newTRENDs

Report on modeling the interaction of prosumagers and energy markets/supply side

Deliverable 5.3

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Datasets and parts of the energy demand models, which are newly developed within this project, will be made open access latest at the end of the project and can then be found at https://github.com/H2020-newTRENDs. All previously existing datasets and model parts are explicitly excluded from this open access strategy.

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Executive Summary

To achieve the Paris Agreement goals, all countries need to implement two central strategies: i) enhancing energy efficiency (EE) and (ii) decarbonizing the remaining energy supply and demand. Scenarios with different focuses and assumptions have been derives to map this development until 2050. In this context, the newTRENDs project prepares the analytical basis for a "2050 Energy Efficiency Vision" by considering New Societal Trends in energy demand modeling.

- First, in Work Package (WP) 2, we identify the new societal trends and their clusters that are expected to be most relevant or disruptive to the future energy demand. The identification is made based on a comprehensive scanning of existing studies and a series of expert workshops. In the end, 14 major trend clusters are identified. Furthermore, for each cluster, we also develop the narrative to describe the potential mechanisms of its controversial impact and disruptiveness for future energy demand.
- Second, in WP 3, we take a closer sectoral perspective to review the impact of the new societal trends on energy demand. Four sectors are considered: industry, transport, tertiary and residential. Then, to quantitatively analyze their impact, we also identify the gaps in modeling the new trends in the models involved in the project.
- Third, in WP 5-7, we concretely improve and enhance the energy demand models to integrate the new trends. Based on the updated models, we evaluate the impact of the trends on the energy demand in each sector. This is closely related to the policy questions identified in WP4. Furthermore, back in WP 3, we also analyze the macroeconomic impacts of the trends.

This deliverable D5.3 “Report on modeling the interaction of prosumagers and energy markets/supply side” describes the model developments performed within Task 5.3 in WP 5 of the project. It offers the rationale and detailed mathematical description of the prosumager model developed as an individual module that can selectively operate in cooperation with the PRIMES model.

Following the gap analysis and the policy assessment performed within WP 3 and WP 4 respectively, the new features needed to cover the various demand trends (selected in WP 2) and demand-side policies are translated into specifications for the prosumager model to enhance the representation of the behavior of prosumagers in the energy modeling.

The prosumager model covers local generation and battery energy storage options for residential consumers. The decision-making process of individuals is formulated as a mathematical programming problem. Such a model may be used to determine the optimal investments in building envelope renovation, heating and electric equipment, including local generation equipment and battery energy storage systems as well as the optimal operation on an hourly basis allowing bidirectional energy exchange with the electricity distribution network under perfect foresight conditions.

The prosumager model shares common ground with the PRIMES Buildings Model (PRIMES-BuiMo), the residential and services sector model of the PRIMES modelling suite, in terms of main building typologies included. However, the prosumager model developed within newTRENDs considers only the residential sector and does not perform useful demand and buildings' stock projection for the services sector.

Core aspects of the prosumager model that enhance the capabilities for modelling the prosumaging trend and testing relevant policies, are the inclusion of local generation and battery energy storage options and the simulation of the hourly operation of the equipment, which allows differentiating the electricity pricing scheme to test demand response options.

The modular way in which the model is developed allows testing aspects of the prosumaging trend. Thus, along with the mathematical formalization, the report aims to showcase the possibilities of the model through a selected case study.

This report is structured as follows: section 1 introduces the rationale and basic principles of the prosumager model; section 2 offers an overview of the available literature in the field of the prosumaging behavior of electricity consumers; in section 3 the mathematical formulation of the prosumager model is presented; in section 4 the model is applied on a selected case and the relevant results are presented; section 5 concludes the report through a discussion on the various model aspects.

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1. Introduction

Defining a long-term strategy for any energy system requires first to identify the developments in the available technological options for covering the energy needs and second to understand and – most importantly – quantify the factors that are expected to determine the final energy demand. New disruptive technologies render demand-side trends non-linear: the transition from consumers via prosumers to prosumagers of electricity is one such case.

Currently, it is the energy needs that shape the behavior of electricity consumers. Electricity is passively demanded and served through energy via the electricity distribution network. By contrast, prosumers may choose to invest in electricity generation and storage units installed on-site, thus locally covering part of their electricity needs but without further changes in their behavioral characteristics.

Equipping the users of electricity that are already prosumers with smart meters transforms them into active electricity consumers, i.e. prosumagers – a term coined within the newTRENDs project as a new step in the evolution of the electricity consumer. The concept describes an entity with on-site generation and storage units that also takes the role of a manager. As a manager, the prosumager implements demand response options which modify the electricity demand on an hourly basis and may also perform trading of electricity with the distribution network.

As a result, the decision-making process of the individual electricity consumer becomes more complex, as several new options are becoming available: technological progress drives the available equipment and appliances towards higher efficiency and, therefore, lower fuel consumption; new types of technologies covering energy needs emerge; additional operational possibilities (i.e. electricity locally produced and stored) for covering the electricity needs are available. These options in essence promote the rational use of energy and are in line with the energy efficiency first (EE1st) principle (European Commission, 2021), (Mandel, Pató, Broc, & Eichhammer, 2022) that prioritizes demand-side solutions over investments in costly energy sources. Additionally, they contribute to increasing the share of renewables in the electricity supply. Thus, several pathways for achieving ambitious climate targets are available to the policy makers.

However, as much as they are needed, new technologies are often not adopted fast, due to barriers. These can be real costs reflecting the market maturity of a technology. This is particularly evident as during the first years of commercialization of new technologies their cost is higher. Additionally, perceived costs may exist. These are related to subjective factors reflecting barriers of physical nature (e.g., architectural restrictions), non-market barriers (e.g., subjective cost of capital), indirect penalties on fuel costs to name a few. The perceived costs hinder the selection of an option that would otherwise be optimal in terms of real costs. Removing those barriers may be seen as part of the policy-making process, which entails not only exploring the different pathways but also developing practical tools for their realization.

Throughout the last decades, energy demand modelling has been (and continues to be) applied as a tool for testing existing and emerging policies or highlighting the need for new ones. PRIMES Buildings Model (PRIMES-BuiMo) is such a model focusing on the residential (and services) sector (Fotiou, de Vita, & Capros, 2019). As part of the PRIMES modelling suite, PRIMES-BuiMo applies a hybrid economic-engineering approach and covers all aspects of the building sector: building stock projection, selection of renovation plans for the building envelope, equipment choice and equipment operation. This is done by segmenting buildings and consumers into several classes to capture consumer heterogeneity and by modelling – on household level - the various end-uses detailed to the level of technology type and efficiency class as well as the fuel type.

Within newTRENDs, the effort to identify New Societal Trends regarding prosumaging indicates that, while several of them are already considered in the PRIMES-BuiMo, improving the existing residential model will allow studying the impact of prosumaging in greater depth: investment decisions in local generation units that use renewables and the implementation of demand response schemes facilitated by smart meters are two key aspects of prosumaging that point towards the development of new model features.

This report describes these model developments concerning the prosumager model. The modular nature makes it possible for the model to be used as an optional add-on to the PRIMES-BuiMo to reflect the aspects indicated above. As it will be made evident, even though the prosumager model shares common ground with PRIMES-BuiMo over several features, it differs both in the approach and in its core decisions.

The prosumager model developed within Task 5.3 describes the decision-making process of individual households (or household classes) regarding investments in building envelope renovation, in appliances and equipment and in local generation units (that is, solar photovoltaic – PV) and battery energy storage system (BESS) as well as regarding the (hourly) operation of the appliances, the equipment, the local generation units and the BESS. The model provides the optimal configuration of the household energy system that is appropriate for meeting the energy demand of the occupants at least cost. Bi-directional power transfer between the distribution electricity network and the household is possible, while thermal uses, i.e., space heating, air cooling, water heating and cooking, are served through the operation of the equipment at levels that ensure the occupants' comfort.

The model is a mathematical programming optimization problem with a horizon up to 2050, a five-year time step and perfect foresight: a specific projection for the future energy needs of the prosumager and the prices of the energy carriers is considered without any source of uncertainty. It can be applied on a variety of building classes by differentiating the examined type of household (in terms of age, location, income, etc.). The model includes a detailed portrayal of policies specific to the residential sector, comprising economic and regulatory policies as well as institutional measures. The long- and short-term aspects referring to the investments on one hand and the hourly operation of the appliances and the equipment on the other are taken into consideration through the simultaneous selection of the investment and operation strategies for the entire optimization horizon (all years belonging in the projection horizon are optimized simultaneously). This is achieved by simulating several typical days per year and typical hours per day.

2. Literature review

The current and proposed European regulatory framework (European Commission, 2021) offers support not only to residential renewable generation intended for self-consumption but also to on-site electricity storage and energy exchange with the electricity distribution network. The active consumer – aka prosumager[1] – is expected to play a complex role and will be called for to be proactive.

Acknowledging the important role of the active consumer, the current body of literature offers a great variety of approaches on the matter:

- operational: resource management and energy scheduling;
- optimal sizing of the equipment: the selection of investments to cover the energy needs is often combined with the operational aspect;
- framework design for selecting pricing schemes and business models that offer proper incentives to the active consumers;
- other approaches such as the energy communities and the provision of (ancillary) services to the electricity distribution network.

