Master's Thesis

Comparative analysis of modeling strategies for decentral photovoltaic and storage in energy system models

Written at
Institute of Energy Systems and Electrical Drives
Energy Economics Group (EEG)
Technische Universität Wien

under the supervision of
Univ.Prof. Dr. Reinhard Haas
Dipl.-Ing. Dr. Franziska Schöniger
Jasper Geipel, MSc
Dipl.-Ing. Dr. Gustav Resch

by
Jovan Stefanovic, BSc

Vienna, November 21, 2023

Abstract

The photovoltaics in the residential sector is driving Austria's PV capacity (3.8 GWpeak) development.[1] The increasing penetration of distributed generation and storage is reshaping customer consumption profiles and thus challenging the energy system. To answer an increasing variability and complexity of prosumer demand and generation profiles, energy system models must account for a wider range of variables and incorporate more data. These encompass considerations such as grid constraints (e.g. bidirectional power flow dynamics), the charging and discharging behavior of energy storage systems, and changing economic and policy factors.

This thesis aims to assess the impact of two modeling approaches to decentralized PV and storage dispatch on the results of the energy system model: one maximizing self-consumption rates of households, and another (the system-optimal approach) modeling prosumers[2] as separate entities: consumers and producers. Additionally, the thesis examines the advantages of prosumers sharing their extra electricity with others in energy communities, looking at the benefits for both the prosumers themselves and the overall energy system.

A *prosumer model* was developed in MATLAB with the task of modifying energy system data to depict the behavior of residential prosumers toward the electricity grid. Within the model, residential prosumers in Austria are portrayed as a single energy agent maximizing self-consumption. Using the prosumer model, various energy system scenarios were developed for Austria in the year 2030 and then quantified using the open-source energy system model Balmorel (GAMS). These scenarios vary in terms of the percentage of total decentralized PV capacity modeled as prosumers, the capacity of accompanying batteries, and the prosumer's participation in energy communities.

Optimizing decentralized generation for self-consumption in the model reveals an increase in average electricity spot prices, a reduction in total electricity generation costs in the public grid, and a decrease of up to 1.03

[1]According to Biermayr (2023), the PV capacity in operation in Austria at the end of 2022 was 3791.7 MWpeak.

[2]The neologism "prosumer" refers to an electricity consumer that produces part of his/her electricity needs from his/her own power plant and uses the distribution network to inject excess production and to withdraw electricity when self-production is not sufficient to meet his/her own needs (Kopač, 2018).

TWh in grid losses compared to a system-optimal perspective. Additionally, the model results underscore the significance of energy communities in mitigating electricity back-feeding, while also highlighting redundancy (up to 0.55 TWh) between decentralized batteries and pumped hydroelectric energy storage (PHES) for intra-day energy storage in the Austrian energy system in 2030.

Kurzfassung

Die Photovoltaik (PV) im Haushaltssektor treibt die Entwicklung der PV-Kapazität in Österreich (3,8 GWp) voran.[3] Die zunehmende Durchdringung dezentraler Erzeugung und Speicherung formt Verbrauchsprofile und stellt somit das Energiesystem vor Herausforderungen. Um auf die zunehmende Variabilität und Komplexität von Prosumer-Nachfrage- und Erzeugungsprofilen zu reagieren, müssen Energiesystemmodelle eine breitere Palette von Variablen berücksichtigen und mehr Daten integrieren. Dazu gehören Überlegungen wie Netzbeschränkungen (z. B. bidirektionale Energieflussdynamik), das Lade- und Entladeverhalten von Energiespeichersystemen sowie sich ändernde wirtschaftliche und politische Faktoren.

Das Ziel dieser Arbeit ist es, den Einfluss zweier Modellierungsansätze für dezentrale PV- und Speichersteuerung auf die Ergebnisse des Energiesystemmodells zu bewerten: einerseits die Maximierung der Eigenverbrauchsraten von Haushalten und andererseits (der systemoptimale Ansatz) die Modellierung von Prosumern[4] als separate Entitäten: Verbraucher und Produzenten. Zusätzlich untersucht die Arbeit die Vorteile des Teilens von überschüssigem Strom von Prosumern mit anderen in Energiegemeinschaften und betrachtet dabei die Vorteile sowohl für die Prosumer selbst als auch für das gesamte Energiesystem.

Ein *Prosumer-Modell* wurde in MATLAB entwickelt, um Energiesystemdaten zu modifizieren und das Verhalten von privaten Prosumern gegenüber dem Stromnetz darzustellen. Innerhalb des Modells werden private Prosumer in Österreich als ein Energieagent dargestellt, der den Eigenverbrauch maximiert. Mithilfe des Prosumer-Modells wurden verschiedene Energieszenarien für Österreich im Jahr 2030 entwickelt und anschließend mithilfe des Open-Source-Energiesystemmodells Balmorel (GAMS) quantifiziert. Diese Szenarien variieren hinsichtlich des Prozentsatzes der insgesamt dezentralen PV-Kapazität, die als Prosumer modelliert ist, der Kapazität begleitender Batterien und der Beteiligung der Prosumer an Energiegemeinschaften.

Die Optimierung dezentraler Erzeugung für den Eigenverbrauch im Mod-

[3]Gemäß Biermayr (2023) betrug die PV-Kapazität, die Ende 2022 in Österreich in Betrieb war, 3791.7 MWpeak.

[4]Der Neologismus "Prosumer" bezieht sich auf einen Stromverbraucher, der einen Teil seines Strombedarfs aus seiner eigenen Stromerzeugungsanlage deckt und das Verteilnetz nutzt, um überschüssige Produktion einzuspeisen und Strom abzunehmen, wenn die Eigenproduktion nicht ausreicht, um den eigenen Bedarf zu decken (Kopač, 2018).

ell zeigt eine Erhöhung der durchschnittlichen Spotpreise für Strom, eine Reduzierung der Gesamtkosten für Stromerzeugung im öffentlichen Netz und eine Verringerung von bis zu 1,03 TWh an Netzverlusten im Vergleich zur systemoptimalen Perspektive. Darüber hinaus betonen die Modellergebnisse die Bedeutung von Energiegemeinschaften zur Reduzierung der Rückeinspeisung von Strom und verdeutlichen auch Redundanzen (bis zu 0,55 TWh) zwischen dezentralen Batterien und Pumpspeicherwasserkraftwerken (PHES) hinsichtlich der Intraday-Energiespeicherung im österreichischen Energiesystem im Jahr 2030.

Contents

List of Figures

List of Tables

1 Introduction

Photovoltaics (PV) is a fast-growing and highly competitive electricity generation technology. Due to on-site electricity generation, in comparison to centralized electricity generation facilities, decentralized PV offers greater supply flexibility, better space utilization, lower transportation costs, and additional customization options to meet local customer needs and preferences. These options include real-time tracking of own generation and consumption, enabling informed decisions about whether to store or consume energy. With the grid parity[5] reached almost a decade ago (Photovoltaik Austria, 2017), PV in the residential sector became a candidate for widespread development without subsidies or government support. In addition to achieving grid parity, scalability, modularity, and minimal infrastructure requirements have led to annual PV capacity additions of 0.74 GWp in 2021 and 1 GWp in 2022, resulting in 3.8 GWp of operational photovoltaic systems[6] in Austria at the end of 2022 (Biermayr, 2023). The figures, along with the estimated electricity production potential by PV prosumers, accounting for approximately 40% of Austria's total electricity demand by the year 2050 (European Environment Agency, 2022), underscore the pivotal role of prosumers in the transition toward a fully sustainable energy system.

Integrating volatile renewable energy sources (RES) from a multitude of different sources, as opposed to conventional centralized power production, is a complex task that requires profound system planning. To facilitate decisions concerning sustainable and resilient energy infrastructures, and to support policymaking and long-term planning, mathematical representations are employed to analyze the complex interactions of diverse components within an energy system. This analytical approach is commonly referred to as energy system modeling. Fodstad et al. (2022) define four main challenges to energy system modeling: time and space (spatial and temporal resolutions); uncertainty; multi-energy (integration of the operations of different energy carriers and sectors, such as electricity, natural gas, and district heating);

[5]Grid parity occurs when alternative energy sources can produce electricity at a levelized cost of electricity (LCOE) that is less than or equal to the price of electricity from the grid. Grid parity is different depending on whether you are calculating it from the power company's perspective or from the retail consumer's perspective(Renewable Energy Advisor, 2017).

[6]This capacity represents overall installed PV capacity in Austria in the year 2022, including central, decentral, and autark PV capacity. I wasn't able to find the exact percentage of decentral PV for the year 2022, but from the data available for the year 2020 (Fechner, 2022) (where 99% of installed PV capacity is of type decentral PV), one could assume almost all PV capacity as decentralized photovoltaic.

energy behavior and energy transition outlining the lack of and limited inclusion of prosumers (e.g., flexible local markets) in energy system models.

In energy system models, photovoltaics and storage are often modeled as a system optimal dispatch, viewing prosumers as two separate entities (producers and consumers). This approach aims to find the most efficient and cost-effective way to operate the entire energy system, considering factors such as generation sources, storage, and consumption. While system optimal dispatch of photovoltaics provides a comprehensive perspective crucial for the effective integration of RES into the grid, policy assessments, and evaluation of the impact of different regulatory mechanisms on the energy environment, it falls short in capturing the individual behaviors of prosumers, particularly in terms of self-consumption. In reality, under the current tariff design, prosumers aim to maximize self-consumption, and the system ‘sees‘ a reduced load and in consequence a different load profile, similarly to energy efficiency measures.

Incorporating a prosumage[7] concept, where electricity consumers produce electricity from photovoltaics with accompanying battery storage installed, as defined by Green and Staffell (2017), or as end users who sell and supply surplus electricity to local markets, as demonstrated by Schill et al. (2017), allows for a better understanding of the dynamics of decentralized solar generation. These approaches ensure more inclusive and accurate representations in energy planning and facilitate the integration of photovoltaics and storage into more comprehensive energy management strategies, enabling further optimization of electricity usage.

The primary research question of this thesis is: "How do energy system modeling results differ when decentralized PV and storage are modeled as prosumers maximizing self-consumption, in contrast to modeling decentralized PV generation as two distinct entities, consumers and producers optimized from the system perspective?"
The secondary objective is to describe the change of the impact on the energy system with an increasing share of decentralized PV and storage in the system.
Finally, the thesis explores the prospective advantages associated with prosumers sharing surplus electricity generation within energy communities, considering the viewpoints of both prosumers and the energy system. This serves as a prime example of the enhanced value and expanded options facilitated

[7]PROSUMAGE = PROducer+conSUMer+storAGE

by the modeling of prosumage.

Mengolini (2017) argues that the best-suited tool to study emergent behaviors in energy consumption patterns and practices is agent-based modeling[8] and develops a subjective individual model of a prosumer (SIMP). I agree that modeling prosumers as separate agents in the energy system depicts the energy system state more accurately, but it comes with increased costs in terms of data demand and model complexity. Between the high level of detail required for individual agent-based models and the omission of self-consumption in system optimal modeling, I aggregate residential prosumers into a single agent, providing a middle ground where the self-consumption of prosumers in the household sector can be modeled with lower data requirements and model complexity, yielding more cost-effective solutions.

The thesis is structured into several key sections. Section 1 introduces the research, outlining the thesis structure and providing an overview of the state of the art in energy system modeling. Section 2 details the Balmorel energy system model and the concept of prosumers, including sub-model implementation, nationwide scaling, and data sources. In Section 3, the research findings are presented, covering topics such as optimal dispatch modeling, annual generation, prosumer battery impacts, backfeeding, and cost comparisons. A concise conclusion is presented in Section 4, and Appendix A includes the MATLAB code used in the research, providing technical details.

[8]Fodstad et al. (2022): 'ABMs are computational models that simulate the interactions and actions of what are termed as "agents". These simulated agents (e.g. individuals, households, or broader organizations) can be assumed to be perfectly rational, but do not have to be. Rather, an ABM creates the rules that these agents follow.

2 Method

This section forms the foundation for the research, commencing with a detailed overview of the research methodology. Section 2.2 introduces the Balmorel energy system model, covering topics such as the time representation, electricity consumption in Austria in 2020 and 2030, the specifics of generation technologies, as well as data sources used. Section 2.3 delves into the concept of a single household residential prosumer, explaining the prosumer's goals and the implementation the single household prosumer submodel. Furthermore, it includes a comparison between consumer, prosumer with PV installations and prosumer with PV and storage. Section 2.4 extends the discussion to the nationwide prosumer model, offering an overview of its structure, inputs, outputs, model variables, scaling up of the single household sub-model, data restructuring, and a comprehensive explanation of the model's assumptions and limitations.

2.1 Method of Approach

Given the increasing complexity of energy system models, such as Balmorel, I had to develop subroutines to simplify and outline parameter interrelations in the code for a complete overview of model functionalities and structure. This facilitated the identification of efficient placement opportunities for the prosumer concept within the existing structure, minimizing alterations of data sets and parameter interrelations, as well as detecting missing data necessary for modeling decentralized prosumers.

The data describing various aspects of the energy system is stored in large data sets accompanying the Balmorel model. These data sets encompass demand, generation, fuel sources, environmental factors, policy-related cost parameters, and more. In its current state, Balmorel functions as a cost-minimization model, dispatching all generation in a system-optimal way, inclusive of residential PV. To incorporate the concept of a prosumer maximizing household self-consumption (or local consumption within an energy community), adjustments to the integrated data sets are necessary. I developed a prosumer model in Matlab to imitate prosumer behavior towards the grid and facilitate the necessary data modifications.[9] The prosumer submodel scope includes the definition of a prosumer concept, a single-house

[9]In the thesis, I use the term "prosumer sub-model" to refer to the model of a photovoltaic system with or without batteries on a single house. The prosumer sub-model is a pivotal part of the nationwide "prosumer model" in Austria in the year 2030.

prosumer sub-model (refer to Section 2.3), and the development of a battery optimization strategy. The prosumer sub-model underwent a scaling-up process into a nationwide prosumer model (refer to Section 2.4). This was achieved through the aggregation of decentralized prosumers into one "big house". A dynamic element was introduced, allowing for the adjustment of the percentage of decentralized PV modeled as a prosumer, and a spectrum was defined, ranging from a prosumer share of 0.0, signifying that all decentralized PV would be modeled as a system-optimal dispatch, to a prosumer share of 1.0, representing 100% of decentralized PV in Austria being modeled as a prosumer, thus maximizing self-consumption in Austria. Additionally, sharing excess electricity within energy communities is incorporated into the prosumer model.

Using the prosumer model, various energy system scenarios are developed and quantified via the open-source energy system model Balmorel (GAMS), provided by the Energy Economics Group. The scenarios differ in the share of decentral PV modeled as a prosumer, the type of PV installation (with and without an accompanying battery), and whether the prosumer shares excess electricity in the local energy community or not. An overview of the developed scenarios is given in Table 7. Subsequently, an analysis of various scenarios for the year 2030 is conducted outlining differences arising from distinct modeling approaches, the impacts of accompanying batteries, and the advantages of electricity sharing within an energy community. Additionally, a sensitivity analysis of electricity fed into the grid is conducted, considering modeled prosumer types and their share in decentralized PV capacity within the Austrian energy system in the year 2030.

2.2 Balmorel energy system model

Balmorel, short for *BALtic Model for Regional Electricity Liberalisation*, is a partial equilibrium model, optimizing economically efficient dispatch or capacity expansion solution for the represented energy system, if dispatch is not feasible (Wiese et al., 2018). The model is implemented as a linear optimization problem in the GAMS modeling language and it allocates available energy resources to meet the demand while minimizing costs. Balmorel was developed to support analyses of the energy sector, with an emphasis on electricity and combined heat and power (CHP) systems. The model is suited for energy and environmental analyses of relevant economic and policy-related issues, as well as technical analyses of power and CHP systems (*Balmorel User Guide*, n.d.). The model has been applied in projects in many countries[10], and it's commonly used for analyses of the security of electricity supply, flexible electricity demand, wind power development, market power, heat transmission and pricing, and the expansion of electricity transmission (Balmorel, 2023).

2.2.1 Integration of Prosumer model into Balmorel

An energy system model comprises two fundamental elements: data inputs and the framework. Data inputs encompass a broad spectrum of information, such as energy sources, consumption patterns, environmental factors, and economic variables. The framework of an energy system model is the mathematical and computational structure developed to represent the interactions and constraints of an energy system. The developed prosumer model modifies data inputs only, as indicated in Figure 3. This approach enables the creation of energy system scenarios using different energy model frameworks and allows for a framework-independent analysis of the impact caused by differences in decentral PV and storage modeling approaches. In this thesis, I employed the Balmorel energy system model to quantify energy system scenarios created using the Prosumer model.

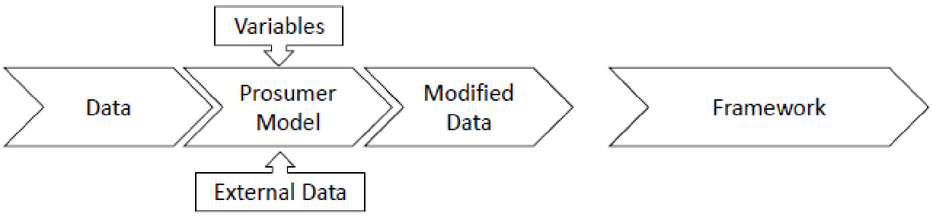

Figure 1: Prosumer Model in Energy System Model

2.2.2 Time representation in Balmorel model

The representation of the passage of time is fundamental to any dynamic power system model. In the Balmorel model, one modeled year (e.g. 2030) corresponds to 52 seasons each consisting of $7 * 24 = 168$ terms. A season represents a week, and a term a single hour, whereas a month is not modeled in itself, but for representation purposes, a month is defined as a

[10] Although initially developed for the Baltic region, the model has been expanded, adapted, and used in many countries. Some examples of modeling Austrian energy sector are: Aghaie et al. (2020), McKenna et al. (2021), Hasengst (2022) and SECURES project (www.secures.at).

period consisting of 728 terms or $4\frac{1}{3}$ seasons. The agreement is year starts with Monday 00:00-01:00 and ends with a Sunday. This approach simplifies modeling and comparison between different years, but as a consequence any real data requires small modification prior to its usage in the model.

2.2.3 Consumption in Austria in 2030 in the Balmorel model

The hourly electricity consumption in Austria is an exogenous parameter in the Balmorel model calculated by multiplying the total annual consumption with the variation in electricity demand (normalized hourly load profile).

External parameter variation in electricity demand is a modified version of the actual load profile for Austria in the year 2020, retrieved from the ENTSO-E platform. Two adjustments were made. Firstly, the load profile for the last two days of 2019 (Monday and Tuesday) was incorporated into the 2020 data to enable the week to commence on a Monday. Secondly, to account for the leap year in 2020, which consisted of 366 days, two surplus days were eliminated, resulting in a data set comprising 364 days. These modifications were introduced to align the load profile with the desired time frame and eliminate the influence of the leap year on the data set.

The modified ENTSO-E hourly consumption in Austria is used as a parameter variation in electricity demand in Austria in the year 2030. This parameter is used in all simulations for easier observation and assessment of the change in load profiles due to different modeling approaches of PV & storage dispatch, and PV penetration levels. As a consequence, simulated hourly load in Austria in the year 2020 differs from the hourly load in the year 2030 only in the multiplication factor, namely: different total annual consumption (see Figure 2).[11]

[11] The annual net consumption for Austria in 2020 is set at 60.9 TWh (TYNDP, 2021).

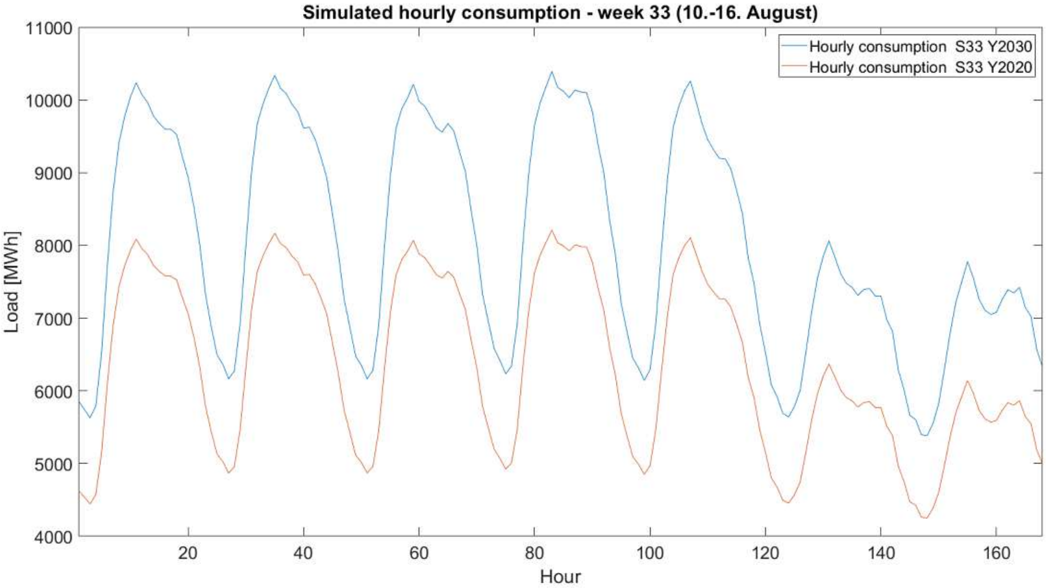

Figure 2: Total Hourly Consumption Comparison

2.2.4 Generation technologies and their capacities in Austria in years 2020 and 2030 in the Balmorel Model

To answer the increased demand described in the previous section, TYNDP (2021) predicts generation capacities increase in Austria in the year 2030, summarized in the Table 1.

MW	Austria 2030
Geothermal	8
Natural gas	3349
Oil	15
Waste	150
PV central	776
PV decentral	10751
Hydro reservoirs	3531
Hydro pump storage	4800
Hydro run-of-river	6 807
Biogas	73
Biomass	349
Wind onshore	6 870
Sum	37 479

Table 1: Generation Technologies in Austria

The data describing generation technologies in Austria in Balmorel model itself is far more detailed than represented in Table 1. Instead of using simple electricity generation capacities by energy source, the Balmorel model considers various generation technologies utilizing these resources. These technologies differ in efficiency, the technology they use, construction date, the commodities they produce (electricity and/or district heat), fuel types, generation costs, and other specific technology data. An overview of modeled generation technologies in Austria and their installed capacities in 2020 and predicted capacities in 2030 is provided in Table 3. Acronyms used in naming convention define technology type, fuel, technology group, location and commissioning year, and they are summarized in Table 2. The last part of a generation technology name is the commissioning year of the power plant. The "K5" and "GNR" at the beginning of a name stand for the classification of aggregated power and plant specifications.

