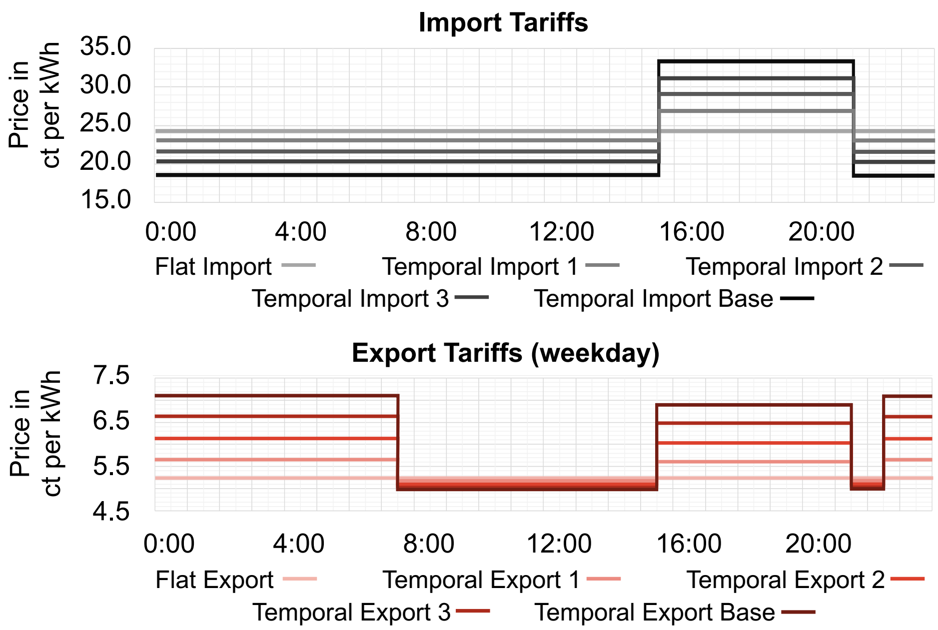

Figure 3.6: Investigated Import and Export Tariffs for Case Study 2: Impacts of Tariffs on System Operation in Australia

3.4.3 Overview of Case Studies 1 and 2

In Case Studies 1.1 and 1.2, three scenarios consisting of different electricity price developments, respectively, BESS prices are computed for the three tariff structures (FI-FE, TI-FE, and TI-TE). In Case Study 2, the system operation is analysed for the three base tariff structures, as well as six intermediary tariffs. This leads to a total of nine investigations per case study. Considering 400 households for the Australian and 72 households for the German context, each case study encompasses a total of 3,600 and 648 household results, respectively. In total, almost 12,750 household results are optimised. Note that in Case Studies 1.1 and 1.2, three solution spaces (PV-only, BESS-only, PV-BESS) are calculated for each household, with the overall household result yielding the maximum NPV. Table 3.4 gives an overview of the case studies and the underlying assumptions for each country.

Table 3.4: Overview of the Australian and German Case Studies

Case Studies Australia		**Variations**	
AUS.1. Rational Investment for FI-FE, TI-FE and TI-TE			
AUS.1.1 El. Price Development	-5 %/a	±0 %/a	+5 %/a
AUS.1.2 BESS Pricing	300 $/kWh	400 $/kWh	500 $/kWh
A.2. Impacts of Tariffs on System Operation			
AUS.2 Tariff Variations	FI-FE	TI-FE	TI-TE
	(base)	(base, 1, 2, 3)	(base, 1, 2, 3)
Case Studies Germany		**Variations**	
GER.1. Rational Investment for FI-FE, TI-FE and TI-TE			
GER.1.1 El. Price Development	-3 %/a	+2 %/a	+7 %/a
GER.1.2 BESS Pricing	400 €/kWh	500 €/kWh	600 €/kWh
GER.2. Impacts of Tariffs on System Operation			
GER.2 Tariff Variations	FI-FE	TI-FE	TI-TE
	(base)	(base, 1, 2, 3)	(base, 1, 2, 3)

The specific values for Australia and Germany on the FI-FE, TI-FE and TI-TE tariffs, as well as the intermediary tariffs, are listed in Tables A.5 and A.6, respectively.

4 Results and Discussion

In this chapter, modelling results are presented and their implications are critically discussed. First, the Australian modelling outcomes are considered in Section 4.1, followed by an investigation of similarities and differences for the German context in Section 4.2.

The results for each country are subdivided into two case studies. Case Study 1 focusses on economically rational investment decisions in PV and/or BESS, whereas Case Study 2 investigates the technical system operation in detail. Within each case study, the effects of flat import and flat export (FI-FE), temporal import and flat export (TI-FE), as well as temporal import and temporal export (TI-TE) tariffs are considered.

4.1 Modelling Results Australia

4.1.1 Case Study AUS.1: Rational Investment Decision

In the following, the impact of different electricity tariff structures on economically rational investment decisions is investigated for the Australian context. In Case Study AUS.1.1, the effect of different electricity price developments is focused, while Case Study AUS.1.2 investigates the impacts that BESS pricing has.

AUS.1.1 Electricity Price Development

As explained in Section 3.2, according to the regression analysis, no changes in the electricity price are expected. Therefore, $\pm 0\,\%/\text{a}$ is set as the base scenario which is first elaborated, followed by an analysis of a strong price increase of $+5\,\%/\text{a}$ and a significant decline of $-5\,\%/\text{a}$.

If electricity prices are not subject to change in the next decade, it is expected that around 12 % of the investigated households that are subject to a FI-FE tariff invest in a PV system, while only 7 % do so in the TI-FE and TI-TE cases. No household invests in a BESS. This finding suggests that for current upfront costs and electricity prices, temporal tariffs reduce PV adoption and, in the context of this study, BESS typically do not break-even within their operational lifespan. Furthermore, a consistent set of households installs PV across all tariff structures. A profitable investment under any of the temporal tariffs is also always profitable under the flat tariff structure. Referring to Table 4.1, a median nominal capacity of 7.6 kWp is installed under the flat tariff, which is slightly lower than the median of 7.8 kWp for the temporal tariff cases.

Table 4.1: Techno-Economic Key Results with Median Values only Corresponding to installing Households (AUS.1.1, ±0 %/a)

El. Price Scenario [%/a]	Tariff Structure [-]	PV-only Inst. Share [%]	PV-BESS Inst. Share [%]	median PV size [kWp]	median NPV [$]
±0	FI-FE	12.3	-	7.6	645
±0	TI-FE	6.8	-	7.8	565
±0	TI-TE	6.8	-	7.8	545

Figure 4.1 shows the size of the PV installation and the annual electricity consumption of each investigated household, suggesting a strong correlation between high electricity demand and the profitability of a PV investment. The lowest annual consumption of a household investing in the ±0 %/a scenario is 5,600 kWh/a across all tariff structures. However, households that have a higher demand do not necessarily decide to invest, as seen in Figure 4.1. The average underlying load profiles for summer and winter that depict which household opts for a PV system are shown in Figure A.1, confirming the observation of a generally higher electricity consumption. It is notable that in particular daytime consumption is significantly higher for the average households installing compared to non-installing households, whereas consumption during the evening and night does not differ as much. However, the TI-FE and TI-TE tariffs yield very similar results, since not only do exactly the same households invest in solar PV, but the sizes of the installed systems differ by less than 0.1 kWp.

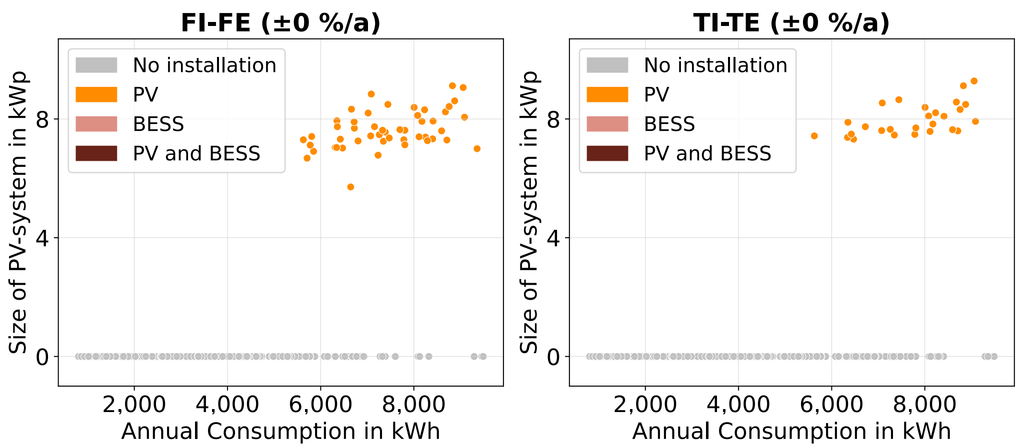

Figure 4.1: Installed PV System Size over Annual Household Consumption for FI-FE and TI-TE tariffs (AUS.1.1, ±0 %/a)

The strong similarity between TI-FE and TI-TE investigations applies not only to the technical side but also to the NPV findings. In Figure 4.2, the NPV is depicted for the set of consistent households that install under all investigated tariff structures and the additional ones, only investing in a PV system for flat tariff structures. Although Table 4.1 already suggests that the FI-FE tariff enables higher profitability, this finding is reinforced when distinguishing between the consistent set of households that always invest, and the additional ones that only reach profitability for the FI-FE tariff. For the consistent set, the median NPV of the FI-FE tariff lies around 1,100 $, leading to a median NPV gap of more than 500 $ between the same group of households under flat and temporal tariffs. In contrast, the difference between TI-FE and TI-TE lies around 20 $. Therefore, it is evident that the import tariff is the primary economic driver of the installation behaviour.

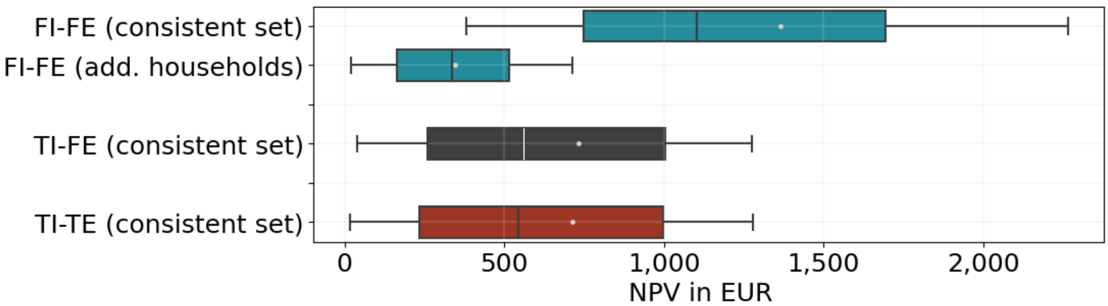

Figure 4.2: NPV for the Set of Consistent and Additional Households investing in a PV system (AUS.1.1, ± 0 %/a)

Interestingly, even with no PV-BESS investment, the temporal tariffs generally produce lower (reference) electricity costs than the flat tariff for the investigated households. Note that no behavioural change is assumed. For the time horizon of 10 years and the assumption of no change in electricity prices, the average discounted reference bill for all households is around 250 $ lower under the temporal tariff structure than under the flat tariff.

However, if a PV-only system is installed, the reverse is observed. When comparing the average discounted electricity bill of households that install a PV-only system, the FI-FE electricity bill is approximately 225 $ lower than the TI-FE and TI-TE one. The differences between the TI-FE and TI-TE tariffs are minor (<10 $). As the same households install very similar system sizes under temporal import tariffs, this difference is mainly caused by the diverging feed-in tariffs, supporting the argument that the import tariff is the primary driver for investment.

Regarding technical system operation, no BESS installation means that surplus electricity generation is either fed into the grid or curtailed, leading to high feed-in rates during the day and residual demand from the grid in the afternoon. This, in turn, results in a net load profile that resembles the duck curve. Figure 4.3 illustrates this phenomenon, showing the annual net load for an average household under the FI-FE tariff that invests in a PV system. Due to the large PV-sizes and the lack of BESS installations, all households investigated for the base-scenario of ±0 %/a become electricity net-exporters, meaning that they feed more electricity into the grid than their annual import.

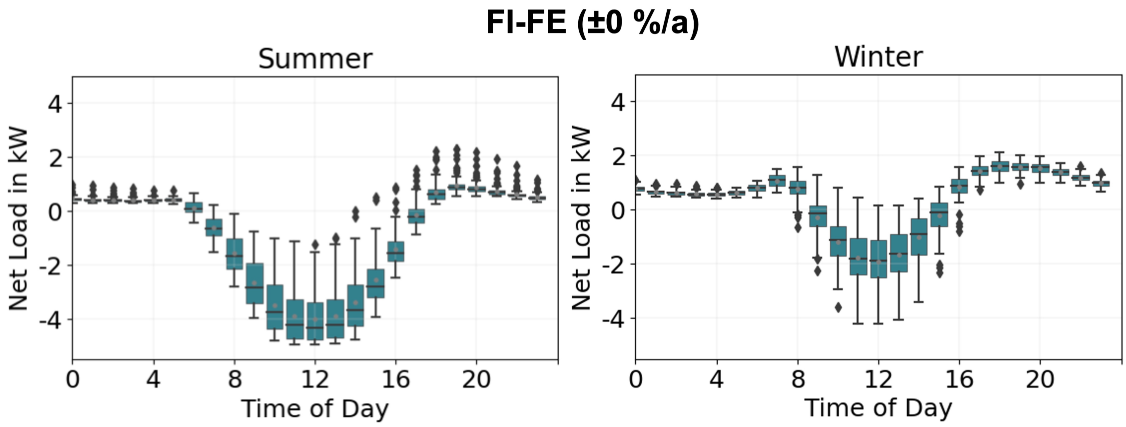

Figure 4.3: Average Hourly Net Load Distribution across all Households installing a PV system with a FI-FE Tariff Structure in Summer and Winter (AUS.1.1, ±0 %/a)

Concerning the implications that increasing and decreasing electricity prices have on DER adoption, size, and profitability, Table 4.2 lists the key results for scenarios +5 %/a and -5 %/a.

Table 4.2: Techno-Economic Key Results with Median Values only Corresponding to Installing Households (AUS.1.1, +5 %/a and -5 %/a)

El. Price Scenario [%/a]	Tariff Structure [-]	PV-only Inst. Share [%]	PV-BESS Inst. Share [%]	median PV size [kWp]	median NPV [$]
+5	FI-FE	16.8	-	6.7	1,075
+5	TI-FE	12.3	-	6.9	680
+5	TI-TE	12.3	-	6.9	665
-5	FI-FE	10.5	-	8.6	415
-5	TI-FE	5.0	-	8.8	275
-5	TI-TE	6.0	-	8.9	290

In comparison to the base-scenario (±0 %/a), a strong electricity price increase leads to a surge in PV installations and NPV, while decreasing prices lead to a reduction. BESS installations remain unprofitable.

The finding in the base scenario (±0 %/a) that there is a consistent set of households installing under all tariff structures, with additional households installing only in the flat-tariff case, generally also holds for the increasing and decreasing price development scenarios. The only exceptions are two of the 400 households investigated in the -5 %/a scenario, which reached a positive NPV (< 20 $) for the TI-FE tariff and not for the TI-TE tariff.

Similarly to the findings in the base scenario, the average load profile of households that invest in a PV system in the +5 %/a and -5 %/a scenarios exhibit particularly high daytime consumption before investment. In the event of a rise in electricity prices, the observed daytime load difference between investing and non-investing households becomes less pronounced, as the investment becomes viable for an increasing number of households. The reverse is observed for a decrease in electricity price development.

Furthermore, it is observed that the gap between the median NPVs of flat and temporal tariffs is reduced due to the additional households only investing under the flat tariff structure. Although the median NPV for all households installing a PV system in the +5%/a scenario shows only a difference of approximately 410 $ between flat and temporal tariffs, this number increases to approximately 750 $ when only considering the consistent set of households. The same principle holds for the -5%/a scenario, where the median NPV difference increases from around 140 $ (all households investing) to more than 540 $ (consistent set).

Due to the investment in relatively large PV systems, households generally become net-exporters to the grid. As batteries are never installed, the net load of the household closely reflects the duck curve behaviour with a high-power feed-in during the midday and a steep increase in demand in the afternoon. In all scenarios, the average self-consumption of generated solar energy is between 28 % and 32 %, while self-sufficiency lies between 41 % and 47 %, underlining the continued dependence on the grid during the high demand periods in the afternoon and early evening.

In Figure 4.4, the average annual electricity flows for a household installing solar PV system are compared across all scenarios.

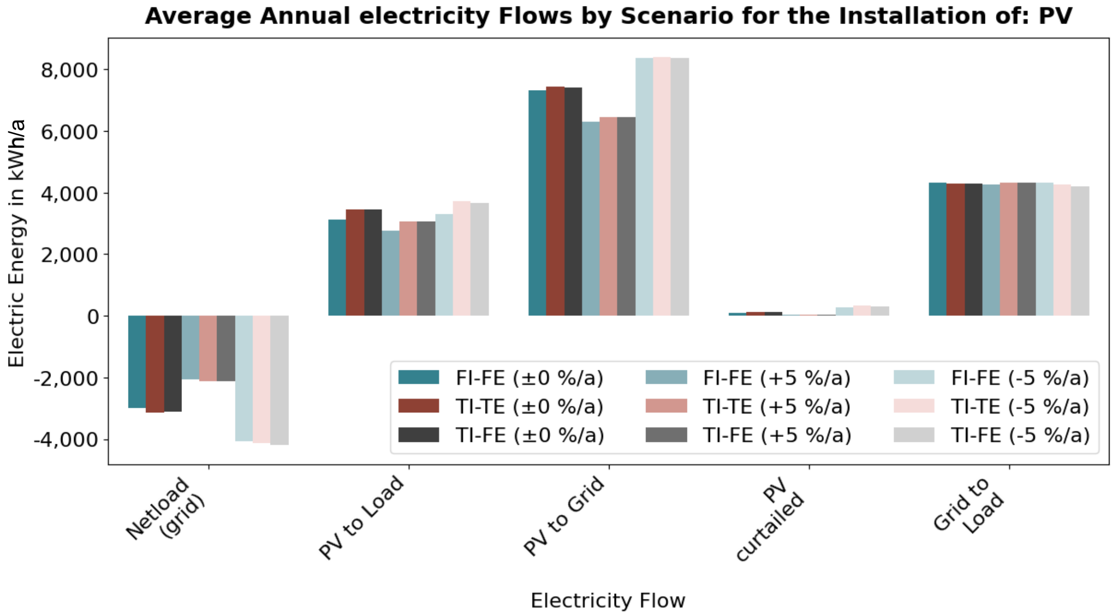

Figure 4.4: Annual Electricity Flows across all Scenarios for an average Household installing a PV system (AUS.1.1)

AUS.1.2 BESS-Pricing

After examining the effects that different electricity price developments have on household DER adoption, it becomes apparent that for current battery prices, an investment in BESS is generally not profitable within the system's operational lifespan. However, small-scale BESS investment is an important component of the energy transition. Therefore, this case study investigates the required battery price levels to incentivise households to invest in BESS under the assumption that the price of electricity does not change over the next decade. The aim of the investigation is to identify a tipping point, where investment behaviour starts to change, and to analyse subsequent implications. In this case study, battery prices of 300 $/kWh, 400 $/kWh and 500 $/kWh are set, in contrast to the BESS price of 1.300 $/kWh in Case Study AUS.1.1. PV prices remain the same. First, the 400 $/kWh case is evaluated, followed by an analysis of variations in cases with higher and lower BESS prices.