Resource management, optimal sizing, or combined approach

Hedegaard & Balyk (2013) present a model for an individual household optimizing the investment in heat storage and the operation of the installed heat pump considering the building thermal dynamics. The examined cases feature time-varying electricity prices, consider several single-family houses, and illustrate the flexible operation of the heat pump in combination with the use of thermal storage for load shifting, thus resulting in peak load shaving, and ensuring adequate production capacity and reserve margin.

Heinen, Burke, & O'Malley (2016) explore how the large-scale deployment of hybrid heating technologies contributes to the operational and investment decisions of the entire energy system. This is done through the formulation of a least-cost investment model as a linear programming problem. Decision variables are, on one side, the capacity and the generated energy per electricity and heat generation technology as well as for thermal storage tanks, and on the other side, the share of each technology in the hybrid device as well as the heat appliance hourly dispatch.

A two-stage stochastic programming model is developed in Beraldi, Violi, & Carrozzino (2020) to tackle the problem of an individual prosumer optimally performing energy management under uncertainty around the electricity demand of the so-called “unschedulable” loads and the electricity production by the on-site photovoltaic (PV) panels. Configurations including a storage system are also considered, indicating that the optimal use of the storage may lead to economic benefits.

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[1] Throughout this section, the term "prosumager“ is used as mentioned in the current literature.

An evolutionary algorithm is applied in Angenendt, Zurmühlen, Rücker, Axelsen, & Sauer (2019) for solving the problem of an individual household optimizing the heat and power system in terms of operation and sizing of the components (PV system, batteries, heat pump, domestic hot water storage, heat storage). This is performed in two steps: first, the economic evaluation of the operation strategies is performed, followed by the optimal selection of component size conditional on the operation strategy.

Based on occupancy profiles of a specific household, separate models for domestic water heating, space heating, cooking and electrical appliances are developed in Good, Zhang, Navarro-Espinosa, & Mancarella (2015), providing the energy demand profiles per domestic use. For space heating, a separate sub-model for the building dynamics is implemented (thus capturing the thermal storage possibility in the building envelope), while several options for heating units are considered (gas boiler, combined heat and power system, electric heat pump). The model is also applied on aggregations of dwellings and allows estimating, among others, the distribution network peak demand, the potential for demand side flexibility and the impact of technology adoption in the network.

In Oluleye, Allison, Hawker, Kelly, & Hawkes (2018), prosumers are considered a source of flexibility for the distribution network, given the appropriate incentive (in the form of a price signal), thus fitting best in the newTRENDs definition of 'prosumager'. These prosumagers adjust their decisions regarding the capacity and technology of the system (serving space heating, hot water, lighting needs and the operation of electrical and electronic devices) and dispatch strategies, which allow them to absorb surplus electricity. This is achieved through the application of two models: 1. a multi-period mixed-integer linear programming problem to design the energy system of the dwelling that meets the energy needs and 2. a linear programming problem for identifying the prosumager price signal that is appropriate for absorbing renewable generation surplus.

The methodology proposed in Erdinc, Paterakis, Pappi, Bakirtzis, & Catalão, (2015) provides the optimal capacity of a rooftop PV and an energy storage system for a smart household, equipped with a home energy management system (HEM), that allows for dynamic pricing. The mixed-integer linear programming model comprises an objective function that incorporates various cost components (capital, maintenance cost for PV and energy storage, energy purchase cost) and revenue sources (revenues from energy sales) as well as a set of operational constraints per time interval (electricity balance, energy storage system balance, EV battery operation).

In Worighi, et al. (2019), a multi-objective optimization approach is developed to select the optimal sizing of a grid-connected PV and a battery system that achieves minimization of voltage deviations at the lowest cost. Here the PV and the battery are not installed in the household premises, rather they are grid-connected, while the domestic loads are considered on the aggregated level of several households.

Framework design

In Han, Morstyn, & McCulloch (2019), collaboration among prosumers is modelled as a cooperative game: a profit-sharing scheme is developed for centrally optimizing the energy management of each prosumer's energy storage system. The reward offered to the players can be selected in such a way that no player benefits from deviating, i.e., not participating in the coalition, thus allowing to study cases where the prosumer coalition provides services such as peak shaving and increased load shifting, thus utilization of locally produced electricity.

The researchers in Grimm, Orlinskaya, Schewe, Schmidt, & Zöttl (2021) propose bi-level models to determine the tariff design of a retailer that depends on the decisions of a prosumer. The prosumer selects the operation of the PV, the BESS, the electrically driven heat pump, and the heat storage unit installed in the premises as well as the energy exchange with the retailer (energy sales to and purchases from the main grid). Analysis of several tariff schemes (fixed price, real-time pricing/RTP, time-of-use/TOU pricing, and critical peak pricing) indicates that real-time pricing offers high flexibility on the prosumer side, thus resulting in high additional profits for the retailer.

In Zhou, et al. (2018), the two dimensions of the prosumer's decision-making process, i.e., the investment and the operational dimension, are considered as two distinct but interdependent optimization problems that form part of a bi-level model: the upper level describes the investment decisions on PV and BESS minimizing the total investment cost and variable operation cost; the lower level describes the optimal operation of the BESS and the energy exchange with the electricity distribution network (bidirectional electricity flows are considered). The uncertainty in the PV generation profile is considered using a scenario-based method and the application of a K-means clustering method. The proposed methodology is applied for assessing the impact of different types of electricity tariffs (TOU, RTP, stepwise) indicating that RTP and TOU pricing incentivize investments both in PV and BESS, as differences in peak-valley electricity prices are better exploited.

Other approaches

GfK Belgium Consortium (2017) offers an overview of the existing regulatory framework for residential prosumers with solar PV in the 27 countries of the European Union (EU), the United Kingdom, Norway, and Iceland. Projections for the uptake of solar PV by households up to 2030 are presented as well as results of prosumer survey focusing on aspects such as technology selection, decision drivers (e.g., government subsidies, energy bills savings, etc.), grid connection and remuneration for feeding electricity into the grid. The study also presents the results of the implementation of a behavioral experiment for extracting insights about the decision-making process of consumers interested in becoming prosumers.

Lüth, Weibezahn, & Zepter (2020) formulate a mixed complementarity model for assessing design options for the integration of energy communities into the market. Cases explored refer to self-consumption combined with local energy exchange, local storage, or both. The current regulatory framework in Germany is considered as well as an extension that includes an independent power producer.

Researchers in Gkatzikis, Koutsopoulos, & Salonidis (2013) formulate a hierarchical market model comprising three levels: household consumers, each one having a contract with an aggregator; competing aggregators; and the utility operator. The proposed market design is assessed by comparing the model results to a benchmark scenario that considers full knowledge of the end-user characteristics by the operator.

In Yang, Xiong, Qiu, Qiu, & Dong (2016), the concept of interconnected energy hubs is examined. The purpose of each hub is to serve the heating/cooling and electricity loads of the prosumers belonging to it. Bidirectional energy flows are analyzed while the grid topology is considered (interconnected buses form a radial electricity grid and a ring heating/cooling network). The aim is to determine the optimal operational strategies (dispatch) per time interval considering TOU pricing as to the following aspects: energy purchases, PV generation, charging/discharging of plug-in electric vehicle batteries and thermal energy storage, operation of natural gas boilers. The application on selected cases featuring a contingency (outage of gas turbine) or independent operation of the hubs allows evaluating the positive effect of the energy hubs in the system operation cost and in the utilization of the energy resources.

Mancarella, 2014 offers an overview of modelling approaches for the assessment of the technical, economic and environmental aspects of distributed generation systems where multiple energy carriers coexist. The researchers also include options for the aggregation of distributed energy resources into the power system (e.g., microgrids, Virtual Power Plants – VPPs) and relevant assessment criteria.

Lesage-Landry, Wang, Shames, Mancarella, & Taylor (2020) study the real-time energy management in buildings incorporating flexibility options (the building's thermal inertia, battery energy storage, thermal energy storage), local generation from PV panels (bidirectional electricity flow with the grid) and sources of uncertainty with variation over time (weather, human behavior, scheduling prediction error). A two-level mathematical programming problem is formulated comprising a mixed-integer linear program for scheduling the consumption and an online convex optimization algorithm for the real-time decision making.

In Wang, Good, & Macarella (2017), a mixed-integer linear programming model is formulated for assessing the operational and economic aspects of the participation of a set of residential buildings (comprising an energy community) in the ancillary service markets offering energy and frequency control. Modelling of various flexible resources focuses on space heating and cooling, BESS, and building thermal dynamics. Different price signals and frequency control ancillary service types are examined in order to assess the revenues of each business case.

Chapman, Zhang, Good, & Macarella (2016) explore the cooperation of domestic electric heat pumps with thermal energy storage within a cluster of domestic buildings for offering reserve capacity to the grid. At the same time, the impact on the comfort level of the household occupants due to the resulting deviations from the baseline indoor temperature is assessed.

Energy management of prosumer communities is tackled in (Verschae, Kato, & Matsuyama (2016). The considered devices are categorized as controllable and uncontrollable, and the management procedure is divided into two stages: in the off-line stage, each agent determines its intended power consumption; in the real-time stage, deviations from the intended profile of each agent are received by the coordinator and the community compensates the aggregated deviation.