Technology Type		**Main Fuel**		**Technology Group**		**Location**
Acronym	Definition	Acronym	Definition	Acronym	Definition	Acronym
CC	Combined Cycle	FUELOIL	Fossil Oil	CND	Condensing	ONSHORE
ST	Steam Turbine	NGAS	Natural Gas	BP	Back Pressure	CENTRAL
GT	Gas Turbine	COAL	Coal	EXT	Extraction	DECENTRAL
GEO	Geothermal	BGAS	Biogas	PMP	Pumping	
WT	Wind Turbine	WOODCHIPS	Wood Chips	NOPMP	No Pumping	
RES	Reservoir	WIND	Wind	BO	Boiler	
ROR	Run Of River	WTR	Water			
PV	Photovoltaic	SUN	Sun			
BO	Boiler	MSW	Municipal Solid Waste			

Table 2: Acronyms and Definitions

	Capacity [MW]	
Generation technologies in AT	2020	2030
K5_CC_NGAS_CND_Y-1990-1994	30,8	0,0
K5_CC_NGAS_CND_Y-2000-2004	147,6	139,0
K5_CC_NGAS_CND_Y-2005-2009	1424,2	1341,2
K5_CC_NGAS_CND_Y-2010-2014	708,7	667,4
K5_CC_NGAS_EXT_Y-1990-1994	1,7	0,0
K5_CC_NGAS_EXT_Y-2000-2004	682,5	2731,7
K5_GNR_ST_FUELOIL_CND	178,0	15,0
K5_GT_NGAS_CND_Y-1990-1994	10,7	0,0
K5_GT_NGAS_CND_Y-1995-1999	20,1	0,0
K5_GT_NGAS_EXT_Y-2000-2004	977,0	920,1
K5_ST_COAL_EXT_Y-1985-1989	246,0	0,0
K5_ST_NGAS_EXT_Y-1990-1994	11,5	0,0
K5_GNR_ST_BIOGAS_EXT_2020	0,0	73,0
K5_GNR_ST_WOODCHIPS_EXT_2020	497,0	349,0
K5_GNR_GEOTHERMAL_2020	0,0	8,0
K5_GNR_WT_WIND_ONSHORE_2020	3133,0	6870,0
K5_GNR_RES_WTR_PMP_2020		4800,0
K5_GNR_ROR_WTR_2020	5558,0	6807,0
K5_GNR_RES_WTR_NOPMP_2020	2440,0	7851,0
K5_GNR_PV_SUN_DECENTRAL_2020	0,0	10750,9
K5_GNR_PV_SUN_CENTRAL_2020	1333,0	776,1
K5_GNR_ST_MSW_BPR_2020	150,0	150,0
K5_GNR_BO_WOODCHIPS_2020	2898,3	3239,6
K5_GNR_BO_GEOTHERMAL_2020	143,0	28,0
K5_GNR_BO_NGAS_2020	1066,7	0,0

Table 3: Generation Capacities in Austria for the Years 2020 and 2030

2.2.5 Data used in the model and its sources

The following data are used in the Balmorel model to describe the Austrian energy system. More data is available, but in this context, only the data used within the scope of the thesis is presented.

- The hourly data set Variation of electricity generation is derived from actual load data for the year 2020, as provided by ENTSO-E (2020). This data set serves as a representative consumption profile for Austria.
- Variation of household sector consumption is obtained from synthetic

load profiles from APCS, 2022. This data set serves as a simulated representation of how the electricity demand of the residential sector varies over time.

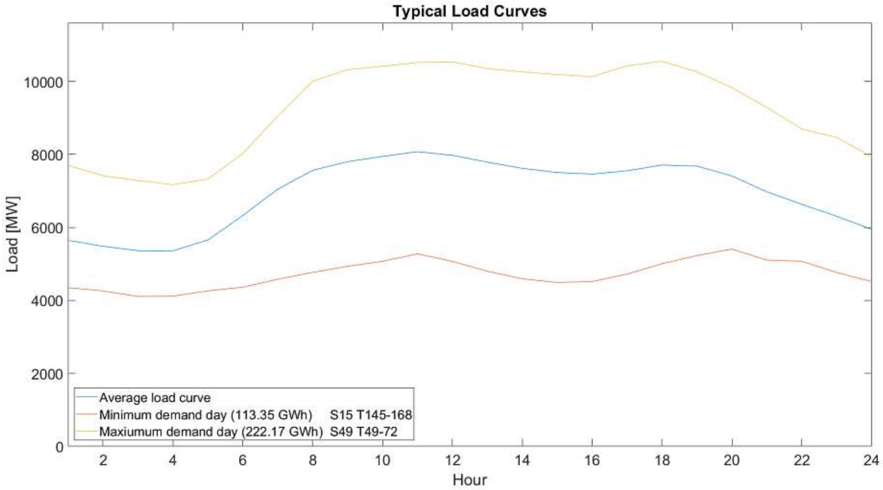

Figure 3: Daily Load Curve in Austria 2020

- Generation profiles for PV, wind, and hydro generation are derived from weather data for the year 2008. Data was provided by the Energy Economics Group (Vienna University of Technology).
- The CO2 price is set at 52.8 €/t CO2 (TYNDP, 2021).
- Parameters for electricity and district heating demand and conventional capacities are sourced from the AURES II project (AURESII, 2022).
- The allocation of renewable capacities for PV, wind, and hydro run-of-river is aligned with the national trends scenario from TYNDP (2021).
- Assumptions for Austria are drawn from the national energy and climate plan, specifically from WAM scenario (NECP, 2019).
- Renewable capacities are refined in accordance with the 100% renewable target until 2030 set in Renewable Energy Expansion Act (Government of Austria, 2021).
- NIP (2023) sets household sector net energy consumption at 20.3 TWh in the year 2021. I assumed no significant change in this value and used the value of 20.6 TWh for modeling.

2.3 Single household residential prosumer

This section introduces a single household prosumer sub-model by

- explaining the basic concept of residential prosumer
- defining prosumer goal of self-consumption maximisation
- introducing functionalities of a single household prosumer sub-model

2.3.1 Basic concept of a residential prosumer

The neologism "prosumer" refers to an electricity consumer that produces part of his/her electricity needs from his/her own power plant and uses the distribution network to inject excess production and to withdraw electricity when self-production is not sufficient to meet his/her own needs (Kopač, 2018).

Figure 4 shows a concept of decentral residential PV and storage used in the prosumer sub-model. The prosumer installation consists of PV panels (2), a battery (3), and an inverter (5). The inverter transforms direct current (DC) sources (solar panels or battery storage) with alternating current consumers such as household loads (1) and electrical grid (4).

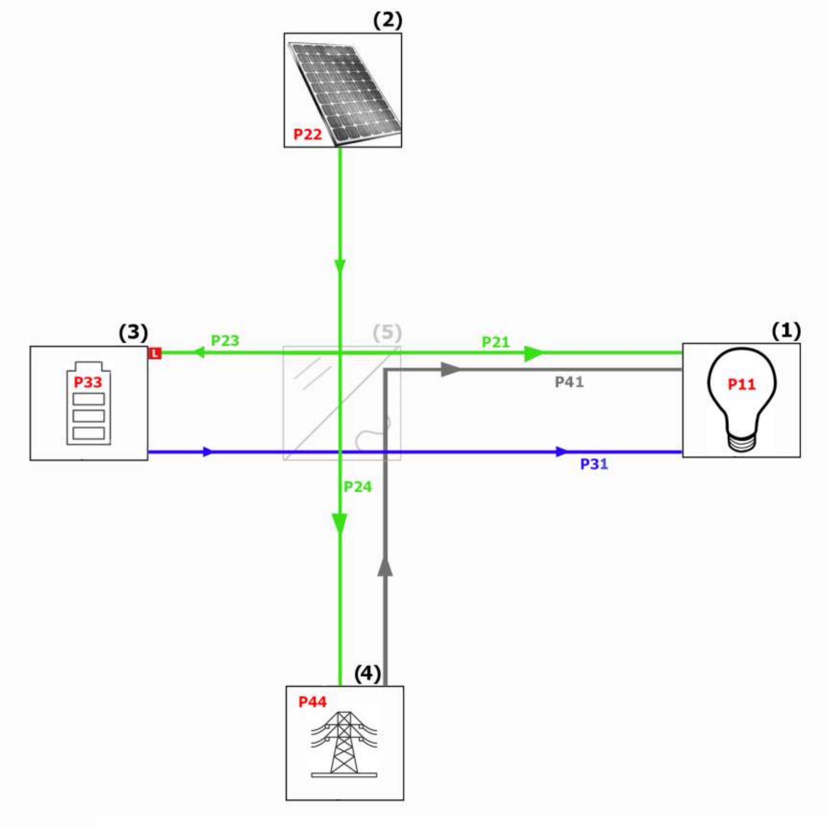

Figure 4: Power Flow Modeling

The power flow in the prosumer system is divided into three categories:

Green: PV generated power which can flow into the grid (P_{24}), into the battery (P_{23}), and be immediately consumed by the household loads (P_{21})

Gray: Power taken from the grid with the purpose of satisfying household demand (P_{41})

Blue: Power flowing from the battery towards the household consumers (P_{31})

The power flow is instantaneous and it is modeled in an hourly resolution, where the index of a parameter represents the power flow in an hour i $(1 \leq i \leq 8736)$. A summary and description of prosumer parameters and variables is given in Table 4.

P_{11i}	Household consumption profile
P_{21i}	Instantaneous self consumption
P_{22i}	PV generation profile
P_{23i}	Battery charging
P_{24i}	Feed into the grid
P_{31i}	Battery discharging
P_{33i}	Battery profile $(P_{23i} - P_{31i})$
P_{41i}	Consumption from the grid
P_{44i}	Prosumer profile $(P_{41i} - P_{24i})$
C_{bat}	Installed battery capacity

Table 4: Description of Parameters

2.3.2 Prosumer's goal: Maximisation of self-consumption

Based on the current grid tariff design described in European Environment Agency (2022), the cost-optimal prosumer behavior is the maximization of electricity self-consumption, or, to put it differently, the minimization of electricity consumption from the grid by utilizing local PV generation and available battery storage. The following equations and constraints describe this goal:

General problem	
$\min \sum_{i=1}^{8736} P_{41i}$	
Equality constraints	
PV generation	$P_{22i} = P_{21i} + P_{23i} + P_{24i}$
Household demand	$P_{11i} = P_{21i} + P_{31i} + P_{41i}$
Battery charging/discharging profile	$P_{33i} = P_{23i} - P_{31i}$
Inequality constraints	
Battery DOD	$0 \leq P_{33i}$
Battery capacity	$\sum_{1}^{i} P_{33i} \leq C_{bat}, \forall i \in [1, 8736]$

Table 5: Self-Consumption Maximisation

2.3.3 Annual Consumption and Installed PV capacity

In the prosumer sub-model, parameters *Annual consumption* and *Installed PV capacity* are not directly used. They are included within hourly data sets: *Household consumption profile* and *PV generation profile*.

1. The *Household hourly consumption* is obtained by multiplication of

the total *Annual consumption* of household with *Variation of household consumption* (normalized hourly load profile sourced from APCS (2022)).

2. The PV generation profile is obtained by multiplication of the *Installed PV capacity* with parameter *Full load hours* and normalized hourly data set *Variation of solar generation* (sourced from TYNDP, 2021).

The Balmorel model doesn't consider a single household at all; hence, there is no annual consumption of a household and its PV generation. The whole purpose of a prosumer sub-model is to introduce a single household perspective to the energy system model. The prosumer model achieves this by imitating the behavior of different prosumer households and aggregating their consumption and generation. To achieve this without vast amounts of additional data describing specific household annual demand and their installed PV capacity, an assumption is made that the PV installation is scaled to generate electricity equal to the annual consumption by the household.

$$\begin{aligned} AnnualPVgeneration &= AnnualConsumption \\ &= Full\ load\ hours \times InstalledPVcapacity \end{aligned} \tag{1}$$

This assumption allows us to describe annual consumption and annual PV generation with one variable, namely *Installed PV capacity*. Additionally, aggregating multiple households with the same type of PV installation is as simple as adding their installed PV capacities, and this will be very useful for simulations of the entire country.

2.3.4 Implementation of single household prosumer sub-model

The sub-model is represented in Figure 5 is implemented in Matlab (refer to Appendix A) and it operates as follows:

1. It begins by reading and normalizing two key external inputs:
   - *Variation of solar generation*, an hourly distribution of solar generation in Austria over the year 2030.
   - *Variation of household consumption*, an hourly distribution of household sector consumption in Austria in the year 2030.
2. Hourly consumption profile scaling:

$$\begin{aligned} &Available\ consumption = \\ &Variation\ of\ household\ consumption \times Annual\ consumption \end{aligned} \tag{2}$$

3. Hourly prosumer PV generation profile scaling:

$$\begin{aligned} &Prosumer\ PV\ generation = \\ &Variation\ of\ solar\ generation \times annual\ PV\ generation \end{aligned} \tag{3}$$

4. Hourly prosumer profile calculation:

$$\begin{aligned} &Prosumer\ profile = \\ &Available\ consumption - Prosumer\ PV\ generation \end{aligned} \tag{4}$$

5. The sub-model searches for the optimal battery capacity through the following steps:

    - It varies the battery capacity from zero to five times the maximum value of *Prosumer PV generation*.
    - The sub-model then iterates through different battery capacities, assigning hourly values from the *Prosumer profile* to the *Battery profile* if there is sufficient capacity available / energy stored ($0 \leq$ *Battery state of charge* $\leq$ *Battery capacity*).
    - For each variation in battery capacity, it sums the positive values of the generated *Battery profile* and calculates the *annually stored energy* for that specific capacity.[12].
    - The *optimal battery capacity* is found as the one that maximizes the *annually stored energy* while ensuring there are at least 100 full charge cycles annually.[13]

6. Once the optimal battery capacity is determined, the model calculates an hourly *Battery prosumer profile* by subtracting the *Battery profile* from the *Prosumer profile*.

7. The model's outputs consist of two 8736 by 1 vectors (see Figure 5). The first output, *Prosumer profile*, corresponds to a PV system without a battery, whereas the second model output, *Battery prosumer profile*, incorporates the battery with optimal capacity set to charge when there is an excess of locally generated electricity and discharge during periods

[12]Positive values in *Battery profile* correspond to battery charging in specific hour

[13]The 100 full charge cycles of a battery capacity increase is set as a lower limit for a battery to pay back the initial investment by storing energy. Assuming: savings of 0.2 € for every kWh stored and consumed, an average price of batteries of approximately 200 € per kWh and a battery life estimate of 10 years, the battery needs to be charged at least 100 times a year to pay back the initial investment.

of scarcity. The positive values in output vectors represent reduced hourly household load and the negative values depict generation excess as observed from the grid.

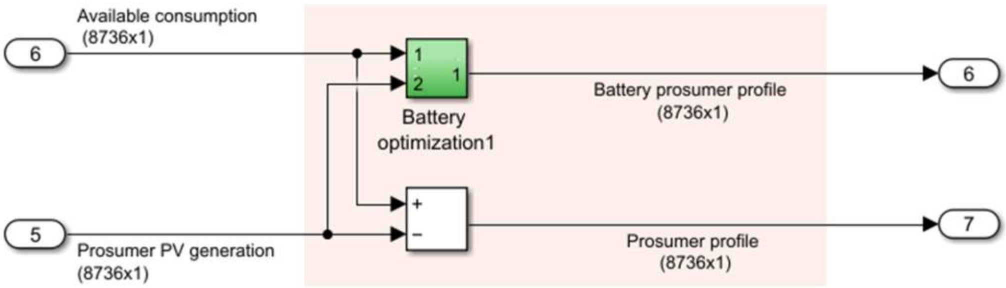

Figure 5: Single Household Prosumer Sub-Model

To illustrate the battery optimization process, a typical 4-person household with an annual consumption of 5 MWh is selected as a representative case study. The simulation is conducted using a single household prosumer sub-model. According to Equation 1, to meet an annual electricity demand of 5 MWh (accounting for 954 full load hours for photovoltaic in Austria), a required PV capacity of 5.24 kW is calculated. The battery optimization process yields an optimal battery capacity of 5.26 kWh.
The optimization results are graphically depicted in Figure 6, where the annual stored energy (left y-axis) and the number of charge cycles of the last capacity increase in a year (right axis) are plotted as a function of various battery sizes for a PV system described in the previous section. The installation of a 5.26 kWh battery enables the prosumer to effectively store 1.26 MWh of electricity over the course of the year 2020, corresponding to approximately 240 full charge cycles and around 25% of household annual demand.

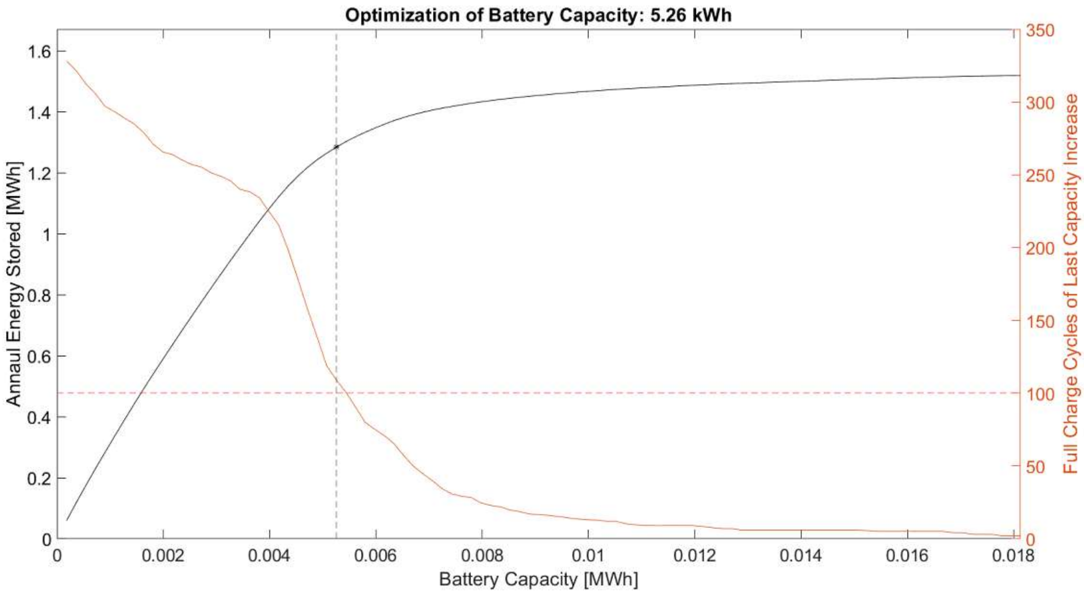

Figure 6: Optimization of Battery Capacity

2.3.5 Simplifications and assumptions

Following simplifications and assumptions are made in the sub-model regarding inverter and battery:

1. The inverter losses and line losses within the decentral PV system are neglected in the Balmorel model, and inheritably in the prosumer sub-model as well.

2. The power flow is not limited by the inverter

3. In order to simplify the modeling the sub-model neglects battery storage losses and it assumes 100 % depth of discharge of the decentral batteries ($SOC_{min} = 0\%,\ SOC_{max} = 100\%$).

2.4 Nationwide prosumer model

The previous section described the functionality of a single household prosumer sub-model. However, to analyze the impact of decentral PV and storage modeling approaches on energy system models, it is necessary to "scale up" the sub-model to imitate all residential prosumers within the household sector.

Besides scaling up a prosumer sub-model to a countrywide level, this section describes a prosumer model structure, data restructuring required for a prosumer model to run on the original Balmorel data structure, and additional functionalities available on a country level, such as variable share of decentral photovoltaics modeled as prosumers and sharing excess generation within energy communities.[14]

2.4.1 Simplified overview of prosumer model structure

A simplified overview of a nationwide prosumer model is presented in Figure 7, while a comprehensive prosumer model is illustrated in Figure 14. The prosumer model extracts data detailing the consumption and generation of prosumers from the provided data, subsequently optimizing the prosumer's self-consumption. In the end, it returns the modified (reduced) consumption and solar generation data for Austria in the year 2030, which will be fed into the energy system model.

[14]The Term "energy community" used in this thesis refers to increased electricity consumption (demand) available to prosumers to share the excess electricity generated by PV instead of feeding it back to the grid. The term used considers only this "sharing" aspect and not any other. As such it deviates from the renewable energy directives definitions for Renewable Energy Community and Citizens Energy Community described in Roberts et al. (2019).

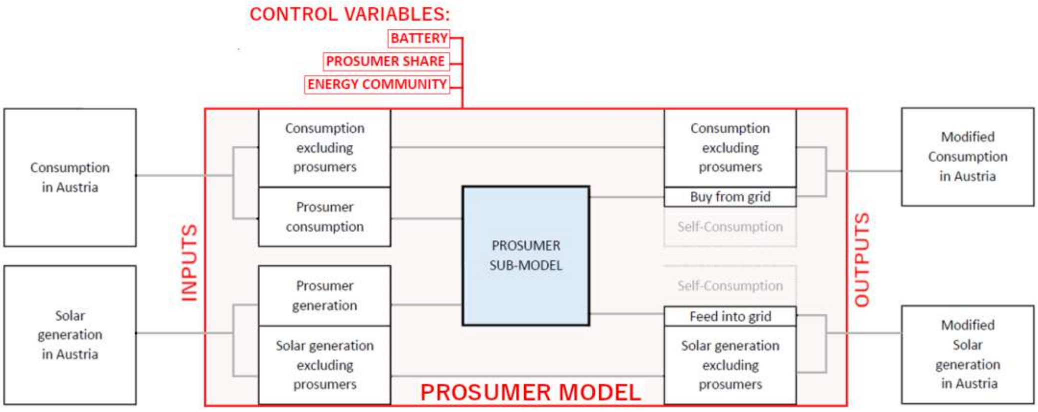

Figure 7: Prosumer Model Concept

2.4.2 Inputs, outputs and model variables

The prosumer model modifies the Balmorel input data ("Blm") to represent prosumer behavior and provides the modified data as output (refer to Table 6). The missing prosumer data ("Exo") required for the modifications comes from exogenous sources.[15]

Size	Input type	Name
8736 × 1	Exo	(Standardized) Household load profile
8736 × 1	Blm	Variation of electricity demand
8736 × 1	Blm	Variation of solar generation
1 × 1	Blm	Annual consumption in Austria (77.1 TWh)
1 × 1	Exo	Household sector annual consumption (20.1 TWh)
1 × 1	Blm	Full load hours for photovoltaic (954h)
1 × 1	Blm	Decentral PV capacity (10.75 GW)
1 × 1	Blm	Central PV capacity (0.77 GW)

Size	Output Name
8736 × 1	Modified variation of electricity demand
8736 × 1	Modified variation of solar generation
1 × 1	Modified annual consumption in Austria
1 × 1	Full load hours for photovoltaic (954h)
1 × 1	Modified decentral PV capacity
1 × 1	Modified central PV capacity

Table 6: Prosumer Model Inputs and Outputs

[15]The sources for all data in Table 6 are referenced in Section 2.2.5.

The prosumer model variables control the process of data modification in the following way:

- The variable *Prosumer share* in the range [0,1] represents the share of decentral PV in Austria modeled as prosumer maximizing self-consumption.[16] For example: the total installed capacity of decentral PV in Austria in 2030 is set at 10751 MWp (TYNDP, 2021). With prosumer share set at 0.3 (30 %), 3225 MWp will be simulated as prosumers and 7526 MWp of decentral PV will be modeled as system optimal dispatch.

- The sharing of excess generation within energy communities is controlled via the binary variable *Energy community*. Values "1" or "0" allow/ prohibit the formation of energy communities for the purpose of sharing locally generated electricity. Simply put, when its value is "1", the electricity generated by prosumers' PV installations can be consumed within the whole household sector without being fed back into the grid.[17] Variable *Energy community* is implemented as a selector assigning value to the annual consumption of aggregated prosumers. Value 1 assigns whole household sector consumption, and value 0 assigns a consumption equal to the annual generation of prosumer photovoltaics. The assigned annual consumption value is multiplied with (8736×1) vector *Variation of household consumption* to obtain *Available consumption* and inputted into the prosumer sub-model from Figure 8.