Table 4.3 summarises the key results of the three tariff structures investigated for a battery price of 400 $/kWh. In contrast to Case Study AUS.1.1, overall installation numbers are very similar for flat and temporal tariffs, with around 12.3 % and 13.3 % of households investing, respectively. It is important to note that the median values only refer to households installing a PV system or PV-BESS and that it is not distinguished between installation types, i.e., PV-only and PV-BESS.

Table 4.3: Techno-Economic Key Results with Median Values only Corresponding to Installing Households (AUS.1.2, 400 $/kWh)

BESS-Price Scenario [$/kWh]	Tariff Structure [-]	PV-only Inst. Share [%]	PV-BESS Inst. Share [%]	median PV size [kWp]	median BESS size [kWh]	median NPV [$]
400	FI-FE	1.8	10.5	8.1	3.0	650
400	TI-FE	0.3	13.0	8.5	5.0	675
400	TI-TE	0.3	13.0	8.5	5.2	680

Given the initial conditions of tariff structures and price developments in Case Study AUS.1.1 (±0 %/a), with an additional reduction in BESS prices, the same group of households as in case study AUS.1.1 (±0 %/a) opt for adopting DER. In the FI-FE case, the exact same set invests, although for approximately 85 % of installing households, a PV-BESS becomes the most profitable option, while 15 % stay with a PV-only system. In the context of temporal tariffs, the implementation of DER is not only profitable for households that have already invested in AUS.1.1. (±0 %/a), but also exhibits a nearly twofold increase in adoption rates. Among households installing, PV-BESS significantly dominates the investment choice for temporal tariff structures.

10.25 % of all the households investigated choose a PV-BESS investment, regardless of the tariff structure applied. Household PV systems under temporal tariffs are typically slightly larger compared to those under the flat tariff. The difference in size, however, becomes more pronounced for the BESS. More than three out of four households install the minimum BESS size of 3 kWh in the FI-FE case, while less than 5 % do so when temporal tariffs are applied (Figures A.2 and A.3).

In contrast to the overall median NPV that differs by less than 30 $ over the tariff structures, the consistent set's NPV is more than 245 $ larger for temporal tariff structures than for flat tariffs. However, the additional households that adopt DERs for the TI-FE and TI-TE tariffs have significantly lower NPVs (Figure A.4).

As PV-only installations play a subordinate role in all tariff structures in this investigation, the technical implications assessment focusses on households adopting PV-BESS.

Figure 4.5 depicts the normalised net load of households under the FI-FE tariff who install a PV-BESS in summer and in winter. The figure shows the average hourly net load distribution over all installing households for every hour of each day during the specific season. In the

FI-FE case, the classic duck-curve shaped net load can be identified. During summer, the feed-in is particularly high, although 5 kW is never exceeded because this value represents the maximum feed-in power allowed in Victoria. As flat tariffs do not encourage households to store energy for use at a later point in time, the BESS operates on the basis of the simple (dis-)charging algorithm, storing excess solar generation and discharging when demand falls below generation.

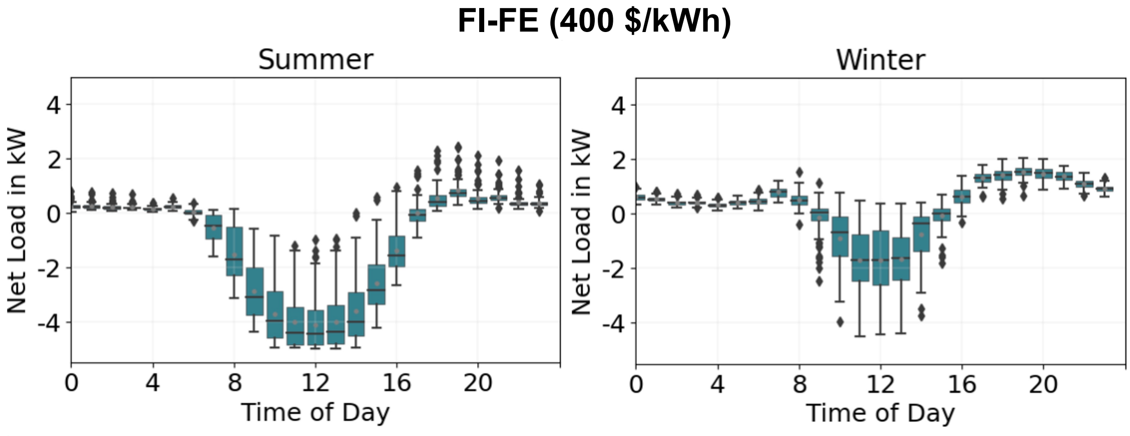

Figure 4.5: Average Hourly Net Load Distribution across all Households installing PV-BESS with a FI-FE Tariff Structure in Summer and Winter (AUS.1.2, 400 $/kWh)

Figure 4.6 shows the average net load for households that install PV-BESS and are subject to the TI-TE tariff in this scenario. The vertical lines in the graph indicate the points in time when the tariffs are subject to change. The dark grey lines represent changes in the import tariff, while the red lines show when the export tariff varies.

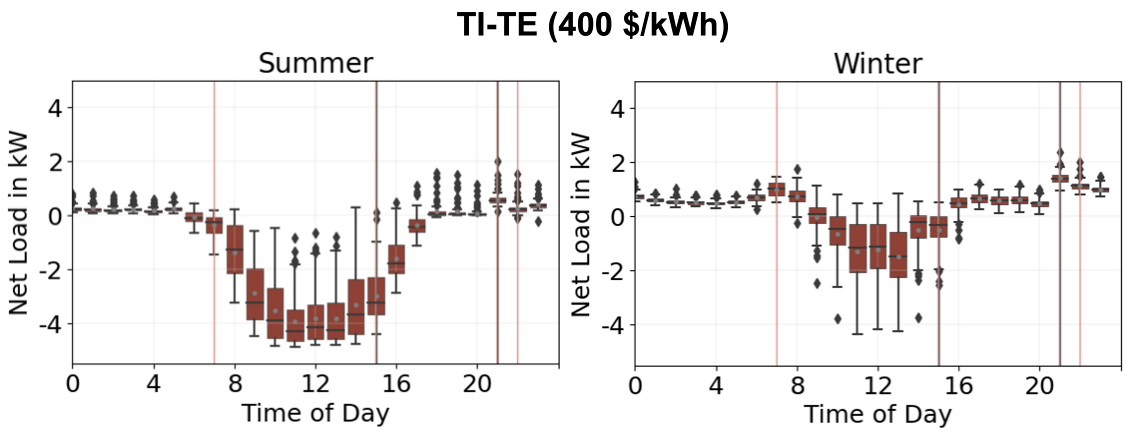

Figure 4.6: Average Hourly Net Load Distribution across all Households installing PV-BESS with a TI-TE Tariff Structure in Summer and Winter (AUS.1.2, 400 $/kWh)

Through a TI-FE or TI-TE tariff, where importing electricity from the grid during the peak price periods from 3 pm to 9 pm is very expensive, incentives are created for households to reduce demand during that period of time. When comparing Figure 4.5 and Figure 4.6, it can be seen that households that are subject to a temporal import tariff reduce their demand from the grid in peak price periods and start increasing electricity drawn from the grid after 9 pm. However, when comparing the two tariff structures, it is important to bear in mind that households with temporal tariffs typically opt for larger PV-BESS installations.

The average net load profile of households subject to the TI-FE and TI-TE tariffs is very similar (see Figure A.5 for reference), indicating that temporal import tariffs are the main driver for the adoption and operation of BESS. This finding suggests that the main investment purpose under current electricity prices and DER costs is to increase self-consumption and self-sufficiency.

The key results for lower and higher BESS prices of 300 $/kWh and 500 $/kWh are listed in Table 4.4.

Table 4.4: Techno-Economic Key Results with Median Values only Corresponding to Installing Households (AUS.1.2, 300 $/kWh and 500 $/kWh)

BESS-Price Scenario [$/kWh]	Tariff Structure [-]	PV-only Inst. Share [%]	PV-BESS Inst. Share [%]	median PV size [kWp]	median BESS size [kWh]	median NPV [$]
300	FI-FE	-	19.0	9.0	7.1	870
300	TI-FE	-	20.5	8.7	6.6	820
300	TI-TE	-	20.0	8.7	6.7	830
500	FI-FE	12.3	-	7.6	-	645
500	TI-FE	0.3	9.0	8.4	3.4	635
500	TI-TE	0.3	9.0	8.5	3.5	630

When prices of 300 $/kWh are offered, approximately every fifth household investigated installs a PV-BESS system, regardless of the tariff structure. Technical and economic outcomes are relatively similar for all households that invest, even more so over the consistent subset of households that install under any of the tariff structures. Regarding the operation of the technical system, the fundamental observations for the 400 $/kWh scenario still hold, but are reinforced due to larger BESS sizes. Furthermore, it is noticeable that the grid demand in the afternoon is also reduced for households with the FI-FE tariff, as they opt for larger batteries that continue to discharge during high demand periods. Nevertheless, this effect is much more pronounced for the TI-FE and TI-TE tariffs.

However, for battery prices of 500 $/kWh, BESS adoption is no longer profitable for households subject to the FI-FE tariff and the PV-only investment behaviour from Case Study AUS.1.1 (±0 %/a), which does not include any price reductions, is repeated. However, under temporal tariffs, adopting PV-BESS is still profitable for almost every tenth household investigated. The technical and economic results for households subject to the TI-FE and TI-TE tariffs show strong similarities. Again, observations on system operation from the 400 $/kWh scenario still hold, although less pronounced in the 500 $/kWh scenario due to the smaller dimensions of BESS.

It should be noted that over the households investing in each of the scenarios, the investment in DER yields the best NPV under temporal tariff structures in approximately 60 % of the cases for a BESS-price of 300 $/kWh and 400 $/kWh and in only around 5 % when the BESS costs 500 $/kWh. This finding underlines the critical importance of BESS pricing, that it not only influences BESS adoption but also affects which tariff structure is the most beneficial.

While PV sizes decrease by less than 5 % for temporal tariffs between the BESS price scenarios, the size of the BESS is almost halved when comparing the 300 $/kWh with the 500 $/kWh scenario. This indicates that the BESS is sized more according to its price than according to the dimensions of the PV system.

The findings related to system operation are supported by the average annual electricity flows of households installing PV-BESS in all scenarios, as depicted in Figures 4.7 and 4.8. Figure 4.7 illustrates how net load, as well as grid demand and BESS operation, are affected by tariff structures and BESS pricing.

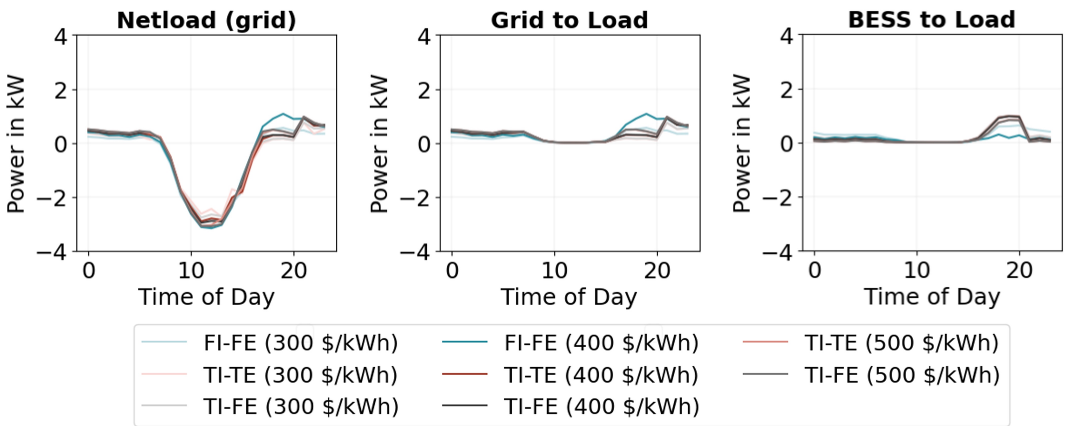

Figure 4.7: Power Flows (Net Load, Grid to Load, BESS to Load) of Households installing PV-BESS, representing the Yearly Average over a 24-Hour Period for all Tariff Structures and BESS-Prices Investigated (AUS.1.2)

Net load impacts are particularly striking for the difference between temporal and flat import tariffs, as BESS serve most of the load during peak price periods when operated under temporal import tariffs. However, for sufficiently large PV systems in combination with BESS, similar effects can be achieved, as the FI-FE scenario (300 $/kWh) demonstrates.

When focussing on the electric flows from the solar PV system to the grid, BESS and load, shown in Figure 4.8, the effect of the temporal export tariff can be discerned. As soon as a BESS is sufficiently large, there is a slight drop in electrical input around 2 pm, so that a higher feed-in may be achieved after 3 pm, when the remuneration is more profitable. However, overall feed-in from the BESS is relatively small, as the system's size is predominantly designed to minimise demand from the grid.

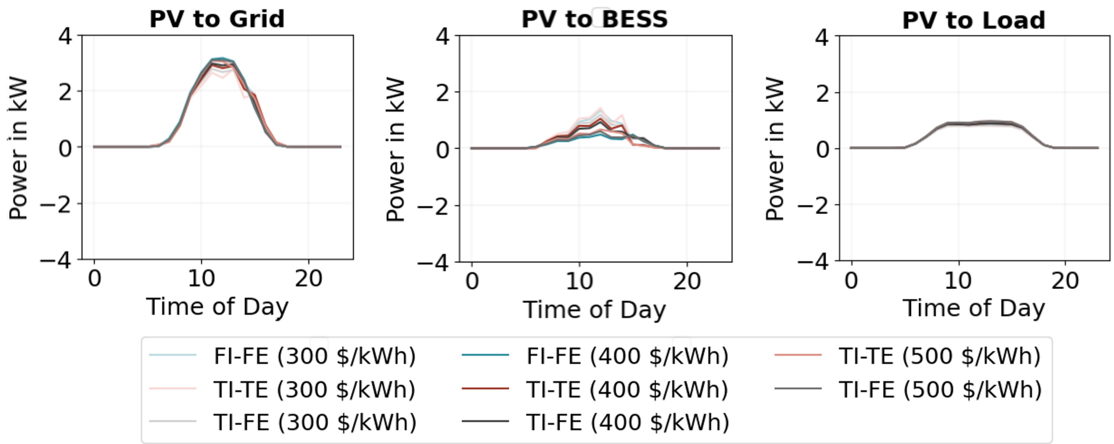

Figure 4.8: Power Flows (PV to Grid, PV to BESS and PV to Load) of Households installing PV-BESS, representing the Yearly Average over a 24-Hour Period for all Tariff Structures and BESS-Prices Investigated (AUS.1.2)

Although grid demand is significantly influenced by the introduction of temporal tariffs, grid feed-in is not subject to major behavioural changes. As the price differences for the temporal import tariff are significantly larger than the ones for the export tariff, the system operation focusses on optimising electricity imports first and export behaviour second.

As seen in Table 4.5, compared to Case Study AUS.1.1 (±0 %), increases in self-sufficiency (10 % to 15 %) and self-consumption (15 % to 31 %) are achieved by installing a PV-BESS under lower battery costs in Case Study AUS.1.2. As battery adoption and optimal system size grow with declining BESS prices, the highest independence from the grid is reached for the lowest-cost BESS.

Table 4.5: Self-Consumption and Self-Sufficiency Values of Households Installing PV-BESS for Different BESS Price Scenarios and Tariff Structures (GER.1.2)

	300 $/kWh			400 $/kWh			500 $/kWh		
	FI-FE	TI-FE	TI-TE	FI-FE	TI-FE	TI-TE	FI-FE	TI-FE	TI-TE
Self-cons.	44 %	45 %	46 %	38 %	42 %	43 %	-	40 %	40 %
Self-suff.	73 %	71 %	72 %	57 %	65 %	65 %	-	60 %	60 %

4.1.2 Case Study AUS.2: Impacts of Tariffs on System Operation

While rational investment behaviour and subsequent system operation were analysed in Case Study AUS.1, Case Study AUS.2 only investigates system operation, given that every household installs an average-sized PV system and BESS of 8 kWp and 12 kWh, respectively. The rationale for adopting this approach lies in the notable trend that Australian households opt for significantly larger BESS than what the optimisation results obtained in case study AUS.1 suggest. This shift, in turn, has a significant impact on the dynamics of the system operation and the possibility of responding to different price signals. Firstly, effects of the FI-FE, TI-FE and TI-TE tariff structures that were also used in case study AUS.1 are analysed. In a second step, additional tariffs are introduced that represent intermediary steps between flat and temporal structures (see Section 3.4.2). The examination of these additional tariffs aims to generate insights into the point at which the economically rational system operation starts to respond to electricity price signals.

As the same PV-BESS sizes are installed in all scenarios, the techno-economic outcomes do not vary to a large extent. Under current electricity and DER prices, no household in the investigation reaches a positive NPV. With an upfront cost of 23,640 $, and discounted overall savings on the electricity bill of around 9,100 $ on average, PV-BESS investments of this dimension are far from profitable for the investigated time horizon of 10 years. Depending on the investigated tariff structure, between 80 % and 85 % of households produce negative electricity bills with the installation of PV-BESS. Generally, households subject to the TI-TE export tariff yield the lowest electricity bills, with an average cost advantage of approximately 420 $ over the FI-FE tariff.

The electricity demand from the grid is considerably reduced, as households under all tariff structures reach a self-sufficiency of around 85 %, which means that they import only 15 % of their total electricity consumption from the grid. Additionally, they only use around one third of their self-generated electricity for self-consumption. Around 40 % of self-consumed electricity originates directly from the PV system and the rest is stored in the BESS between generation and consumption.

For the investigation of the system operation of households under the FI-FE, TI-FE, and TI-TE tariffs, the main findings of case study AUS.1.2 still hold. However, due to the assumption that all households install significantly larger PV-BESS, the operational implications become much more pronounced.

Figure 4.9 shows the average net load per day of all households investigated subject to the FI-FE tariff in summer and winter.

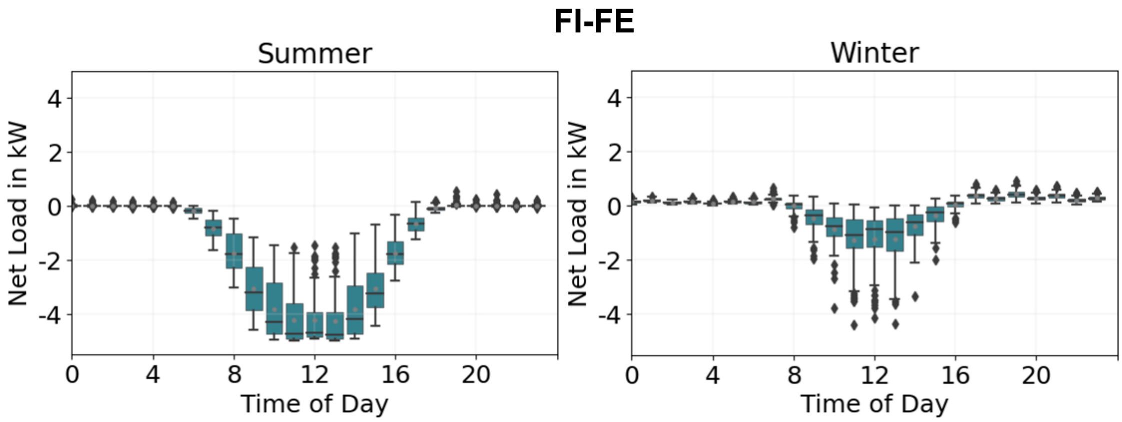

Figure 4.9: Average Hourly Net Load Distribution across all Households with an average-sized PV-BESS under a FI-FE Tariff Structure in Summer and Winter (AUS.2)

Since there are no incentives to adapt the timing of temporal electricity imports or exports under the FI-FE tariff, the BESS only purpose is to satisfy the household electricity demand. Surplus generation that exceeds household consumption is fed into the grid immediately, avoiding efficiency losses and cyclic ageing of the BESS. Due to the large size of the system, imports from the grid during the afternoon and night are significantly reduced.