3. Model description

The prosumager model describes the decision-making process of individual households considering two main dimensions:

- the investments in building envelope renovation interventions, equipment, appliances, and lighting, and
- the hourly operation of the equipment and the appliances.

In acting on these two dimensions, the prosumager is seen as an economic agent that seeks to derive the maximum net revenue considering all income streams and expenses, subject to technical and economic constraints and idiosyncratic preferences.

More specifically, throughout the projection period (practically a timeframe of 30 to 40 years), the prosumager may explore different options regarding investments in:

- equipment for space heating and cooling, water heating and cooking (timing, technology, efficiency class, capacity);
- electrical appliances & lighting (timing, efficiency class, capacity);
- rooftop PV (timing, type, capacity);
- electricity storage (BESS) (timing, capacity);
- energy efficiency measures through renovation of the building envelope (timing, energy intensity of renovation – depth of renovation).

The aim of investing in these different technologies is to cover the household's energy demand through a selected configuration of the above options. Thus, on an hourly basis, the prosumager selects:

- the operation of the equipment and appliances;
- the operation of the rooftop PV;
- the operation of the BESS;
- the interaction with the electricity distribution network.

However, not all investment and operational options available to the prosumager (and even more any combination thereof) are feasible (in technical and economic terms): each household class is characterized by different energy needs in terms of desired useful energy demand, a different level of annual disposable income; the exchange with the electricity distribution network may not exceed the capacity of the power connection to the utility line; the operation of equipment and appliances is governed by specific rules per type of energy use and is constrained by their respective size.

A multitude of configurations of the heating & cooling equipment, the electrical appliances and lighting might comply with the above set of rules. A rational decision-maker – such as the prosumager modelled here – selects the option that achieves maximal revenues at minimum cost. In fact, revenues may refer to actual income obtained through selling excess energy to the electricity distribution network. Costs include investment cost in equipment and energy efficiency measures, fixed operation and maintenance cost, variable costs (e.g., for fuel purchases). The objective function also includes perceived costs reflecting barriers of a physical nature (e.g., architectural restrictions), non-market barriers (e.g., subjective cost of capital), indirect penalties on fuel costs, etc. (Fotiou, de Vita, & Capros, 2019).

3.1 Typologies

Every household[2] features a set of energy uses, each one with distinct characteristics: energy needs for heat uses are covered through the thermal performance of the building envelope and the operation of the equipment at levels ensuring the desirable thermal comfort, which can offer some level of flexibility (e.g., by defining a range instead of a unique temperature set-point); energy needs for cooking, electrical appliances and lighting follow specific patterns depending on the household's occupancy. More specifically, the energy uses considered in the model are:

- space heating;
- water heating;
- air cooling;
- cooking;
- specific electricity uses
    - white appliances (refrigerators and freezers; dishwashers; clothes dryers; washing machines);
    - black appliances (ironing, information and communication, entertainment, vacuum cleaners, small appliances);
    - lighting.

To cover the energy demand for heating and cooling, various technology types are available in the model, which are also associated with different fuels (Table 1).

Table 1 Energy uses, technology types and associated fuels considered in the prosumager model.

Use	Technology	Fuel
Space heating	Boiler (oil)	diesel oil
	Condensing boiler (oil)	diesel oil
	Boiler (gas)	natural gas
	Condensing boiler (gas)	natural gas
	Wood pellets boiler	biomass
	micro Combined Heat and Power (micro-CHP) system – internal combustion engine	natural gas

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[2] The prosumager model is designed to follow the same typology as PRIMES-BuiMo for shared features. For the sake of completeness, the scheme used in the prosumager model is presented in this section.

Use	Technology	Fuel
	micro-CHP – micro Combined Cycle Gas Turbine (mCCGT)	natural gas
	micro-CHP – fuel cell	natural gas
	Gas heat pump (air)	natural gas
	Gas-fired instantaneous combo (gas)	natural gas
	Gas-fired instantaneous combo (Liquefied Petroleum Gas/LPG)	liquefied petroleum gas
	Air-source heat pump	electricity
	Electrical space heater for partially heated houses	electricity
	Ground-source heat pump	electricity
	Thermal solar	solar
	District heating transfer station	steam
	Geothermal ponds	geothermal
	Electrical space heater	electricity
	Stove for solid fuels	solids
	Stove for oil	diesel oil
Water heating	Boiler (oil)	diesel oil
	Condensing boiler (oil)	diesel oil
	Boiler (gas)	natural gas
	Condensing boiler (gas)	natural gas
	Wood pellets boiler	biomass
	micro-CHP – internal combustion engine	natural gas
	micro-CHP - mCCGT	natural gas
	micro-CHP – fuel cell	natural gas
	Gas heat pump (air)	natural gas
	Gas-fired instantaneous combo (gas)	natural gas
	Gas-fired instantaneous combo (LPG)	liquefied petroleum gas
	Air-source heat pump	electricity
	Ground-source heat pump	electricity
	Thermal solar	solar
	District heating transfer station	steam
	Geothermal ponds	geothermal
	Stove for solid fuels	solids
	Heat pump water heater	electricity
	Simple electrical water heater	electricity
Air cooling	Gas heat pump (air)	natural gas
	Air-source heat pump	electricity
	Ground-source heat pump	electricity
	Absorption chiller	natural gas
	Adsorption chiller	natural gas
	District cooling	steam
	Split system air condition	electricity

Use	Technology	Fuel
	Centralized cooling systems	electricity
Cooking	Electric cooker	electricity
	Gas cooker	natural gas
	Liquid cooker	liquefied petroleum gas
	Solid cooker	biomass

Source: PRIMES

Each technology type is further split into four efficiency categories with increasing efficiency and relevant cost, being in-line with the efficiency classification of the eco-design directive:

- ordinary (ORD): currently available technology;
- improved (IMR): standard improvement options;
- advanced (ADV): best available technology (current state of the art);
- future (FUT): best not-yet available technology (on demonstration level).

Furthermore, in the modeling, eight levels of building envelope renovation interventions (as presented in Table 2) are available, each one corresponding to a different energy renovation depth (i.e., each type of renovation intervention results in different energy savings) that are based on data from the ENTRANZE project (ENTRANZE project). It should be noted that type R0 does not include any type of renovation intervention, only common repair, and maintenance works.

Table 2 Levels of building envelope renovation interventions considered in the prosumager model.

Renovation Type	Description
R0	No renovation – only repair and maintenance works
R1	“Light” renovation (windows replacement -U value 2.7 W/m²K)
R2	“Light” renovation (windows replacement -U value 1.7 W/m²K)
R3	“Medium” renovation (windows replacement -U value 2.7 W/m²K, a 5 cm layer of insulation and achievement of air permeability of 27 m³/m²h)
R4	“Medium” renovation (windows replacement -U value 1.7 W/m²K, a 5 cm layer of insulation and achievement of air permeability of 27 m³/m²h)
R5	“Medium” renovation (windows replacement -U value 1.7 W/m²K, a 10 cm layer of insulation and achievement of air permeability rate of 27 m³/m²h)
R6	“Medium” renovation (windows replacement -U value 1.5 W/m²K, a 10 cm layer of insulation and achievement of air permeability rate of to 9 m³/m²h)
R7	“Deep” renovation (windows replacement -U value 1.5 W/m²K, a 20 cm layer of insulation and achievement of air permeability rate of to 9 m³/m²h)
R8	“Deep” renovation (windows replacement -U value 1.0 W/m²K, a 20 cm layer of insulation and achievement of air permeability rate of to 3 m³/m²h)

Source: PRIMES

3.2 Principles – assumptions

The prosumager model is formulated based on a set of principles and assumptions defining several aspects of the decision-making process:

- The model describes one household with given characteristics as to the type of building, the location, the income class, and the existing stock of equipment for heating and cooling.
- The optimal selection of investments in equipment and renovation interventions is performed in tandem with the optimization of the operation.
- The prosumager selects the strategy that minimizes the present value of all cost streams net of eventual revenue streams.
- The optimization is performed in 5-year steps for the entire optimization horizon.
- To simulate the operation of the equipment, the model considers an hourly time resolution.
- Typical days per year and typical hours per day are simulated.
- The desired useful energy demand per energy use is a logistic function of the income and demographic growth (number of persons per household is a logistic function of the income) and the unit cost of energy for households as calculated by the PRIMES-BuiMo (Fotiou, de Vita, & Capros, 2019).
- The building shell covers part of the total desired useful energy for space heating and air cooling via thermal insulation. Depending on the implementation of investments improving the energy efficiency of the building and their depth, the remaining desired useful energy is covered through energy consumption of the operating equipment.
- The heating and cooling equipment, as well as the electrical appliances and lighting – in terms of their operation – are characterized by the following:
    - a specific profile (input parameter);
    - a total volume per year necessary for providing a specific energy service that must be realized to ensure a minimum comfort level for the household occupants (space heating, water heating and air cooling).
- Rooftop PV:
    - Given the available area, the capacity may not exceed a maximum feasible value (maximum site potential).
    - The on-site generation system is an assembly of multiple PV panels.
- Bidirectional electricity flow (i.e., from the electricity distribution network to the household and vice versa) is possible.
- Excess self-production may be sold to the electricity distribution network at a price which decreases as a function of the volume sold per household in a stepwise manner or at a uniform price. Energy purchases may be performed at a price that increases as a function of the volume purchased per household in a stepwise manner or at a uniform price. This could be viewed as a price incentive offered by the electricity supplier to the

prosumager to achieve rational use of electricity through the application of demand response options.
- The household is a price taker (i.e., on annual basis, the household is a net importer of electricity).
- The price of the electricity delivered to the household by the electricity distribution network can be differentiated per typical day and hour.