- The prosumer sub-model (Figure 8) returns two aggregated prosumer profiles, one for PV systems with batteries (*Battery Prosumer Profile*) and one without batteries (*Prosumer Profile*), the selection between these profiles is based on binary variable *Battery*. Value "1" uses *Battery Prosumer Profile* for further data modifications and disregards the *Prosumer profile*, while value "0" does the opposite.[18]

[16]When sharing of excess electricity generation with energy community model maximizes local consumption, instead self-consumption. This as a consequence causes a completely different battery charging/discharging profile and a different behavior from the grid's perspective.

[17]If the sharing of electricity is simulated, the model views the whole household sector as one, ideal, nationwide, renewable energy community.

[18]The prosumer model creates energy system scenarios by aggregating the prosumers of the same type. Consequently, scenarios with prosumers both with and without batteries in one run are not implemented. Assessing the impact of different prosumer types on an energy system is achieved by comparison of different scenarios.

2.4.3 Scaling up of the single household sub-model by aggregation of the same type prosumers

The scaling up of a sub-model to the whole country is relatively easily achieved using Equation 1. Aggregating all decentralized PV generation that we want to model as prosumers of the same type is accomplished by the summation of their PV capacities. With Equation 1, the model calculates the *Annual consumption* of these prosumer households and multiplies it with normalized hourly profiles *Variation of solar generation* and *Variation of household consumption* to obtain the two inputs of the prosumer sub-model (see Figure 8): *Available consumption* and *Prosumer PV generation*. The sub-model then works as described in Section 2.3.4, using aggregated, sector-wide profiles to produce an aggregated prosumer profile, joining decentralized residential prosumers into one energy prosumer. Simply put, the prosumer sub-model views all modeled prosumers in Austria as "one big house".

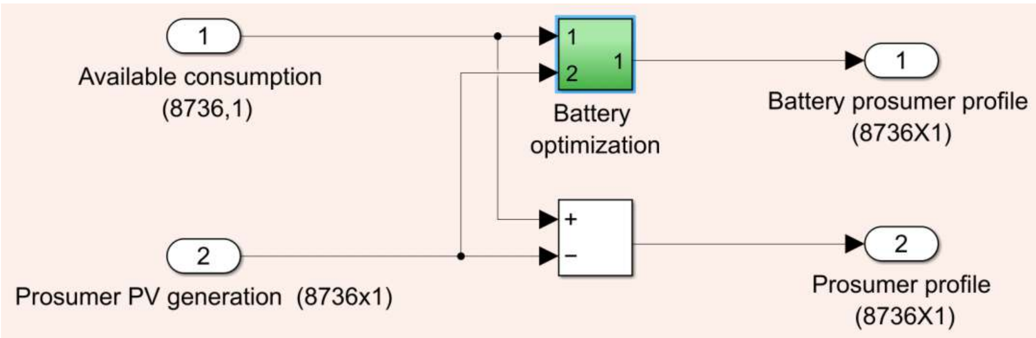

Figure 8: Prosumer Sub-model

The prosumer sub-model illustrated in Figure 8 returns two aggregated prosumer profiles, one for PV systems with batteries (*Battery prosumer profile*) and one without batteries (*Prosumer profile*). The variable *Battery* selects a profile to be used for further data modifications and disregards the other (see Figure 9). The positive and negative values within the chosen sub-model output profile are assigned to the generation and consumption profiles of household sector prosumers, labeled as *HH Prosumer generation* and *HH Prosumer consumption*, respectively.

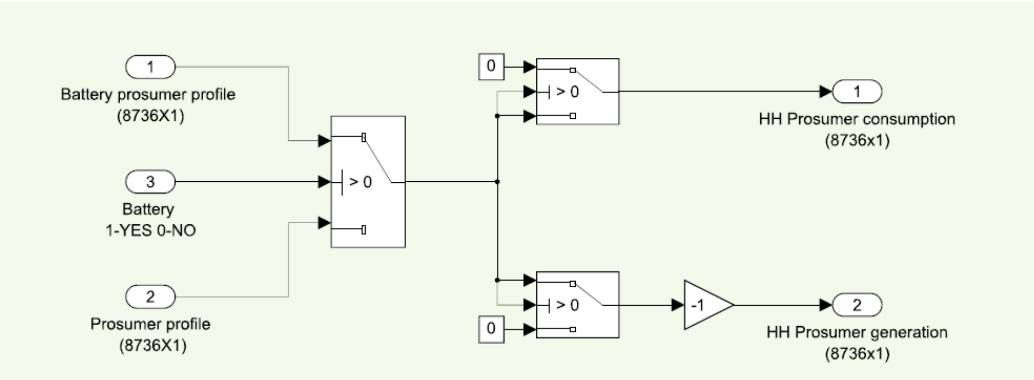

Figure 9: From Sub-model Outputs to Aggregated Consumption and Generation of Prosumers

2.4.4 Data restructuring required for a prosumer model to run on original Balmorel data structure

The Balmorel accompanying data described in Section 2.2.5 the system-optimal dispatch of decentral photovoltaics. As such, the consumption of prosumers is assigned to total consumption in Austria, and their electricity generation is assigned to solar generation in Austria, completely omitting the share of self-consumption. In order to model self-consumption as depicted in Figures 8 and 9, certain data restructuring is required to obtain profiles *Available consumption* and *Prosumer PV generation* from Balmorel accompanying data and to reintegrate the resulting consumption and generation profiles of prosumers into the initial data structure. The following section explains this data restructuring.

Separation of prosumer's consumption from the total consumption in Austria

The *Hourly electricity consumption* is an exogenous parameter in the Balmorel model, obtained by multiplying the total *Annual consumption* with the *Variation in electricity demand* (normalized hourly load profile). The energy system model summarizes the instantaneous electricity demands of different consumer categories and looks for cost-optimal energy dispatch to satisfy this demand. The prosumer model separates total consumption in Austria into to the prosumer available hourly consumption and residual consumption of consumers only (refer to Figure 10). The *Available consumption* is either the own consumption of prosumers (calculated using Equation 1) or the consumption of the household sector if energy sharing is allowed (selector EC on Figure 10).

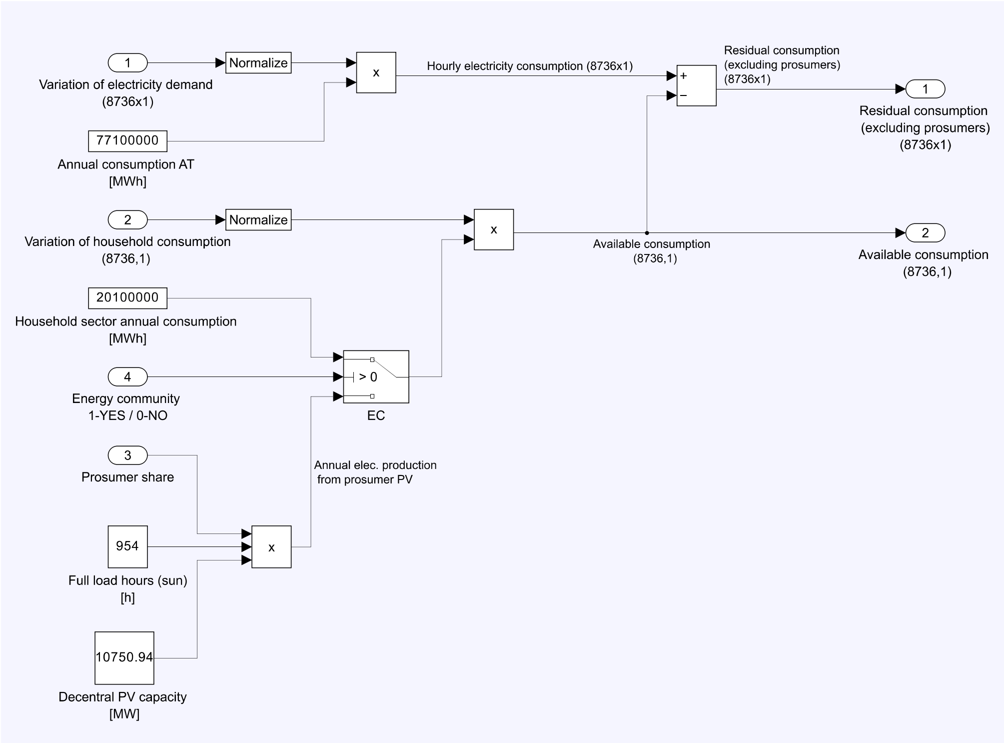

Figure 10: Separation of Consumption

Separation of photovoltaic generation into central, decentral prosumers and decentral producers

Solar generation is calculated as the product of full load hours of sun in Austria, installed capacity, and a data set known as the *Variation of solar generation*. This data set combines irradiance and weather data, such as temperature, along with technology-specific data to create an hourly generation profile for photovoltaic systems. There are two types of photovoltaic technologies modeled in the Balmorel energy system model: central PV and decentral PV. In order to introduce self-consumption, the prosumer model separates decentral prosumers from decentral producers based on the variable *Prosumer share* (refer to Figure 11). The resulting hourly solar generation profiles are:

- *Central PV generation*, generation of centralized photovoltaics
- *Prosumer PV generation*, generation of decentral PV prosumers

- *Residual decentral generation*, generation of decentral PV producers excluding prosumers generation

The hourly profiles *Central PV generation* and *Residual decentral generation* remain constant through the prosumer model, while the *Prosumer PV generation* will be reduced for the share of self-consumption.

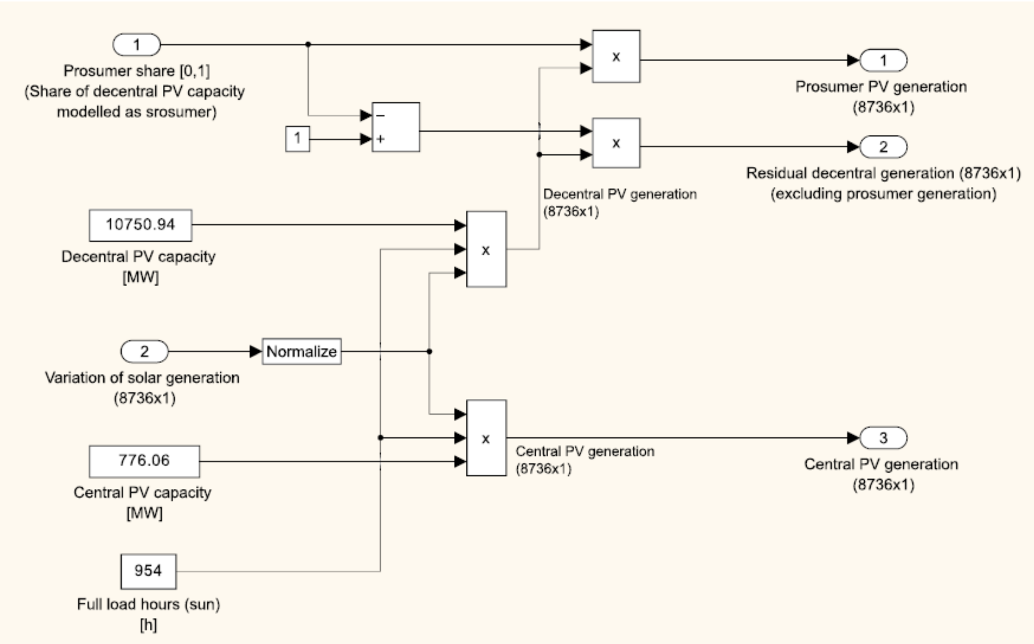

Figure 11: Separation of Solar Generation

Reintegration of prosumer model outputs into Balmorel data inputs

When the generated consumption profiles are added, they yield the *Modified variation of electricity demand* in Austria in the year 2030. Its summation over the year returns *Modified annual consumption* in Austria for the same year (refer to Figure 12).

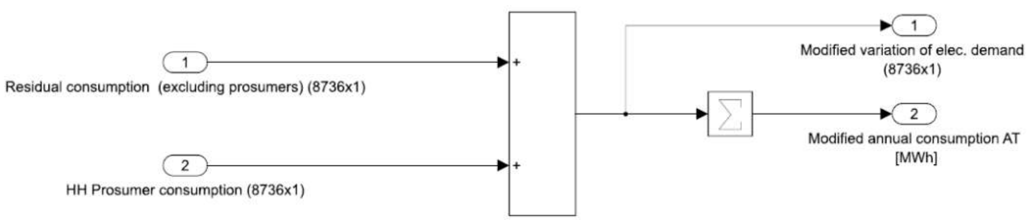

Figure 12: Reintegration of Consumption

By analogy, the addition of the resulting solar generation profiles forms the *Modified variation of solar generation*, and its sum over the year divided by the *Full load hours* returns *Modified decentral PV capacity* (refer to Figure 13).

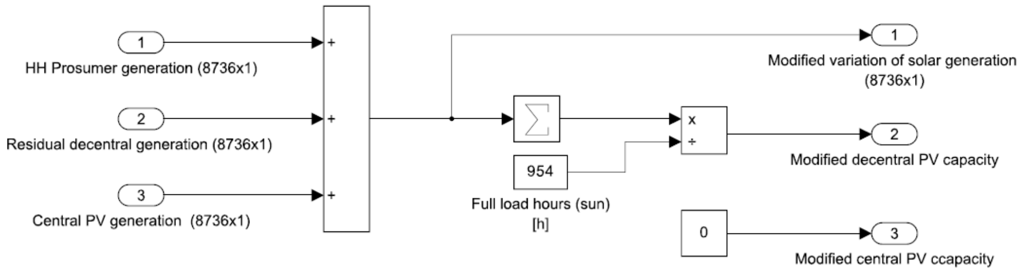

Figure 13: Reintegration of Solar Generation

2.4.5 Prosumer model in details

?? A comprehensive depiction of the prosumer model is provided in Figure 14. The color-coded areas in red, green, violet, yellow, and white correspond to previously described model components as illustrated in Figures 8 through 13. The actual Matlab code of the prosumer model is attached in the Appendix.

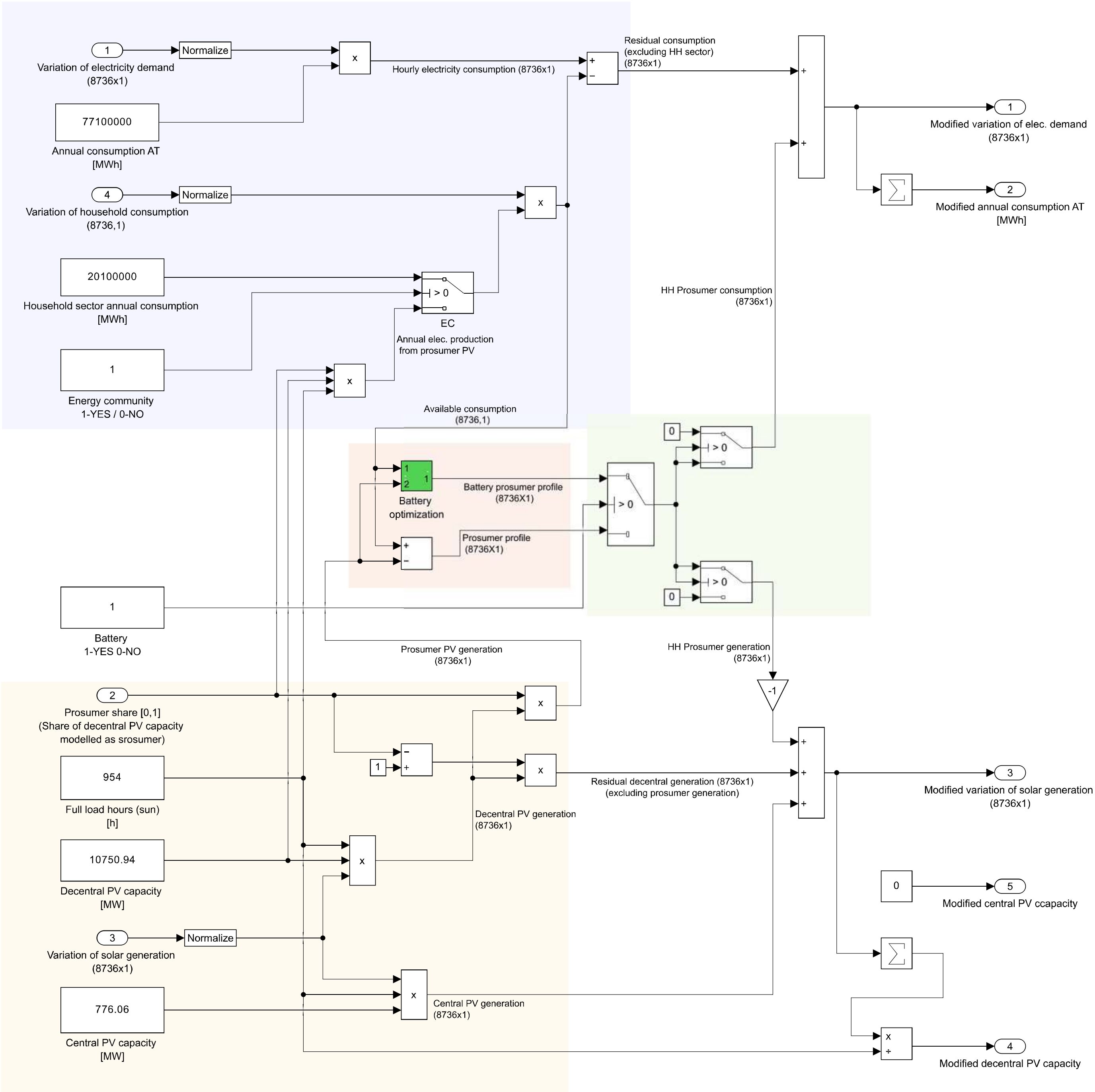

Figure 14: Comprehensive Description of Prosumer Model

2.4.6 Model assumptions and limitations

The following assumptions and limitations play a critical role in shaping the model's outcomes and should be considered when interpreting the results and making any conclusions based on the modeling data.

- The capacity of household PV installations, if installed, is adjusted to generate electricity equivalent to the annual electricity demand of the respective household.
- The total annual generation from decentralized PV installations in Austria does not exceed the annual consumption of the household sector, which is 20.1 TWh.
- The optimization[19] of decentral battery storage is based on the battery utilization curve as represented in Figure 6.
- In the prosumer model all central PV generating capacity is transferred to decentral PV generating capacity. Due to the small percentage of central PV installations in Austria modeled (7%) and the relatively low operating costs of photovoltaic systems, this simplification has no impact on the model results, but it allows for modeling prosumers without framework modifications.

2.5 Scenarios modeled

"Scenarios" refers to a set of energy pathways strategically designed to understand a particular critical issue.The scenario objective is to illuminate the impacts of the various scenario narratives. Through the process of developing strategic scenarios and quantifying the scenario outcomes, one hopes to generate new insights that can facilitate electricity planning (McPherson & Karney, 2014).

A total of 18 scenarios have been developed, as detailed in Table 7. These scenarios vary in the share of decentralized photovoltaics modeled as optimized for self-consumption and as a system optimal dispatch[20] and in terms

[19]Battery capacity optimization maximizes annual energy stored with limiting condition of 100 charge cycles for each capacity increase considered

[20]The variable *Prosumer share* represents the proportion of decentralized photovoltaic capacity modeled as self-consumption optimized prosumers. It ranges from 0 to 1 in increments of 0.1 The remaining share (1- *Prosumer share*) of decentralized photovoltaics is modeled as system optimal dispatch.

of the type of prosumers modeled. The four types of prosumers modeled are:

AT03 - Prosumers with photovoltaic panels only
AT0E - Prosumers with photovoltaics, sharing excess electricity[21]
ATB0 - Prosumers with photovoltaics and battery storage[22]
ATBE - Prosumers with PVs and storage, sharing excess electricity

Name:	Prosume share [%]	[GWp]	Battery Capacity [GWh]	Energy community	Desription
Scenario AT03 00	0	0.00	-	-	PV
Scenario AT03 01	10	1.08	-	-	PV
Scenario AT03 02	20	2.15	-	-	PV
Scenario AT03 03	30	3.23	-	-	PV
Scenario AT03 04	40	4.30	-	-	PV
Scenario AT03 05	50	5.38	-	-	PV
Scenario AT03 06	60	6.45	-	-	PV
Scenario AT03 07	70	7.53	-	-	PV
Scenario AT03 08	80	8.60	-	-	PV
Scenario AT03 09	90	9.68	-	-	PV
Scenario AT03 10	100	10.75	-	-	PV
Scenario AT0E 04	40	4.30	-	YES	PV & EC
Scenario AT0E 07	70	7.53	-	YES	PV & EC
Scenario AT0E 10	100	10.75	-	YES	PV & EC
Scenario ATB0 04	40	4.30	4.31	-	PV & Bat
Scenario ATB0 07	70	7.53	7.55	-	PV & Bat
Scenario ATB0 10	100	10.75	10.79	-	PV & Bat
Scenario ATBE 07	70	7.53	4.43	YES	PV & Bat & EC
Scenario ATBE 10	100	10.75	13.39	YES	PV & Bat & EC

Table 7: Overview of Simulated Energy System Model Scenarios

Owing to the chosen modeling approach, specifically the aggregation of prosumers of the same type into a singular "big house" within the household sector, the surplus of locally generated electricity from decentralized photovoltaics arises when the aggregated generation of this prosumer "house" surpasses the aggregated consumption. The feasibility of modeling prosumers with battery storage and implementing electricity sharing depends on the availability of excess electricity in the first place, this occurs initially when the *prosumer share* exceeds approximately 13 and 35 %, retrospectively. To make the battery an economically viable option with electricity sharing already implemented, sufficient instantaneous excess energy occurs first when the *prosumer share* surpasses 46%. Consequently, scenarios detailing pro-

[21]This thesis views the whole household electricity sector as one perfectly connected energy community

[22]Battery size is optimized in each simulation and it has a different value for each of scenarios (see section 2.3.4).

sumers with batteries or energy communities are formulated for prosumer shares exceeding 40% or, more precisely, 70% when considering both electricity sharing and the utilization of battery storage.

3 Results and Discussion

The structure of the prosumer model and its main component, the prosumer sub-model, facilitates a comprehensive analysis of prosumage. This analysis is conducted from two distinct vantage points: the prosumer perspective, analyzing the outcomes of the prosumer sub-model, and the perspective of the energy system, quantifying scenarios derived from the prosumer model using the Balmorel energy system model.

Sections 3.1 and 3.2 present results from the prosumer perspective, analyzed through a comparison of resulting household profiles: consumption profile, prosumer profile, and battery prosumer profile.[23] Depending on the specifics of the observed behavior, profiles are compared either on an hourly level or by assessing cumulative impact over a longer period (week, month, or year).

Sections 3.3 to 3.7 present the results of Austria's energy system modeling in the year 2030, with a specific focus on the variations in outcomes arising from diverse modeling approaches applied to decentralized photovoltaics and storage systems. Additionally, they illustrate the impact of energy communities in conjunction with decentralized generation.
Given the substantial volume of resultant data, a comprehensive representation of results is undertaken only on the energy system scenario characterizing the system-optimal dispatch of decentralized PV and storage systems in Austria in the year 2030, referred to as "Scenario AT0300." The remaining energy system scenarios developed are analyzed comprehensively as well, but they are represented in a reduced amount of detail and in comparison to the results of scenario AT0300. Simply put, from the perspective of result representation only, scenario AT0300 can be viewed as a "base scenario" serving as a reference point for comparing the outcomes of other energy system scenarios.
Modeling is done in an hourly resolution for a period of 8736 hours, with the data depicting the year 2030 (refer to Section 2.2.5). However, to ensure a

[23]The aspect of sharing excess electricity is not analyzed from the prosumer's perspective.

meaningful and easy comparison of results from various scenarios, the time period chosen for results representation varies between a few hours, one week (either 33rd or 49th week of the year 2030), and a whole year.