The average daily net load of households subject to the TI-FE tariff is shown in Figure 4.10. Due to the temporal import tariff applied in this case, the demand from the grid in peak price periods from 3 pm to 9 pm is reduced further than for the FI-FE case. However, as the set PV-BESS dimensions are able to satisfy most of the electricity demand in either case, particularly during the sun-rich summer months, this reduction becomes more apparent for the winter months. Especially, the increase in electricity imports after 9 pm showcases the financially incentivised discharging behaviour of the BESS during the high-price period of the TI-FE case. As flat export tariffs are applied in both cases, the feed-in behaviour does not differ significantly between the FI-FE and TI-FE cases.

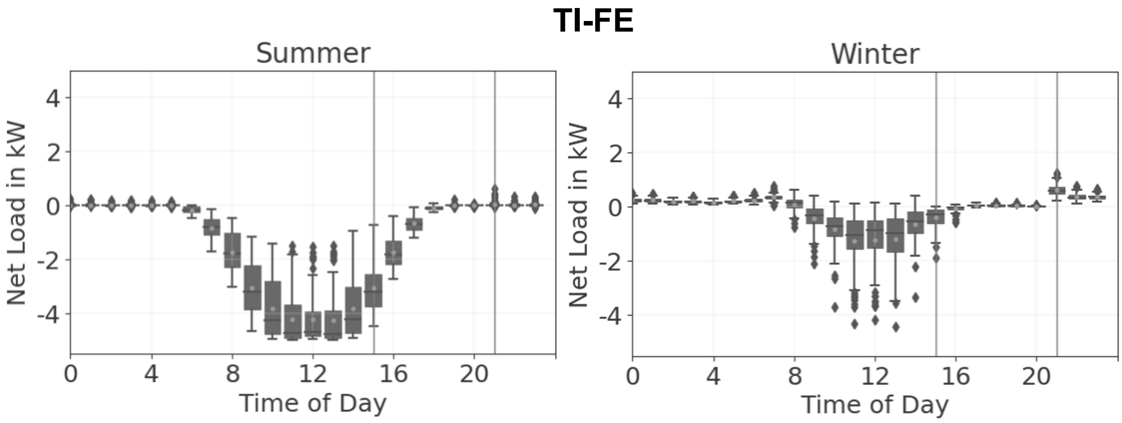

Figure 4.10: Average Hourly Net Load Distribution across all Households with an average-sized PV-BESS under a TI-FE Tariff Structure in Summer and Winter (AUS.2)

However, when temporal export tariffs are introduced, electricity feed-in behaviour changes with larger BESS capacities. Figure 4.11 illustrates the average hourly net load of households subject to the TI-TE tariff for summer and winter. As with the TI-FE tariff, grid imports during peak price periods between 3 pm and 9 pm are avoided as much as possible. However, due to the low remuneration of feed-in during midday and the higher export prices in the evening and at night, electricity exports during the day are reduced, and BESS capacity that is not needed for self-consumption is deployed to discharge during time periods with high feed-in compensation. In particular during the summer months, when there is ample solar generation, households contribute to night-time electricity production. As the price for feed-in drops at 7 am, there is a notable increase in electricity exports one hour before, which may be attributed to the BESS freeing up storage capacity for the next charging process.

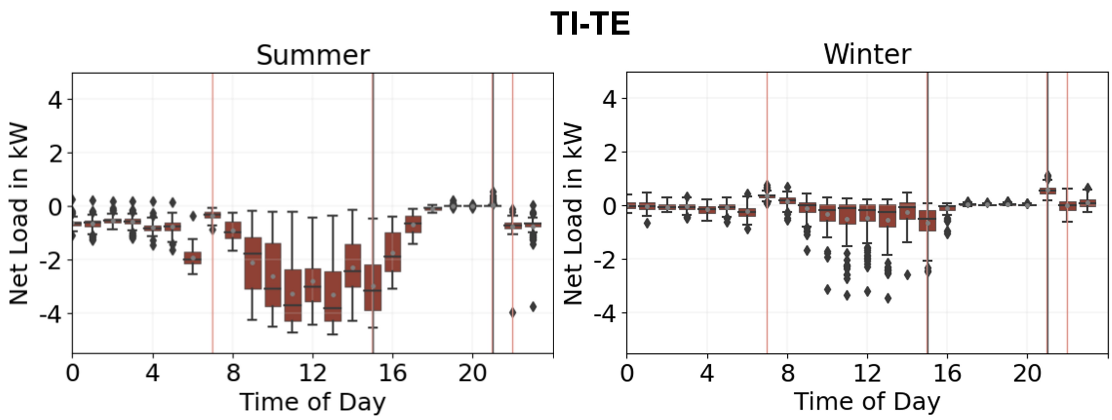

Figure 4.11: Average Hourly Net Load Distribution across all Households with an average-sized PV-BESS under a TI-TE Tariff Structure in Summer and Winter (AUS.2)

These findings are underlined by Figure 4.12, showing the yearly average power flows for the FI-FE, TI-FE and TI-TE tariffs of all households over the course of one day. Power flows from the PV system to the grid and BESS, as well as from the BESS to the grid, are not affected by the temporal import tariff, which is why the FI-FE and TI-FE tariffs show the same system operation behaviour. However, for temporal import tariffs, the power fed into the grid is significantly reduced during the middle of the day, charging the BESS to export electricity during time periods with a high export tariff. The power flows from the grid to the BESS for precharging are negligible under all tariff structures.

As the area under the line-plots in the graph "PV to BESS" represents the energy flowing through the BESS on an average day, it is evident that significantly more of its capacity is being used for the TI-TE case than for the flat export ones.

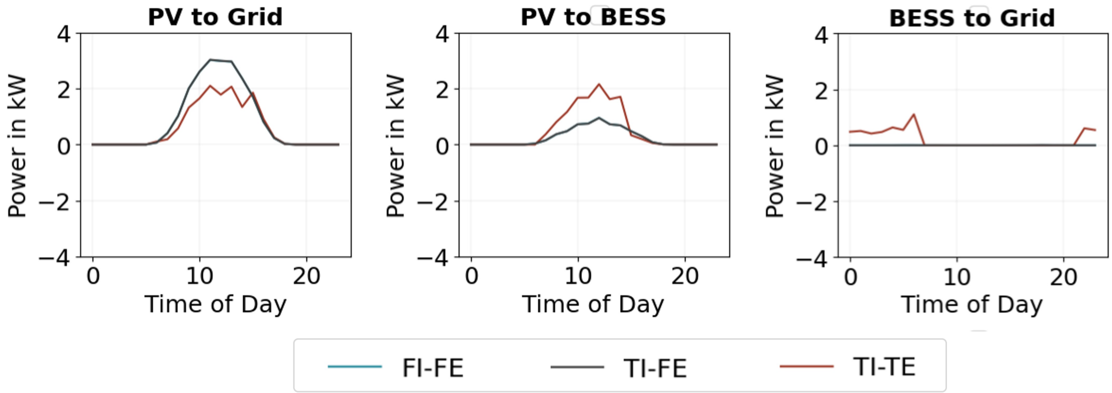

Figure 4.12: Power Flows (PV to Grid, PV to BESS and BESS to Grid) for the FI-FE, TI-FE and TI-TE Tariffs, representing the yearly average over a 24-hour period (AUS.2)

This is affirmed in Figure 4.13, showing the battery's yearly average state of charge over a 24-hour period for the FI-FE, TI-FE and TI-TE cases. It is important to note that this figure illustrates the average daily SoC of all households and on all days throughout the year. SoC profiles, as well as power flow patterns, may vary significantly due to individual consumption patterns and daily fluctuations in solar generation. However, the data indicate clear trends in the usage of BESS among tariff structures. Although almost the entire capacity is used on a regular basis under the TI-TE tariff, BESS usage of households subject to flat export tariffs is limited to only a proportion of it. This insight reveals that precise BESS dimensioning is crucial, as under flat export tariffs there might exist significant untapped potential during the majority of the year. Temporal export tariffs, however, offer a financial incentive to leverage extra capacity by exporting electricity during periods with higher feed-in remuneration. Nonetheless, profitability remains a key consideration, as the additional investment might not be offset by the increased feed-in tariff.

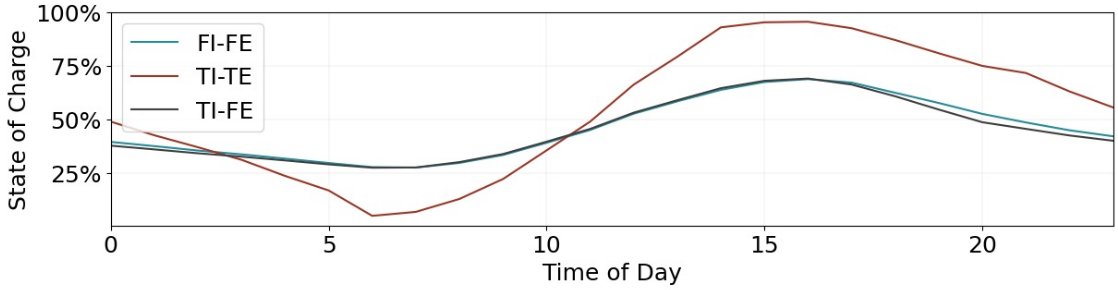

Figure 4.13: State of Charge of the BESS, representing the yearly average over a 24-hour period for the FI-FE, TI-FE and TI-TE cases (AUS.2)

Additionally, it should be considered that batteries are subject to cyclic ageing, leading to a slightly increased (average) capacity loss in batteries under the TI-TE tariff. During the first year of operation, BESS under flat export tariffs show an average capacity loss of around 0.42 kWh, while TI-TE leads to an average decline of around 0.48 kWh. However, 0.3 kWh of this degradation is attributed to calendric ageing.

Apart from techno-economic implications for the households themselves, their (cumulative) system operation has significant impacts on the electricity grid. As the overarching goal of temporal tariffs is to flatten the duck curve and integrate solar generation more efficiently into the energy system, it is crucial to understand how tariffs influence the household's interaction with the grid. Since the duck curve fundamentally consists of a high feed-in during the day, followed by a rapid increase in demand, both of these phenomena need to be considered. However, in particular for the PV-BESS sizes considered in this case study, grid demand is drastically reduced over all tariff structures. Only during the winter months there is still considerable electricity import from the grid.

Figure 4.14 illustrates the frequency per year with which certain net load intervals occur for an average household over a 24-hour period for the FI-FE and TI-FE tariffs. In both cases, electric power exceeding 4.0 kW is fed into the grid with high frequency during the midday. During around 40 % of the year, the highest possible feed-in interval is reached between 11 am and 1 pm.

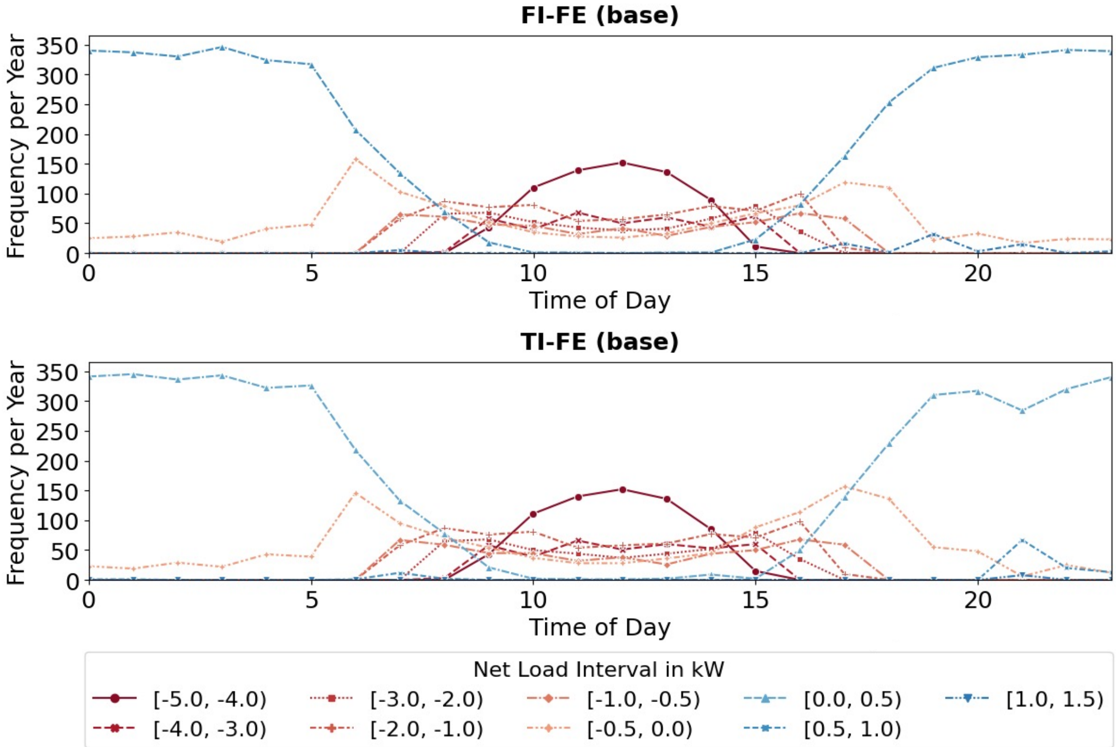

Figure 4.14: Annual Frequency Distribution of Import and Export Power Intervals for an Average Household subject to the FI-FE and TI-FE Tariffs over a 24-hour Period (AUS.2)

However, as seen in Figure 4.15, if temporal import tariffs are introduced, the distribution of power frequencies changes significantly.

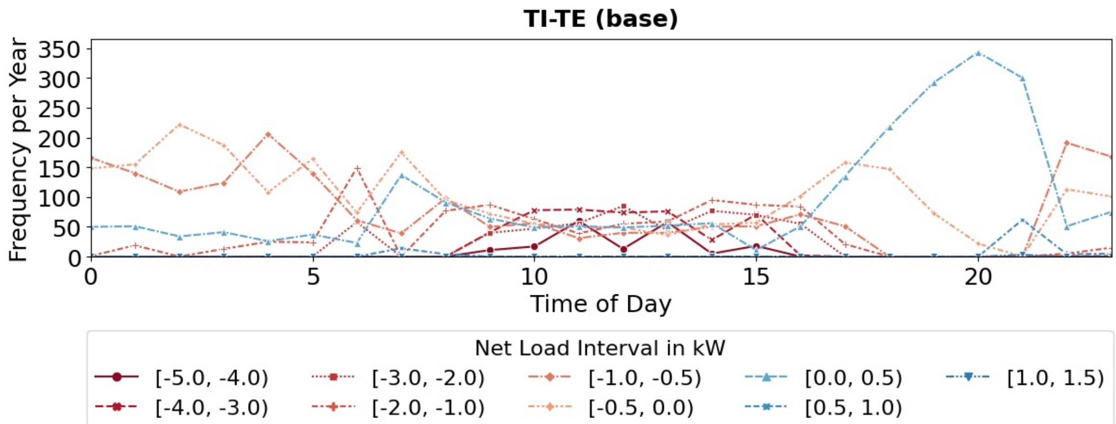

Figure 4.15: Annual Frequency Distribution of Import and Export Power Intervals for an Average Household subject to the TI-TE Tariff over a 24-hour Period (AUS.2)

Compared to the frequency distributions for flat export tariffs, there are significantly fewer instances of high-power feed-in for temporal export tariffs. The number of times that the highest possible feed-in interval is reached between 11 am and 1 pm under the TI-TE tariff is more than halved compared to the case with flat export tariffs. It is notable that the magnitude at which the power is fed into the grid is generally decreased and spread over the entire day. As mentioned above, households start contributing to nighttime electricity production due to high feed-in tariffs after 9 pm. As the sharp difference between daytime generation and afternoon demand causes the duck curve and subsequently potential grid instabilities, the insight that households not only have the potential to flatten this behaviour significantly but also to contribute to electricity generation capacities during time periods without solar radiation is crucial for the realisation of the energy transition.

In order to fully understand at which point households start responding to the price signals, intermediary tariffs between flat and temporal tariffs are investigated. The index 1 represents that the interim tariff is closer to the flat tariff, 2 indicates that it is in the middle between flat and temporal, and 3 that it is closer to the temporal tariff.

Figure 4.16 shows the annual electricity flows by tariff structure for an average household.

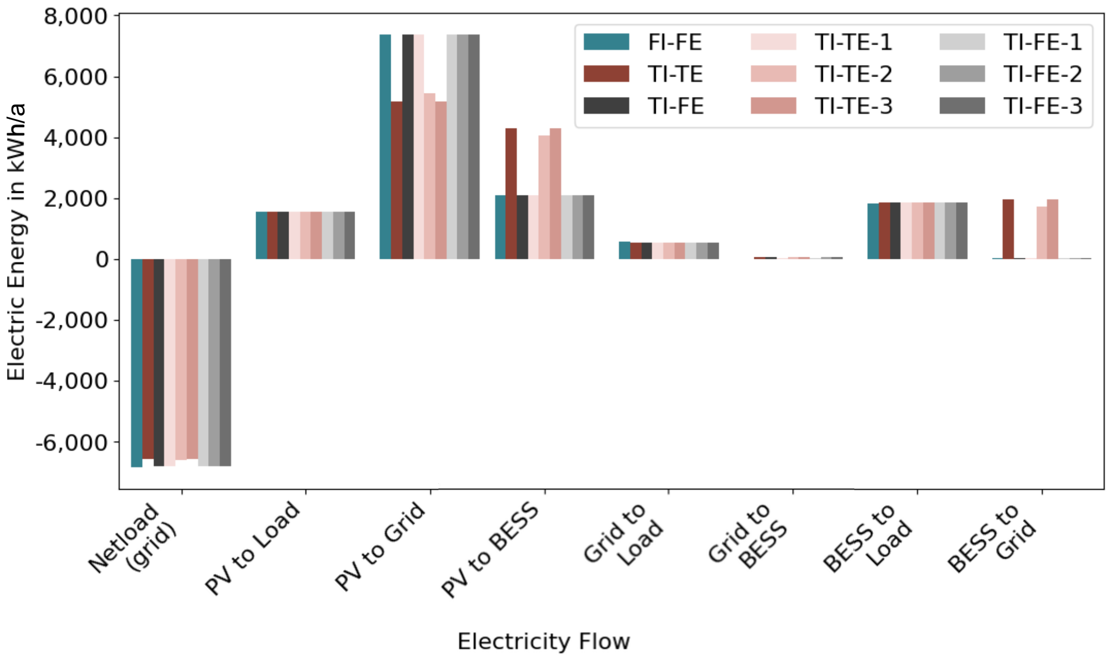

Figure 4.16: Annual Electricity Flows across all Scenarios for an average Household with an average-sized PV-BESS (AUS.2)

Since every household installs the same size PV system, the electricity flow from the PV to load does not differ between the tariffs. Electricity flows from the grid to the load or to the

BESS, and from the BESS to the load also vary only little between the investigated scenarios. Due to large BESS sizes, there is no curtailment in any scenario.

When investigating the different versions of the TI-FE tariff (base, 1, 2, 3), it becomes apparent that the optimisation results in the same operation of the system regardless of the magnitude of the peak price. In the scenarios considered, it is always profitable to store excess self-generated electricity to use it during the peak price period. However, the price difference needs to compensate for efficiency losses and cyclical ageing of the BESS, which is satisfied for all investigated tariff variations. The minimum price spread between peak- and off-peak periods is given in the TI-FE-1 tariff and amounts to 3.7 ct/kWh.