3.3 Input

The first step in prosumager modeling is to define the household's characteristics, for which the model applies. These are as follows:

- location (urban, rural, semi-urban);
- date of construction of the building;
- type of building (single or multi-story);
- income (five income classes are considered);
- desired useful energy demand per energy use for the entire projection period.

Techno-economic assumptions for the equipment covering the energy needs per end use refer to the following features (per technology and efficiency class):

- investment[3] and operational costs per unit;
- energy efficiency.

External conditions stemming from the environment in which the prosumager acts are:

- ambient temperature per typical day and hour: per country meteorological time-series are taken from (De Felice & Kavvadias, 2022) and are properly adjusted to the cooling and heating degree days of each year of the entire projection period;
- solar irradiation on surfaces per typical day and hour: determines the solar gains during the heating season, the thermal load during the cooling season, and, depending on the capacity of the rooftop PV, the generated electricity;
- energy carrier prices;
- policies promoting:
    - the use of renewables;
    - energy efficiency;
    - the decarbonization of heating and cooling.

Varying the values of specific input parameters allows reflecting diverse external conditions driven by policy measures and developments on an international level. For example, retail fuel prices are subject to changes depending on international price developments and energy taxation regimes. Investment costs may decrease as a result of subsidization schemes, while perceived costs

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[3] Technologies are supposed to follow an exogenous learning-by-doing process that leads to cost reductions.

associated with market acceptance of different technology and equipment types are affected by soft-measures like, for example, information campaigns, etc.

3.4 Output

The output of the prosumager model reflects the investment and the operational dimension. Regarding investment, the decisions of the prosumager relate to:

- renovation: implementation year and energy renovation intensity – depth of renovation;
- equipment and appliances per energy use: technology, efficiency class, capacity selection;
- rooftop PV: implementation year and capacity;
- BESS: implementation year and capacity.

Regarding the operational dimension, the prosumager chooses:

- the usage profile per energy use and piece of equipment for space heating, air cooling and water heating;
- the BESS operation;
- the interaction with the electricity distribution network.

Fuel consumption depends on different combinations of the choices mentioned above and adds to the total cost of the household.

3.5 Mathematical formulation

Following the rules mentioned in the previous sections, the prosumager model is mathematically formulated as a mixed-integer linear programming problem. This section is dedicated to its description.

It should be noted that all parameters and variables are defined for one household class of specific vintage, located at a specific country. Since the model applies in one such household, the notation presented here is simplified by dropping the relevant indices.

3.5.1 Nomenclature

Sets

Name	Description
$\boldsymbol{l} \in \mathcal{L}$	levels of electricity supply cost curves
$\boldsymbol{r} \in \mathcal{R}$	renovation intervention types
$\boldsymbol{s} \in \mathcal{S}$	typical hours
$\boldsymbol{t}, \boldsymbol{t}' \in \mathfrak{T}$	time (years)
$\boldsymbol{techn} \in \mathcal{T}$	technologies to cover the energy uses
$\boldsymbol{techpr} \in \mathcal{P}$	energy efficiency class of the equipment
$\mathcal{T}_{BU} \subseteq \mathcal{T}$	subset of technologies corresponding to backup units

Name	Description
$\mathcal{T}_{EA} \subseteq \mathcal{T}$	subset of technologies corresponding to specific electricity uses
$\mathcal{T}_{R} \subseteq \mathcal{T}$	technologies that require backup unit
$\mathfrak{T}_{eq} \subseteq \mathfrak{T}$	implementation year of investment in renovation, equipment, or rooftop PV
$u \in \mathcal{U}$	uses in residential buildings (e.g., space heating, water heating, air cooling, cooking, etc.)
$\mathcal{U}_{heat} \subseteq \mathcal{U}$	heating and cooling uses in residential buildings, i.e., space heating, water heating, air cooling
$\mathcal{U}_{th} \subseteq \mathcal{U}$	thermal uses in residential buildings, i.e., space heating, air cooling
$\mathcal{U}_{BU} \subseteq \mathcal{U}$	uses in residential buildings that may require backup units, i.e., space heating, water heating

Parameters

General

Name	Units	Description
φ_s	-	frequency per typical hour
c_t^{int}	-	compound interest factor for calculating the present value of the cost components

Renovation

Name	Units	Description
$\alpha_{r,t}$	%	renovation depth – energy savings from renovation

Technologies

Name	Units	Description
$\zeta_{u,techn,techpr}$	years	technical lifetime of technologies per energy use u, technology $techn$, efficiency class $techpr$
ζ^{BESS}	years	technical lifetime of BESS
ζ^{PV}	years	technical lifetime of rooftop PV
$\eta^{tch}_{u,techn,techpr,t}$	-	energy efficiency of equipment per energy use u, technology $techn$, efficiency class $techpr$ during year t
$\pi_{u,techpr,s,t}$	-	normalized demand profile of inflexible uses per energy use u, efficiency class $techpr$ during typical hour s of year t
π_s^{PV}	-	normalized pattern for PV generation during typical hour s
d^{PV}	-	annual PV module degradation
$D^{Desired}_{u,t}$	kWh/year	desired useful demand per use u during year t (for space heating, water heating, air cooling, cooking)
$D^{Desired,EA}_{techn,t}$	no. of electric appliances per household per year	desired useful demand of specific electricity uses technology $techn$ during year t
$\underline{P}^{BESS}$	kW	minimum BESS charging capacity
$\overline{P}^{PV}$	kW	rooftop PV potential per installation site
$\underline{P}^{PV}$	kW	minimum capacity for rooftop PV per installation site (i.e. size of one PV module)

Positive variables

General

Name	Units	Description
$\boldsymbol{vEEV_t}$	EUR/kWh	Energy Efficiency Value – dual variable of an energy efficiency constraint during year t
$\boldsymbol{vRES_t}$	EUR/kWh	Renewable Value – dual variable of a renewable penetration constraint during year t

Renovation

Name	Units	Description
$\boldsymbol{vD^{EE}_{u,r,t}}$	kWh/year	part of desired useful demand covered by energy efficiency measures per use u, revonation intervention measure r, year t
$\boldsymbol{vD^{Effective}_{u,t}}$	kWh/year	part of desired useful demand covered by final energy consumption through the operation of the equipment per energy use u, year t

Technologies

Name	Units	Description
$\boldsymbol{vBESSCap_t}$	kW	total nominal charging/discharging power of BESS at year t
$\boldsymbol{vBESSDoD_{s,t}}$	kWh	BESS depth of discharge during typical hour s at year t
$\boldsymbol{vBESSInv_t}$	kW	nominal charging/discharging power of BESS investment implemented at year t
$\boldsymbol{vBESSPower^D_{s,t}}$	kW	BESS discharging power during typical hour s at year t
$\boldsymbol{vBESSPower^C_{s,t}}$	kW	BESS charging power during typical hour s at year t
$\boldsymbol{vCapTot_{u,techn,techpr,t}}$	kW or no. of appliances/ use/ technology	equipment capacity or number of appliances for specific electricity uses per energy use u, technology $techn$, efficiency class $techpr$ during year t
$\boldsymbol{vCapInv_{u,techn,techpr,t',t}}$	kW or no. of appliances/ use/ technology	capacity investment or number of new appliances for specific electricity uses (implemented in year t') per energy use u, technology $techn$, efficiency class $techpr$ during year t
$\boldsymbol{vCapTot^{BU}_{u,techn,techpr,t}}$	kW/use/ technology	equipment capacity of backup unit per use u, backup technology $techn$, efficiency class $techpr$, year t
$\boldsymbol{vCapInv^{BU}_{u,techn,techpr,t',t}}$	kW	capacity investment for backup unit (implemented in year t') per use u, backup technology $techn$, efficiency class $techpr$, year t
$\boldsymbol{vCHPGen^{elc}_{s,t}}$	kWh/hour	electricity output of micro-CHP unit during typical hour s at year t
$\boldsymbol{vDH_{u,techn,techpr,s,t}}$	kWh/hour/ year	final energy consumption per use u, technology $techn$, technology progress class $techpr$ during typical hour s at year t
$\boldsymbol{vDH^{BU}_{u,techn,techpr,s,t}}$	kWh/hour/ year	final energy consumption of backup unit per use u, backup technology $techn$, efficiency class $techpr$, during typical hour s at year t
$\boldsymbol{vG_{s,t}}$	kWh/hour	electricity generation of rooftop PV during typical hour s at year t
$\boldsymbol{vG^{Cut}_{s,t}}$	kWh/hour	electricity generation of rooftop PV curtailed during typical hour s at year t
$\boldsymbol{vGrid^{G2H}_{s,t}}$	kWh/hour	energy exchange with the electricity distribution network – extraction from network during typical hour s at year t