3.1 Comparison between consumer and prosumer with PV installation, using single household prosumer sub-model

In order to demonstrate the changes in consumption profiles due to local generation and storage, a typical 4-person house with an annual consumption[24] of 5 MWh is chosen as a representative case study and simulated using a single household prosumer sub-model. According to Equation 1, to satisfy an annual electricity demand of 5 MWh (considering 954 full load hours for photovoltaic in Austria), a required PV capacity is 5.24 kW.

Figure 15 displays characteristic consumption, load, and generation profiles of a prosumer household for a sunny week in August.[25] Throughout periods of electricity production from solar panels, local generation consistently exceeds local consumption for most of the time. Within this week, the surplus electricity amounted to 88.9 kWh and was fed into the grid and subsequently sold to other customers. Additionally, on a daily basis, there is a noticeable and not insignificant peak reduction observed. During the 33rd week of 2020, the customer consumed 35.9% of the locally generated electricity, equivalent to 45.2 kWh.

[24] The prosumer sub-model simulates prosumer behavior for 8736-time segments using data described in 2.2.5. Data for household consumption depicts the year 2020, and I use the year "2020" in discussion and plots describing sub-model functionalities.

[25] When illustrating data (regardless of data being input or an output of the model), sometimes it is necessary to showcase data sets on a smaller subset than the original 8736 hourly values so that changes and patterns can be clearly observed on the plots. For this purpose, I chose the 33rd and 49th weeks of the data set as representative weeks in this thesis. They represent a week in August when solar generation is at its peak and a week in December when electricity demand is at its peak and solar generation is significantly reduced.

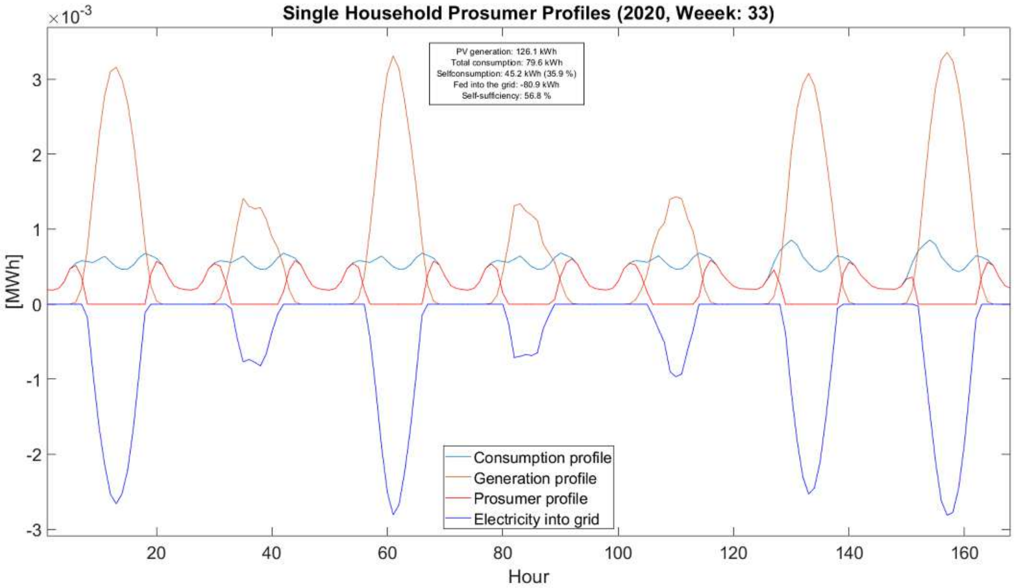

Figure 15: Sub-Model: Single House Prosumer Behavior - Week 33

The single house prosumer sub-model returns prosumer profiles illustrated in Figure 16 for the 49th week of 2020, which corresponds to the beginning of December, are notably distinct from those observed in August. During December, for a significant portion of the time, the local generation fell short of meeting the electricity demands of the household in question. The PV system generated 31.3 kWh, accounting for only 29% of the weekly energy requirements. However, almost all of the generated energy, specifically 28.4 out of the 31.3 kWh, was consumed internally within the household, resulting in a high self-consumption rate of 90.7%.

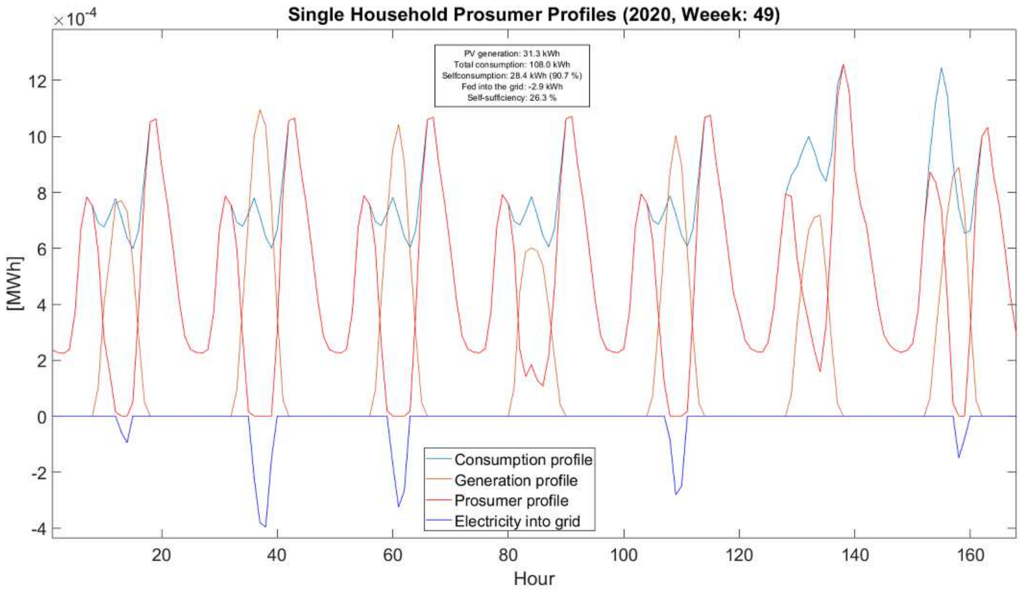

Figure 16: Sub-Model: Single House Prosumer Behavior - Week 49

Observed for a period of the whole year 2020 (refer to Figure 17), the installed PV system generated a total of 5 MWh of electricity in 2020, accounting for 100% of the total annual electricity requirements.[26] However, the distribution of the electricity generation by month ranges from 0.12 MWh in December to 0.66 MWh in May. May is a month with maximum generation from the solar panels, in spite of higher solar irradiance in July and August. This is because the higher temperatures in summer months cause a reduction in efficiency due to the negative temperature coefficient of solar cells. The monthly self-sufficiency[27] lies between 23 and 61 %. Most of the electricity generated in December is instantly consumed and the low percentage of the self-sufficiency is due to insufficient solar generation. However, in May and June, the self-sufficiency is limited from the "upper side" to 61% due to the inability to store energy for later usage.
In the year 2020, 45% of generated electricity, equivalent to 2231 kWh, was consumed locally within the household. Due to the absence of local storage capacity, the remaining 2769 kWh had to be supplied to the electrical grid, where it was subsequently sold to other customers.

[26]The installed PV capacity is scaled to generate electricity equal to the annual consumption of a household.

[27]Self-sufficiency is the percentage of used energy covered by your own production. Self-consumption is the percentage of energy you use of your own production.

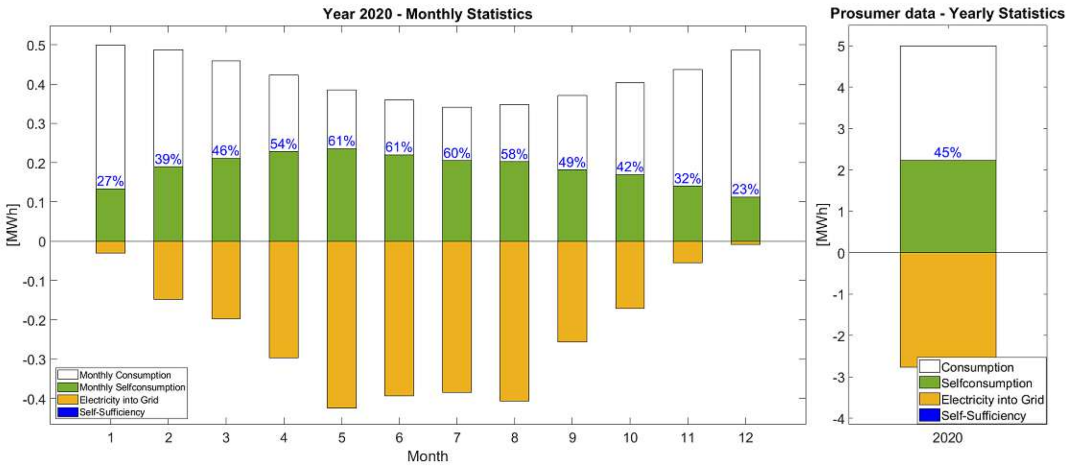

Figure 17: Sub-Model: Monthly and Yearly Statistics

3.2 Impact of the battery storage on prosumer profile, self-consumption and self-sufficiency

When local storage is introduced into the equations, excess electricity can be stored in the battery for use when solar panels are unable to generate sufficient energy to cover the household's load, thereby increasing the self-consumption of a prosumer. Assuming a fixed electricity purchasing price for residential customers, the charging and discharging strategy for the battery is set to charge when there is an excess of locally generated electricity and discharge during periods of scarcity. The outcomes presented in Figures 18 to 22 ilustrate the characteristics of a representative 4-person household, as defined in Section 3.1, with an optimally sized accompanying battery storage of 5.24 kWh, as detailed in Section 2.3.4.

The weekly load and generation profiles of a prosumer with PV and storage are illustrated in Figures 18 and 19, representing one summer week and one winter week. During the summer period, battery utilization is notably high compared to the winter period. This leads to a significant increase in the index of self-sufficiency, reaching 98.2% compared to the 56.8% achieved in the first stage model without a storage option (as seen in Figure 15). However, during winter periods of reduced solar generation, the battery cannot be effectively charged or discharged. Consequently, only minor profile changes are observable when comparing PV installations with and without a battery, as depicted in Figures 16 and 19.

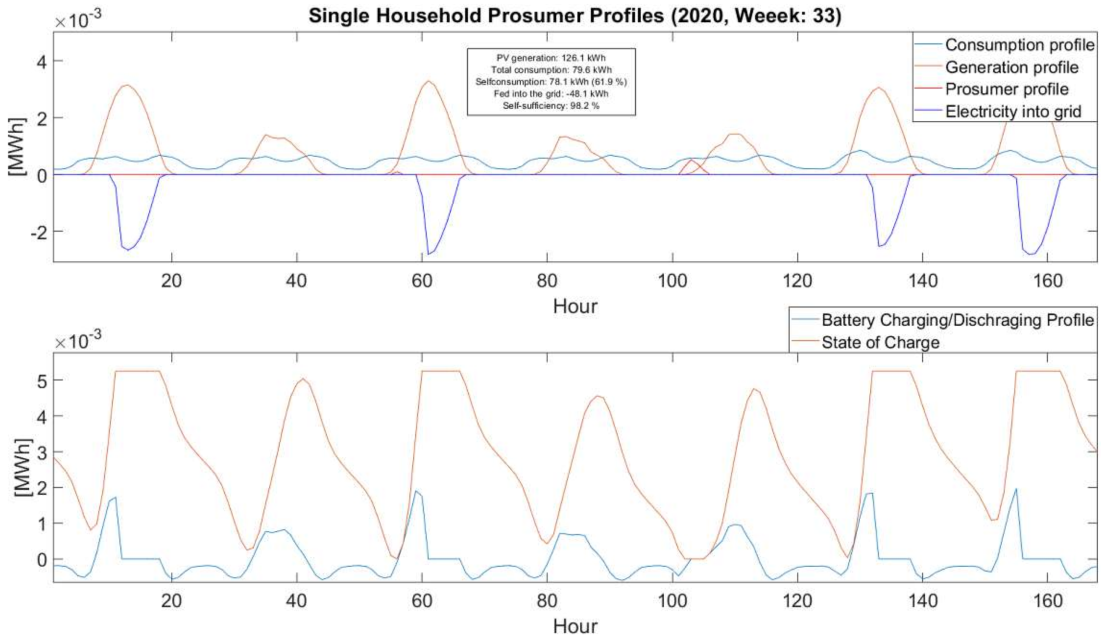

Figure 18: Prosumer Behavior - Week 33

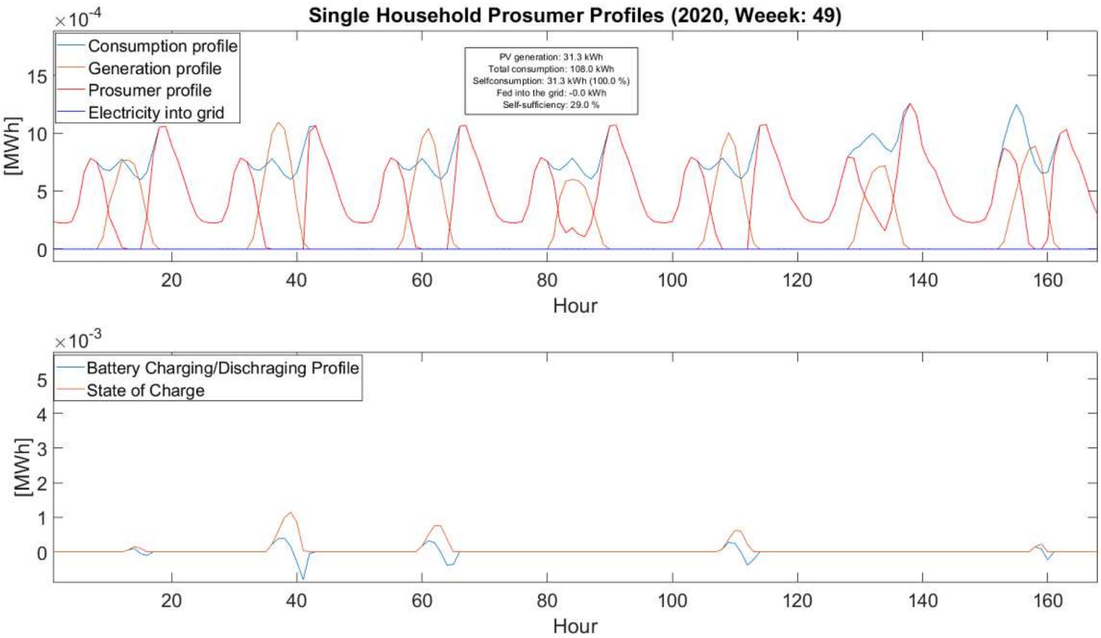

Figure 19: Prosumer Behavior - Week 49

Figure 20 gives an overview of prosumer profiles of a representative household as a consumer only (top), prosumer with PV installation (middle), and prosumer with PV and battery (bottom) over the course of the year 2020. Positive values depict the electricity bought from the grid, and negative values represent electricity fed into the grid. Compared to the consumer only, the prosumer with PV shows reduced load, and it feeds all instantaneous excess electricity into the grid. A prosumer with PV installation including battery storage, shows significant load reduction, especially in the period May to August (hours 2913 to 5824), where due to high solar generation and sufficient intra-day storage capacity almost no electricity is bought from the grid. In the period November to January (hours 7281 -to 728) battery allows for 100 % self-consumption, reducing load profile and completely diminishing the electricity fed back into the grid.

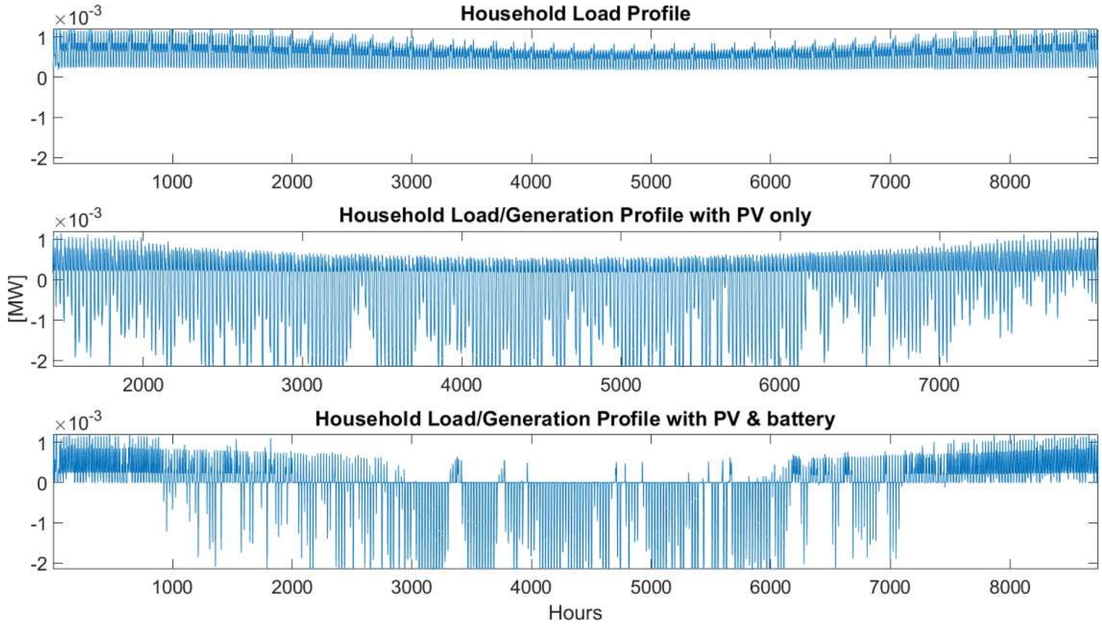

Figure 20: Prosumer Profiles Comparison

The utilization of the battery throughout the year is visualized as the battery state of charge in Figure 21. In the period from November to January (hours 7281 to 728), the electricity generated from the PV array is insufficient to satisfy instantaneous demand and fully charge the battery, leading to lower amounts of energy stored in the battery during this period. In the periods from 1000 to 3000 and 6000 to 7500 hours, the battery charges and discharges fully on an almost daily level, while in the in-between period, during high solar generation, the battery is rarely discharged fully.

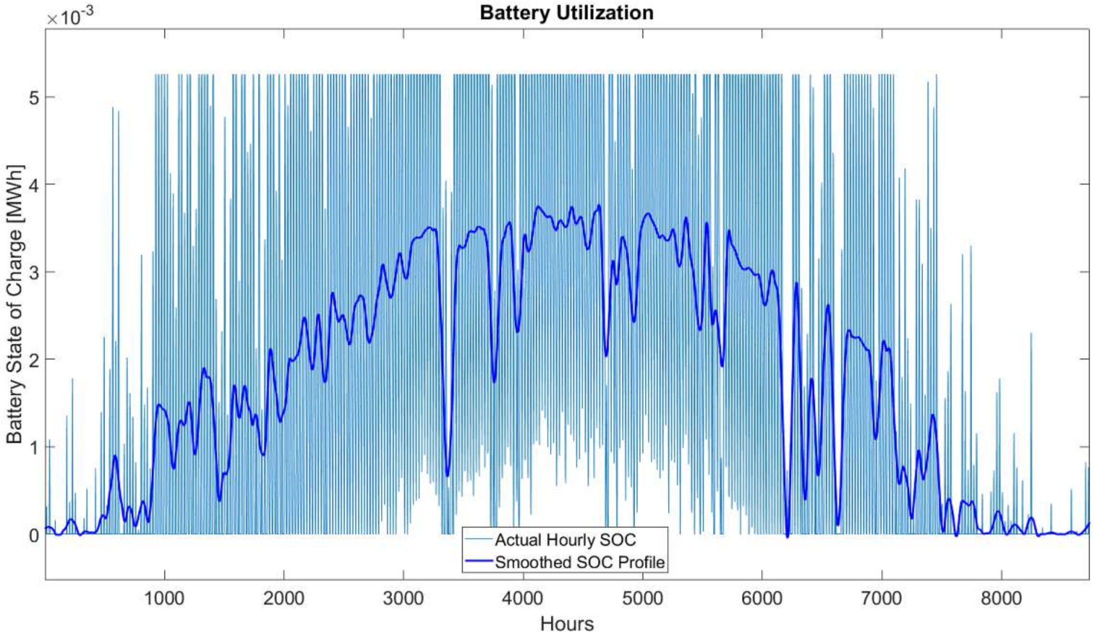

Figure 21: Yearly Battery Utilization (State of Charge)

Monthly and yearly statistics for residential PV with storage are presented in Figure 22. In comparison to PV installations without storage (represented in Figure 17), accompanying battery storage "shifts" local generation bars higher on the graphic, significantly increasing both self-consumption and self-sufficiency. Observed on a monthly level, self-sufficiency is highest (approximately 98%) between May and August, while the energy feed into the grid is completely diminished in the months from November to January (100% self-consumption). Considering the entire year 2020, self-consumption increased from 2.23 to 3.51 MWh, and self-sufficiency rose from 45% to 70%[28] thanks to the accompanying battery.

[28]Due to the PV installation scaling according to Equation 1, where annual household demand is equal to the annual PV generation, self-sufficiency equals self-consumption when calculated for the one-year span.

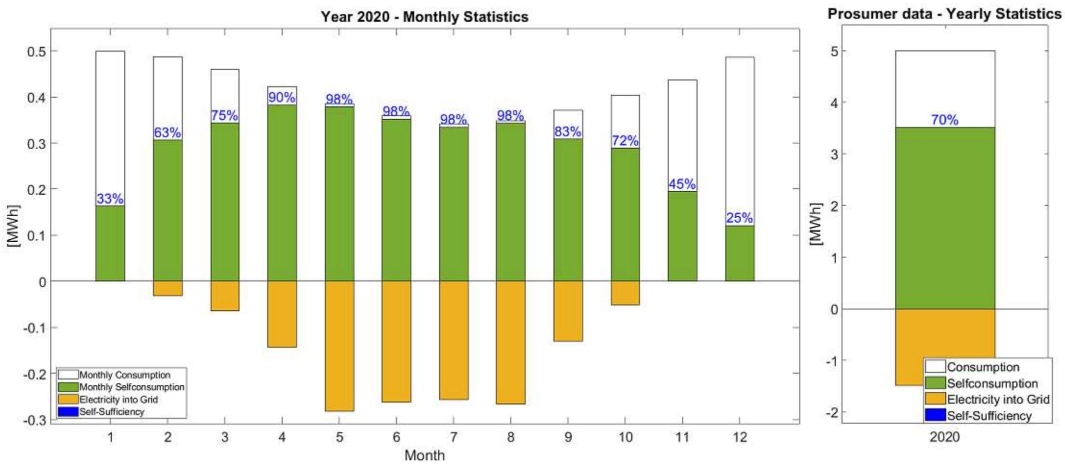

Figure 22: Prosumer with Battery: Monthly and Yearly Statistics

3.3 Modeling system optimal dispatch of decentral photovoltaics in Austria in the year 2030

The simulation labeled "Scenario AT03 00" models the behavior of the energy system in the year 2030 with the prosumer share set to 0.0, indicating that no prosumer is modeled as self-consumption optimized. The following results depict the behavior of the Austrian energy system with decentralized photovoltaic modeled as system-optimal dispatch.