However, when import and export prices are time-dependent, the solution space becomes larger and the optimisation algorithm needs to evaluate the most profitable way to utilise self-generated electricity, considering not only efficiency losses and cyclic ageing, but also electricity price spreads varying over time. While the difference in annual average electricity flows between TI-TE (base) and TI-TE-3 is very small, the gap between those tariffs and TI-TE-2 already becomes visible, as the decreasing electricity export price spread leads to fewer incentives to store surplus electricity for later feed-in. However, under the TI-TE-1 tariff, the price spread is not sufficiently large to justify electricity storage for a later point in time.

Figure 4.17 shows the differences and similarities of the power flows, averaged over one year over a 24-hour period across all tariff variations.

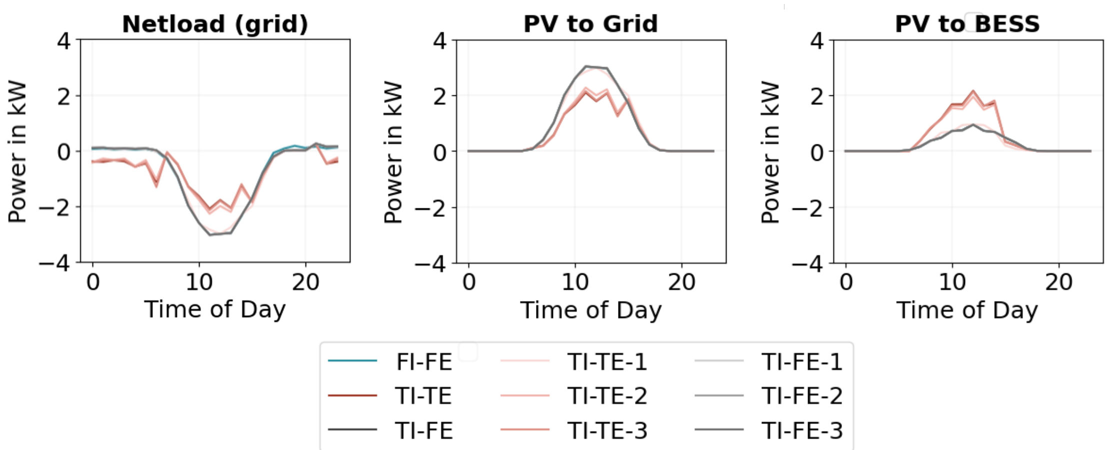

Figure 4.17: Power Flows (Net Load, PV to Grid, PV to BESS) for all Tariff Variations, representing the yearly average over a 24-hour period (AUS.2)

The net load of the FI-FE tariff only differs visibly during the peak price period from the variations of the TI-FE tariff. For all other time periods, as well as the other electricity flows depicted, differences in the system operation behaviour are only marginal, so that the line plots of the average electricity flows appear as one. However, system behaviour under the (majority of) TI-TE tariff variations differs significantly.

The differences between the variations of the TI-TE tariff are additionally illustrated in Figure 4.18. The heat maps represent the net load of an average household for the FI-FE, TI-FE, and TI-TE tariffs, as well as the variations of the TI-TE tariff over a 24-hour period throughout each day of the year, where 0 stands for January 1. The red colour indicates an electricity export, whereas the blue colour represents grid imports. The darker the colour, the higher the magnitude of power import or export.

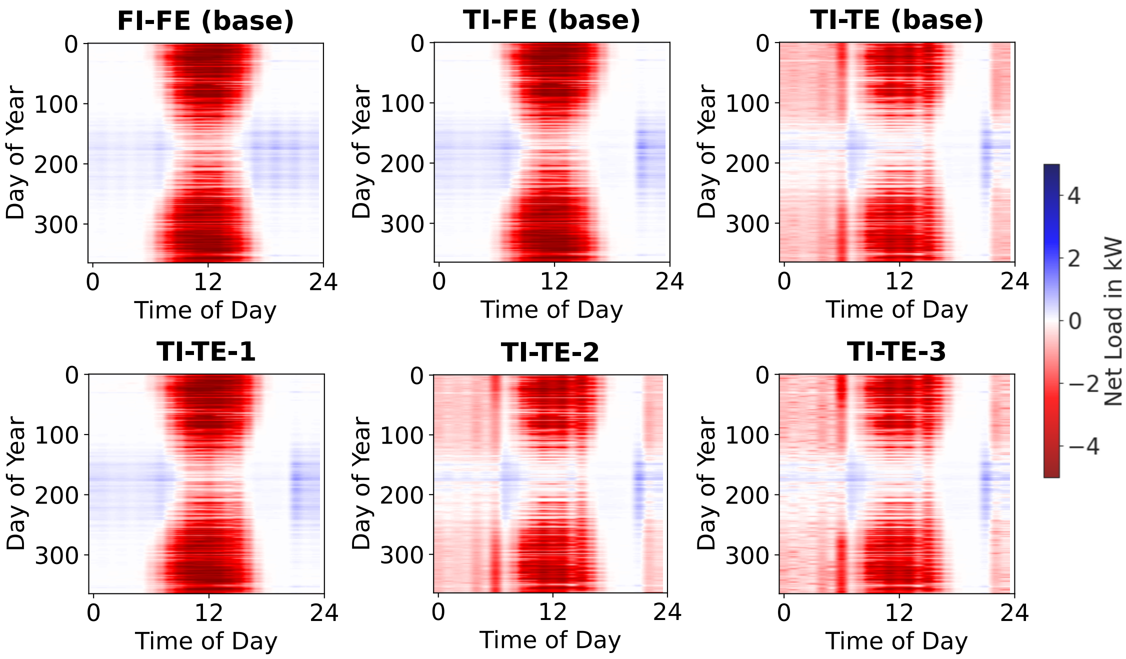

Figure 4.18: Average Net Load for the FI-FE, TI-FE and TI-TE tariffs, and variations of the TI-TE tariff, represented over a 24-hour period for each day of the year (AUS.2)

Although the differences between the TI-TE, TI-TE-2, and TI-TE-3 tariffs are small and mainly detectable for the winter months, TI-TE-1 features the same behaviour as the TI-FE tariff. Therefore, given perfect foresight, the tipping point for it to become more profitable to use the BESS only for self-consumption lies between the TI-TE-1 and TI-TE-2 tariffs, indicating that the effort to store energy is no longer worth the additional remuneration. The minimum price spread to incentivise a household to store electricity for a later feed-in must compensate at least for the underlying storage costs caused by efficiency losses and ageing. The difference between the export tariffs of TI-TE-1 and TI-TE-2, where the behaviour starts to change, is less than 0.5 ct/kWh for each time step during the day. Note that the price spread between the price levels of the export tariff is significantly smaller than the price differences in the import tariff. However, as perfect foresight is assumed for this analysis, the economic benefits will likely be lower for real system operation. The actual price spread needed is therefore expected to be significantly higher than for the TI-TE-2 scenario to provide an incentive for households with PV-BESS to behave similarly to the operational behaviour of the investigated TI-TE(-2/-3/ base) scenarios.

4.2 Modelling Results Germany

4.2.1 Case Study GER.1: Rational Investment Decision

In the following, the impact that electricity tariff structures have on economically rational investment decisions is investigated for the German context. In Case Study GER.1.1, the effect of different electricity price developments is focused, while Case Study GER.1.2 investigates the implications that BESS pricing has.

GER.1.1 Electricity Price Development

As explained in Section 3.2, according to the regression analysis, an increase of approximately +2 %/a in German electricity prices is expected. Therefore, the value of +2 %/a is set as the base scenario, which is analysed first. Similarly to the Australian context, price developments of ±5 % are considered in order to estimate the effect that stronger price changes might have on household DER adoption. In addition to the base scenario, a very strong price increase of +7 %/a is analysed, as well as a price decline of -2 %/a.

Regarding the base scenario of a +2 % price increase, as seen in Table 4.6, only households subject to the FI-FE tariff install a PV system. As soon as temporal tariffs are introduced, potential investments become unprofitable and are not realised. The findings from the Australian case study AUS.1.1 that temporal tariffs reduce the adoption of photovoltaics and BESS remain unprofitable also holds for the German context.

Table 4.6: Techno-Economic Key Results with Median Values only Corresponding to Installing Households (GER.1.1, +2 %/a)

El. Price Scenario [%/a]	Tariff Structure [-]	PV-only Inst. Share [%]	PV-BESS Inst. Share [%]	median PV size [kWp]	median NPV [€]
+2	FI-FE	8.3	-	3.4	130
+2	TI-FE	-	-	-	-
+2	TI-TE	-	-	-	-

Figure 4.19 shows box plot diagrams for the FI-FE, TI-FE, and TI-TE tariffs, illustrating how the household's NPV is affected, if a PV system is installed. As the NPV of every household is higher for a PV-only system than for the installation of a BESS or PV-BESS, only this case is regarded in more detail. Similarly to the results for the Australian boundary conditions, the NPV for households under the flat tariff is generally higher than for the ones

under temporal tariffs and there is only little difference between the financial results for the TI-FE and the TI-TE tariff. Given that the ideal average investment in a PV system across all tariff structures exceeds 5.000 €, it is worth noting that Figure 4.19 illustrates significantly higher - although still negative - values for the NPV. Therefore, it can be expected that the installation of a PV system could become profitable for a substantial number of households within its projected operational lifetime of 20 years.

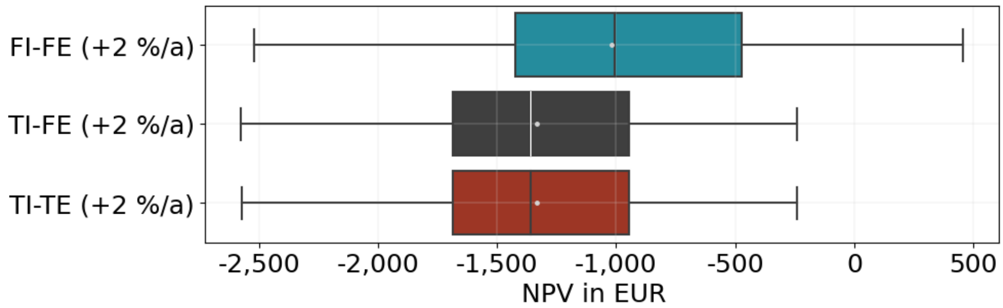

Figure 4.19: Statistical Overview of the NPV for a financial Horizon of 10 Years across all Households and Tariff Structures, if a PV System is installed (GER.1.1, +2 %/a)

Similarly to the Australian framework, the reference electricity bill is higher for an average household subject to the flat tariff structure than for households under temporal tariffs. Over the modelled time period of 10 years and the assumption of an electricity price increase of +2 %/a, the average discounted reference bill across all households is around 600 € lower for the TI-FE and TI-TE tariffs than for the FI-FE tariff.

In contrast to case study AUS.1, it is notable that the installed PV system sizes in Germany are significantly smaller, being only around half the size modelled for the Australian boundary conditions. The reason for this variation could be the cheaper PV system cost per kWp and the greater availability of solar resources in Australia.

The average daily net load of households subject to flat tariffs that install a PV system is shown in Figure 4.20 for summer and winter. As households invest in a PV-only system, the average hourly net load distribution resembles the shape of the duck curve. However, since the PV system is relatively small, feed-in during summer does not exceed 3 kW and in winter the electricity consumption is usually greater than the generation.

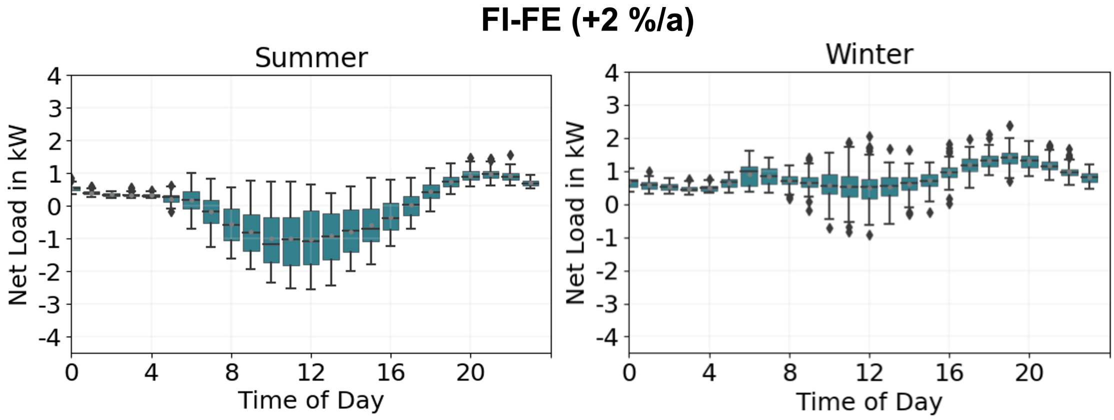

Figure 4.20: Average Hourly Net Load Distribution across all Households installing a PV system with a FI-FE Tariff Structure in Summer and Winter (GER.1.1, +2 %/a)

Techno-economic key results for an increase in the electricity price of +7 %/a or a decrease of -3 %/a are listed in Table 4.7.

Table 4.7: Techno-Economic Key Results with Median Values only Corresponding to Installing Households (GER.1.1, +7 %/a and -2 %/a)

El. Price Scenario [%/a]	Tariff Structure [-]	PV-only Inst. Share [%]	median PV size [kWp]	median NPV [€]
+7	FI-FE	49	3.6	875
+7	TI-FE	31	3.7	430
+7	TI-TE	31	3.7	430
-2	FI-FE	-	-	-
-2	TI-FE	-	-	-
-2	TI-TE	-	-	-

If electricity prices decrease at a rate of -3 %/a, no household invests in any DER. However, for the scenario of a strong price increase, almost half of the households under the FI-FE tariff and a third of the households under temporal tariffs reach profitability within the financial horizon of 10 years. The sizes of the optimal PV system increase slightly; however, they remain small compared to the results of Case Study AUS.1.1. As for the Australian context, the NPV for flat tariffs is significantly higher than if temporal tariffs are applied.

Furthermore, the decision whether to invest in a PV system as well as its size is again strongly correlated with annual electricity consumption, which is illustrated in Figure 4.21. In the German context, households that choose to invest for the +7 %/a price change scenario have an annual demand exceeding 3,900 kWh/a under the FI-FE tariff, and a demand of more than 4,350 kWh/a under the temporal tariff structures. However, if the base scenario price increase of +2 % is assumed, where only households subject to the FI-FE tariff invest, this number increases to more than 5,700 kWh. The average underlying load profiles for summer and winter that show households adopting a PV system are shown in Figure A.6. The observation of a generally higher underlying consumption is confirmed. As for the Australian case, in particular, average daytime consumption is higher for the households installing. Additionally, it is noteworthy that non-installing households show a higher demand in the evening hours during summer and a later peak-demand in winter than the installing households for both the FI-FE and the TI-TE tariff.

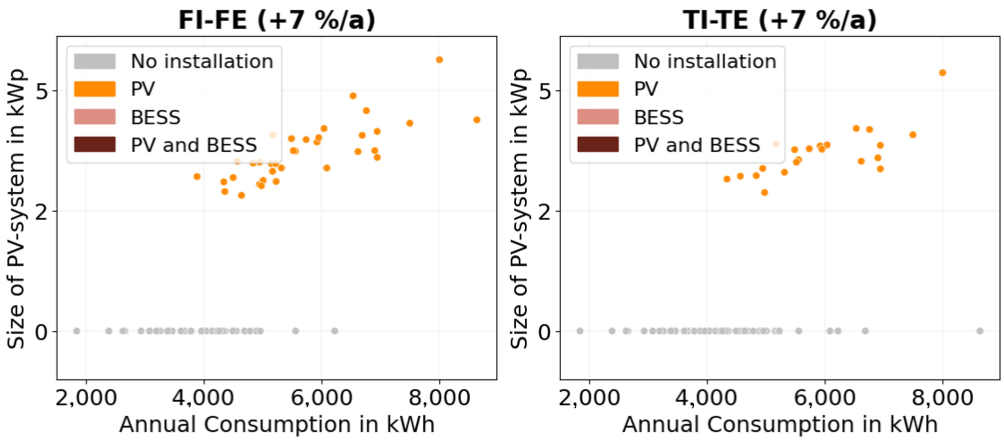

Figure 4.21: Installed PV system Size over Annual Household Consumption for FI-FE and TI-TE tariff (+7 %/a, Germany)

Since relatively small (or no) PV systems and no BESS are installed in all investigated cases, households continue to import more electricity from the grid than they feed into it. With no batteries installed, the net load of households resembles the shape of the duck curve with a feed-in of surplus electricity during the midday and a steep increase in demand in the afternoon. However, as system sizes are generally relatively small, this behaviour is much less pronounced than in the Australian context. The self-consumption of installing households is between 50 % and 60 %, while self-sufficiency lies around 30 % under all tariff structures in the +7 %/a scenario, as well as under the flat tariff structure in the +2 %/a scenario. Households demonstrate a high continued dependency on the grid, in particular during the peak-demand periods in the afternoon and early evening.

GER.1.2 BESS-Pricing

The results of case study GER.1.1 show that, relative to the Australian case with current DER and electricity prices, an investment in BESS is generally not profitable within the financial horizon of 10 years. Therefore, a tipping point for BESS cost, where investment behaviour starts changing, is investigated and subsequent implications are analysed. In this case study, battery prices of 400 €/kWh, 500 €/kWh and 600 €/kWh are considered. First, the medium price scenario of 500 €/kWh is regarded, followed by the evaluation of higher and lower BESS prices.

Table 4.8 summarises the technical key results of the flat and temporal tariff structures investigated for a battery price of 500 €/kWh.

Table 4.8: Techno-Economic Key Results with Median Values only Corresponding to Installing Households (GER.1.2, 500 €/kWh)

BESS-Price Scenario [€/kWh]	Tariff Structure [-]	PV-only Inst. Share [%]	BESS-only Inst. Share [%]	PV-BESS Inst. Share [%]	median PV size [kWp]	median BESS size [kWh]
500	FI-FE	8.3	-	-	3.4	-
500	TI-FE	-	-	8.3	3.9	4.1
500	TI-TE	-	-	8.3	3.9	4.1

For all tariff structures, 8.3 % of the households invest in DER. Under flat tariffs, the installation behaviour of case study AUS.1.1 is repeated, where a PV-only system is installed. However, the same group of households who opt for PV systems under the FI-FE tariff decides to invest in PV-BESS under temporal tariff structures, when the BESS price is set to 500 €/kWh. PV-BESS sizes of households under the temporal price structures are very similar; however, their PV systems tend to be slightly larger than under the flat-tariff structure. While households under the flat tariff reach a median NPV of approximately 130 €, households under the TI-FE and TI-TE tariffs yield median NPVs of around 325 € and 340 €, respectively.

Table 4.9 lists the technical key results for the lower and higher BESS costs of 400 €/kWh and 600 €/kWh.

Table 4.9: Techno-Economic Key Results with Median Values only Corresponding to Installing Households (GER.1.2, 400 €/kWh and 600 €/kWh)

BESS-Price Scenario [€/kWh]	Tariff Structure [-]	PV-only Inst. Share [%]	BESS-only Inst. Share [%]	PV-BESS Inst. Share [%]	median PV size [kWp]	median BESS size [kWh]
400	FI-FE	2.8	-	8.3	3.4	3.0
400	TI-FE	-	66.7	20.8	3.9	3.3
400	TI-TE	-	66.7	20.8	3.9	3.3
600	FI-FE	8.3	-	-	3.4	-
600	TI-FE	-	-	2.8	4.3	3.5
600	TI-TE	-	-	2.8	4.4	3.6

When the price of BESS is increased to 600 €/kWh, there is a significant reduction in the adoption of PV-BESS by households under the temporal tariff structures. Although the median and average values for the sizes of PV and BESS are higher in the 600 €/kWh than in the 500 €/kWh scenario, this does not hold for individual households. This is due to the fact that households with a smaller, yet profitable, system size in the 500 €/kWh scenario choose not to invest anymore for a BESS price of 600 €/kWh.