Name	Units	Description
$\boldsymbol{vGrid^{H2G}_{s,t}}$	kWh/hour	energy exchange with the electricity distribution network – injection to network during typical hour s at year t
$\boldsymbol{vGridLev^{G2H}_{l,s,t}}$	kWh/hour	stepwise function for electricity exchange with the electricity distribution network – extraction from network assigned to level l during typical hour s at year t
$\boldsymbol{vGridLev^{H2G}_{l,s,t}}$	kWh/hour	stepwise function for electricity exchange with the electricity distribution network – injection to network assigned to level l during typical hour s at year t
$\boldsymbol{vPVCap_t}$	kW/ technology	rooftop PV capacity per year t
$\boldsymbol{vPVInv_t}$	kW/ technology	rooftop PV investment per vintage t

Binary variables

Name	Description
$\boldsymbol{vBESSi_t}$	implementation of investment in BESS in year t
$\boldsymbol{vRen_{r,t}}$	renovation package r is selected during year t

Integer variable

Name	Description
$\boldsymbol{vPVNo_t}$	number of PV modules installed at year t

3.5.2 Constraints

Total annual desired useful energy demand for space heating and air cooling (i.e., subset $\mathcal{U}_{th}$) is covered through energy efficiency measures applied on the building envelope and the operation of the equipment on an hourly basis (effective demand). Choosing a renovation intervention that is characterized by higher levels of insulation results in lower useful energy demand while, at the same time, the dwelling occupant enjoys the desired level of services. This is reflected in the hourly operation of the equipment used for space heating and air cooling, as the selected renovation package affects the heat losses and the thermal load experienced during the heating and cooling season.

For water heating and cooking, the effective demand equals the desired useful energy demand, i.e., these two uses are not affected by the efficiency measures selected for the building envelope.

$$\boldsymbol{D^{Desired}_{u,t} = vD^{Effective}_{u,t} + \sum_{r} vD^{EE}_{u,r,t}\Big|_{u\in\mathcal{U}_{th}}, \forall u \in \mathcal{U}, t \in \mathfrak{T}} \tag{1}$$

For specific electricity uses, the useful demand corresponds to the total number of appliances.

$$\boldsymbol{D^{Desired,EA}_{techn,t} \leq \sum_{u,techpr} vCapTot_{u,techn,techpr,t}, \forall techn \in \mathcal{T}_{EA}, t \in \mathfrak{T}} \tag{2}$$

Each year in the projection period, the household selects the type of renovation to implement, if any (binary variable $vRen_{r,t}$). This means that each year one type of renovation intervention may be selected. In case type R0 is selected, i.e., standard repair and maintenance works, there is no effect in the energy demand for space heating and air cooling. By contrast, types R1-R8, when selected, decrease the useful energy demand of these two uses by an amount that is higher when moving from lighter to deeper renovation interventions and is mathematically represented through parameter $\alpha_{r,t}$.

$$\boldsymbol{vD^{EE}_{u,r,t} = vRen_{r,t} \cdot \alpha_{u,r,t} \cdot D^{Desired}_{u,t}}, \forall \boldsymbol{u} \in \boldsymbol{\mathcal{U}_{th}}, \boldsymbol{r} \in \boldsymbol{\mathcal{R}}, \boldsymbol{t} \in \boldsymbol{\mathfrak{T}} \tag{3}$$

Final energy demand of thermal uses (i.e., space heating, air cooling, water heating and cooking) is satisfied on an hourly basis by the operation of the installed equipment (primary and backup unit).

$$\begin{aligned}\boldsymbol{vD^{Effective}_{u,t}} = \sum_{\boldsymbol{techpr,s}} \boldsymbol{\varphi_s} \\ \cdot \left(\sum_{\boldsymbol{techn}} \boldsymbol{vDH_{u,techn,techpr,s,t}} \cdot \boldsymbol{\eta^{tch}_{u,techn,techpr,t}} \right. \\ \left. + \left(\sum_{\boldsymbol{technn' \in \mathcal{T}_{BU}}} \boldsymbol{\eta^{tch}_{u,techn',techpr,t}} \cdot \boldsymbol{vDH^{BU}_{u,techn',techpr,s,t}} \right) \Bigg|_{\boldsymbol{techn \in \mathcal{T}_R}} \right), \forall \boldsymbol{u} \in \boldsymbol{\mathcal{U}_{th}}, \boldsymbol{t} \\ \in \boldsymbol{\mathfrak{T}}\end{aligned} \tag{4}$$

3.5.2.1 Investments

For all types of equipment, electrical appliances and lighting, the total installed capacity ($vCapTot_{u,techn,techpr,t}$) corresponds to existing capacity within its lifetime not decommissioned yet, existing equipment (of reduced capacity) after the end of its lifetime that is granted lifetime extension or a new piece of equipment (new investment the timing of which is selected endogenously) ($vCapInv_{u,techn,techpr,t',t}$).

When a new piece of equipment is installed, the total capacity is equal to the sum of all existing equipment.

$$\begin{aligned}\boldsymbol{vCapTot_{u,techn,techpr,t}} = \sum_{\boldsymbol{t'|_{t-t'<\zeta_{u,techn,techpr}}}} \boldsymbol{vCapInv_{u,tech,techpr,t',t}}, \forall \boldsymbol{u} \in \boldsymbol{\mathcal{U}}, \boldsymbol{techn} \\ \in \boldsymbol{\mathcal{T}}, \boldsymbol{techpr} \in \boldsymbol{\mathcal{P}}, \boldsymbol{t} \in \boldsymbol{\mathfrak{T}}\end{aligned} \tag{5}$$

When a specific technology is selected and, depending on whether it requires a backup unit, an additional investment takes place: an appropriately sized backup unit ($vCapInv^{BU}_{u,techn,techpr,t',t}$) is purchased to support the operation of the primary unitapplying an appropriate sizing factor.

$$\begin{aligned}\boldsymbol{vCapTot^{BU}_{u,techn,techpr,t}} = \sum_{\boldsymbol{t'|_{t-t'<\zeta_{u,techn,techpr}}}} \boldsymbol{vCapInv^{BU}_{u,techn,techpr,t',t}}, \forall \boldsymbol{u} \in \boldsymbol{\mathcal{U}_{BU}}, \boldsymbol{techn} \\ \in \boldsymbol{\mathcal{T}_{BU}}, \boldsymbol{techpr} \in \boldsymbol{\mathcal{P}}, \boldsymbol{t} \in \boldsymbol{\mathfrak{T}}\end{aligned} \tag{6}$$

For space heating and water heating, a micro-CHP unit is an available option. Such units, however, due to their size are economically viable options mainly for services sector buildings that have higher thermal and electric needs, compared to households. Thus, even though such options are modelled in the prosumager model, it is seen as a futuristic option – out of the current scope – replacing e.g., the boiler, where – in the framework of prosumaging – the electricity produced may be either used for covering local needs or used for charging the BESS. Regarding the year of implementation of each investment and the selected efficiency, for space heating, water heating, air cooling and cooking, each year, at most one new investment per use may take place and this may be of specific technology and efficiency class. For electric appliances, any new investment during a specific year may be of a specific efficiency class. For uses requiring backup unit, investment in one backup unit per use is allowed to be implemented.

Potential investments in rooftop PV are restricted by the available area (i.e., a site potential is considered). This correlates to the space that is available for the installation: each solar panel requires a minimum floor area.

$$\sum_{\boldsymbol{techpr,t'}\in\mathfrak{T}_{eq}} \boldsymbol{vPVInv_{t'}} \leq \overline{\boldsymbol{P}}^{\boldsymbol{PV}}, \forall \boldsymbol{t'} \in \mathfrak{T} \tag{7}$$

$$vPVCap_{t'} = \underline{P}^{PV} \cdot vPVNo_{t'}, \forall t' \in \mathfrak{T}_{eq} \tag{8}$$

The modular nature of PV is translated into an integer variable indicating the number of modules to be installed ($vPVNo_{t'}$). Thus, the sizing of the PV is discrete.