The resulting annual generation mix satisfying net electricity demand of 77.1 TWh in the year 2030 is represented in Table 8. The difference between the total electricity generated (82.74 TWh) by power plants and the electricity consumption of end users is primarily due to power losses that occur in the distribution of electricity and efficiency losses of storage systems (e.g. pumped hydro storage).[29] In total, the losses in the simulated scenario amount to approximately 7.3% of the end user's net demand.

Source	[TWh])
Wood chips	1.91
Biogas	0.02
Municipal waste	1.31
Waste heat	0.06
Wind	12.85
Water	42.01
Natgas	11.51
PHES	2.38
Sun	10.71
Total	82.74
-Net Demand	-77.1
Grid Losses	5.64

Table 8: Annual Electricity Generation Mix

The electricity source labeled PHES in Table 8 represents electricity generation from the potential energy of water stored in pumped hydro reservoirs. High production peaks from renewable resources, in combination with continuous base-load sources like run-of-river power plants, often exceed electricity demand at certain hours. During these periods, electricity tends to be cheaper, providing a perfect opportunity for charging available storage

[29]There are no transmission losses because they are only coming up in the model when exports/imports with other countries are simulated

systems and storing excess energy for later use.

The simulation results for the 33rd week, spanning from the 12th to the 18th of August 2030, and illustrated in Figures 23 to 26, serve as an exemplary time frame, capturing substantial utilization of pumped hydro storage at an hourly level, as evidenced in Figure 26 and price fluctuations due to the firing of gas-powered stations depicted in Figure 25.

Figure 23 portrays the hourly electricity demand throughout the 33rd week. Notably, it exhibits a recurring pattern of daily fluctuations, with heightened electricity demand from 8 AM to 6 PM, peaking in the early evening between 6 and 9 PM, and a noticeable dip in electricity demand during weekends, primarily influenced by variations in daily routines and economic activities.

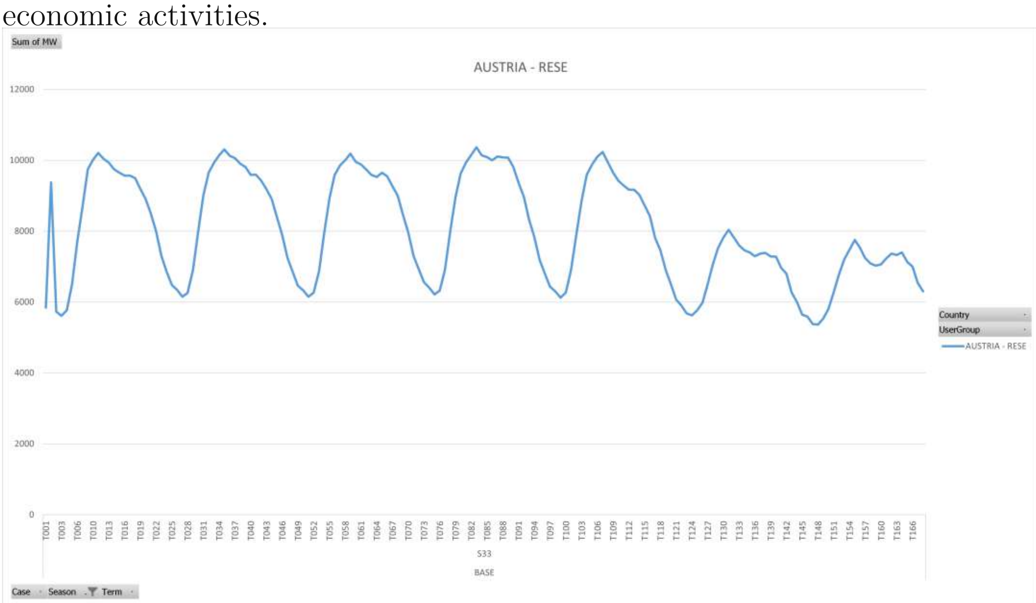

Figure 23: Austrian electricity demand Week 33 of 2030

The visual representation of the resulting generation mix during the 33rd week is shown in Figure 24. During hours 31 to 91, there are many instances where heightened energy demand coincides with a decrease in renewable generation. This situation necessitates the utilization of stored energy reserves and the operation of gas-powered stations.[30]

[30]In simulated scenarios, only Austria is considered, which excludes importing and exporting electricity as an option during periods of increased demand or generation.

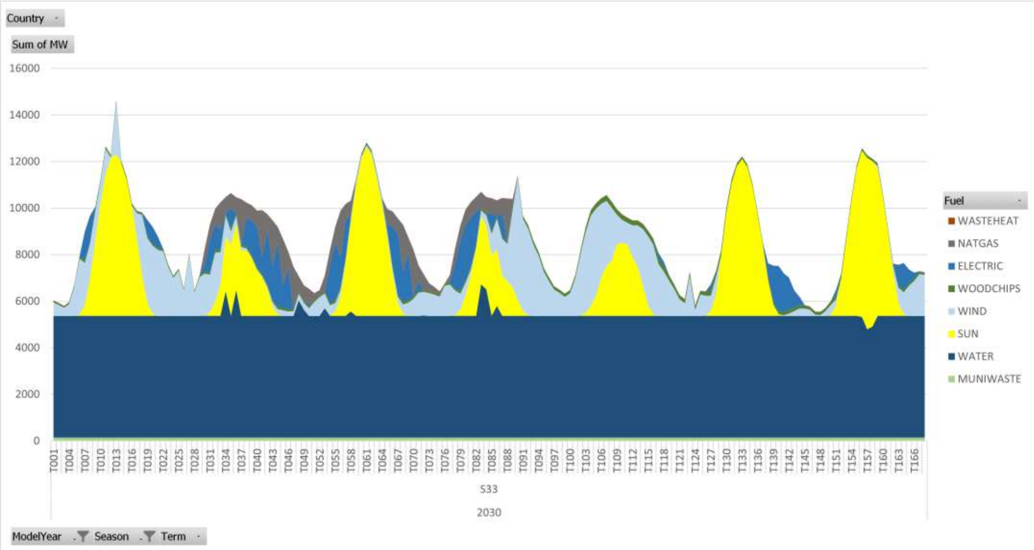

Figure 24: Generation Mix for Week 33 of 2030

In the energy market, the electricity price is determined by the "merit order," which is the sequence in which power stations contribute power to the market. Electricity power generated from renewable installations, such as wind turbines and photovoltaic systems, typically incurs almost no operating costs since they don't require fuel or extensive manpower(Appunn, 2015). When we compare the weekly data from the generation mix (Figure 24) with the model's price output shown in Figure 25, it becomes evident that the power plant setting the price is a gas-powered station.

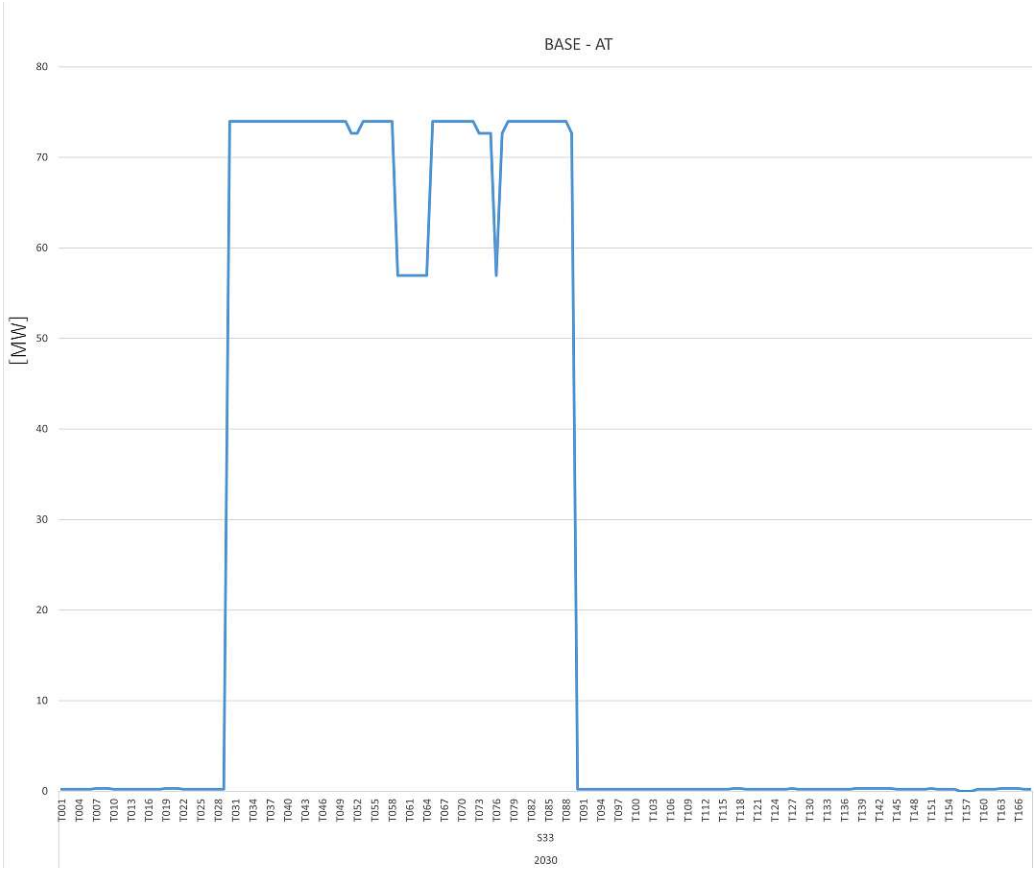

Figure 25: Electricity Prices for Week 33 of 2030

Figure 26 illustrates the utilization of pumped hydro-storage during the 33rd week. Pumped hydro-storage is not only a solution for storing excess energy from the grid and using it during periods of high prices, but is also the largest-capacity form of grid energy storage available, making it highly effective for load balancing. It's important to note that despite its significant power capacity, the energy-to-power ratio of pumped hydro-storage is less than 12.

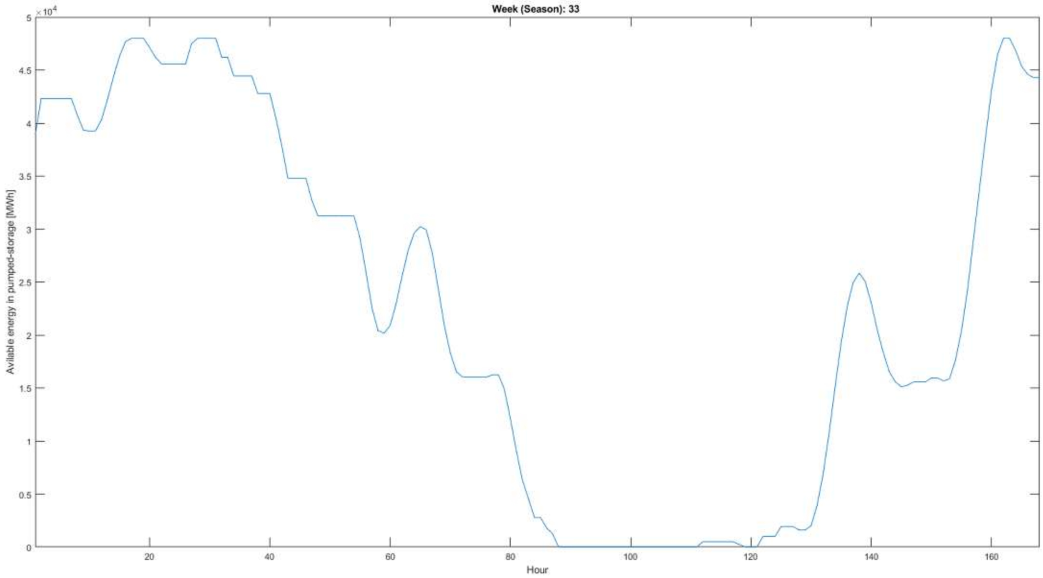

Figure 26: Utilization of Pumped Hydroelectric Energy Storage - Week 33

The figures 23 to 26 depict a summer week characterized by high electricity generation from wind turbines and photovoltaics. These results exhibit significant differences when compared to periods marked by low renewable generation and elevated electricity demand, as exemplified by a cold and overcast winter day in December, represented in Figure 27. During this winter day, the majority of electricity is generated by run-of-river and gas-powered plants.

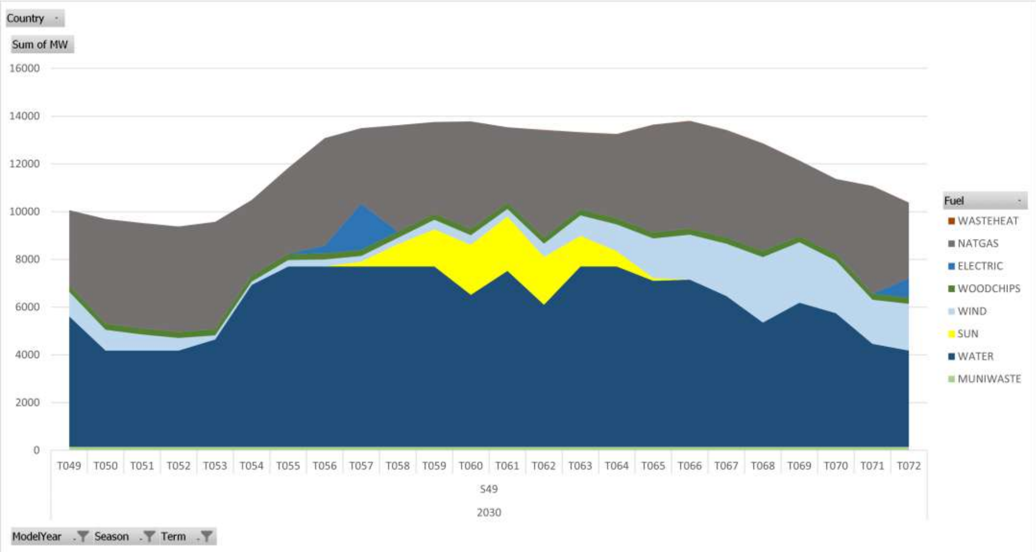

Figure 27: Generation Mix of Maximum Electricity Demand Day

Considering factors such as reduced solar irradiance in the winter, shorter daylight hours, and increased electricity demand due to heating requirements, one can anticipate a heightened utilization of gas power stations during winter periods, as demonstrated in Figure 28.

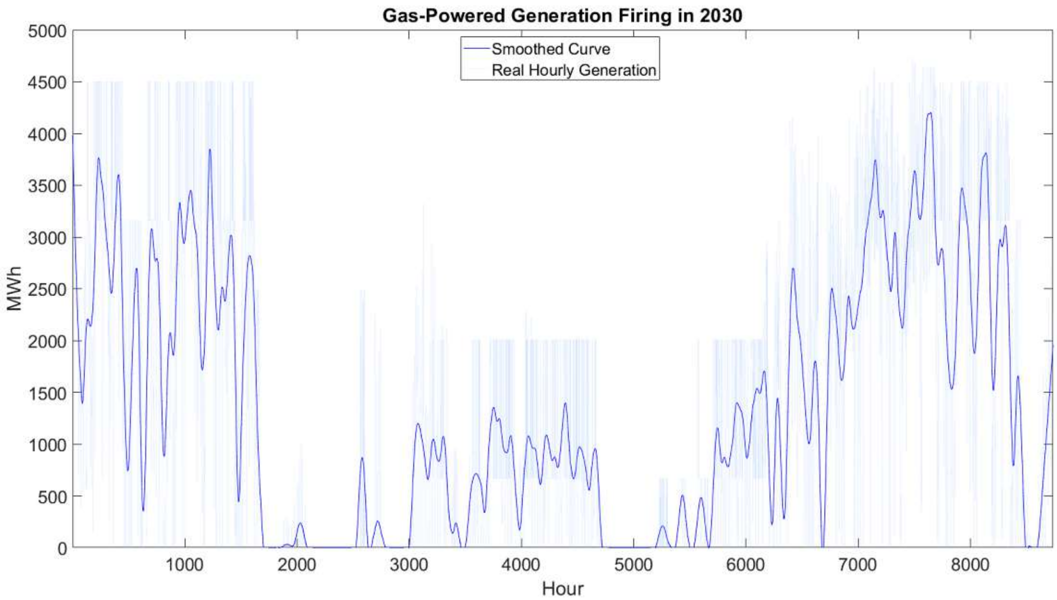

Figure 28: Electricity Generation from Natural Gas in 2030

Despite substantial capacity enhancements in renewable generation, as indicated in Table 3, the annual electricity generation mix for Austria in the year 2030, showcased in Table 8 and depicted in Figure 29, reveals a significant volume of electricity, totaling 11.51 TWh, still being generated by gas-fired power stations. This intriguing interplay between the expansion of renewables and the ongoing generation of electricity from gas sources underscores the complexities of the energy transition in the pursuit of sustainability.

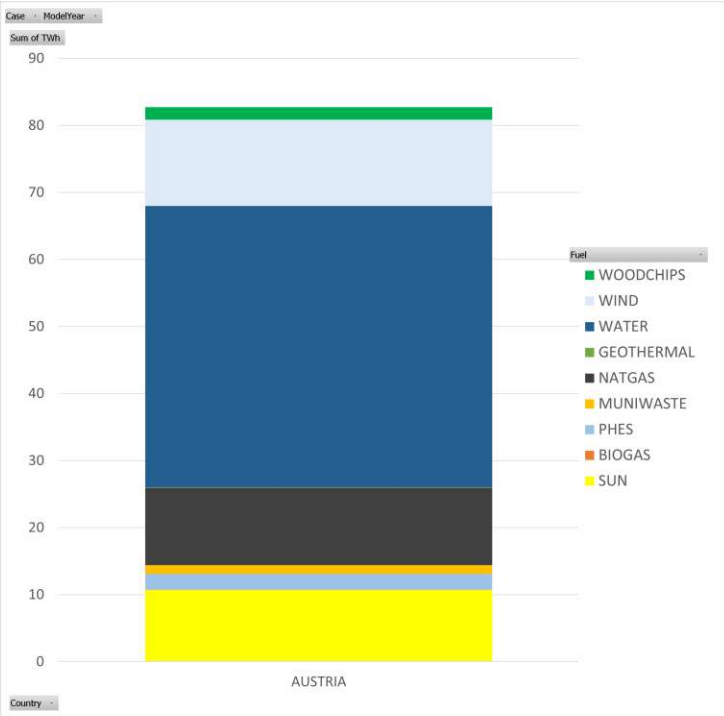

Figure 29: Annual Generation Mix of 2030

To achieve its 2030 goal of achieving 100% renewable energy in an interconnected system, Austria would need to export an amount of electricity equal to or surpass the quantity generated from fossil fuels annually. Assuming no substantial alterations in fossil fuel generation, Austria would be required to produce an additional 11.5 TWh of electricity from renewable sources to fulfill its targets. Meeting this increased demand would mandate a doubling of the simulated generation capacities of solar PV to 23 GWpeak or wind turbines to 13 GW.

3.4 Annual generation for different scenarios

The data presented in Table 9 provides an overview of the annual electricity generation for all simulated scenarios (refer to Table 7). Within this data set, the columns labeled Equivalent Solar Cap and Annual Consumption have been generated through data adjustments performed by the prosumer model described in Section 2.4. The growing proportion of modeled prosumers leads to higher levels of energy self-consumption by prosumers, resulting in a decrease in both the electricity generated by solar PV (*Equivalent Solar Capacity* × *Full load hours*) and the electricity demand perceived by the energy system (*Annual Consumption*).[31]

				Annual Generation [TWh]									
Scenario	Prosumer share [%]	Equivalent Solar Cap [MW]	Annual Consumption [TWh]	Total	WOOD CHIPS	BIOGAS	MUNI WASTE	WASTE HEAT	WIND	WATER	NATGAS	ELECTRIC	SUN
AT03	000	11527.00	77.10	82.74	1.91	0.02	1.31	0.06	12.85	42.01	11.51	2.38	10.71
AT03	010	11047.00	76.64	82.27	1.91	0.02	1.31	0.06	12.84	41.97	11.50	2.38	10.29
AT03	020	10568.00	76.18	81.88	1.91	0.02	1.31	0.06	12.84	42.01	11.49	2.44	9.81
AT03	030	10088.00	75.73	81.37	1.91	0.02	1.31	0.06	12.84	41.97	11.48	2.42	9.38
AT03	040	9609.00	75.27	80.87	1.91	0.02	1.31	0.06	12.83	41.94	11.47	2.40	8.94
AT03	050	9129.00	74.81	80.40	1.91	0.02	1.31	0.06	12.83	41.97	11.46	2.40	8.46
AT03	060	8649.00	74.35	79.91	1.91	0.02	1.31	0.06	12.83	41.95	11.45	2.39	8.01
AT03	070	8170.00	73.90	79.48	1.91	0.02	1.31	0.06	12.83	41.93	11.44	2.42	7.58
AT03	080	7690.00	73.44	79.00	1.91	0.02	1.31	0.06	12.82	41.92	11.43	2.41	7.13
AT03	090	7210.00	72.98	78.55	1.91	0.02	1.31	0.06	12.82	41.93	11.42	2.43	6.67
AT03	100	6731.00	72.52	78.04	1.91	0.02	1.31	0.06	12.82	41.90	11.41	2.40	6.23
AT0E	040	7334.00	73.10	78.72	1.91	0.02	1.31	0.06	12.82	41.92	11.43	2.47	6.79
AT0E	070	5251.00	71.11	76.64	1.91	0.02	1.31	0.06	12.81	41.86	11.39	2.45	4.85
AT0E	100	4016.00	69.93	75.42	1.91	0.02	1.31	0.06	12.80	41.83	11.36	2.45	3.70
ATB0	040	8504.00	74.22	79.39	1.91	0.02	1.31	0.06	12.79	41.91	11.40	2.10	7.91
ATB0	070	6236.00	72.05	77.08	1.91	0.02	1.31	0.06	12.76	41.90	11.34	2.04	5.76
ATB0	100	3969.00	69.89	74.76	1.91	0.02	1.31	0.06	12.74	41.79	11.29	1.97	3.68
ATBE	070	4600.00	70.49	75.78	1.91	0.02	1.31	0.06	12.78	41.86	11.33	2.28	4.24
ATBE	100	1712.00	67.74	72.35	1.91	0.02	1.31	0.06	12.72	41.72	11.22	1.83	1.58

Table 9: Yearly Generations in Simulated Energy Model States (Scenarios)

Modeling the self-consumption of prosumers reduces electricity demand by up to 9.36 TWh, leading to a total reduction of 10.39 TWh in electricity generation and consequently a different distribution of generation between generating units. To illustrate these changes, a visually limited representation of the annual generation mix is presented in the form of a stacked column chart in the Figure 30, where the generation mix for an individual scenario is depicted as a column with the contributions from various energy sources stacked on top of each other.

[31] It's important to note that the modeling operates at an "instantaneous," hourly level, and as a consequence, in addition to the mentioned disparities in annual values for and equivalent solar capacity, there are significant differences in the hourly distributions of these values.