In the 400 €/kWh scenario, a divergent trend to previous observations emerges. While the investment in PV-BESS starts to become profitable for approximately 8 % of households under the FI-FE tariff, almost two-thirds of households under temporal tariffs adopt only a BESS and 20 % a PV-BESS. In the case of flat tariffs, (almost) the same group of households invests as in the higher BESS price scenario, with PV-BESS always featuring the smallest available battery size of 3.0 kWh. While the ratio of nominal PV capacity to nominal BESS capacity is >1 for flat tariffs, where BESS is only used to increase self-consumption, households with temporal tariffs generally have a significantly lower ratio. This is because households subject to temporal tariffs precharge the BESS with electricity imported from the grid during off-peak time periods to serve their load by discharging it during peak price periods. For the same reason, most investigated households decide to invest in a BESS-only option. For these households, the price difference between peak and off-peak hours is large enough to justify the investment, when the BESS price is only 400 €/kWh. For all tariff structures, the median NPV of the 400 €/kWh and 600 €/kWh scenario lies between 130 € and 200 €, with the lowest applying to the FI-FE tariff and the highest to the TI-TE tariff. Although individual NPVs of households increase due to the lower upfront cost, the overall average and median NPV do not necessarily reflect this behaviour, as investment starts to become profitable for more households, featuring lower NPVs.

It should be noted that over the households investing in each of the scenarios, the investment in PV and/or BESS yields the best NPV under temporal tariff structures in almost all cases for a BESS price of 400 €/kWh and in 85 % of cases for 500 €/kWh. However, for a BESS price of 600 €/kWh, the PV-only investment opportunity under the FI-FE tariff is always the most profitable.

Similarly to case study AUS.1.1, the system operation is investigated in detail only for the PV-BESS configuration in the medium BESS price scenario. As PV investment decisions under the FI-FE tariff are the same as for case study AUS.1.1 (+2 %/a), the associated average daily net load for the PV-only system is illustrated in Figure 4.20. Figure 4.22 shows the average daily net load for households that install PV-BESS and are subject to the TI-TE tariff for a BESS price of 500 €/kWh.

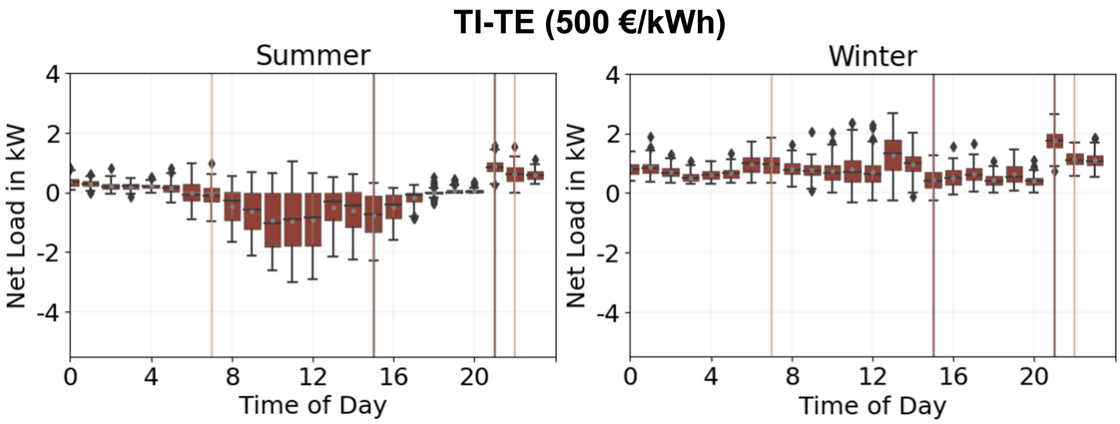

Figure 4.22: Average Hourly Net Load Distribution across all Households installing a PV-BESS system with a TI-TE Tariff Structure in Summer and Winter (GER.1.2, 500 €/kWh)

Concerning the import of electricity from the grid by households subject to the TI-TE, it is apparent that consumption is reduced as much as possible during the peak price period between 3 pm and 9 pm. As soon as the price drops at 9 pm, the grid imports increase again. Additionally, in winter, the grid consumption increases during the time just before the peak price period, which is caused by the BESS precharging. As self-generated electricity is consumed almost completely during the winter months, changes in export behaviour are more noticeable in the summer months. Similar to the pre-charging behaviour observed during winter, the BESS is predominantly charged with PV generation at the time just before the peak price period. However, in summer the reasoning is not only to store electricity for later use, but also to feed more electricity into the grid during higher export tariff pricing after 3 pm. This finding is also illustrated in Figure 4.23, where the net load, as well as the PV flows, to the grid and to the BESS are depicted. As the same households install very similar PV-BESS under the TI-FE and TI-TE tariffs, their average daily net load of installing households is generally very similar. However, because of the variation of the feed-in tariffs and the previously mentioned increased feed-in for higher prices, there are differences in the timing when the BESS is charged. Nonetheless, these differences are not very pronounced, as the BESS is, similar to Case Study AUS.1.2, mainly sized to increase self-consumption and avoid peak import prices.

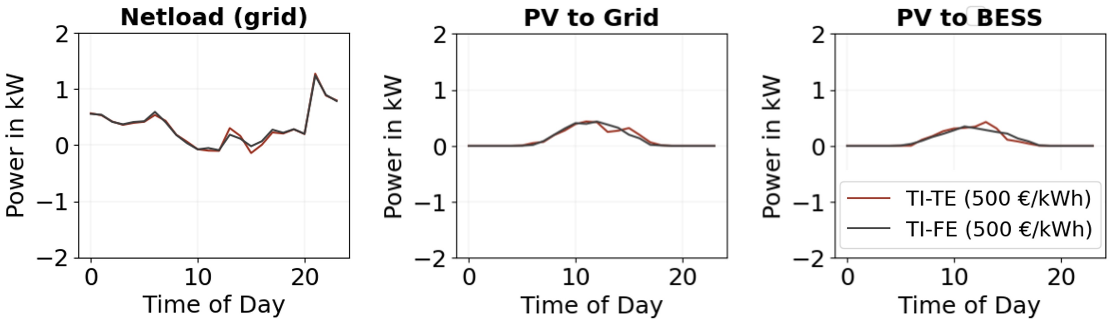

Figure 4.23: Power Flows (Net Load, PV to Grid and PV to BESS) for the TI-FE and TI-TE tariffs, representing the yearly average over a 24-hour period (GER.1.2)

Across all scenarios and tariff structures, households remain net-importers from the grid (Figure A.8). The self-consumption and self-sufficiency values of an average household that decides to invest in a PV-BESS system are listed in Table 4.10.

Table 4.10: Self-Consumption and Self-Sufficiency Values of Households Installing PV-BESS for Different BESS Price Scenarios and Tariff Structures (GER.1.2)

	400 €/kWh			500 €/kWh			600 €/kWh		
	FI-FE	TI-FE	TI-FE	TI-TE	TI-TE	FI-FE	TI-TE	FI-FE	TI-TE
Self-cons.	67 %	75 %	75 %	-	74 %	74 %	-	71 %	71 %
Self-suff.	43 %	56 %	56 %	-	52 %	52 %	-	46 %	46 %

Comparing the results of Case Studies AUS.1.2 and GER.1.2, the self-consumption rates for each increase in the investigated BESS-price levels are around 30 % higher in Germany than in Australia, while self-sufficiency is always approximately 15 % lower. This finding indicates the different focal points of the optimal investment strategies in each country. In Australia, the focus lies on very large solar systems featuring a high grid feed-in. In contrast, system sizes tend to be significantly smaller in Germany, primarily aimed at satisfying household demand.

4.2.2 Case Study GER.2: Impacts of Tariffs on System Operation

While Case Study GER.1 focusses on rational investment behaviour and subsequent system operation, Case Study GER.2 investigates system operation, specifically in the context of each household adopting an average-sized PV system of 9 kWp and a BESS of 9 kWh. Similarly to the Australian context, economically rational investment decisions generally lead to smaller system dimensions than what is observed in real applications in Germany. However, adopting a large PV-BESS significantly alters the system's operation and its reaction to different price signals. First, the implications of the FI-FE, TI-FE and TI-TE tariff structures, which were also examined in case study GER.1, are analysed. Second, additional tariffs are introduced that represent intermediary steps between flat and temporal tariffs.

Due to the choice of a consistent PV-BESS size for all households, the economic results are similar across all scenarios. The initial cost for the adoption of the PV-BESS amounts to 25,150 €, resulting in average discounted bill savings of around 14,500 €. For the German model, a negative discounted electricity bill is achieved for around 35 % of households under the FI-FE tariff and for approximately 50 % and 55 % under the TI-FE and TI-TE tariffs, respectively. Current DER and electricity prices prevent any household in the study from achieving a positive NPV for a 10-year time horizon.

Concerning the technical system operation, the larger PV-BESS size reinforces the operational implications of case study GER.1.2, and the dependence of households on the grid decreases significantly. For an average household, self-sufficiency is around 70 %, while the average self-consumption rate is around 40 %. Additionally, under all tariff structures investigated, the average household transitions into an electricity net-exporter to the grid.

Figure 4.24 shows the average net load per day across all households investigated when the FI-FE tariff is applied. Since there is no incentive to store electricity for consumption or feed-in during specific time periods, the BESS is charged with excess solar electricity and discharged when consumption starts exceeding generation. In the summer months, this results in a very high electricity feed-in during the day, whereas most of the electricity consumption is covered by the BESS when there is no solar generation available. Unlike in Australia, there is no feed-in power limitation, leading to power inputs of more than 6 kW for an average household between 10 am and 2 pm. However, in winter, electricity consumption outweighs electricity generation on most days. The demand from the grid is reduced during the midday and increases again in the afternoon.

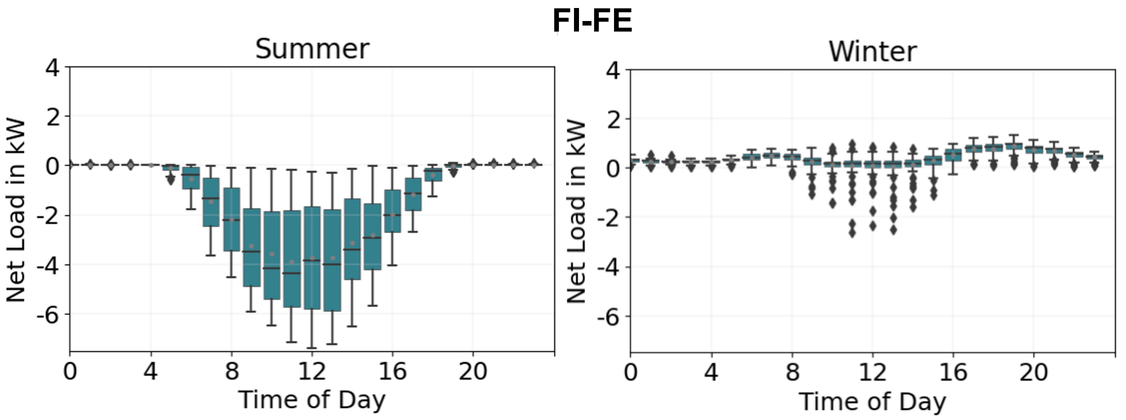

Figure 4.24: Average Hourly Net Load Distribution across all Households with an average-sized PV-BESS under the FI-FE Tariff Structure in Summer and Winter (GER.2)

The average daily net load of households when a temporal import tariff is introduced is shown in Figure 4.25. As household demand is satisfied by solar generation and electricity stored in the BESS during the summer months regardless of the tariff structure, there is little difference between the FI-FE and TI-TE cases. However, in winter, households under the TI-FE tariff reduce their demand to almost zero in the high price period between 3 pm and 9 pm. In contrast to Australia, solar generation in Germany is insufficient to charge the BESS and satisfy household consumption in the afternoon in winter. The BESS is therefore pre-charged with electricity from the grid before and after the peak price period.

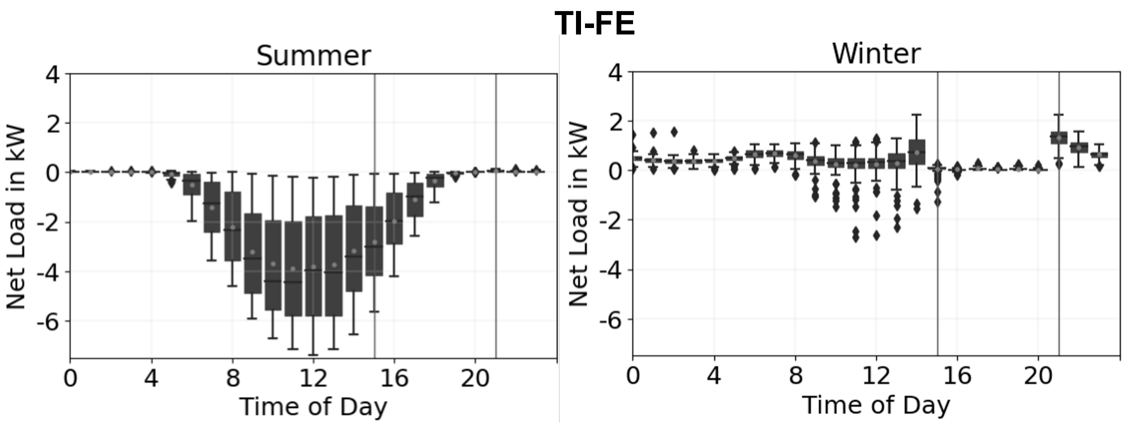

Figure 4.25: Average Hourly Net Load Distribution across all Households with an average-sized PV-BESS under the TI-FE Tariff Structure in Summer and Winter (GER.2)

In the case of the TI-TE, depicted in Figure 4.26, temporal export tariffs are also introduced.

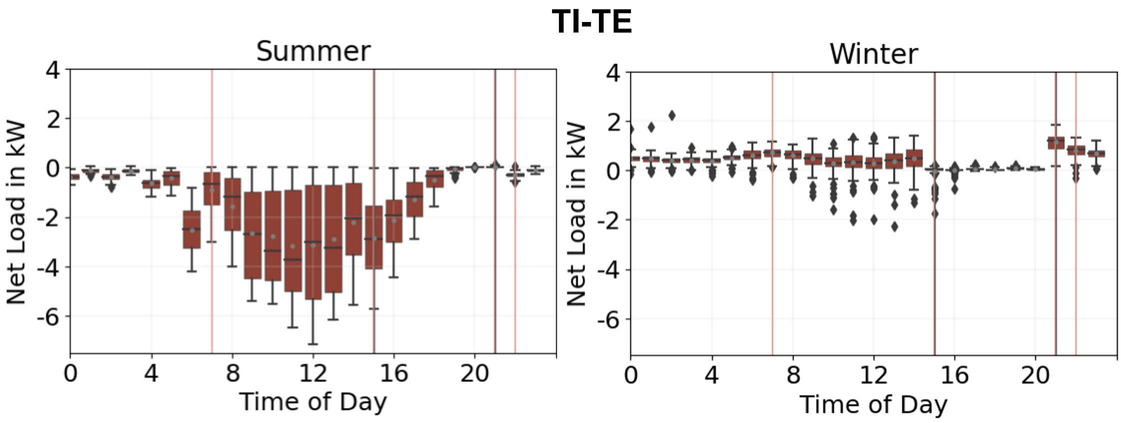

Figure 4.26: Average Hourly Net Load Distribution across all Households with an average-sized PV-BESS under the TI-TE Tariff Structure in Summer and Winter (GER.2)

Although there is hardly any difference between the TI-FE and TI-TE cases in winter due to a lack of solar generation, the impacts of the change in feed-in tariff are clearly visible in summer. The feed-in behaviour matches the one already observed in Case Study AUS.2. On the one hand, electrical export is avoided during low-price periods, especially just before the high-price period starts at 3 pm, in order to charge the BESS. On the other hand, it increases during high price periods, particularly before low price periods at 7 am, to free up the storage capacity of the BESS and make use of the high export remuneration.

Figure 4.27 illustrates how the yearly average state of charge over the course of a day differs between the different tariff structures.

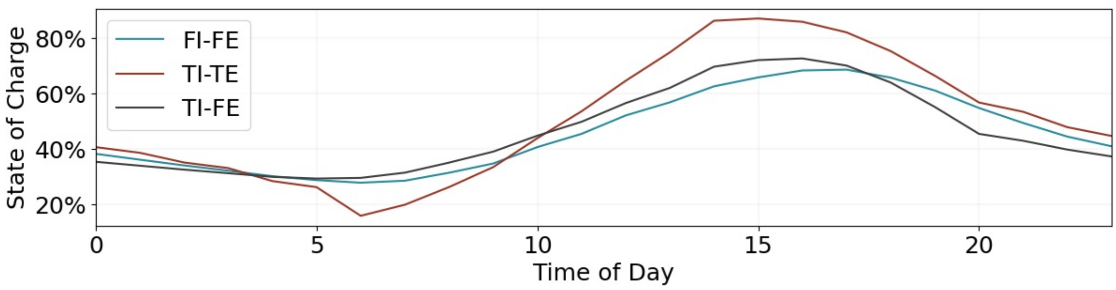

Figure 4.27: State of Charge of the BESS, representing the yearly average over a 24-hour period for the FI-FE, TI-FE and TI-TE cases (GER.2)

As for the Australian context, households subject to the TI-TE tariff generally make the most use of the available capacity. Although the range of the capacity used is very similar for the

FI-FE and TI-FE cases, the SoC profile is slightly more flat for the FI-FE tariff. This is due to the discharging behaviour of households subject to the temporal import tariff during the peak price periods. It can be seen that the discharge rate for the TI-FE and TI-FE cases is very similar during the peak price period, which is indicated by the parallel decrease in SoC in the afternoon.

A notable difference between BESS usage in the Australian and German cases is the supposedly smaller usage of the available BESS capacity, although the installed nominal capacity is significantly smaller in the German model. However, since the shown SoC profile represents a yearly average, and the winter months are characterised by insufficient solar radiation to charge the BESS, the actual SoC profile in summer generally features a higher spread, and the one in winter a lower spread.

Similarly to the Australian analysis, it is important to evaluate how the effects of the duck curve on the grid are mitigated through the temporal tariff structures. To do so, the frequency and magnitude of demand and feed-in power throughout the year is analysed. Figure 4.28 shows the frequency distribution of electrical power drawn from the grid for an average household subject to the FI-FE and the TI-FE tariff over a 24-hour period across each day of the year.