The total capacity of solar PV installed each year of the projection horizon is determined by the capacity of the selected investments in such units.

$$\boldsymbol{vPVCap_t} = \sum_{\boldsymbol{t'}|_{\boldsymbol{t'-t<\zeta^{PV}}}} \boldsymbol{vPVInv_{t'}}, \forall \boldsymbol{t} \in \mathfrak{T} \tag{9}$$

Total BESS capacity is the sum of all active investments.

$$\boldsymbol{vBESSCap_t} = \sum_{\boldsymbol{t'}|_{\boldsymbol{t'-t<\zeta^{BESS}}}} \boldsymbol{vBESSInv_{t'}}, \forall \boldsymbol{t} \epsilon \mathfrak{T} \tag{10}$$

For the investment in BESS ($vBESSInv_t$), if implemented – as indicated by the binary variable $vBESSi_t$ – the size that can be selected should be higher than a minimum threshold ($\underline{P}^{BESS}$) corresponding to the specifications of equipment available in the market.

$$\underline{\boldsymbol{P}}^{\boldsymbol{BESS}} \cdot \boldsymbol{vBESSi_t} \leq \boldsymbol{vBESSInv_t}, \forall \boldsymbol{t} \epsilon \mathfrak{T} \tag{11}$$

3.5.2.2 Operation

Equipment

The hourly demand profile is constrained by the installed capacity for heat uses (i.e., space heating, air cooling, water heating) and for cooking in case of a technology using a fuel other than electricity. This capacity constraint is defined per technology (not per use), as certain technologies may cover more than one uses.

$$\sum_{u} \boldsymbol{vDH_{u,techn,techpr,s,t}} \leq \sum_{u} \boldsymbol{vCapTot_{u,techn,techpr,t}}, \forall \boldsymbol{u} \in \boldsymbol{\mathcal{U}}, \boldsymbol{techn} \in \boldsymbol{\mathcal{T}}, \boldsymbol{techpr} \in \boldsymbol{\mathcal{P}}, \boldsymbol{s} \in \boldsymbol{\mathcal{S}}, \boldsymbol{t} \in \boldsymbol{\mathfrak{T}} \tag{12}$$

For the inflexible uses of electricity (i.e., cooking when electricity is selected as fuel, electric appliances and lighting), the hourly demand derives based on a specific normalized profile (inflexible) determined by the occupancy of the household by its tenants.

$$\boldsymbol{vDH_{u,techn,techpr,s,t}} = \boldsymbol{\pi_{u,techpr,s,t}} \cdot \boldsymbol{vCapTot_{u,techn,techpr,t}}, \forall \boldsymbol{u} \in \boldsymbol{\mathcal{U}}, \boldsymbol{techn} \in \boldsymbol{\mathcal{T}}, \boldsymbol{techpr} \in \boldsymbol{\mathcal{P}}, \boldsymbol{s} \in \boldsymbol{\mathcal{S}}, \boldsymbol{t} \in \boldsymbol{\mathfrak{T}} \tag{13}$$

The operation of the space heating and air cooling equipment on an hourly basis during the winter and summer months, respectively, serves the heating and cooling needs of the household (i.e., keeping the indoor temperature within a predefined range).

Depending on the selected renovation package:

- for space heating, the operation considers heat gains (solar gains depending on the solar irradiation, internal heat gains during heating season, recoverable heat losses within the envelope that depend on the insulation of the building envelope, ventilation heat recovery) and heat losses (heat transfer by transmission, ventilation, and heat loss of space heating storage system) that depend on the difference between the indoor target temperature and the external temperature[4];
- for air cooling, the operation considers the sources of thermal load (solar depending on the solar irradiation, internal, heat transfer by transmission, ventilation) as well as heat losses.

The operation of water heating on an hourly basis serves the demand for hot water (depends on the number of occupants, the income of the household, the cold-water temperature and the desired hot water temperature as indicated by a predefined range) and the overall heat losses of the system.

On an annual basis, the backup unit operates during the hours when the primary system does not and its hourly operation ($vDH^{BU}_{u,techn,techpr,s,t}$) is constrained by the installed capacity ($vCapTot^{BU}_{u,techn,techpr,t}$).

$$\boldsymbol{vDH^{BU}_{u,techn,techpr,s,t}} \leq \boldsymbol{vCapTot^{BU}_{u,techn,techpr,t}}, \boldsymbol{u} \in \boldsymbol{\mathcal{U}_{heat}}, \boldsymbol{techn} \in \boldsymbol{\mathcal{T}_{BU}}, \boldsymbol{techpr} \in \boldsymbol{\mathcal{P}}, \boldsymbol{t} \in \boldsymbol{\mathfrak{T}} \tag{14}$$

In the general case, when micro-CHP unit is selected for covering the space heating and water heating needs, its operation is such that the output heat covers the needs of all the uses that require it. The fuel consumption and the

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[4] For the analytical methodology see the relevant TABULA Documentation (Loga & Diefenbach, 2013). It should be noted that the TABULA calculation procedure applies the seasonal method according to EN ISO 13790 on the basis of a one-zone model.

electricity output of the unit derive from the heat rate and the heat-to-electricity ratio of the micro-CHP unit.

Local generation (rooftop PV)

The total energy generated by the rooftop PV is determined by the combination of a normalized PV generation profile π_s^{PV} (reflecting the per hour variation of the hourly solar irradiation throughout the year) with the selected installed capacity ($vPVCap_{t'}$), taking into account the annual PV module degradation (d^{PV}) that is observed (Feldman, et al., 2021). The total amount of energy generated by the solar PV is either used ($vG_{s,t}$) or curtailed ($vG_{s,t}^{Cut}$).

$$\left(\boldsymbol{vG_{s,t}} + \boldsymbol{vG_{s,t}^{Cut}}\right) = \boldsymbol{\pi_s^{PV}} \cdot \sum_{\boldsymbol{t' \in \mathfrak{T}_{eq}}} \left(\mathbf{1} - \boldsymbol{d^{PV}}\right) \cdot \boldsymbol{vPVCap_{t'}}\, , \forall \boldsymbol{s} \in \boldsymbol{\mathcal{S}}, \boldsymbol{t} \in \boldsymbol{\mathfrak{T}} \tag{15}$$

BESS

The charging and discharging of the BESS are constrained by the selected size of the BESS observing a minimum current and the maximum number of the charging-discharging cycles on an annual basis.

The battery state of charge (SOC) depends on the status of the battery, while, if idle, self-discharge takes place. Additionally, the operation of BESS is limited by upper and lower limits for the SOC, ensuring battery health.

Electricity exchange with distribution network

The electricity balance per typical hour is defined: total electricity demand is covered through operation of local generation units, BESS discharge, micro-CHP operation and imports from the electricity distribution network. At the same time, on an annual basis, the prosumager remains a net importer.

$$\begin{aligned} &\left[\sum_{\boldsymbol{u,techn,techpr}} \left(\boldsymbol{vDH_{u,techn,techpr,s,t}} + \sum_{\boldsymbol{techn' \in \mathcal{T}_{BU}}} \boldsymbol{vDH_{u,techn',techpr,s,t}^{BU}} \Bigg|_{\boldsymbol{techn \in \mathcal{T}_R}} \right) \right. \\ &\qquad \left. + \boldsymbol{vBESSPower_{s,t}^{C}} \right] \\ &\qquad = \left[\boldsymbol{vG_{s,t}} + \boldsymbol{vCHPGen_{s,t}^{elc}} + \boldsymbol{vBESSPower_{s,t}^{D}} + \boldsymbol{vGrid_{s,t}^{G2H}} - \boldsymbol{vGrid_{s,t}^{H2G}}\right], \boldsymbol{s} \in \boldsymbol{\mathcal{S}}, \boldsymbol{t} \\ &\qquad \in \boldsymbol{\mathfrak{T}} \end{aligned} \tag{16}$$

$$\sum_{s} \varphi_s \cdot \left(vGrid_{s,t}^{G2H} - vGrid_{s,t}^{H2G}\right) \geq 0, t \in \mathfrak{T} \tag{17}$$

To also test scenarios with electricity grid price varying as a function of the electricity volume exchanged, the exchange of electricity with the electricity distribution network is assigned to a different level (bin) of an electricity supply cost curve.

$$\sum_{\boldsymbol{l}} \boldsymbol{vGridLev_{l,s,t}^{G2H}} = \boldsymbol{vGrid_{s,t}^{G2H}}, \boldsymbol{s} \in \boldsymbol{\mathcal{S}}, \boldsymbol{t} \in \boldsymbol{\mathfrak{T}} \tag{18}$$

$$\sum_{l} vGridLev_{l,s,t}^{H2G} = vGrid_{s,t}^{H2G}, s \in \mathcal{S}, t \in \mathfrak{T} \tag{19}$$

3.5.3 Objective function

The objective function to minimize includes the present value of all cost components, i.e., discounted, as follows:

$$\sum_{t} \boldsymbol{c_t^{int}} \cdot \left(\boldsymbol{C_t^{Ren}} + \boldsymbol{C_t^{Eq,Cap}} + \boldsymbol{C_t^{PV,Cap}} + \boldsymbol{C_t^{BESS,Cap}} + \boldsymbol{C_t^{Eq,OM}} + \boldsymbol{C_t^{PV,OM}} + \boldsymbol{C_t^{Fuel}} + \boldsymbol{C_t^{ELC}} + \boldsymbol{V_t^{EE}}\right) + \boldsymbol{\Pi_t} \tag{20}$$

1. The renovation cost is a function of the selected type of renovation: higher for deeper types of renovation.

$$\boldsymbol{C_t^{Ren}} = \boldsymbol{f^{Ren}\left(vRen_{r,t}\right), t} \in \mathfrak{T} \tag{21}$$

2. The capital cost for equipment (primary and backup units), rooftop PV and BESS is a function of the selected capacity or number of appliances. More advanced technologies have higher unit costs than currently available technologies.

$$\boldsymbol{C_t^{Eq,Cap}} = \boldsymbol{f^{Eq}\left(vCapInv_{u,techn,techpr,t}, vCapInv_{u,techn,techpr,t}^{BU}\right), t} \in \mathfrak{T} \tag{22}$$

$$C_t^{PV,Cap} = f^{PV}(vPVInv_t), t \in \mathfrak{T} \tag{23}$$

$$C_t^{BESS,Cap} = f^{BESS}(t), t \in \mathfrak{T} \tag{24}$$

3. Fixed operation and maintenance costs of equipment (primary and backup units), rooftop PV and BESS are a function of the selected capacity or number of appliances.