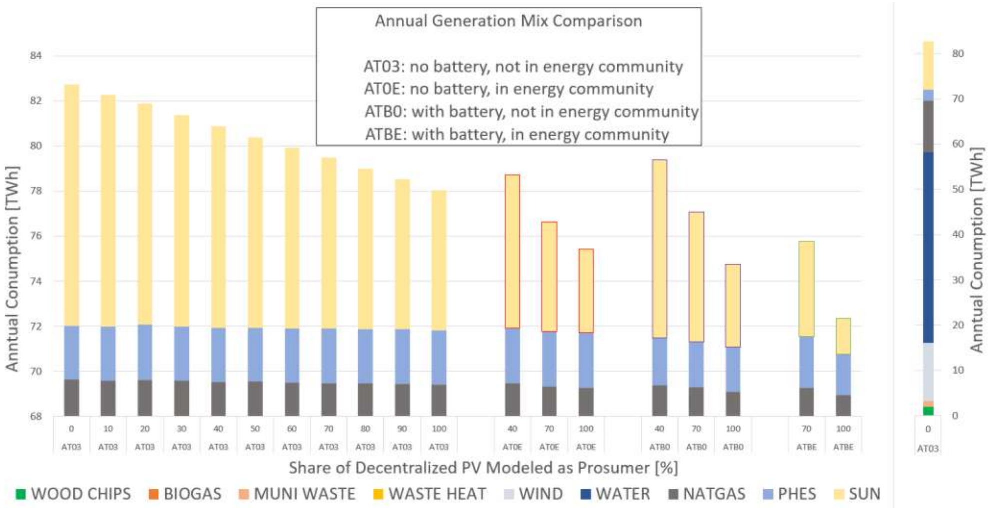

Figure 30: Annual Generation Mix Comparison

The most notable reduction in generation, amounting to 10.39 TWh, is observed between the scenario representing the system optimal dispatch of decentralized solar generation (AT03 00) and the scenario wherein all decentralized generation is modeled as prosumers with accompanying storage, sharing excess electricity within the energy community (ATBE 10), as illustrated in Figure 30. This reduction is due to the self-consumption of 9.36 TWh reflected in decreases in the annual electricity demand and solar generation (Table 9, columns: Annual demand and Sun). The difference of 1.03 TWh between these two values quantifies the reduction in grid losses due to modeling prosumer self-consumption compared to the system optimal dispatch of decentralized PV.

The comparison of grid losses between modeled scenarios is depicted in Figure 31 as a function of the share of decentralized photovoltaics modeled as prosumers for four types of prosumers: AT03, AT0E, ATB0, and ATBE. [32]

[32] For an explanation of prosumer types refer to the legend on the Figure 31 or to the Section 3.

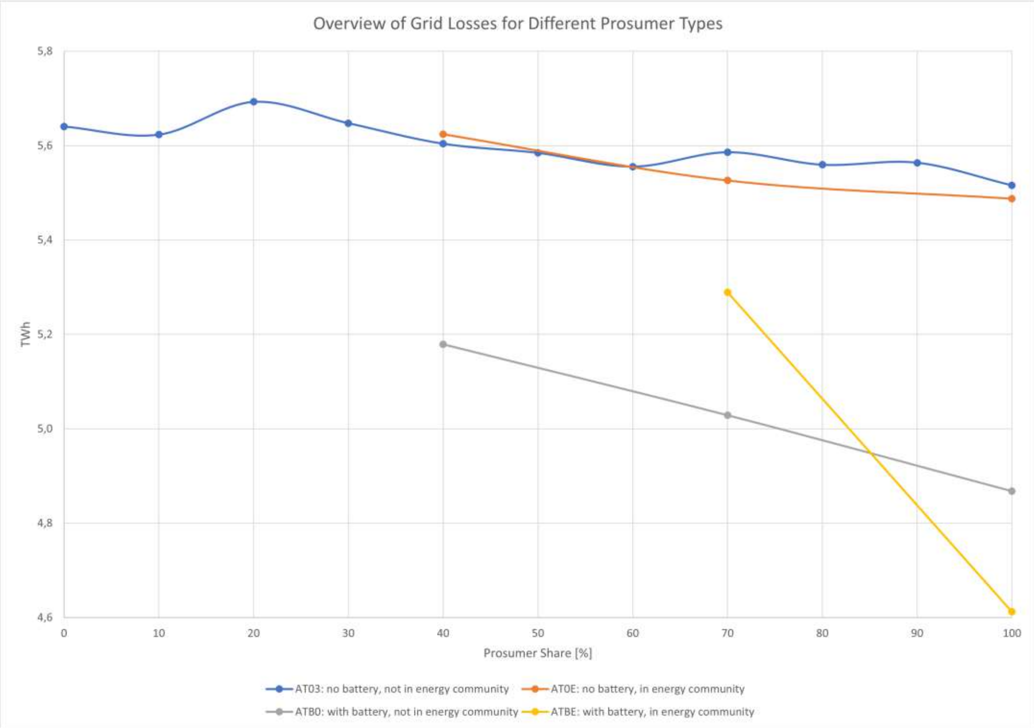

Figure 31: Comparison of Annual Grid Losses

The prosumer types modeled without accompanying batteries exhibit an almost linear correlation between the reduction in grid losses and the increasing share of decentralized PV modeled as prosumers maximizing self-consumption, as illustrated in Figure 31. Modeling prosumers with batteries reveals a significantly higher gain in grid loss reductions.

To explain the minor deviation from linearity in the reduction of grid losses for prosumer type AT03 and the significantly higher reductions in the case of prosumers with batteries (ATB0 and ATBE), it's necessary to consider the substantial differences in the contributions of different technologies to grid losses. Specifically, this includes the inherently low grid losses associated with decentralized PV generation (as referenced in Hu et al. (2017)), and the relatively high losses in the pumping/generation cycle of PHES, estimated at around 20% (as stated in Blakers et al. (2021)), in contrast to the actual transmission and distribution (T&D) losses in Austria, which amount to 4.61% of net electricity demand (as reported in (Enerdata, 2023)).

The notable decrease in grid losses, as depicted in Figure 31, among prosumers with accompanying batteries (prosumer types ATB0 and ATBE), can be attributed to the capacity of batteries to store surplus energy for later use.

The use of batteries enables a temporal shift in energy generation and consumption which, in turn, further increases the self-consumption. This effect occurs independently of its impact on the energy system, such as changes in merit order and the generation mix during the affected time periods. To assess the impact of this prosumer-driven change in the energy system, one must examine the cumulative effects over an extended time period. In this context, Table 9 provides the following insights:

- There is no change in electricity generation from wood chips, biogas, municipal waste, and geothermal across the modeled scenarios.
- A marginal reduction in electricity generation is noted for run-of-river power plants, wind turbines, and natural gas (up to 1% for wind and water and up to 3% for coal). However, this reduction cannot be solely ascribed to the influence of decentralized batteries. Similar reductions are also observed in scenarios modeling prosumers without accompanying batteries, suggesting that these decreases primarily result from savings in grid losses unveiled through self-consumption modeling.
- In contrast, a substantial reduction in generation from pumped hydro-storage is exclusively observed in simulations involving prosumers with accompanying batteries, indicating a reduction in utilization of PHES due to the coexistence of decentralized batteries.

In scenarios where a battery is simulated in combination with prosumer PV generation (ATB0 and ATBE) there is a noticeable reduction in the generation from pumped hydro-storage as indicated in the "Overlap" column in Table 10. Depending on the installed battery size, the reduction in energy generated from pumped hydro-storage can be up to 0.55 TWh annually, which is a 24 % reduction compared to the base scenario (AT03 00). This reduction occurs because both the pumped hydro-storage and the battery partially utilize the same "excess" electricity generated from decentralized PV to charge. This "overlap" in charging leads to a decrease in the generation from pumped hydro-storage and reductions of associated electricity loss.

Scenario	Prosumer share [%]	Battery size [MWh]	PMP-hydro generation [TWh]	An. energy stored in batteries [TWh]	Overlap [TWh]
AT03	0	0	2.38	0	0.00
ATB0	40	4325	2.10	1.05	0.28
ATB0	70	7551	2.04	1.84	0.34
ATB0	100	10787	1.97	2.63	0.41
ATBE	70	4426	2.28	0.62	0.10
ATBE	100	13391	1.83	2.2	0.55

Table 10: Reduction in Energy Stored in Pumped Hydro Reservoirs

The hourly generation mix in Austria during the 33rd and 49th week of the year 2030 is shown in Figure 3.4 for 7.53 GWp (70%) of decentral photovoltaic modeled as (top to bottom):

- prosumer with PV only
- prosumer with PV and storage
- prosumer with PV only in an energy community
- prosumer with PV and storage in an energy community

Figure 3.4 illustrates the small variations in the utilization of hydro storage resulting from load displacement via decentralized PV and storage. This is exemplified in week 33. The figure also highlights a substantial reduction in the solar generation share due to the modeling of various prosumer types. Additionally, it shows negligible variations in the generation mix among different types of prosumers during periods of reduced solar generation, as seen in week 44.

Given the high capacity of pumped storage and the simulated solar generation capacity (approximately 11.5 GWp), there is no significant shift in generation sources on an annual level due to the utilization of batteries. In essence, the simulated decentralized batteries store electricity that would either be stored by pumped hydro storage or consumed instantly by other consumers in the system.

From the perspective of Austria's annual generation mix, batteries provide no added value in terms of changing the overall energy source composition. However, it's important to note that decentralized batteries bring valuable grid advantages that extend beyond the scope of this thesis, such as demand/response, integration of renewable energy sources into the grid, and enhancement of grid resilience. It's worth highlighting that the situation is quite different from the prosumer perspective where significant increases in self-consumption, self-sufficiency, and electricity cost savings are observed due to the utilization of batteries, as discussed in Section 3.2.

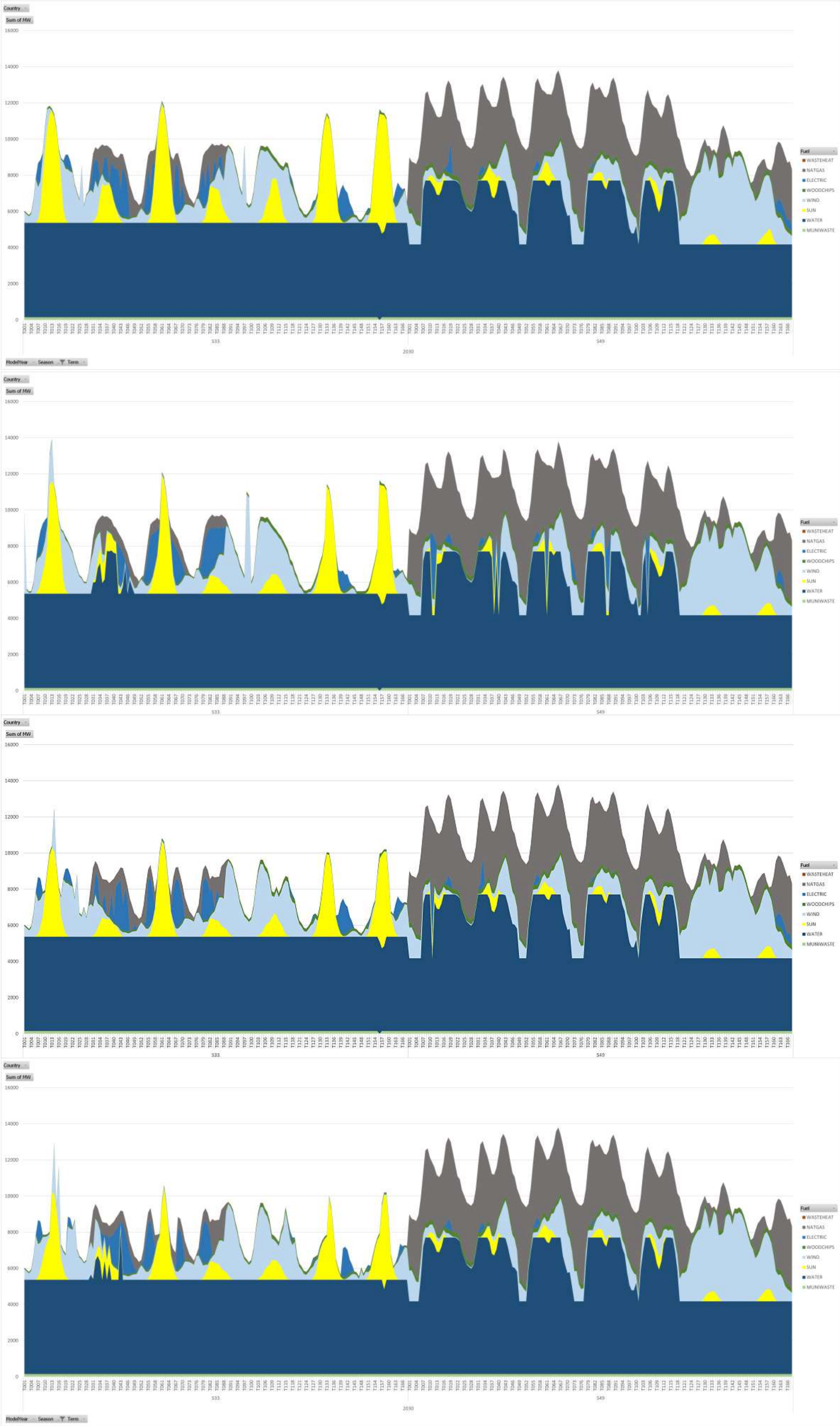

Figure 32: Generation Mix, Week 33, Prosumer Share = 0.7 (70%)
a) AT0307 b) ATB007 c) AT0E07 d) ATBE07

3.5 Impact of prosumer batteries on consumption profile

Figure 33 shows us total consumption profiles in Austria for the 33^{rd} and 49^{th} week in the year 2030. Three plotted profiles represent:

(blue) initial consumption profile without prosumer modeling

(red) modified consumption profile in Austria for 70% of decentral PV modeled as prosumer

(yellow) modified consumption profile in Austria for a prosumer share of 70 % inside an energy-sharing community

The difference between the blue and red profiles represents the "hiding" of electricity self-consumption from the grid, as described in Section 3.4. During summer months, solar panels generate electricity for longer periods of the day, leading to benefits such as peak shaving and a flattened demand curve. However, during winter periods, solar panels primarily generate electricity during off-peak hours, and the advantages seen in summer weeks are not as prominent.

The difference between the red and yellow profiles represents the additional "hiding" of household sector consumption within energy communities. In this model, energy communities are simulated as increased consumption available to prosumers, allowing electricity to be used locally without feeding it back to the grid. The sharing of locally generated electricity with the energy community is more prevalent during summer periods with higher solar generation, such as in August (33rd week), compared to winter periods where electricity generated from PV barely covers its own needs during generation peaks, as seen in December (49th week).

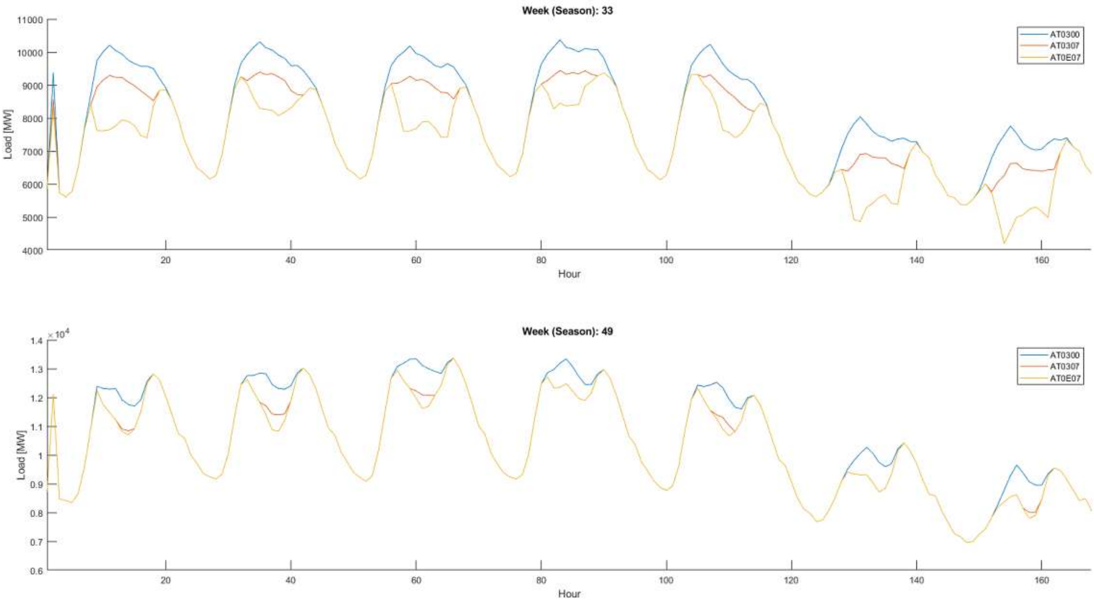

Figure 33: Changes in Demand Profile Due to Prosumer and Energy Communities Modeling Approach

Figure 34 illustrates the impact of decentralized battery storage on the consumption profile in Austria, using data from scenarios with a 100% prosumer share. The higher two consumption profiles, AT0300 (blue) and AT0310 (red) represent consumption data for modeling from a system optimal perspective and a 100% prosumer share, respectively. The data set ATB010 (yellow) represents a newly obtained consumption profile in Austria, including decentralized battery storage with a total capacity of 10.8 GWh. In the plot for the summer week (33rd), significant battery utilization is observed, as indicated by the difference between the red and yellow curves. Consequently, consumption peaks are significantly lower and "shaved," alleviating the strain on the overall power generation and distribution system. Batteries not only smooth out fluctuations but also ensure a stable voltage output, thereby enhancing the reliability of the power supply.

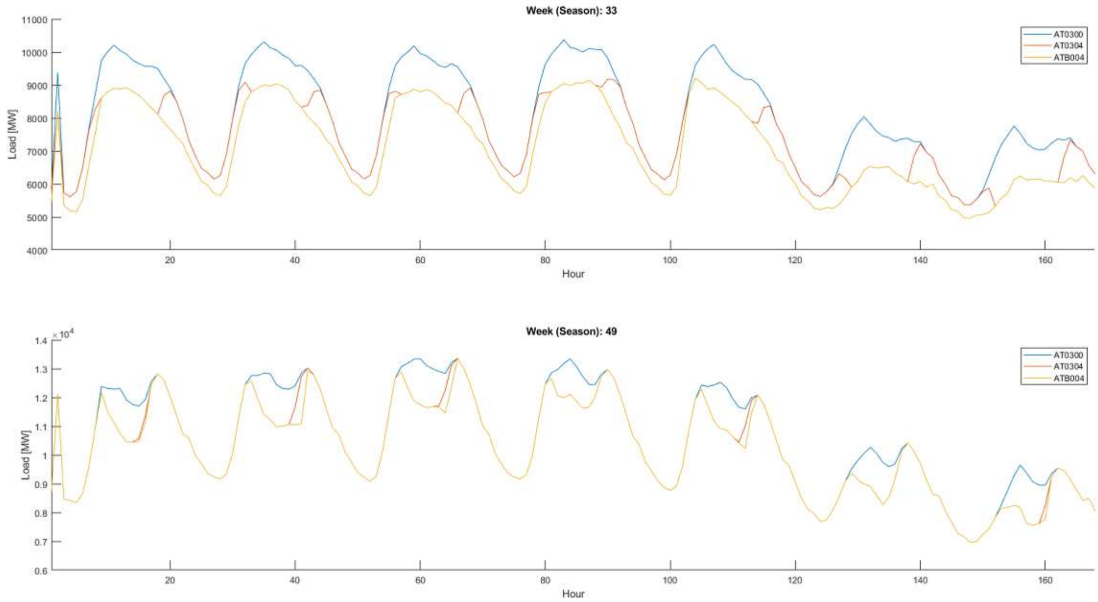

Figure 34: Changes in Demand Profile Due to Prosumer with Storage Modeling

3.6 Backfeeding

Backfeeding in a distribution grid refers to the situation where electricity flows backward from distributed energy resources into the grid. Depending on the current grid state and the amount of reverse flow, it can pose some challenges for distribution grid planning and operation (e.g. voltage regulation, coordination of protections, investment requirements in bi-directional equipment, etc.), which are not covered by this work. Figure 35 quantifies reverse flow caused by simulated prosumers as a percentage of annual electricity generated from decentralized PV being fed back into the grid. The observations are as follows:

- A typical residential prosumer with PV installations generating 14 % of his annual demand will consume all generation instantly.
- If energy communities are spread and formed through the household sector, the decentral generation with a capacity of 2.9 GWp (corresponding to *Prosumer share* of 27 %) could be installed without reverse flow occurrence (without decentral batteries).

- If installed decentral PV capacity is lower than 5.8 GWpeak (corresponding to *Prosumer share* of 54 %) the energy communities are more efficient in reducing reverse flow than decentral batteries, keeping the annual reverse flow under 9 % of annual PV generation.

- Through the utilization of both batteries and energy communities annual reverse flow of electricity could be kept under 9 % of annual solar generation for an installed decentral capacity of 10.7 GWp (corresponding to *Prosumer share* 100 %).

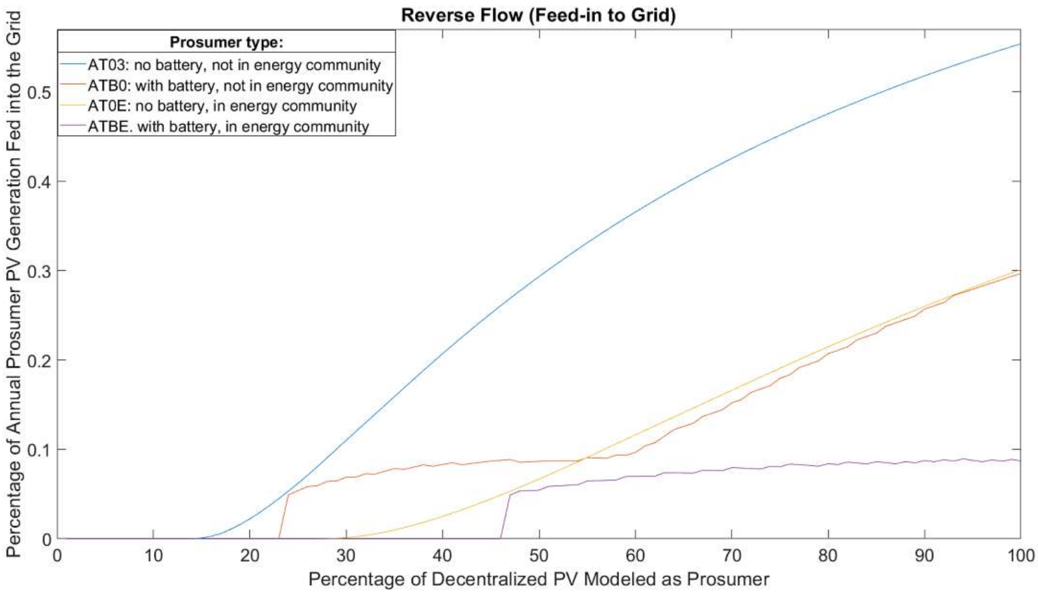

Figure 35: Reverse Flow Caused by Different Types of Prosumers

Figure 35 represents reverse power flow as the sum of annual electricity flowing into the grid for the entire country. It does not necessarily mean that reverse power flow cannot be higher during periods of increased solar generation or at specific locations in the distribution grid. Here is a brief overview of assumptions made in the model with potential impacts on the results presented in Figure 35:

- The installed decentral power capacity is scaled to match the annual demand of a prosumer.