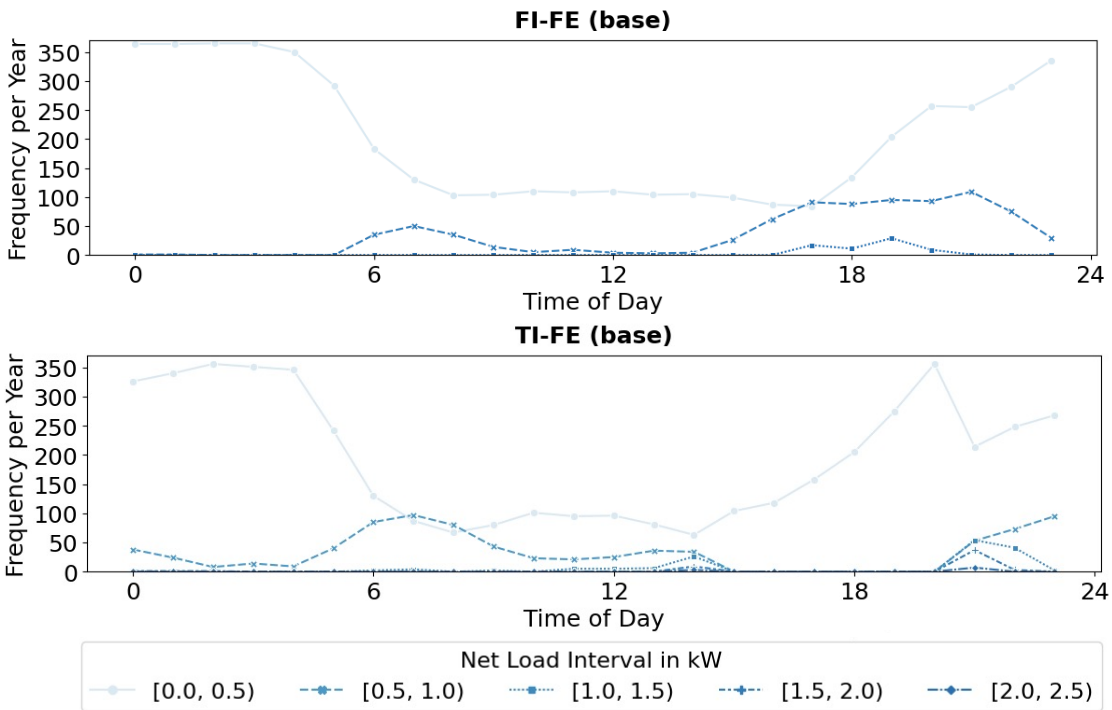

Figure 4.28: Annual Frequency Distribution of Import Power Intervals for an Average Household subject to the FI-FE and the TI-TE Tariff over a 24-hour Period (GER.2)

Under the FI-FE tariff, an average household's demand from the grid is reduced during the midday due to solar generation, followed by the classic rise in demand in the afternoon. However, when temporal import tariffs are introduced, demand is reduced as much as possible between 3 pm and 9 pm. It should be noted that the occurrence of grid power demand in the TI-FE case during the peak price period only applies to the interval of $[0.0, 0.5)$, which also includes no grid interaction, as well as very low power demand. Therefore, the highest demand of households under the TI-FE tariff does not occur in the afternoon anymore, but primarily between 5 am and 9 am.

Since the installation of a large PV system is assumed, evaluating the effects of the tariff structure on (cumulative) household grid exports and their magnitude is crucial for a secure operation of the grid. The model results show an increased number of high feed-in power occurrences during the midday for flat export tariffs, which is illustrated in Figure 4.29.

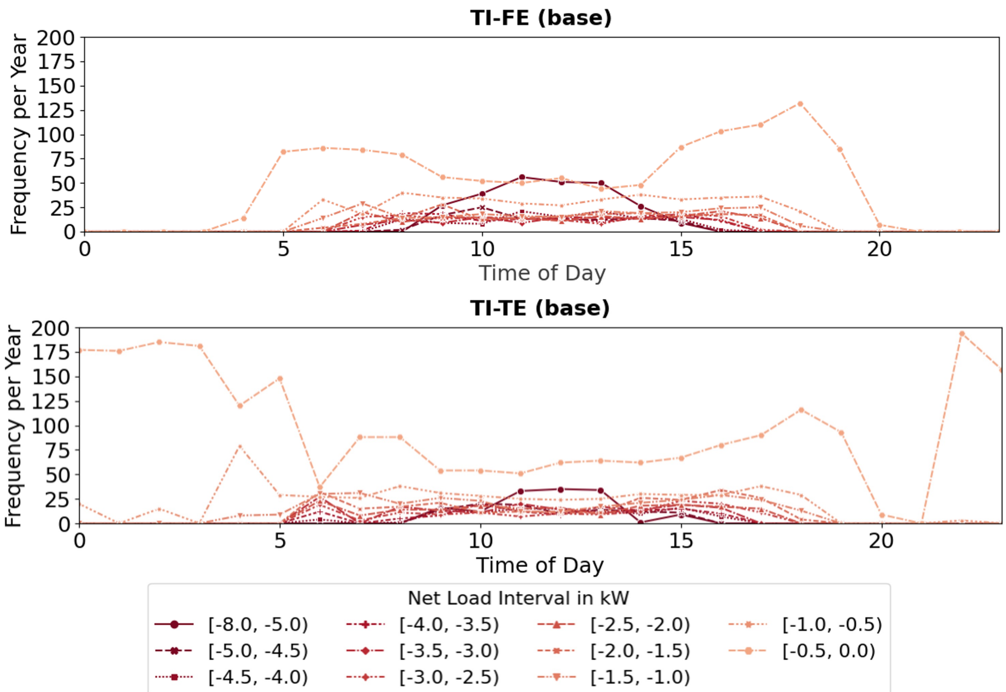

Figure 4.29: Annual Frequency Distribution of Export Power Intervals for an Average Household subject to the TI-FE and the TI-TE Tariff over a 24-hour Period (GER.2)

Due to the large dimensions of PV systems and the absence of feed-in limitation, the feed-in power exceeds 4 kW between 11 am and 2 pm on approximately 70 days per year for the TI-FE case. Although the size of the PV system is larger in the German context compared to Australia, the solar resource is significantly weaker, leading to an overall flatter distribution of feed-in power. While the modelling results for flat export tariffs in Australia suggest a feed-in rate exceeding 4 kW occurring on around 140 days between 11 am and 1 pm, this value is approximately halved in the German model. However, similar to the Australian case, when applying a temporal export tariff, households are incentivised to export electricity during time periods with high feed-in remuneration. The higher feed-in price under the TI-TE tariff from 10 pm to 7 am causes the BESS to be discharged during that time period, contributing to the production of electricity at night.

After having investigated implications of the base FI-FE, TI-FE and TI-TE tariffs on a standard size PV-BESS, intermediary tariffs between flat and temporal tariffs are investigated. The aim is to examine at which point households start to respond to the price signals and to what extent. Again, index 1 represents that the interim tariff is closer to the flat tariff, 2 indicates that it is in the middle between flat and temporal, and 3 that it is closer to the temporal tariff.

Figure 4.30 depicts the annual electricity flows across all base tariff structures, as well as the intermediary steps for an average household. Although some of the electricity flows are more pronounced than for Case Study AUS.2, key findings and their reasoning still hold.

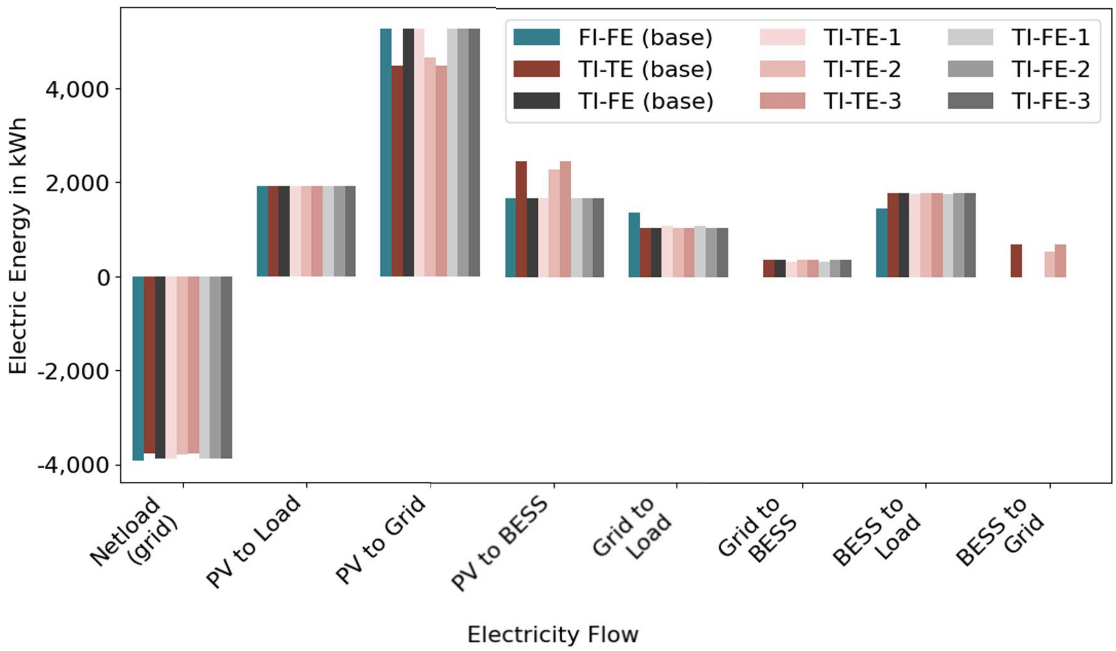

Figure 4.30: Annual Electricity Flows across all Scenarios for an average Household with an average-sized PV-BESS (GER.2)

As with the results of the Australian model, changes in the TI-FE tariff with respect to the magnitude of the peak price do not significantly affect operational results. However, variations in the TI-TE tariff are more pronounced in the German modelling results. Figure 4.31 illustrates the annual average power flows from PV to the grid and BESS, as well as the net load for the base tariff structures and the variations of the TI-TE tariff over a 24-hour period.

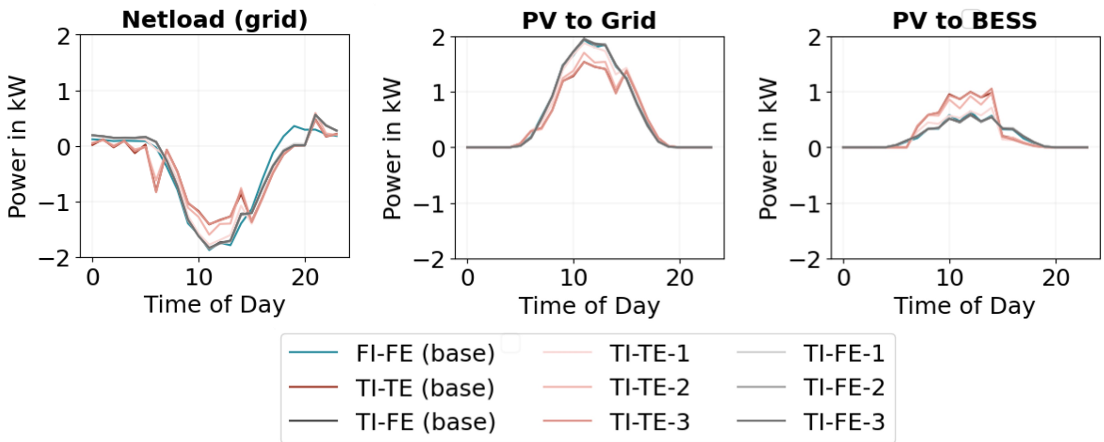

Figure 4.31: Power Flows (Net Load, PV to Grid, PV to BESS) for the Base Tariff Structures and the TI-TE Variations, representing the yearly average over a 24-hour period

While the (average) power flows among the intermediary TI-TE tariffs in the Australian context are very similar to each other, differences can clearly be seen in the German modelling results. However, the fundamental observations of the Australian results can still be applied to the German ones. The larger differences for the German framework may be due to the increased price spread in electricity prices, as the set price for the flat tariffs is notably higher, resulting in a larger price spread for the temporal tariffs.

Figure 4.32 shows heat maps of the average net load for the FI-FE, TI-FE, and TI-TE tariffs, and variations of the TI-TE tariff, represented over a 24-hour period for each day of the year. While the red colour indicates the power fed into the grid, the blue represents the electricity imports. The TI-TE-1 tariff leads households to behave similarly to the TI-FE case, whereas the results for TI-TE-3 are almost the same as those for the base TI-TE case. Although TI-TE-2 is financially in the middle between TI-TE-1 and TI-TE-3, the results for this tariff structure also lean notably more towards the TI-TE base tariff case. This indicates a slightly stronger influence of the feed-in tariff on system behaviour.

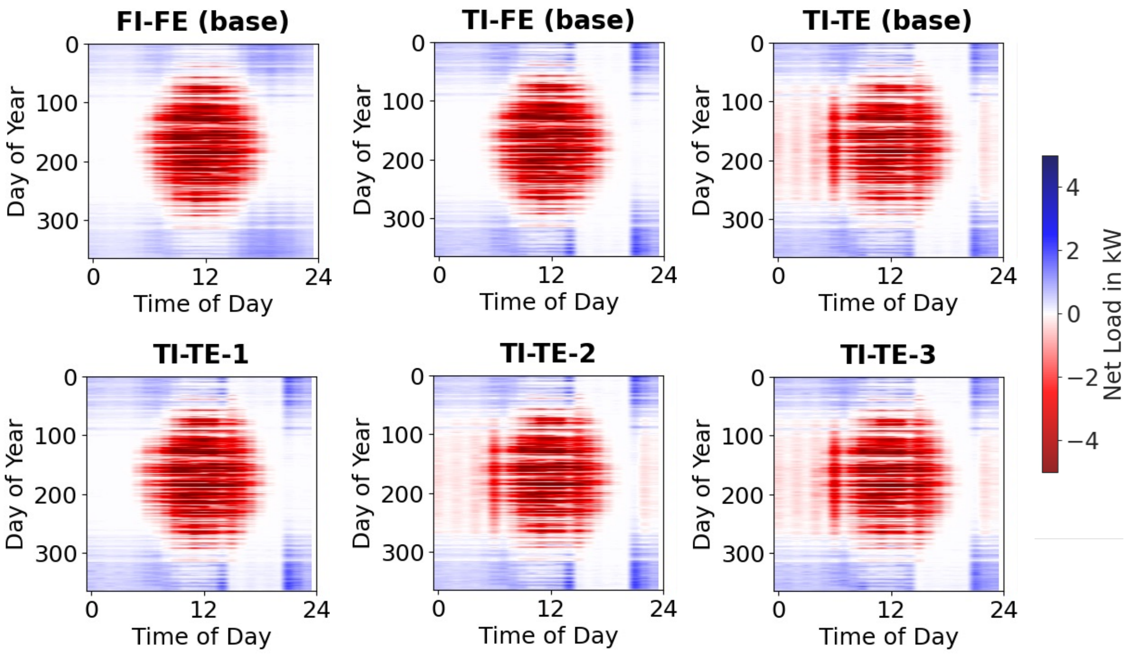

Figure 4.32: Average Net Load for the FI-FE, TI-FE and TI-TE tariffs, and variations of the TI-TE tariff, represented over a 24-hour period for each day of the year (GER.2)

With the set PV-BESS, households across all tariffs reach an average self-consumption rate of around 38 % as well as a self-sufficiency of approximately 71 %. In particular, during the winter months, there is a continuing dependency of households on grid imports.

A notable difference between German and Australian results regarding the annual import and export behaviour is the strong concentration of solar generation in the summer months in Germany, whereas in Australia there is an abundance of solar radiation almost all year round. The lower availability of solar energy with a generally higher household electricity demand leads to significantly less electricity being fed into the grid by an average household in Germany. This becomes particularly apparent when comparing Figures 4.18 and 4.32, as well as when considering the total amount of electricity fed into the grid per year, which is around 6,750 kWh/a in Australia and 3,800 kWh/a in Germany.

4.3 Summary and Discussion of the Case Study Results

When summarising the results for both the Australian and German context, many similarities can be identified; however, several differences should also be highlighted. Following the structure of the case studies, the outcomes for the investigation of rational investment under various developments in the price of electricity and the BESS costs are evaluated first. Second, the effects that the tariff structure has on the operation of an average-sized PV-BESS are addressed.

Regarding the baseline situation in Australia and Germany, which is the reference case of an average household with no DER adoption, there is a slightly lower discounted electricity bill under temporal tariffs than under flat tariffs in all scenarios. This finding indicates not only that flat and temporal tariffs yield comparable outcomes but also that they can compete even under the assumption of no behavioural change.

Rational Investment under different Electricity Price Developments

The results of case studies AUS.1.1 and GER.1.1 clearly show that in both countries an investment in DER is not profitable for most households within the investigated time horizon of 10 years. In particular, no investment in BESS is made under current electricity and BESS prices.

In the Australian base scenario, where no change in electricity price is assumed, 12 % of households install a PV system when subject to flat tariffs. Installation numbers and profitability of investments under the TI-FE and TI-TE tariffs are always lower than under the FI-FE tariff. Every household investing in the base scenario, as well as under the assumption of electricity price developments of ±5 %, would prefer the flat tariff structure over a temporal one. With a median PV system size of 7.6 kWp, the average household installing under the FI-FE tariff consumes around 30 % of the PV-generated electricity itself, while achieving a self-sufficiency of more than 40 %. This results in an electricity feed-in of approximately 7,300 kWh/a into the grid, while demand drops to 4,300 kWh/a. In particular, when projecting the findings on the large scale of around 70,000 household system installations annually in Victoria, a need for action becomes apparent [59]. The cumulative effects would add up to an expansion in PV generation capacity of 530 MW per year. While the private sector's electricity demand from the grid would decrease by around 300 GWh/a, more than 500 GWh/a is additionally exported. Furthermore, high feed-in power becomes an increasing problem for the grid. During almost a third of the year, the household feed-in power would exceed 280 MW between 11 am and 2 pm. Note that these effects stem from the PV expansion of one year only.

However, in the German base scenario with an electricity price increase of +2 %/a, PV adoption is only ever profitable under flat tariff structures with an installation share of 8 %. In contrast to the large PV system sizes observed under the Australian framework, the German PV system is significantly smaller with a median size of only 3.4 kWp, notably altering the outcomes concerning system operation. An average household in this scenario remains an electricity net-importer, reducing its dependence on the grid from 6,800 kWh/a to around 4,800 kWh/a, while exporting approximately 1,500 kWh/a. As the projected PV size is significantly smaller than in the Australian context, large-scale effects are less likely. However, in scaling results for the around 400,000 PV systems added in Germany in the last year, additional capacities would amount to 1,360 MW and an electricity feed-in of around 580 GWh [105].

The results of both countries for increasing electricity prices indicate a rise in the number and profitability of PV systems installed. Vice versa, the opposite effects are observed when a decrease in electricity prices is assumed. For both countries and all price development scenarios evaluated, flat tariffs are always more profitable than temporal ones if a PV-only system is installed.

Since there is no investment in BESS in any of the price development scenarios, households are not capable of reacting to the price signals from temporal tariffs without behavioural change. However, policymakers and system operators stand to benefit from households responding to temporal pricing, indicating the potential for schemes such as subsidies to incentivise the adoption of PV-BESS. Therefore, the next section will evaluate the effect that different BESS price levels have on rational investment.

Rational Investment for different BESS Prices

In the second step of the case studies on rational investment, different BESS price levels of 300 $/kWh, 400 $/kWh and 500 $/kWh, as well as 400 €/kWh, 500 €/kWh and 600 €/kWh, were investigated in the Australian and German contexts, respectively. Although the actual BESS prices are in the range of 1,300 $/kWh and 1,300 €/kWh, the battery price development of electric vehicles that feature prices of around 235 $/kWh (135 €/kWh) has demonstrated that there is a potential for significant reductions in the future [106].