$$\boldsymbol{C_t^{Eq,OM}} = \boldsymbol{f^{Eq,OM}\left(vCapTot_{u,techn,techpr,t}, vCapTot_{u,techn,techpr,t}^{BU}\right), t} \in \mathfrak{T} \tag{25}$$

$$C_t^{PV,OM} = f^{PV,OM}(vPVCap_t), t \in \mathfrak{T} \tag{26}$$

$$C_t^{BESS,OM} = f^{BESS,OM}(vBESSCap_t), t \in \mathfrak{T} \tag{27}$$

4. Fuel cost of primary and backup units depend on the operation levels (defining the fuel needs), the fuel cost and the carbon price applied (if relevant).

$$\boldsymbol{C_t^{Fuel}} = \boldsymbol{f^{fuel}\left(vDH_{u,techn,techpr,s,t}, vDH_{u,techn,techpr,s,t}^{BU}\Big|_{techn \in \mathcal{T}_{BU}}, vGridLev_{l,s,t}^{G2H}\right), t} \in \mathfrak{T} \tag{28}$$

5. Revenues from electricity exports to the electricity distribution network and expenses for electricity purchases are a function of the electricity exchanged with the distribution network per level of the supply cost function and the respective price.

$$\boldsymbol{C_t^{ELC}} = \boldsymbol{f^{ELC}\left(vGridLev_{l,s,t}^{H2G}\right), t} \in \mathfrak{T} \tag{29}$$

6. Penalties for the curtailment of PV generation and BESS depth-of-discharge (DoD) are also included in the objective function and depend on the volume of on-site generation not used in any way and the DoD. Thus, the available on-site generation is not wasted and the battery health is preserved.

$$\boldsymbol{\Pi_t = f^{penalties}\left(vG^{Cut}_{s,t}, vBESSDoD_{s,t}\right), t \in \mathfrak{T}} \tag{30}$$

Additionally, policies are included such as those promoting energy efficiency (energy efficiency value for supporting renovation choices) and renewables (renewables value seen as a subsidy promoting installation of on-site generation).

$$\boldsymbol{V^{EE}_t = f^{policies}\left(vEEV_t \cdot vD^{EE}_{u,r,t}, vRES_t \cdot vG_{s,t}\right), t \in \mathfrak{T}} \tag{31}$$

3.5.4 Variable limits

To ensure a well-defined problem, the following upper limits are set in addition to those described in the previous paragraph:

1. Binary variables allowing the implementation of investment in renovation interventions are allowed a maximum value of one only if the specific type of renovation is an option for the specific household.
2. For the first year of the optimization, the maximum investment capacity for the technologies that cannot occur according to the already installed equipment and the feasible technology transitions are set to zero. Also, the maximum investment capacity for the technologies that can occur based on the same feasible technology transitions is set to non-zero.
3. Hourly generation and hourly generation curtailment of local generation units cannot be higher than the site potential multiplied by the generation pattern.
4. The electricity exchange with the network should be less than a maximum capacity indicating the capacity of the power connection to the utility line.
5. The set point for the space heating temperature, air cooling and water heating lies between a desirable lower and upper limit ensuring the comfort of the occupants.
6. The investment in equipment (primary and backup) is allowed per household, use and technology, only if feasible based on the specific type of dwelling and the available space allowing its installation (e.g. a ground-source heat pump is available as an option only for single-family households).
7. Maximum micro-CHP capacity (site potential).
8. Lower and upper limits for BESS SOC ensuring the health of the battery.
9. Upper limit for charging/discharging BESS capacity.

4. Application

This section presents the possibilities of the prosumager model through a case study with the following configuration:

- optimization horizon: 2025-2050
- country: Germany
- household type: dwelling located in a multi-family building in an urban area; high-income household
- vintage household (i.e., date of construction of the building): 1970
- initial stock of equipment per energy use:
    - space heating: conventional oil boiler
    - air cooling: split system air conditioning
    - water heating: electric water heater
    - cooking: electric cooker
- desired useful energy demand for heat uses as presented in Table 3
- for specific electricity uses, the number of appliances is the equivalent to the desired useful energy demand:
    - freezing, ironing, dishwashers, dryers, refrigeration, vacuum cleaners: the total number of appliances remains constant for the entire projection period and equals one for all uses except refrigeration (two units correspond to the specific use – representing one large refrigeration unit). In other words, the household is equipped with one unit of each of the above-mentioned electrical appliances.
    - stock of small appliances (e.g., chargers, TVs, etc.): during the last historic year (2020), the household is equipped with ten small appliances, and their number increases by one each year of the projection horizon as a result of income growth. By 2050, the household is equipped with 16 small appliances.
    - washing machines, information & communication, entertainment, lighting: the total number increases once throughout the projection period by one (for washing machines, the increase by one indicates that a larger unit is acquired).
- flat electricity price

An additional case is also studied, where the electricity grid price for the quantities injected to the grid and extracted from the grid are priced according to stepwise functions. That is, for the electricity that the household imports from the grid, the price is an increasing function of the volume demanded. For the electricity that the household exports to the grid, the price is a decreasing function of the sold volume.

In both cases, the prosumager performs the decision-making process in an energy policy framework compatible with the “Fit for 55” policy package (i.e. with an ambitious target of a 55% reduction in greenhouse gas emissions by 2030, relative to 1990 levels for the EU, an EU-level target for energy efficiency for 2030 that corresponds to a 9% reduction of final energy consumption compared to the Reference scenario 2020 (European Commission, 2021), and a target of at least 40% share of renewable energy in the overall energy mix for the EU in 2030 (European Commission, 2021)).

Table 3 Desired useful energy demand per energy use for heating and cooling uses (i.e., space heating, water heating, air cooling, cooking) (toe/year/household)).

Use	2020	2025	2030	2035	2040	2045	2050
Space heating	1.26	1.26	1.26	1.30	1.33	1.37	1.40
Water heating	0.49	0.49	0.49	0.49	0.49	0.49	0.49
Air cooling	0.03	0.04	0.04	0.04	0.05	0.05	0.05
Cooking	0.08	0.09	0.09	0.09	0.09	0.09	0.09

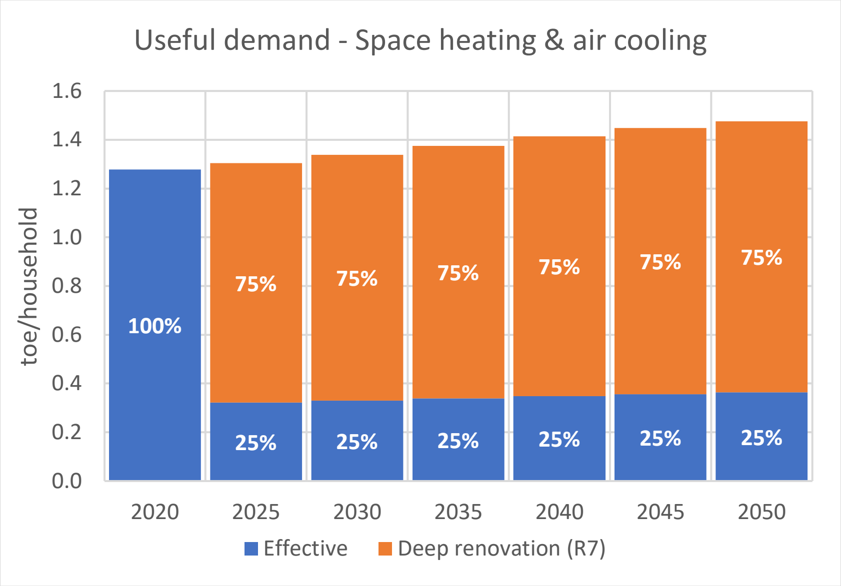
Source: newTRENDs

4.1 Investments

The household opts for a deep renovation of the building envelope (replacement of windows and application of thick insulation in external walls, roof and basement), which results in energy savings of around 75%, in terms of the desired useful energy demand for space heating and air cooling (Figure 1).

Even though the policy framework modelled here aims at reaching the energy efficiency target in 2030, the household invests in the renovation of the building envelope already in 2025, as this contributes to reducing the energy needs. This is a high-income household, facing fewer barriers to energy efficiency (i.e., it is not affected by fund-raising scarcity, has low opportunity cost of cash-flow etc.) and is therefore keener on implementing such an investment compared to a low-income household. In the model, this is captured via a low discount rate (i.e., around 5%) to calculate the annuity factor applying on investment cost for this specific household. The associated investment expenditure is approximately 10.2 thousand euros.

Figure 1 Annual desired useful energy demand: total, effective (to be covered by the operation of the heating and cooling equipment) and energy savings due to the renovation of the building envelope – space heating and air cooling (toe per household).



Source: newTRENDs – own calculation

The selected type of renovation, resulting in reduced useful energy demand for space heating and air cooling, allows a switch in the technology used to cover the associated needs (Table 4). Since the household implements an investment that enhances the insulation of the building cell, maintaining the existing oil boiler to cover lower energy needs would result in underutilization of this piece of equipment. Thus, the household selects to prematurely decommission the existing oil boiler and replace it by an air-source heat pump (ASHP) in the same year that the efficiency upgrade of the building envelope takes place. The heat pump chosen is of lower capacity compared to the old oil boiler, indicating at the same time that heat pumps are economically appropriate for well-insulated buildings.