- The charging and discharging strategy for batteries is designed to maximize self- or local consumption, depending on whether the prosumer is part of an energy community or not.

- The model scales battery capacity so that every last kilowatt-hour (kWh) of installed capacity is charged and discharged at least 100 times in a year.
- The model neglects battery losses.

3.7 Comparison of energy system costs for different types of distributed generation modeling approaches

Figure 36 provides a comparison of average electricity spot prices under different energy system modeling scenarios.

The data shows an increase in average electricity spot prices with an increasing share of prosumer-modeled decentral PV without batteries. While the observed increase in average electricity prices is relatively small, ranging from 0 to 1.5%, it is still noticeable. For simulations of prosumer types without accompanying storage (AT03 and AT0E), this increase correlates with higher levels of self- and local consumption of electricity.

The increase in average electricity spot prices is due to the removal of cheap electricity generated by decentral photovoltaics from the energy mix.

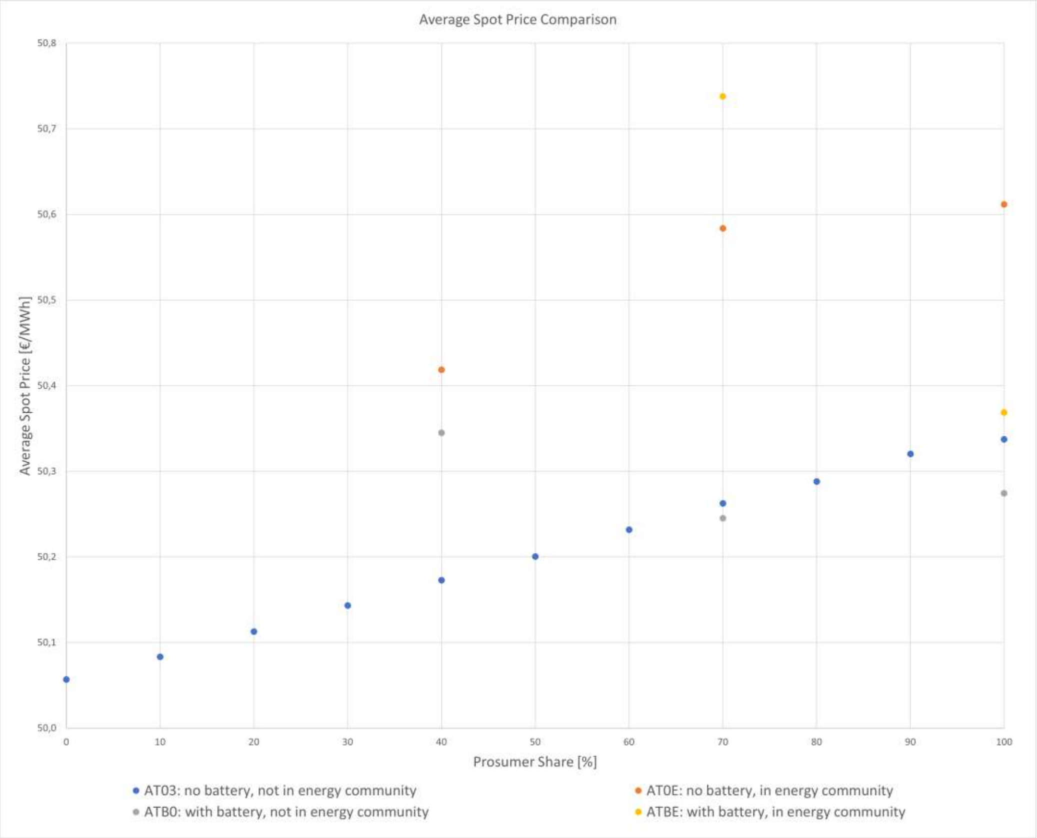

Figure 36: Comparison of Average Electricity Spot Prices

In the scenarios where prosumers are modeled with local generation and consumption along with access to battery storage, there is an observed increase in electricity prices. However, this increase in prices does not exhibit a noticeable linear correlation with an increasing share of prosumers or a reduction in electricity demand from the grid. This deviation from the previously described economies of scale effect can be attributed to the implemented charging and discharging strategy of the batteries.

The battery charging and discharging strategy employed in the energy system model prioritizes self- or local consumption maximization. In simple terms, the battery charges when local generation exceeds local consumption and discharges when the opposite occurs. However, this strategy does not account for other factors, such as the availability of other electricity-generating resources, peak and low demand periods, or energy system cost factors. In contrast, Balmorel considers these factors and adds the significant factor of momentous consumption (battery charging) or generation (battery discharging). This has varying impacts on spot prices, depending on the current situation in the energy system.

Figure 37 illustrates the diverse effects of batteries on electricity spot prices for system-optimized, self-consumption-optimized, and local-consumption-optimized modeling approaches during selected hours of the 33rd week. In hours 58-60 (red), battery charging (additional demand) maintains prices at around €74/MWh (middle subplot) instead of dropping to €57/MWh, as seen in the case without batteries (upper subplot). Conversely, during hours 51-53 and 73-77 (green), batteries discharging reduces spot prices. The lowest plot in the figure shows the spot prices for prosumers with storage in energy communities. Due to differences in energy community consumption compared to the consumer's own consumption, the battery charging/discharging profile is different, causing different variations in spot price impacts (yellow).

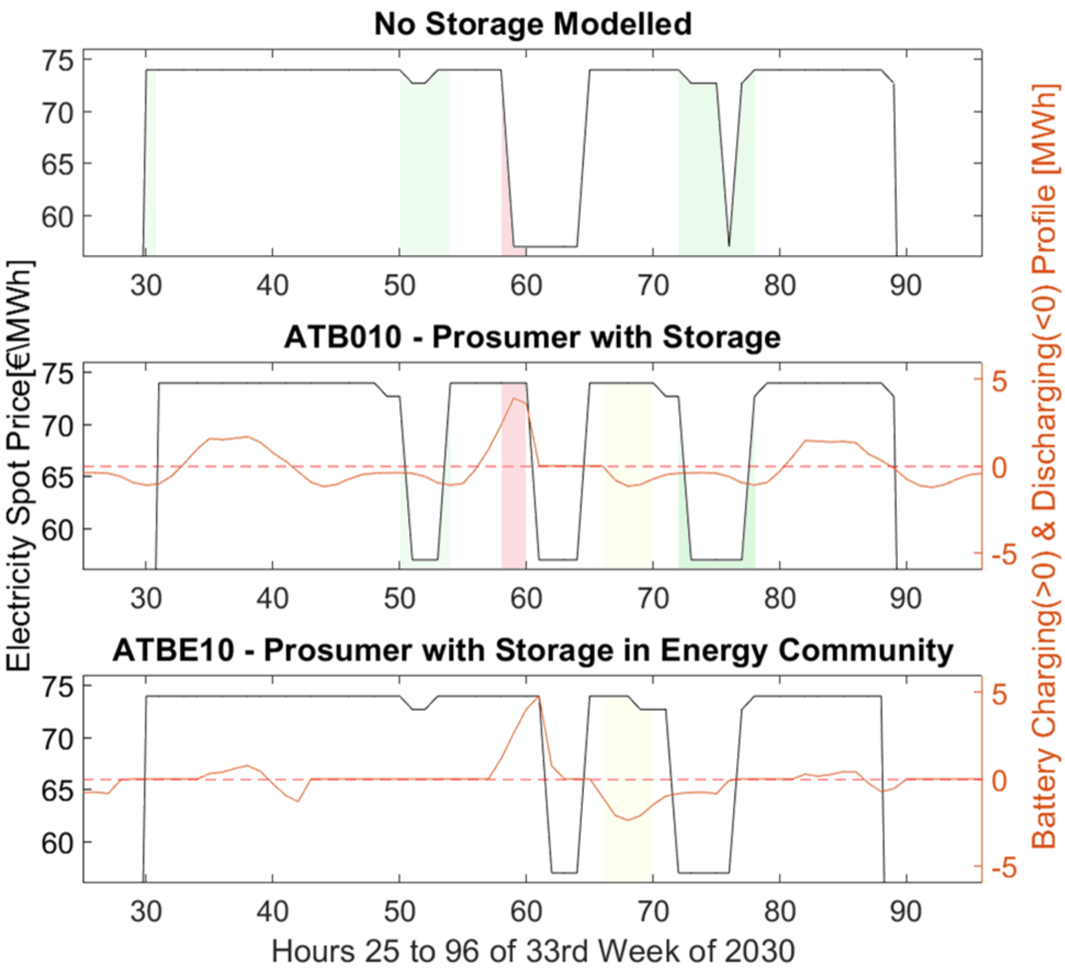

Figure 37: Battery Storage Impact on Spot-Price in Austria

Even with the increase in average electricity spot prices, the total system cost of electricity generation reduces significantly. Depending on the model approach, reductions of up to 15% in total costs are noticeable (see Figure 38). This is due to a significant reduction in annual electricity demand from the electricity grid, through the utilization of decentralized PV, batteries, and energy communities.

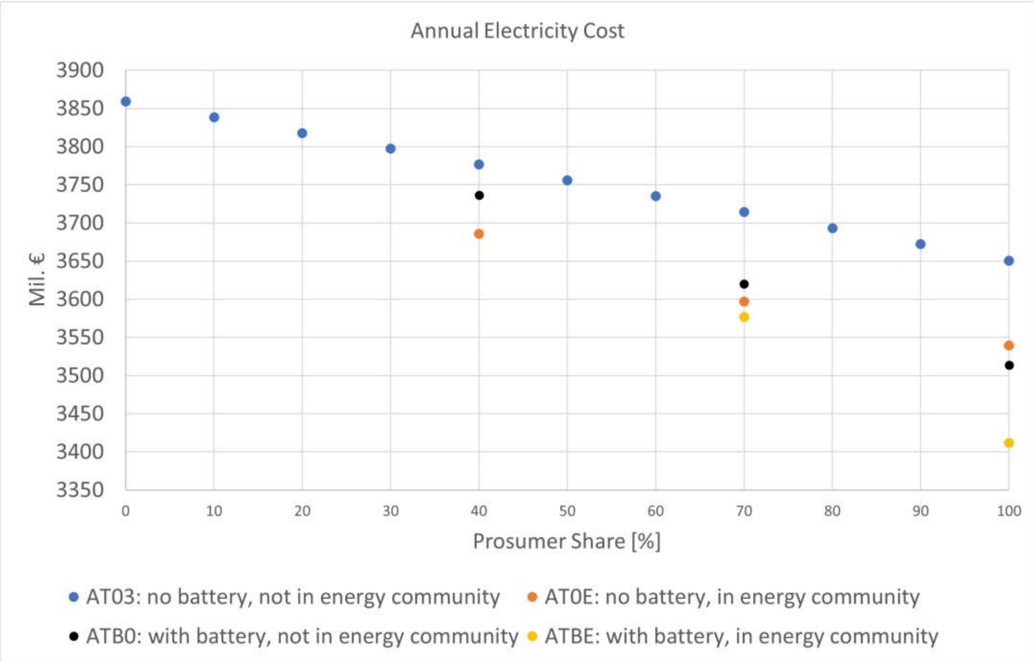

Figure 38: Total Electricity Generation Costs for Different Modeled Scenarios

4 Conclusion

This thesis has explored the impact of two distinct modeling approaches for decentralized photovoltaic (PV) and storage dispatch in the residential sector of Austria. The results emphasize the benefits of optimizing self-consumption and the significance of energy communities in shaping the future of the energy system.

The first approach, concentrating on maximizing the self-consumption rates of residential prosumers, unveiled an error in estimating grid losses, resulting in up to 1.05 TWh of electricity overestimation when modeling decentralized PV and storage as system optimal dispatch in Austria in the year 2030. This discrepancy stems from the omission of the self-consumption of decentral prosumers.

Decentralized batteries, optimized for self-consumption, demonstrated minimal influence on the annual energy generation mix. The study highlighted a potential convergence between the utilization of decentralized batteries and central storage, such as pumped hydro-storage, suggesting an excess energy storage capacity within the system. In light of the 2030 targets for electricity generation and the estimated remaining generation by natural gas of 11.5 TWh in the year 2030, this surplus storage capacity could be harnessed for additional integration of renewable energy sources, contributing to the realization of 100% carbon-free electricity generation.

Concerning the energy system model, the increasing share of decentral photovoltaics exhibited a small linear increase in electricity spot prices and a significant reduction in electricity generation costs for the energy system. This reduction was achieved through the shift of investment costs (and revenues) from large-scale utility power plants to individual prosumers.

Modeling prosumers and their storage as an entity maximizing self-consumption revealed a substantial instantaneous impact of cumulative decentral battery capacity and their charging and discharging strategies on electricity spot prices, hinting at the potential for an economically viable large-scale battery management system.

Additionally, the research underscores that, from both the perspective of the energy system and prosumers, the advantages of energy communities surpass those of decentralized batteries in terms of maximizing self-consumption and minimizing reverse flow. Establishing an energy community significantly postpones the need for local energy storage, and when the need for batteries arises, it is more reasonable to invest in large-scale central batteries within the energy community. These central batteries offer cost savings in terms of euros per kilowatt-hour (kWh) of electricity storage and enable effective battery management and control, facilitating enhanced load shifting, better demand/supply response, and the potential reduction of fossil fuel-based generation.

A final takeaway from this research is the importance of prosumer awareness and understanding of their energy surroundings. To fully harness the advantages of decentralized generation and energy communities, prosumers need to be well-informed and engaged in their energy consumption and sharing practices.

Several questions remain unanswered: Should policies be reevaluated and oriented toward incentivizing prosumers to participate in or establish energy communities rather than subsidizing decentralized batteries for self-consumption maximization? How would the outcomes differ if prosumers were modeled using an agent-based approach that incorporates a variety of prosumer types, such as stores, small businesses, garages, etc.? Furthermore, as the impact of energy communities has only been superficially modeled, its true potential remains to be explored in more focused research.

Literature

Aghaie, H., Leoni, P., Schmidt, R., & Roman. (2020). Sdh perspectives in austria.

Balmorel. (2023). The balmorel open source project. http://www.balmorel.com/

Balmorel user guide [Balmorel User Guide Presentation]. (n.d.). Ea Energy Analyses.

Biermayr, P. (2023). *Innovative energietechnologien in österreich marktentwicklung 2022* (Berichte aus Energie- und Umweltforschung No. 36a/2023). Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität,Innovation und Technologie (BMK).

Blakers, A., Stocks, M., Lu, B., & Cheng, C. (2021). A review of pumped hydro energy storage. *Progress in Energy*, *3*, 022003. https://doi.org/10.1088/2516-1083/abeb5b

Directorate-General for Energy, E. C. (2022, September). Solar energy – harnessing the power of the sun. https://commission.europa.eu/news/focus-solar-energy-harnessing-power-sun-2022-09-13_en

Enerdata. (2023, March). *Austria energy report* (tech. rep.). https://www.enerdata.net/estore/energy-market/austria/

ENTSO-E. (2010). *Load and consumption data: Specificities of member countries* (tech. rep.). European Network of Transmission System Operators for Electricity. https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/ce/Load_and_Consumption_Data.pdf

European Environment Agency. (2022). *Energy prosumers in europe – citizen participation in the energy transition*. Publications Office of the European Union. https://doi.org/doi/10.2800/030218

Fodstad, M., Crespo del Granado, P., Hellemo, L., Knudsen, B. R., Pisciella, P., Silvast, A., Bordin, C., Schmidt, S., & Straus, J. (2022). Next frontiers in energy system modelling: A review on challenges and the state of the art. *Renewable and Sustainable Energy Reviews*, *160*, 112246. https://doi.org/https://doi.org/10.1016/j.rser.2022.112246

Government of Austria. (2021). *Federal act on the expansion of energy from renewable sources (renewable energy expansion act)*.

Green, R., & Staffell, I. (2017). "prosumage" and the british electricity market. *Economics of Energy and Environmental Policy*, *6*(1), 33–49. https://doi.org/10.5547/2160-5890.6.1.rgre

Haas, R., Lettner, G., Auer, H., & Duic, N. (2013). The looming revolution: How photovoltaics will change electricity markets in europe fundamentally. *Energy*, *57*, 38–43. https://doi.org/https://doi.org/10.1016/j.energy.2013.04.034

Hasengst, F. (2022). An analysis of the energy storage requirements of the austrian federal state of tyrol depending on transmission network capacities in 2050. *The Future of Global Energy Systems, 17th IAEE European Conference, September 21-24, 2022*.

Hu, J., Harmsen, R., & Crijns-Graus, W. (2017). Developing a method to account for avoided grid losses from decentralized generation: The eu case [Power and Energy Systems Engineering]. *Energy Procedia*, *141*, 604–610. https://doi.org/https://doi.org/10.1016/j.egypro.2017.11.080

International Energy Agency. (2022). Solar pv. https://www.iea.org/reports/solar-pv

Kopač, J. (Ed.). (2018). *Policy guidelines on the grid integration of prosumers*.

Lopion, P., Markewitz, P., Robinius, M., & Stolten, D. (2018). A review of current challenges and trends in energy systems modeling. *Renewable and Sustainable Energy Reviews*, *96*, 156–166. https://doi.org/https://doi.org/10.1016/j.rser.2018.07.045

McKenna, R., Hernando, D. A., ben Brahim, T., Bolwig, S., Cohen, J. J., & Reichl, J. (2021). Analyzing the energy system impacts of price-induced demand-side-flexibility with empirical data. *Journal of Cleaner Production*, *279*, 123354. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.123354

McPherson, M., & Karney, B. (2014). Long-term scenario alternatives and their implications leap model application of panamas electricity sector. *Energy Policy*, *68*, 146–157. https://doi.org/https://doi.org/10.1016/j.enpol.2014.01.028

Mengolini, A. (2017). Prosumer behaviour in emerging electricity systems. *PhD diss. Politecnico di Torino*.

Photovoltaik Austria. *9 jahre sonnenwärts. zwischenbilanz.* 2017, April. https://elektro.at/wp-content/uploads/2017/04/PV-Bilanzbroschuere_2017.pdf

Renewable Energy Advisor. (2017). What is grid parity? http://www.renewable-energy-advisors.com/learn-more-2/what-is-grid-parity

Roberts, J., Frieden, D., & Herbemont, S. (2019, May). *Energy community definitions* (tech. rep.). https://main.compile-project.eu/wp-content/uploads/Explanatory-note-on-energy-community-definitions.pdf

Schill, W.-P., Zerrahn, A., & Kunz, F. (2017). Prosumage of solar electricity: Pros, cons, and the system perspective. *Economics of Energy and*

Environmental Policy, *6*(1), 7–32. https://www.jstor.org/stable/26189569
Vuthi, P., Peters, I., & Sudeikat, J. (2022). Agent-based modeling (abm) for urban neighborhood energy systems: Literature review and proposal for an all integrative abm approach jo - energy informatics. *Energy Informatics*, *5*. https://doi.org/10.1186/s42162-022-00247-y
Wiese, F., Bramstoft, R., Koduvere, H., Pizarro Alonso, A., Balyk, O., Kirkerud, J. G., Tveten, Å. G., Bolkesjø, T. F., Münster, M., & Ravn, H. (2018). Balmorel open source energy system model. *Energy Strategy Reviews*, *20*, 26–34. https://doi.org/https://doi.org/10.1016/j.esr.2018.01.003

Data Sources

APCS. (2022). Synthetic load profiles [APCS, Power Clearing and Settlement]. https://www.apcs.at/en/clearing/physical-clearing/synthetic-load-profiles
APG. (2020, August). Day-ahead preise [10.08.-16.08]. https://markttransparenz.apg.at/de/markt/Markttransparenz/Uebertragung/EXAA-Spotmarkt
Appunn, K. (2015). Setting the power price: the merit order effect. https://www.cleanenergywire.org/factsheets/setting-power-price-merit-order-effect
AURESII. (2022). *Auctions for renewable energy support ii. horizon 2020 framework programme, grant agreement no. 817619.* (tech. rep.). http://aures2project.eu/
BMK. (2021). *Energie in österreich zahlen, daten, fakten* (tech. rep.). Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität,Innovation und Technologie. https://www.bmk.gv.at/themen/energie/publikationen/zahlen.html
ENTSO-E. (2020). European association for the cooperation of transmission system operators (tsos) for electricity [Total Load - Day Ahead / Actual]. https://transparency.entsoe.eu/
Fechner, H. (2022). *National Survey Report of PV Power Applications in Austria* (tech. rep.). International Energy Agency.
NECP. (2019, December). *Integrated National Energy and Climate Plan for Austria* (tech. rep.). Federal Ministry for Sustainability and Tourism. https://energy.ec.europa.eu/system/files/2020-03/at_final_necp_main_en_0.pdf
NIP. (2023, July). *Integrierter österreichischer netzinfrastrukturplan* (tech. rep.) (Entwurf zur Stellungnahme). Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität,Innovation und Technologie (BMK).