In the 400 $/kWh scenario for Australia, approximately every seventh household subject to a temporal tariff would opt for a PV-BESS, while under flat tariff structures, the share of households installing, as well as the size of the system, decreases. However, compared to the case study AUS.1.1, households generally invest in larger systems, leading to a self-consumption of 40 % and a self-sufficiency of 65 % for investments in PV-BESS under temporal tariff structures. As the FI-FE tariff does not incentivise households to adapt charging and discharging according to price signals, the BESS is simply charged when there is surplus generation and discharged, when demand is greater than PV generation. However, when temporal tariffs are applied with higher prices between 3 pm and 9 pm, the electricity demand in the afternoon and evening is reduced as much as possible. As the system sizes are relatively small and the import price is the main driver of system operation, there are only small differences in the net load between the TI-FE and TI-TE tariffs. When comparing the profitability of all households that decide to invest for a BESS price of 400 $/kWh, adopting a temporal tariff is the most beneficial option in 60 % of cases. The average advantage in NPV of households that prefer to invest under a temporal tariff over a flat one is around

250 \$. In this context, it should be noted that while the (dis-)charging behaviour of the BESS under the FI-FE tariff is not influenced by the perfect-foresight assumption, temporal tariffs benefit from it. As its time-dependent nature is associated with more uncertainty, it needs to be evaluated if the advantage in NPV over the investigated time horizon is sufficient to compensate not only for the actual variance in consumption and PV generation, but also the risk associated with the tariff by the household. In the 300 \$/kWh scenario, approximately every fifth household invests in a PV-BESS with system sizes and NPV generally increasing, as the upfront cost decreases. It is still more beneficial for around 60 % of households investing to do so under a temporal tariff. For a BESS price of 500 \$/kWh, PV-BESS are only installed under temporal tariffs. However, installing a PV-only system under the FI-FE tariff is more profitable for 95 % of the households investing in DER in this scenario.

For the German context, there are several similarities to the Australian framework for the three price levels investigated; however, there are also several distinctions. While around 8 % of the households subject to temporal tariffs invest in PV-BESS for a BESS price of 500 €/kWh, the same group of households would opt for PV-only systems under the FI-FE tariff. Again, compared to the case study GER.1.1, generally larger systems are installed, leading to average self-consumption rates of almost 70 % and a self-sufficiency of around 50 % for households that adopt a PV-BESS under the TI-FE or TI-TE tariff. In contrast to the PV-BESS operation observed for the case study AUS.1.2, there is not only a strong reduction in the import of electricity from the grid in the afternoon and evening, but the changes caused by the temporal feed-in tariff are more pronounced, as an increase in the feed-in of electricity is observed after 3 pm. Another striking difference between the Australian and the German model outcomes is that, while for the Australian context precharging from the grid is negligible due to the abundance of solar radiation, this phenomenon is much more pronounced in the German operational behaviour, in particular in winter. Comparing the profitability of households adopting any DER in the 500 €/kWh scenario, the TI-TE tariff is the most beneficial in almost 85 % of the cases, outperforming the NPV under a FI-FE tariff by 210 € on average. For a BESS price of 400 €/kWh, the TI-TE tariff is the most profitable for almost all households investing in DER. However, it is important to note that for this BESS price, battery-only investments become profitable for almost two-thirds of households subject to temporal tariffs as they profit from low prices during most of the day and avoid importing electricity during peak-price periods by precharging the BESS. When a price of 600 €/kWh is set, the adoption of a PV-only system under the FI-FE tariff is always the most profitable option among the viable investment opportunities.

Since the aim of temporal tariffs in combination with PV-BESS is to incentivise grid-friendly system operation, i.e. counteracting the duck-curve, it is necessary to carefully evaluate effects that different BESS prices or subsidy levels might have on DER and tariff adoption. It is notable that the BESS sizes in this case study are optimised mainly according to self-consumption and electricity imports. However, if a change in system operation is desired with respect to the frequency and magnitude of high-power being fed into the grid, larger batteries are necessary to allow for export optimisation as well. As the case studies AUS.1.2 and GER.1.2 have shown, while very low costs for BESS can lead to BESS-only adoption, there might be no adoption of BESS at all for higher costs. The case studies on BESS pricing in Australia and Germany suggest that the price range that triggers these phenomena, as well as the financial advantage of adopting temporal tariffs over flat tariffs, is not necessarily very large.

Optimal System Operation under different Tariff Structures

As system sizes actually being installed are generally much larger than the optimisation suggests, optimal system operation is investigated for both the Australian and the German context, assuming an investment in an average-sized PV-BESS. For the Australian model, a PV-BESS of 8 kWp and 12 kWh is set, whereas the German model features a 9 kWp and 9 kWh system. For both countries, the TI-TE tariff offers the lowest electricity bill for all households after having installed PV-BESS. However, for current electricity and DER prices, the investment is not profitable within the 10-year operational life-span of the BESS. Additionally, not only the average Australian household becomes a net-exporter through the adoption of DER anymore, but also the average German household.

The average Australian household investigated in this case study reaches a self-sufficiency of around 85%, mainly relying on imports from the electricity grid during the winter months. The fundamental operational implications for PV-BESS evaluated in case study AUS.1.2 still hold; however, they are much more pronounced due to the larger system sizes. Around one-third of the electricity generated by the PV system serves self-consumption, resulting in 67 % of the generation being fed into the grid. Since households under the FI-FE and TI-FE tariffs use BESS only to optimise self-consumption, they feed on average 7,400 kWh/a directly from the PV system into the grid. However, households subject to the TI-TE tariff decide not only to reduce their dependence on electricity imports but also to capitalise on higher feed-in tariffs during the evening and night. In doing so, around 5,200 kWh/a is fed into the grid directly from the PV system, while 2,200 kWh/a is stored in the BESS and exported during time periods with a higher feed-in remuneration, providing nighttime electricity generation to the grid. Furthermore, a significant reduction in high-power feed-in can be observed for households subject to the TI-TE tariff, as they store electricity when generation is particularly high for a delayed export, easing midday stress on the grid.

An average German household in this case study reaches self-sufficiency rates of around 70 %, also relying on the grid mainly during the winter months with a lack of solar generation. Self-consumption is around 40 %, leading to around 5,300 kWh being fed into the grid directly by an average household under the FI-FE and the TI-FE tariff, while under the TI-TE tariff only

4,500 kWh is directly exported by the PV system and around 700 kWh via the BESS. Similarly to the Australian modelling result, nighttime electricity production is enabled by the high feed-in remuneration between 10 pm and 7 am. However, as solar radiation in Germany is particularly weak during winter, and there is generally a higher household electricity demand, precharging before the peak price period becomes necessary and is much more pronounced than for the Australian case. Electricity imported from the grid under the TI-TE tariff is more than 8 times higher for an average household in Germany than for the average Australian household. Although the frequency of high-power feed-ins is significantly lower for the German context, there is no limitation on the magnitude of power exported, potentially leading to high stress for an electricity grid with high PV penetration. However, as for the Australian case, the TI-TE tariff incentivises electricity storage during high generation times for later export, reducing the frequency with which a peak feed-in of more than 4 kW occurs by more than 60 %.

In addition, intermediary tariffs between flat and temporal tariffs have been investigated, showing that a minimum price spread in the electricity price needs to be surpassed to trigger a reaction from the household. While the investigated levels for the peak price in a TI-FE tariff did not lead to changes in system operation, variations of the temporal export price demonstrated that below a certain price-spread, electricity storage and later export become unprofitable.

5 Summary and Future Research

In this work, the impacts that temporal tariffs have on household prosumage have been assessed by deploying a techno-economic optimisation model for the Australian and German contexts. As rooftop photovoltaics and battery installations are expanding in both countries, they are already having significant real-world impacts on the grid. The objective of this research is to first evaluate rational investment decisions in DER and its influences, followed by an analysis on the capability of temporal tariffs to incentivise households (with an average-sized PV-BESS) to better complement the operation of the power system.

Based on the technical and economic fundamentals, as well as the current state-of-the-art, suitable boundary conditions and parameters are selected for the optimisation model. In particular, this research improves on the literature by using 400 individual household load profiles in Australia and 72 in Germany. Furthermore, the electricity tariffs evaluated not only consider time-varying import charges but also recently introduced time-varying export prices.

The optimisation model deployed in this work evaluates the profitability of an investment in a PV system, BESS or PV-BESS based on the maximum achievable NPV for every household individually. The most important techno-economic inputs include the household load profiles, techno-economic parameters of the PV system and BESS, as well as the assumed electricity price and its development over time. For each household, the FI-FE, TI-FE, and the TI-TE tariffs are investigated. Subsequently, the NPV is maximised by determining the optimal system size and operation for every load profile provided. The results include not only the techno-economic indicators such as the NPV, PV and BESS size or the upfront cost, but also the system operation consisting of the electrical flows between the household, the grid and, if applicable, the DER.

To fully assess the impact of temporal tariffs on household prosumage, three case studies were conducted. First, the impacts on rational investment are evaluated for different electricity price developments in Case Study 1.1, followed by an investigation of the effects that the BESS price has in Case Study 1.2. Second, Case Study 2 focusses on the impact of tariff structures on optimal system operation, when an average-sized PV-BESS is installed.

For Case Study 1.1, the expected development of electricity prices in each country was estimated by linear regression, resulting in the baseline scenarios of no change in electricity prices for Australia and an increase of +2 %/a for Germany. The findings of the AUS.1.1 and

GER.1.1 case studies reveal that, within the modelled 10-year period of time, investment in DER remains unprofitable for the majority of households in both countries. In particular, no investment in BESS occurs at existing electricity and BESS prices in any of the scenarios investigated. In the baseline scenario, 12 % of Australian households under the FI-FE tariff are encouraged to install PV systems with a median size of 7.6 kWp, while 8 % of German households under the flat tariff do so with a significantly smaller size of 3.4 kWp. The sensitivity analysis of electricity price developments (5 %/a higher and lower than the baseline scenarios) shows that an increase in electricity price is generally correlated with higher profitability and additional PV system adoption. Conversely, for price decreases, the opposite behaviour is observed. In any case, the investment is mainly profitable for households with higher annual electricity consumption, and temporal tariffs are generally less profitable than the flat tariff for PV-only system installations.

In Case Study 1.2, a BESS price tipping point is identified based on rational investment in Australia and Germany. This tipping point corresponds to PV-BESS becoming the most favourable configuration under temporal tariffs. In Australia, a change in investment behaviour is found to be for a BESS price of 400 $/kWh with 13 % of households opting for PV-BESS under temporal tariffs. In Germany, the tipping point lies at a BESS price of 500 €/kWh, with 8 % of households subject to a temporal tariff investing in PV-BESS. These tipping points are particularly important findings, as the installation of BESS enables households to respond to price signals of temporal tariffs without the need for behavioural change. Concerning the operation of the PV-BESS, for households subject to the FI-FE tariff, the BESS is simply charged when there is surplus generation and discharged when demand exceeds PV generation. However, under temporal import tariffs that feature higher prices between 3 pm and 9 pm, electricity demand is reduced as much as possible during that period of time. Although charging the BESS with PV generation covers most of the afternoon electricity consumption in Australia, precharging from the grid is observed in the German context, particularly during winter. As the system sizes in both countries are relatively small and the import price is the main driver of the operation of the system, there are only small differences regarding the behaviour of electricity export between the TI-FE and TI-TE tariffs.

Since the actual installed system sizes are much larger than the optimisation results suggest, Case Study 2 focusses on optimal system operation, assuming an investment in an average-sized PV-BESS. The Australian model features a PV-BESS of 8 kWp and 12 kWh, while in the German model a system of 9 kWp and 9 kWh is assumed. The principal operational implications of Case Study 1.2 still apply; however, they are more pronounced due to the larger system dimensions. In addition to the impacts of the temporal import tariff, changes in feed-in behaviour caused by the temporal export tariff become apparent. Due to a lower feed-in remuneration during the midday, the BESS is charged when high-power feed-ins usually occur, mitigating stress on the grid, and contributing to nighttime electricity production by discharging when the price for exporting is the highest. To investigate the price point, when households start responding to electricity price signals, additional intermediary tariffs between flat and temporal structures are investigated. It is found that a certain threshold must be surpassed to trigger a reaction from households. Although the investigation of different price levels in the TI-FE tariff did not trigger changes in system operation, variations in the TI-TE tariff demonstrated that below a certain price spread, electricity storage for nighttime feed-in becomes unprofitable.

Overall, this work showcases that temporal tariffs have a high potential to incentivise households to operate their PV-BESS in a grid-friendly manner. However, since an investment in BESS is generally not profitable within its operational lifetime, yet there needs to be a widespread adoption of PV-BESS to leverage the potential of temporal tariffs, an adequate battery price is needed. As highlighted in case study 1.2, ideal BESS are generally sized to optimise for high self-consumption rates and low grid dependence. However, if export behaviour should be adapted as well, the adoption of TI-TE tariffs and significantly larger systems is required. While the temporal import tariff enables relief of afternoon peak demand, the reduction of high-power feed-in during the midday and the provision of nighttime electricity production capacities are promising benefits of temporal export tariffs. The interplay between tariff structures and household response shows the potential for sophisticated system operation strategies.

Although this study has addressed important issues, there is potential for future research in various areas. In particular, the incorporation of electric vehicles (EVs) as an additional means of energy storage could be an interesting area of research. Investigating the opportunity that arises from the application of EVs as additional energy storage capacity could play a crucial role in facilitating the energy transition and mitigating negative effects on the energy grid. However, it is important to note that the primary purpose of purchasing an EV remains mobility, which requires complex boundary conditions when integrating it as a storage system in an optimisation model. Another option for future research is the investigation of dynamic tariffs that are increasingly offered by electricity retailers. By passing wholesale market fluctuations on to the end-consumer, the real price of electricity at a specific time is used as an incentive for grid-friendly electricity consumption. However, the implementation of dynamic tariffs is associated with additional uncertainty, making the modelling assumption of perfect foresight questionable. Lastly, a detailed assessment of the impacts on the grid imposed by the adoption of PV-BESS in combination with temporal tariffs could provide additional insights, such as managing congestion of the distribution network. The interplay between the avoided costs for grid expansion, stability measures, and curtailment, as well as the price incentives for the adoption of PV-BESS offers a promising landscape for future research and policy considerations in sustainable energy systems.

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Appendix

A Appendix

A.1 Techno-Economic Equations

Electricity generated by the PV-system may be consumed by the load, fed into the grid, charge the BESS and/or be curtailed:

$$E_{PV-Gen.}(t) = E_{PV\rightarrow Load}(t) + E_{PV\rightarrow Grid}(t) + E_{PV\rightarrow BESS}(t) + E_{PV\rightarrow Curtail}(t) \tag{A.1}$$

The exogenously given existing household load (all positive values from the household load profile) has to be met by the solar system, the grid and/or the BESS or be curtailed:

$$E^{exo}_{Ex.\,Load}(t) = E_{PV\rightarrow Load}(t) + E_{Grid\rightarrow Load}(t) + E_{BESS\rightarrow Load}(t) \tag{A.2}$$

The electrical flows from the exogenously given existing household grid feed-in (all negative values from the household load profile, minimum is the feed-in limitation) and curtailment (the surplus generation, if the negative value surpasses the feed-in limitation) have to be fed into either the grid, be curtailed or be stored in the BESS:

$$E^{exo}_{Ex.\rightarrow Grid}(t) + E^{exo}_{Ex.\rightarrow Curtail}(t) = E_{Ex.\rightarrow Grid}(t) + E_{Ex.\rightarrow Curtail}(t) + E_{Ex.\rightarrow BESS}(t) \tag{A.3}$$

$$\forall\ t \in n$$

Table A.1: Electricity Flows and Energy States

Variable	**Symbol**
El. flow: PV → Load	$E_{PV \to Load}$
El. flow: PV → Grid	$E_{PV \to Grid}$
El. flow: PV → BESS	$E_{PV \to BESS}$
El. flow: PV → Curtail	$E_{PV \to Curtail}$
El. flow: Grid → Load	$E_{Grid \to Load}$
El. flow: Grid → BESS	$E_{Grid \to BESS}$
El. flow: BESS → Load	$E_{BESS \to Load}$
El. flow: BESS → Grid	$E_{BESS \to Grid}$
El. flow: Existing → Grid	$E_{Ex. \to Grid}$
El. flow: Existing → BESS	$E_{Ex. \to BESS}$
El. flow: Existing → Curtail	$E_{Ex. \to Curtail}$
El. generation from PV	$E_{PV\text{-}Gen.}$
State of Health (PV)	SOH_{PV}
State of Charge of (BESS)	SOC_{BESS}
State of Health of (BESS)	SOH_{BESS}

A.2 Model Parameters

Table A.2: Parameter Values

Tag	Value	Unit	Description
Financial and Grid Specifications			
$Financial\ Horizon\ T$	10	years	Number of years in the NPV calculation
$Modelled\ time\text{-}steps\ \Delta\, t_{sec}$	1	hour	Modelling time-steps
$Discount\ Rate\ r\ (AUS)$	6	%	Discount rate in the NPV calculation (Australia)
$Discount\ Rate\ r\ (GER)$	4	%	Discount rate in the NPV calculation (Germany)
$Max.\ Grid\ Feed\text{-}in\ (AUS)$	5	kW	Max. grid feed-in until curtailment (Australia)
$Max.\ Grid\ Feed\text{-}in\ (GER)$	-	kW	Max. grid feed-in until curtailment (Germany)
PV Specifications			
$Min.\ PV\text{-}size$	1	kW	Minimum PV-capacity available for purchase
$EOL\text{-}Capacity_{PV}$	80	%	PV generation capacity remaining at EOL
$EOL\text{-}Years_{PV}$	25	years	Number of years to reach EOL
$SoH_{PV}(t=0)$	100	%	Starting state of health of the PV system
BESS Specifications			
$Min.\ BESS\text{-}size$	3	kWh	Minimum BESS-capacity available for purchase
$Energy\text{-}to\text{-}Power\text{-}Ratio_{BESS}$	2.4	ratio	Energy to power ratio of the BESS being considered
$EOL\text{-}Years_{BESS}$	10	years	Number of years until BESS is considered end of life
$EOL\text{-}Cap._{BESS}$	70	%	Energy storage capacity remaining at EOL (calendric)
$EOL\text{-}Cycles_{BESS}$	10,000	cycles	Number of cycles to reach EOL (cyclic)
$SoH_{BESS}(t=0)$	100	%	Starting state of health of the BESS
η_{charge}	93.81	%	Efficiency of charging the BESS
$\eta_{discharge}$	93.81	%	Efficiency of discharging the BESS

Table A.3: Overview of Parameters utilized in the Case Studies for Australia

AUS.1. Rational Investment			
Description	**Value 1**	**Value 2**	**Value 3**
AUS.1.1 El. price development	±0 %/a	+5 %/a	-5 %/a
AUS.1.2 Cost of BESS	300 \$/kWh	400 \$/kWh	500 \$/kWh
AUS.2. System Operation			
Description	**Value 1**	**Value 2**	**Value 3**
AUS.2.1 Tariff Structure (Base)	FI-FE	TI-FE	TI-TE
AUS.2.2 Tariff Structure Variation (TI-FE)	TI-FE-1	TI-FE-2	TI-FE-3
AUS.2.3 Tariff Structure Variation (TI-TE)	TI-TE-1	TI-TE-2	TI-TE-3

Concerning case study AUS.2, the term FI-FE refers to the "base-cases" that were also utilized in case study AUS.1 and have been listed in tables 3.1 and 3.2. The terminology used for temporal import and flat export tariffs used case study 2 defines TI-FE-1 for example as a combination of TI-1 (see table A.5) and the flat export tariff. Temporal import and temporal export tariffs such as TI-TE-2 combine the TI-2 and TE-2.