STATISTIK. (2021). *Energiebilanzen Österreich 1970–2021*. https://www.statistik.at/statistiken/energie-und-umwelt/energie/energiebilanzen
TYNDP. (2021). *Ten-year network development plan (tyndp) 2020* (tech. rep.). ENTSO-E. https://tyndp.entsoe.eu/scenarios
WEMAG. (2022). Durchschnittlicher Stromverbrauch im 1, 2, 3 und 4 Personen Haushalt. https://www.wemag.com/energiesparberatung/stromverbrauch-single-2-3-4-personen-haushalt

A Matlab Code

A.1 Prosumer Model

```
%% MODEL RUN CONTROL
% Prosumer Model returns modified data as an output
% Model ouputs start with letter M (see Workspace after model run).
% File Output.xlsx contains outputs:
%   1) M_variation_of_elec_demand
%   2) M_variation_of_solar_generation
%   *Remaining skalar outputs can easily be coppied from the workspace

close all
clc
global Control_week Control_sim Control_year Prosumer_share Battery
    Energy_community

%REPRESENTATION OF RESULTS
Control_plotting=1; %Controls figure plotting:  1-ON      0-OFF
Control_week=33; % Chooses a week to plot for purposes of representation (
    Value in [1,52])
Control_sim=0; % 1-single house simulation      0-nationwide simulation
Control_reverseflow=1; % Do Backfeeding sensitivity analysis?  1-YES   0-NO
Control_year=2030; %Has no impact on model results, it serves only to write
    a year on the figures
set(0,'defaultAxesFontSize',20) %increases font in the figures


%% MODEL VARIABLES
Prosumer_share=0.6; % in [0,1] for single house data presented in paper
    Prosumer_share=0.76335877862
Energy_community=1; %valid only for country simulations (not valid for
    single house sim)
Battery=1; %1-sim with optimal battery capacity      0-sim with PV only


if (Control_sim==0)
    display('Nationwide simulation started')
    display('...PV')
    if Energy_community==1
        display('...EC')
    end
    if Battery==1
        display('...BAT')
    end
else
    display('Single household simulation started')
end

%% READING (Variation) DATA FROM TABLES and scalling it to 1

    %Variation ofsolar generation in Austria (no unit)
    Variation_of_solar_generation=table2array(readtable('SolarVariation.xlsx
        '));
    Variation_of_solar_generation=Variation_of_solar_generation/sum(
        Variation_of_solar_generation);

    %Variation of electricity demand
     Variation_of_electricity_demand=table2array(readtable('
         Total_Load_Balmorel.xlsx'));
```

```
    Variation_of_electricity_demand=Variation_of_electricity_demand/sum(
        Variation_of_electricity_demand);


    %Household sector load distribution
     Variation_of_household_consumption=table2array(readtable('
         Household_Synthetic.xlsx'));
     Variation_of_household_consumption=Variation_of_household_consumption/
         sum(Variation_of_household_consumption);

%% SETTING CONSTANTS

 %Annual Consumption in MWh,  PV generation capacities in MW
 Annual_consumption_AT=77100000;
 DecentralPVcapacity=10750.93921;
 CentralPVcapacity=776.060791;

 %Full load hours of sun in Austria [h]
 Full_load_hours=954;

 %Household sector consumption = 20.1/77.1 total annual consumption
 Household_sector_annual_consumption=20100000;


%% Simulation for single household
if Control_sim>0

    %Load Curve of a single household (Annual consumption 5 MWh, installed
        PV capacity 0.00524 MW)
    AvailableConsumption=5*Variation_of_household_consumption;
    %Hourly generation curve of a single solar installataion on a household
        in MWh
    ProsumerPVgeneration=Full_load_hours*0.00524*
        Variation_of_solar_generation*Prosumer_share;
    [Prosumer_profile, BAT_prosumer_profile] =Prosumer_Sub_model(
        AvailableConsumption,ProsumerPVgeneration,Control_plotting);

    %PLOTTING
    % Plots yearly prosumer statistics
    prosumer_year_extract(ProsumerPVgeneration, Prosumer_profile,
        AvailableConsumption,Control_plotting)
    %Plots prosumer statisctics for each month
    prosumer_exctract_months(AvailableConsumption,ProsumerPVgeneration,
        Prosumer_profile,Control_plotting)
    % Plot prosumer curves for a single week
    prosumer_week_extract(AvailableConsumption,ProsumerPVgeneration,
        Prosumer_profile,Control_plotting,1)
    %Plots prosumer with battery statisctics for each month
    prosumer_exctract_months(AvailableConsumption,ProsumerPVgeneration,
        BAT_prosumer_profile,Control_plotting)
    % Plots yearly prosumer (battery) statistics
    prosumer_year_extract(ProsumerPVgeneration,BAT_prosumer_profile,
        AvailableConsumption,Control_plotting)
    %Compares profiles
    compare_consumptions(AvailableConsumption,Prosumer_profile,
        BAT_prosumer_profile,Control_plotting)
end

%% Simulation of whole household sector
if Control_sim==0
%Hourly electricity consumption in Austria in MWh
Hourly_electricity_consumption=Variation_of_electricity_demand*
```

```
    Annual_consumption_AT;
%Hourly Consumption of resedential sector in Austria in MWh
HH_sector_consumption= Variation_of_household_consumption*
    Household_sector_annual_consumption;

if Energy_community==1
    AvailableConsumption=HH_sector_consumption;
else
    AvailableConsumption=Prosumer_share*DecentralPVcapacity*Full_load_hours*
        Variation_of_household_consumption;
end

Residual_consumption=Hourly_electricity_consumption-HH_sector_consumption;
Consumer_HH_consumption=HH_sector_consumption-AvailableConsumption;

DecentralPVgeneration=DecentralPVcapacity*Full_load_hours*
    Variation_of_solar_generation;
ProsumerPVgeneration=Prosumer_share*DecentralPVgeneration;
Residual_decentral_generation=(1-Prosumer_share)*DecentralPVgeneration;
CentralPVgeneration=CentralPVcapacity*Full_load_hours*
    Variation_of_solar_generation;


[Prosumer_profile,BAT_prosumer_profile] =Prosumer_Sub_model(
    AvailableConsumption,ProsumerPVgeneration,Control_plotting);

if Battery==1
    HH_prosumer_consumption=BAT_prosumer_profile.*(BAT_prosumer_profile>=0);
    HH_prosumer_generation=BAT_prosumer_profile.*(BAT_prosumer_profile<0);
else
    HH_prosumer_consumption=Prosumer_profile.*(Prosumer_profile>=0);
    HH_prosumer_generation=Prosumer_profile.*(Prosumer_profile<0);
end

%Output variations are not scalled to 1, so they correspond to actual e.
    demand and actual sol.generation in AT
M_variation_of_elec_demand=Residual_consumption+Consumer_HH_consumption+
    HH_prosumer_consumption;
M_variation_of_solar_generation=Residual_decentral_generation-
    HH_prosumer_generation+CentralPVgeneration;

M_annual_consumption_AT=sum(M_variation_of_elec_demand);
M_annual_solar_generation=sum(M_variation_of_solar_generation);
M_decentralPVcapacity=M_annual_solar_generation/Full_load_hours;


xlswrite('Output.xlsx',[ M_variation_of_elec_demand
    M_variation_of_solar_generation]);
if sum((Hourly_electricity_consumption+HH_prosumer_generation)<0)>0
    display('...Exceded total consumption')
end
end


%% Analysis of reverse flow

if Control_reverseflow==1

RF=zeros(100,4);
for i=1:100
   Control_sim=1;
   Prosumer_share=i/100;
```

```
    Battery=0;
    Energy_community=0;
    RF(i,1)=reverse_flow(Variation_of_solar_generation,
        Variation_of_household_consumption,...
        DecentralPVcapacity,Full_load_hours,
            Household_sector_annual_consumption);
end
for i=1:100
    Control_sim=1;
    Prosumer_share=i/100;
    Battery=1;
    Energy_community=0;
    RF(i,2)=reverse_flow(Variation_of_solar_generation,
        Variation_of_household_consumption,...
        DecentralPVcapacity,Full_load_hours,
            Household_sector_annual_consumption);
end
for i=1:100
    Control_sim=0;
    Prosumer_share=i/100;
    Battery=0;
    Energy_community=1;
    RF(i,3)=reverse_flow(Variation_of_solar_generation,
        Variation_of_household_consumption,...
        DecentralPVcapacity,Full_load_hours,
            Household_sector_annual_consumption);
end
for i=1:100
    Control_sim=0;
    Prosumer_share=i/100;
    Battery=1;
    Energy_community=1;
    RF(i,4)=reverse_flow(Variation_of_solar_generation,
        Variation_of_household_consumption,...
        DecentralPVcapacity,Full_load_hours,
            Household_sector_annual_consumption);
end
RF=RF*(-1);
figure
plot(1:100,RF*100)
hold on
ylim([0 57])
title('Backfeeding (Feed-in to Grid)')
ylabel('Percentage of Annual Prosumer PV Generation Fed into the Grid')
xlabel('Percentage of Decentralized PV Modeled as Prosumer')
leg=legend('AT03: no battery, not in energy community','ATB0: with battery,
    not in energy community','AT0E: no battery, in energy community','ATBE.
    with battery, in energy community');
title(leg,'Prosumer type:')
hold off
end

display('Simulation finished')
```

A.2 Prosumer Sub-model

```
function [Prosumer_profile, BAT_prosumer_profile] = Prosumer_Sub_model(
    AvailableConsumption,ProsumerPVgeneration,plotting)
%{
```

```
DESRIPTION:

Function returns newly generated hourly household load profiles for a house
    with PV installation (Prosumer profile)
and for a house with PV and battery installed (Bat prosumer profile).
Negative values in the profile mean that houshold is consuming electricity
    from the grid in observed hour,
while positive values mean that household is feeding locally generated
    electricity into the grid

Battery Profile represents hourly charging (positive) and discharging (
    negative) profile of the battery
Batter SOC (state of charge) represents hourly data on how much energy is
    stored in battery in current hour
%}

global Control_week Control_sim Control_year Prosumer_share Battery

Prosumer_profile=AvailableConsumption-ProsumerPVgeneration;

Battery_utilization=zeros(100,2);
AddedValue=zeros(100,1);
step=max(ProsumerPVgeneration)*5/100; %for battery optimisation, assume max
    battery capacity of 5 x max (generation) x 1h, and devide it in 100
    optimisation steps (broj nije promeljiv zbog drugih funkcija)
Battery_Optimal=0;

for j=1:101
Battery_Capacity= j*step; %MWh
if j==101
    Battery_Capacity= Battery_Optimal; %previoucely found optimal value in
        MWh
end
Battery_SOC=zeros(8736,1);
Battery_profile=zeros(8736,1);
BAT_prosumer_profile=zeros(8736,1);
if min(Prosumer_profile)>=0
    Battery_Optimal=0;
else

for i=1:8736
   if Prosumer_profile(i)<0.0 && Battery_SOC(i)<Battery_Capacity
       if i==1
       Battery_SOC(i)=min(-Prosumer_profile(i),Battery_Capacity);
       Battery_profile(i)=Battery_SOC(i);
       else
       Battery_SOC(i)=min(Battery_SOC(i-1)-Prosumer_profile(i),
           Battery_Capacity);
       Battery_profile(i)=Battery_SOC(i)-Battery_SOC(i-1);
       BAT_prosumer_profile(i)=Prosumer_profile(i)+Battery_profile(i);
       end
   else
       if i==1
       Battery_SOC(i)=max(-Prosumer_profile(i),0);
       Battery_profile(i)=Battery_SOC(i);
       BAT_prosumer_profile(i)=Prosumer_profile(i)+Battery_profile(i);
       else
       Battery_SOC(i)=max(Battery_SOC(i-1)-Prosumer_profile(i),0);
       Battery_profile(i)=Battery_SOC(i)-Battery_SOC(i-1);
       BAT_prosumer_profile(i)=Prosumer_profile(i)+Battery_profile(i);
       end
   end
```

```
end
    if j~=101
    Battery_utilization(j,1)=sum(Battery_profile.*(Battery_profile>0));
    Battery_utilization(j,2)=sum(Battery_profile.*(Battery_profile<0));
    if j==1
        AddedValue(1,1)=Battery_utilization(1,1)/(step);
    elseif j<101
        AddedValue(j,1)=(Battery_utilization(j,1)-Battery_utilization(j-1,1)
            )/(step);
    end
    if j>1 && AddedValue(j)>100
       Battery_Optimal=(j-1)*step;
    end
    end

end

end
if Battery_Optimal>0
if (plotting==1 && ~(Control_sim<1 && Battery<1))
%plot 1
figure
plot((1:1:100)*step,Battery_utilization(:,1),'*-','MarkerIndices',
    Battery_Capacity/step+1,'Color','black')
hold on
xline(Battery_Capacity,'--')
ylabel('Annaul Energy Stored [MWh]')
xlabel('Battery Capacity [MWh]')
if Control_sim<1
    title(sprintf('Optimization of Battery Capacity: %3.2f GWh',
        Battery_Capacity/1000))
else
    title(sprintf('Optimization of Battery Capacity: %3.2f kWh',
        Battery_Capacity*1000))
end
%m = (Battery_utilization(2,1)-Battery_utilization(1,1))/step;
%plot((1:1:100)*step,m*(1:1:100)*step);
ylim([0 1.1*max(Battery_utilization(:,1))])
xlim([0 100*step])
yyaxis right
plot((1:1:100)*step, AddedValue)
ylabel('Full Charge Cycles of Last Capacity Increase')
yline(100,'--','Color','red')

hold off

%plot 2
figure
plot(1:8736,Battery_SOC)
hold on
plot(smooth(1:8736,Battery_SOC,168/8736,'loess'),'LineWidth',2,'Color','blue
    ')
ylim([-0.1*Battery_Capacity 1.1*Battery_Capacity])
xlim([1 8736])
xlabel('Hours')
ylabel('Battery State of Charge [MWh]')
title('Battery Utilization')
legend('Actual Hourly SOC','Smoothed SOC Profile')
hold off


%plot 3
```

```
figure
subplot(2,1,1)
prosumer_week_extract(AvailableConsumption,ProsumerPVgeneration,
    BAT_prosumer_profile,1,0)
subplot(2,1,2)
hold on
box on
plot(1:168,week_extract(Battery_profile));
lowerYlimit=min(1.1*min(week_extract(Battery_profile)));
higherYlimit=max(1.1*max(week_extract(Battery_profile)),Battery_Capacity
    *1.1);
ylim([lowerYlimit higherYlimit])
ylabel('[MWh]')
xlim([1 168])
clear lowerYlimit higherYlimit
plot(1:168,week_extract(Battery_SOC));
legend('Battery Charging/Dischraging Profile','State of Charge')
xlabel('Hour')
hold off
end
else
   BAT_prosumer_profile=Prosumer_profile;
end


end
```

A.3 Functions

```
function [] = prosumer_year_extract(Generation_profile,Prosumer_profile,
    Consumption_profile,plotting)
%Plots yearly prosumer statistics
global Control_week Control_sim Control_year Prosumer_share
scale=Control_sim;
year=Control_year;
    if ~exist('scale','var')
      scale = 1;
    end

    if ~exist('year','var')
      year = 2020;
    end

    if ~exist('plotting','var')
      plotting = 0;
    end

   if plotting


Yearly_production=sum(Generation_profile);
Yearly_feed_into_grid=sum(Prosumer_profile.*(Prosumer_profile < 0));
Yearly_selfconsumption=Yearly_production+Yearly_feed_into_grid; %feed into
    grid is negative of value
Yearly_consumption=sum(Consumption_profile);

f4=figure;
bar(year,Yearly_consumption,1.5,'FaceColor',[1 1 1])
hold on
```

```
bar(year,Yearly_selfconsumption,1.5,'FaceColor',[0.4660 0.6740 0.1880])
A=num2str(Yearly_selfconsumption/Yearly_consumption*100,'%2.0f');
A(:,3)='%';
text(year,Yearly_selfconsumption,A,'vert','bottom','horiz','center','Color',
    'blue','fontsize',20);
bar(year,Yearly_feed_into_grid,1.5,'FaceColor',[[0.9290 0.6940 0.1250]])
lowerYlimit=1.5*min([Yearly_consumption Yearly_selfconsumption
    Yearly_feed_into_grid]);
higherYlimit=1.1*max([Yearly_consumption Yearly_selfconsumption
    Yearly_feed_into_grid]);
bar(NaN,NaN,'Facecolor',[0 0 1])
ylim([lowerYlimit higherYlimit])
ylabel('[MWh]')
if scale
    title('Prosumer data - Yearly Statistics')
else
    title('Household Sector - Yearly Statistics')
end
legend({'Consumption','Selfconsumption','Electricity into Grid','Self-
    Sufficiency'},'Location','best')
hold off
   end

end

function [] = prosumer_week_extract(HOUSE_distribution,
    HOUSE_generation_profile,HOUSE_prosumer_profile,plotting,new_figure)
%plots prosumer profile
global Control_week Control_sim Control_year Prosumer_share
week=Control_week;
scale=Control_sim;
year=Control_year;

if ~exist('scale','var')
      scale = 1;
    end

 if ~exist('year','var')
      year = 2020;
 end

 if ~exist('plotting','var')
      plotting = 0;
    end

   if plotting
if new_figure==1 figure; end;

p1=week_extract(HOUSE_distribution,0);
plot(1:168,p1)
hold on
p2=week_extract(HOUSE_generation_profile,0);
plot(1:168,p2)

c=week_extract(HOUSE_prosumer_profile,0);
plot(c.*(c >= 0),'r')
plot(c.*(c < 0),'b')
xlabel('Hour')
ylabel('[MWh]')
legend({'Consumption profile','Generation profile','Prosumer profile','
    Electricity into grid'},'Location','south')
if scale ==1
```

```
    str1=sprintf('Single Household Prosumer Profiles (%i, Weeek: %i)',year,
        week);
else
    str1=sprintf('Household Sector Profiles  (%i, Weeek: %i)',year,week);
end
title(str1)
xlim([1 168])
ylim([1.1*min([min(p1) min(p2) min(c) -0.0001]) 1.5*max([max(p1) max(p2) max
    (c)])])

Weekly_production=sum(week_extract(HOUSE_generation_profile,0));
Weekly_consumption=sum(week_extract(HOUSE_distribution,0));
Weekly_selfconsumption=Weekly_consumption-sum(c.*(c >= 0));
Weekly_feed_into_grid=sum(c.*(c < 0));

if scale>0
str1=sprintf('PV generation: %3.1f kWh',Weekly_production*1000);
str2=sprintf('Total consumption: %3.1f kWh',Weekly_consumption*1000);
str3=sprintf('Selfconsumption: %3.1f kWh (%3.1f %%)',Weekly_selfconsumption
    *1000,Weekly_selfconsumption/Weekly_production*100);
str4=sprintf('Fed into the grid: %3.1f kWh',Weekly_feed_into_grid*1000);
str5=sprintf('Self-sufficiency: %2.1f %%',Weekly_selfconsumption/
    Weekly_consumption*100);
else
str1=sprintf('PV generation: %5.2f GWh',Weekly_production/1000);
str2=sprintf('Total consumption: %5.2f GWh',Weekly_consumption/1000);
str3=sprintf('Selfconsumption: %5.2f GWh (%3.1f%%)',Weekly_selfconsumption
    /1000,Weekly_selfconsumption/Weekly_production*100);
str4=sprintf('Fed into the grid: %5.2f GWh',Weekly_feed_into_grid/1000);
str5=sprintf('Self-sufficiency: %2.1f%%',Weekly_selfconsumption/
    Weekly_consumption*100);
end

dim = [0.15 0.65 0.7 0.25];
str = {str1,str2,str3,str4,str5};
annotation('textbox',dim,'String',str,'FontSize',10,'FitBoxToText','on','
    BackgroundColor','white','HorizontalAlignment','center','
    VerticalAlignment','top');

hold off
   end

end

function [] = prosumer_exctract_months(HOUSE_consumption,
    HOUSE_generation_profile,HOUSE_prosumer_profile,plotting)
%Plots prosumer statisctics for each month
%Each month consists of 728 hours
global Control_week Control_sim Control_year Prosumer_share

 if ~exist('plotting','var')
      plotting = 0;
 end

 if ~exist('year','var')
   year = 2020;
 end

   if plotting
M_consumption=zeros(12,1);
M_production=zeros(12,1);
M_selfconsumption=zeros(12,1);
```

```
M_feed_into_grid=zeros(12,1);
M_SF_percentage=zeros(12,1);
negativeIndexes=HOUSE_prosumer_profile.*(HOUSE_prosumer_profile < 0);

for i=1:8736
    if mod(i,728)==0
    month=floor(i/728);
    else
    month=floor(i/728)+1;
    end
    M_consumption(month)=M_consumption(month)+HOUSE_consumption(i);
    M_production(month)=M_production(month)+HOUSE_generation_profile(i);
    M_feed_into_grid(month)=M_feed_into_grid(month)+negativeIndexes(i);
end
M_selfconsumption=M_production+M_feed_into_grid; %feed into the grid is
    negative value
M_SF_percentage=M_selfconsumption./M_production*100;
Selfsufficiency_percentage=M_selfconsumption./M_consumption*100;

figure
bar(1:12,M_consumption,0.5,'FaceColor',[1 1 1])
hold on
bar(1:12,M_selfconsumption,0.5,'FaceColor',[0.4660 0.6740 0.1880])
A=num2str(Selfsufficiency_percentage,'%2.0f');
A(:,3)='%';
text(1:12,M_selfconsumption,A,'vert','bottom','horiz','center','Color','blue
    ','FontSize', 20);
bar(1:12,M_feed_into_grid,0.5,'FaceColor',[[0.9290 0.6940 0.1250]])

lowerYlimit=1.1*min([min(M_consumption) min(M_selfconsumption) min(
    M_feed_into_grid)]);
upperYlimit=1.1*max([max(M_consumption) max(M_selfconsumption) max(
    M_feed_into_grid)]);
ylim([lowerYlimit upperYlimit])
xlabel('Month')
ylabel('[MWh]')
bar(NaN,NaN,'Facecolor',[0 0 1])
legend({'Monthly Consumption','Monthly Selfconsumption','Electricity into
    Grid','Self-Sufficiency'},'Location','southwest','FontSize',14)
if Control_year==2020
title('Year 2020 - Monthly Statistics')
else
title('Year 2030 - Monthly Statistics')
end
hold off


   end

end

function [RF] = reverse_flow(Variation_of_solar_generation,
    Variation_of_household_consumption,DecentralPVcapacity,Full_load_hours,
    Household_sector_annual_consumption)
global Control_sim Prosumer_share Battery Energy_community
if Control_sim>0
    if Energy_community==1
    AvailableConsumption=1.9598*5*Variation_of_household_consumption;
    else
    AvailableConsumption=5*Variation_of_household_consumption;
    end
    ProsumerPVgeneration=Full_load_hours*0.00524*
```

```
        Variation_of_solar_generation*Prosumer_share;
    [Prosumer_profile, BAT_prosumer_profile] =Prosumer_Sub_model(
        AvailableConsumption,ProsumerPVgeneration,0);
end

if Control_sim==0
HH_sector_consumption= Variation_of_household_consumption*
    Household_sector_annual_consumption;

    if Energy_community==1
      AvailableConsumption=HH_sector_consumption;
    else
      AvailableConsumption=Prosumer_share*DecentralPVcapacity*
          Full_load_hours*Variation_of_household_consumption;
      %Installed PV power is scalled to annual yearly consumption of a
          household
    end

DecentralPVgeneration=DecentralPVcapacity*Full_load_hours*
    Variation_of_solar_generation;
ProsumerPVgeneration=Prosumer_share*DecentralPVgeneration;
[Prosumer_profile, BAT_prosumer_profile] =Prosumer_Sub_model(
    AvailableConsumption,ProsumerPVgeneration,0);

end

if Battery==1
    if Prosumer_profile==BAT_prosumer_profile
        RF=0;
    else
    RF=sum(BAT_prosumer_profile.*(BAT_prosumer_profile<0))/sum(
        ProsumerPVgeneration);
    end
else
RF=sum(Prosumer_profile.*(Prosumer_profile<0))/sum(ProsumerPVgeneration);
end
end

function Week = week_extract(data,plotting,new_figure,optionalYlabel)
global Control_week
season=Control_week;
%% Returns data from specic week in year (e.g. weekly consumption)
   Week=data((season-1)*24*7+1:season*24*7,1);
    if ~exist('optionalYlabel','var')
      optionalYlabel='Load [MWh]';
    end
       if ~exist('new_figure','var')
      new_figure = 0;
    end

    if ~exist('plotting','var')
      plotting = 0;
    end

   if plotting
   if new_figure ==1 figure;end;
   plot(1:24*7,Week);
   xlabel('Hour');
   ylabel(optionalYlabel);
   title(sprintf('Week (Season): %i ',season));
   xlim([1 168])
   end
```

```
end

function [] = compare_consumptions(HOUSE_consumption_profile,
    HOUSE_PV_prosumer_profile,HOUSE_BAT_prosumer_profile,Control_plotting)
if Control_plotting>0
figure;
hold on
p1=subplot(3,1,3);
plot(1:8736,HOUSE_BAT_prosumer_profile)
title('Household Load/Generation Profile with PV & battery')
xlim([1 8736])
xlabel('Hours')

p2=subplot(3,1,2);
plot(1:8736,HOUSE_PV_prosumer_profile)
title('Household Load/Generation Profile with PV only')
xlim([1 8736])
ylabel('[MW]')
p3=subplot(3,1,1);
plot(1:8736,HOUSE_consumption_profile)
title('Household Load Profile')
xlim([1 8736])
linkaxes([p1 p2 p3],'y')


hold off
clear p1 p2 p3
end
end
```