Table A.4: Overview of Parameters utilized in the Case Studies for Germany

GER.1. Rational Investment			
Description	**Value 1**	**Value 2**	**Value 3**
GER.1.1 El. price development	+2 %/a	+7 %/a	-3 %/a
GER.1.2 Cost of BESS	400 €/kWh	500 €/kWh	600 €/kWh
GER.2. System Operation			
Description	**Value 1**	**Value 2**	**Value 3**
GER.2.1 Tariff Structure (Base)	FI-FE	TI-FE	TI-TE
GER.2.2 Tariff Structure Variation (TI-FE)	TI-FE-1	TI-FE-2	TI-FE-3
GER.2.3 Tariff Structure Variation (TI-TE)	TI-TE-1	TI-TE-2	TI-TE-3

Table A.5: Case Study AUS.2: Import and Export Tariffs in Australia

Pricing Type	Price in $/kWh	Time
Flat Import (Base)	0.243	*Always*
TI-1	0.228	$9\,pm - 3\,pm$
	0.265	$3\,pm - 9\,pm$
TI-2	0.214	$9\,pm - 3\,pm$
	0.287	$3\,pm - 9\,pm$
TI-3	0.199	$9\,pm - 3\,pm$
	0.310	$3\,pm - 9\,pm$
Temporal Import (Base)	0.184	$9\,pm - 3\,pm$
	0.332	$3\,pm - 9\,pm$
Flat Export (Base)	0.052	*Always*
TE-1	0.056	$3\,pm - 9\,pm$ (*only weekdays*)
	0.057	$10\,pm - 7\,am$
	0.052	*all other times*
TE-2	0.061	$3\,pm - 9\,pm$ (*only weekdays*)
	0.062	$10\,pm - 7\,am$
	0.051	*all other times*
TE-3	0.065	$3\,pm - 9\,pm$ (*only weekdays*)
	0.066	$10\,pm - 7\,am$
	0.051	*all other times*
Temporal Export	0.069	$3\,pm - 9\,pm$ (*only weekdays*)
	0.071	$10\,pm - 7\,am$
	0.050	*all other times*

Table A.6: Case Study GER.2: Import and Export Tariffs in Germany

Pricing Type	Price in $/kWh	Time
Flat Import (Base)	0.357	*Always*
TI-1	0.335	$9\,pm - 3\,pm$
	0.390	$3\,pm - 9\,pm$
TI-2	0.314	$9\,pm - 3\,pm$
	0.422	$3\,pm - 9\,pm$
TI-3	0.292	$9\,pm - 3\,pm$
	0.455	$3\,pm - 9\,pm$
Temporal Import (Base)	0.271	$9\,pm - 3\,pm$
	0.487	$3\,pm - 9\,pm$
Flat Export (Base)	0.082	*Always*
TE-1	0.089	$3\,pm - 9\,pm$ (*only weekdays*)
	0.089	$10\,pm - 7\,am$
	0.081	*all other times*
TE-2	0.095	$3\,pm - 9\,pm$ (*only weekdays*)
	0.097	$10\,pm - 7\,am$
	0.080	*all other times*
TE-3	0.102	$3\,pm - 9\,pm$ (*only weekdays*)
	0.104	$10\,pm - 7\,am$
	0.080	*all other times*
Temporal Export	0.109	$3\,pm - 9\,pm$ (*only weekdays*)
	0.112	$10\,pm - 7\,am$
	0.079	*all other times*

A.3 Case Study Visualisation

AUS.1.1

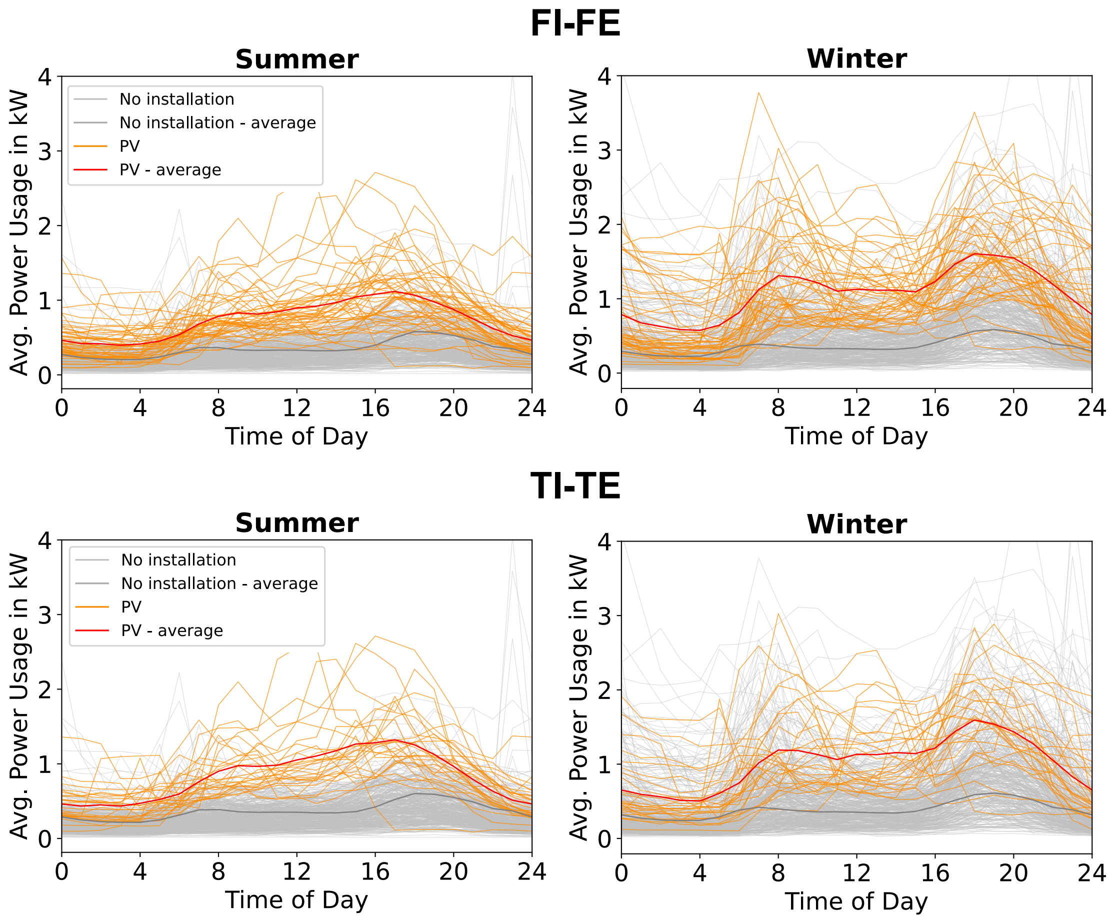

Figure A.1: Average underlying Household Load Profiles for Summer and Winter indicating which Households opt for a PV-system under the FI-FE and TI-TE tariffs (AUS.1.1, ±0 %/a)

AUS.1.2

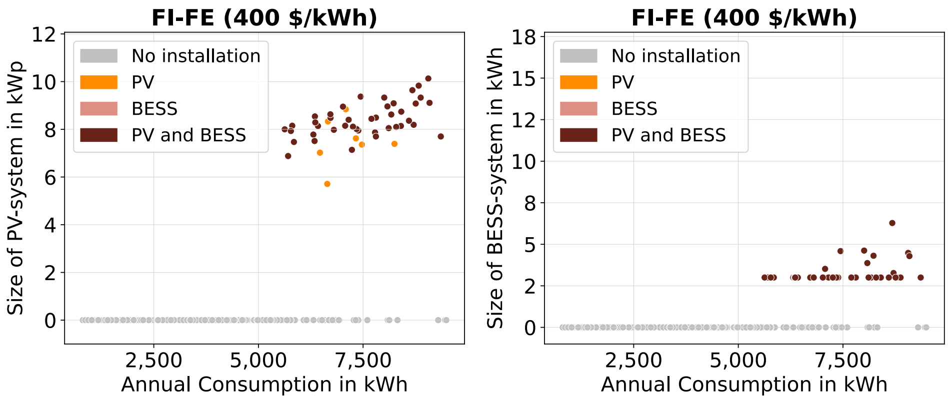

Figure A.2: Installed PV and BESS Size over Annual Household Consumption for the FI-FE tariff (AUS.1.2, 400 $/kWh)

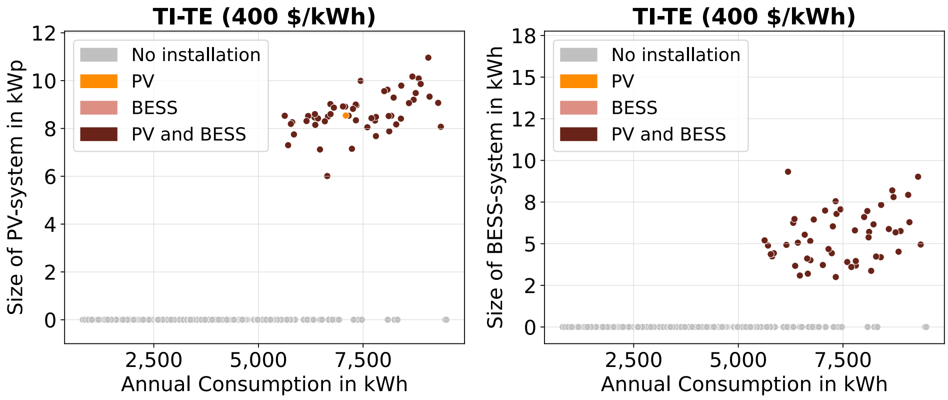

Figure A.3: Installed PV and BESS Size over Annual Household Consumption for the TI-TE tariff (AUS.1.2, 400 $/kWh)

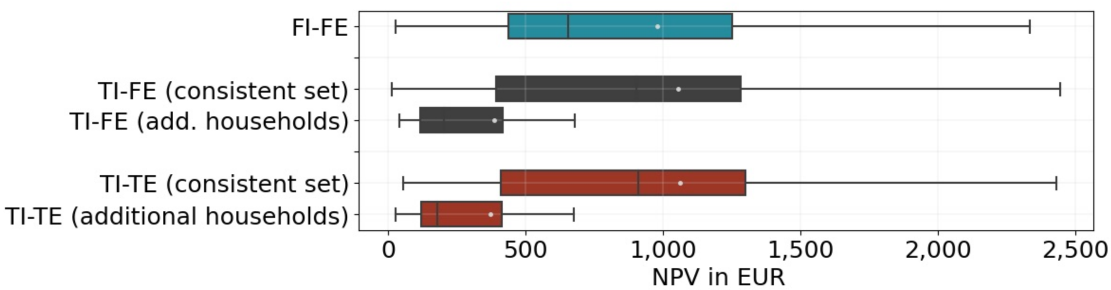

Figure A.4: NPV for the Set of Consistent and Additional Households (AUS.1.2, 400 $/kWh)

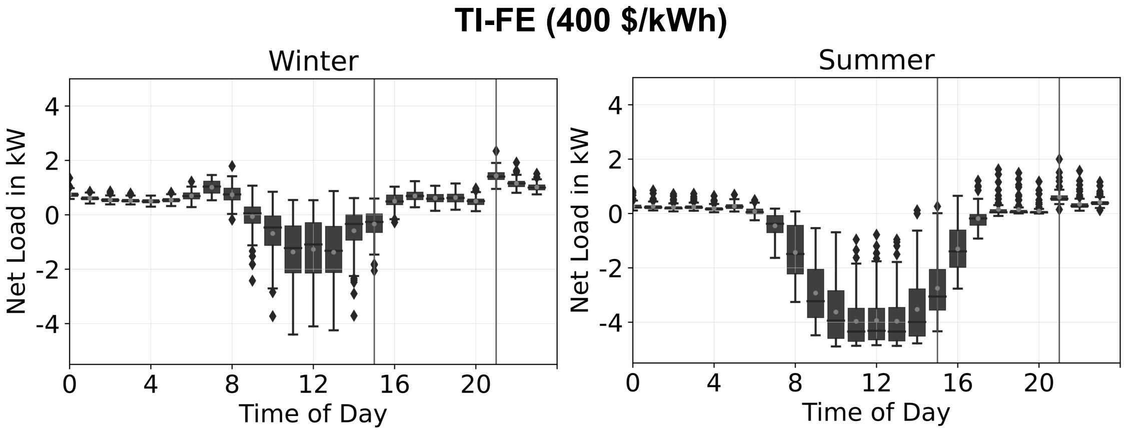

Figure A.5: Average Hourly Net Load Distribution across all Households with an average-sized PV-BESS under a FI-FE Tariff Structure in Summer and Winter (400 $/kWh)

GER.1.1

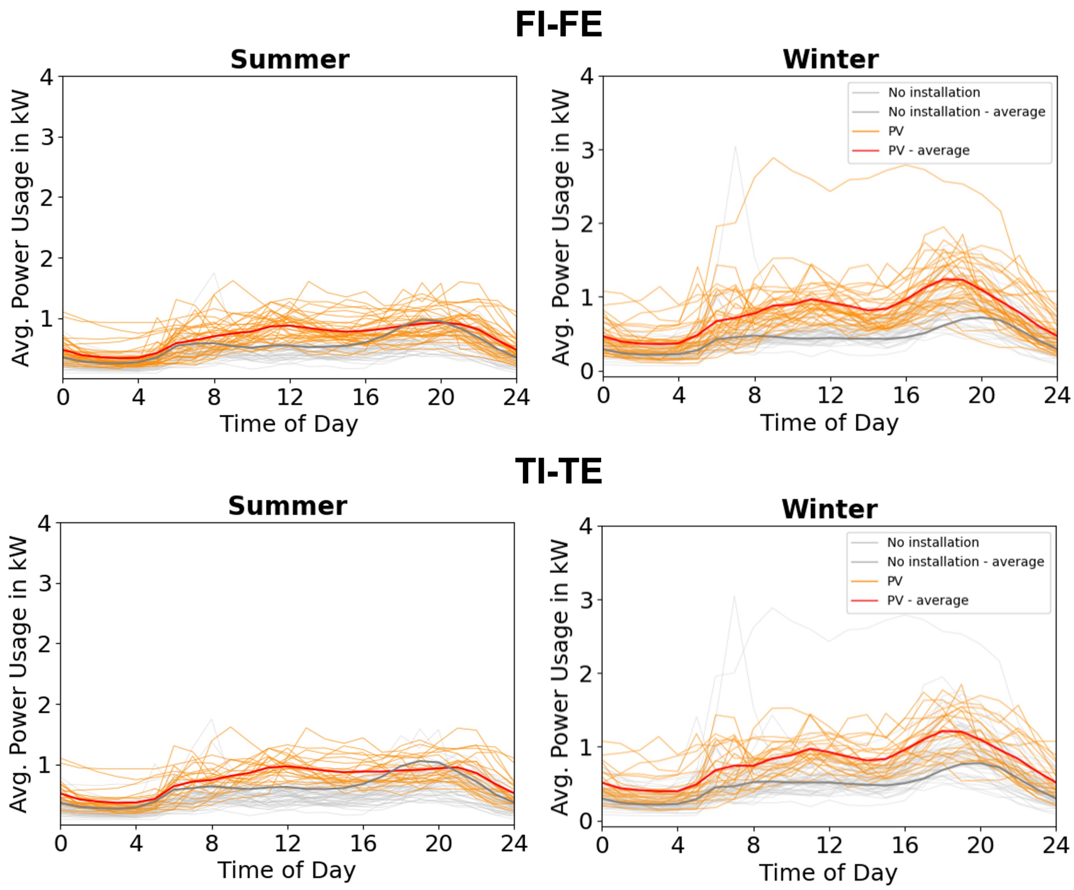

Figure A.6: Average underlying Household Load Profiles for Summer and Winter indicating which Households opt for a PV-system under the FI-FE and TI-TE tariffs (GER.1.1, +7 %/a)

GER.1.2

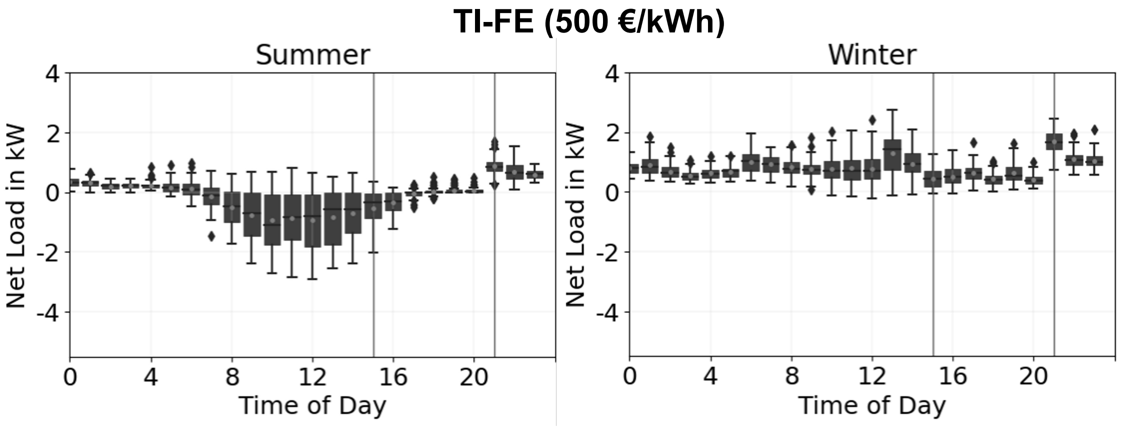

Figure A.7: Average Hourly Net Load Distribution across all Households with an average-sized PV-BESS under a FI-FE Tariff Structure in Summer and Winter (GER.1.2, 500 €/kWh)

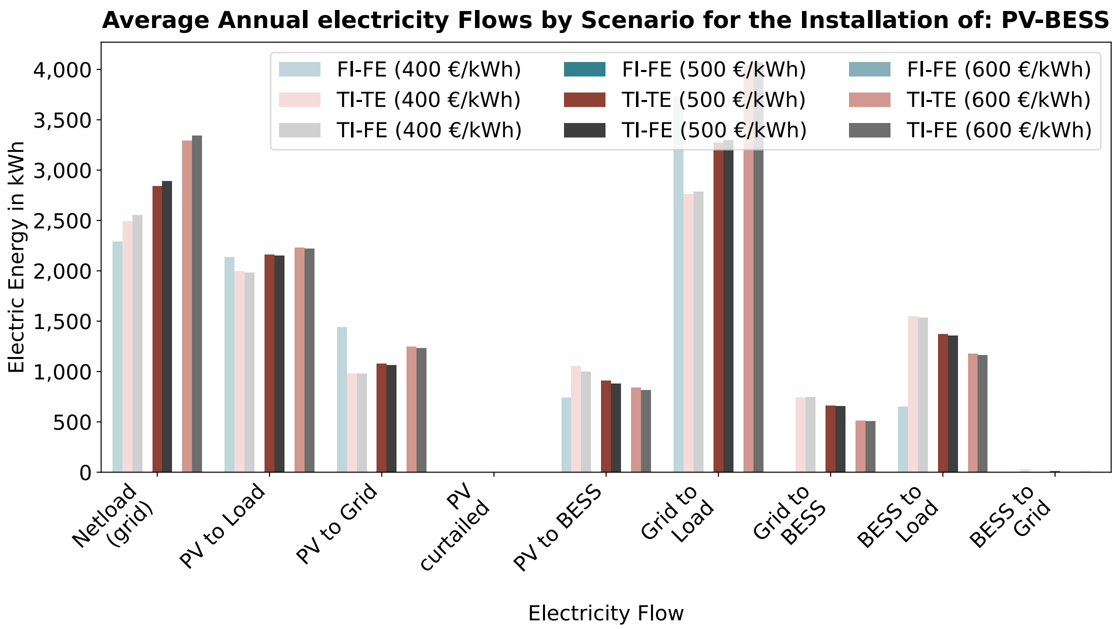

Figure A.8: Annual Electricity Flows across all Scenarios for an average Household with an average-sized PV-BESS (GER.1.2)

Declaration of Originality

I hereby declare that this thesis and the work reported herein was composed by and originated entirely from me. Information derived from the published and unpublished work of others has been acknowledged in the text and references are given in the list of sources. This thesis has not been submitted as exam work in neither the same nor a similar form. I agree that this thesis may be stored in the institutes library and database. This work may also be copied for internal use.

Melbourne, Tuesday 22nd August, 2023

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