In parallel, due to the relatively low demand for air cooling, a synergy takes place: the split system air-condition is no longer necessary and is decommissioned. In its place, the already installed ASHP covering the space heating needs is also used during the rest of the year, to cover the air cooling needs of the household.

The water heating equipment is also replaced: the household, being a high-income one, invests in 2025 in a heat pump water heater (HPWH) – a technology of higher efficiency compared to the existing electric water heater.

Both the ASHP and the HPWH technologies require backup systems, so relevant investments take place during the respective years.

As the years advance and the equipment reaches the end of its technical lifetime, replacement occurs. The same technology is selected for these four uses and, in the case of cooking, a shift towards equipment of improved efficiency takes place. For the rest of the uses, the appliances stock is also renewed each time they reach their technical lifetime (Table 5) and, in some cases, to more efficient options depending on the cost incurred relative to the gains from fuel savings achieved by the switch.

Table 4 Existing equipment and equipment choice for the projection period (technology, efficiency class, year of implementation) per heating and cooling use.

Use	Technology 2020	Projection period (2025-2050)
Space heating	Boiler (oil) (ORD/2010)	Air-source heat pump (ORD/2025, 2045), backup unit – electric space heater (ORD/2025, 2045)
Water heating	Electric water heater (ORD/2020)	Heat pump (FUT/2025, 2040), backup unit – electric water heater (ORD/2035)
Air cooling	Split system air condition (ORD/2015)	-
Cooking	Electric cooker (ORD/2020)	Electric cooker (ORD/2030, 2040, FUT 2050)

Source: newTRENDs

Table 5 Existing appliances and appliance choice for the projection period (efficiency class and year of implementation) per specific electricity use (electrical appliances and lighting).

Use	Technology 2020	Projection period (2025-2050)
Freezing	ORD/2020	ORD/2030, 2040, 2050
Refrigeration	ORD/2020	ORD/2030, 2040, 2050
Ironing	ORD/2015	FUT/2025, 2040
Information & communication	ORD/2015	ORD/2025, 2040
Entertainment	ORD/2015	FUT/2030, 2045
Vacuum cleaners	ORD/2015	FUT/2025, 2040
Small appliances	ORD/2015	FUT/2025, 2040
Dishwashers	ORD/2020	ORD/2030, 2040, IMR/2050
Dryers	ORD/2020	ORD/2030, 2040, 2050
Washing machines	ORD/2020	ORD/2030, 2040, IMR/2050
Lighting	ORD/2020	FUT/2025, 2035, 2045

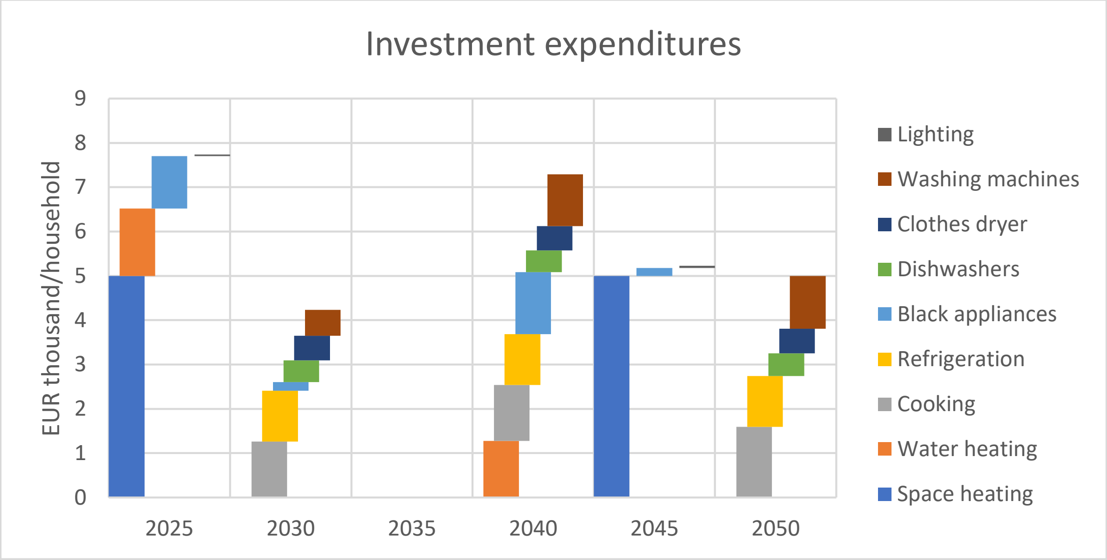
Source: newTRENDs

An investment in rooftop PV takes place in 2035. The capacity of the PV is 8.1 kW (18 modules) and the associated investment expenditure is 4.4 thousand euros. At the same year, the household decides to also invest in a BESS. The capacity of the BESS is 4.8 kW and the associated investment expenditure is 1.8 thousand euros.

After the end of the technical lifetime of the BESS installed in 2035 (i.e., 15 years), a new investment of 4.1 kW in size (cost 1.2 thousand euros) takes place in 2050, thus allowing the continued exploitation of the renewable resource captured by the PV that has not yet surpassed its technical lifetime of 30 years. However, due to the annual PV module degradation, the sizing of the BESS in 2050 is reduced to a level that matches the available PV generation.

In total, the combination of the specific capacities for PV and BESS is such that the household remains a net importer on a yearly basis. Each time a piece of equipment is replaced by a new one or a new appliance is selected, expenditure for the relevant investment is incurred as presented in Figure 2. Evidently, the ASHP for space heating contributes largely to the investment expenditures. However, such a choice is facilitated by the reduced energy needs due to the upgrade of the insulation of the building envelope. On the other hand, no expenditure occurs for air cooling equipment, as this is no longer necessary thanks to the achieved synergy with the space heating use.

Figure 2 Investment expenditures for purchases of equipment, electric appliances and lighting for all years of the projection period (EUR thousand/household).



Source: newTRENDs – own calculation

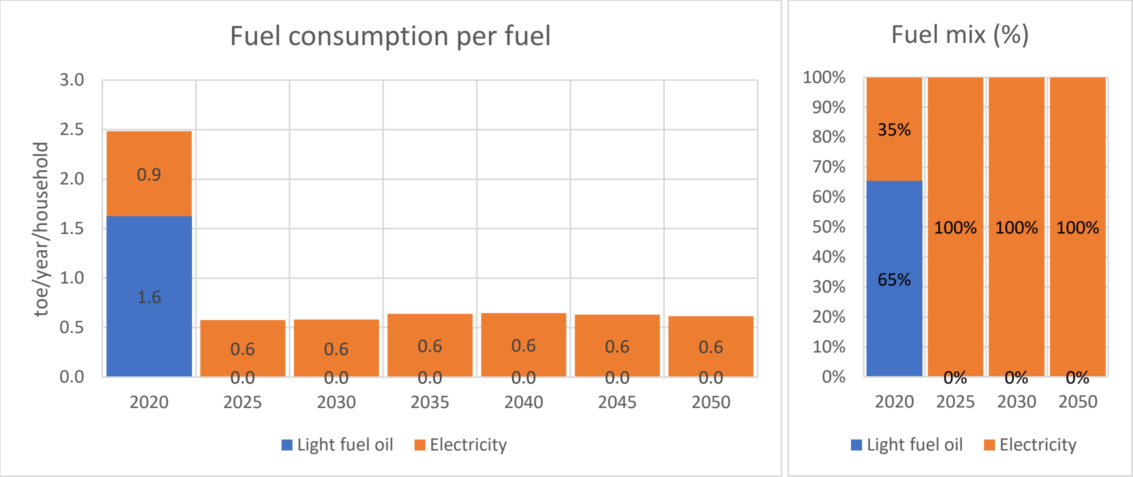
4.2 Operation

4.2.1 Fuels

Starting from a total final energy consumption of almost 2.5 toe in 2020, the household, implementing investment in renovation, sees a decrease in the final energy consumption of almost 77% in 2025 (Figure 3). This improvement is brought about both by the reduced useful energy demand thanks to the renovation of the building envelope and by the selection of more efficient equipment and appliances in almost all energy uses, as mentioned in the previous section. For the rest of the projection period, the total fuel consumption is almost stable and reduces slightly, as more efficient equipment and appliances are installed.

The existing stock of equipment and appliances in the historical year 2020 results in a fuel mix comprising of 65% light fuel oil that is necessary for covering the energy intensive use of space heating. As the household switches to the ASHP in 2025, this use is also electrified and, thus, the household uses only electricity from that year onwards.

Figure 3 Final energy consumption per fuel (toe/year/household) and fuel shares in fuel mix (%) for the historical year 2020 and for the projection period (2025-2050).



Source: newTRENDs – own calculation

The electrification of the space heating use in 2025 is evident also when examining the structure of the annual electricity demand of the household per use and/or appliance (Figure 4). Also, the achieved energy savings in 2025 thanks to the two aforementioned reasons (renovation of the building envelope and improved efficiency of equipment and appliances) result in a reduction of the total electricity consumption in 2025 by about 33% compared to 2020. Since, in 2025, the household is entirely dependent on imports of electricity from the electricity distribution network, an equal amount of reduction for imported electricity is observed in 2025.

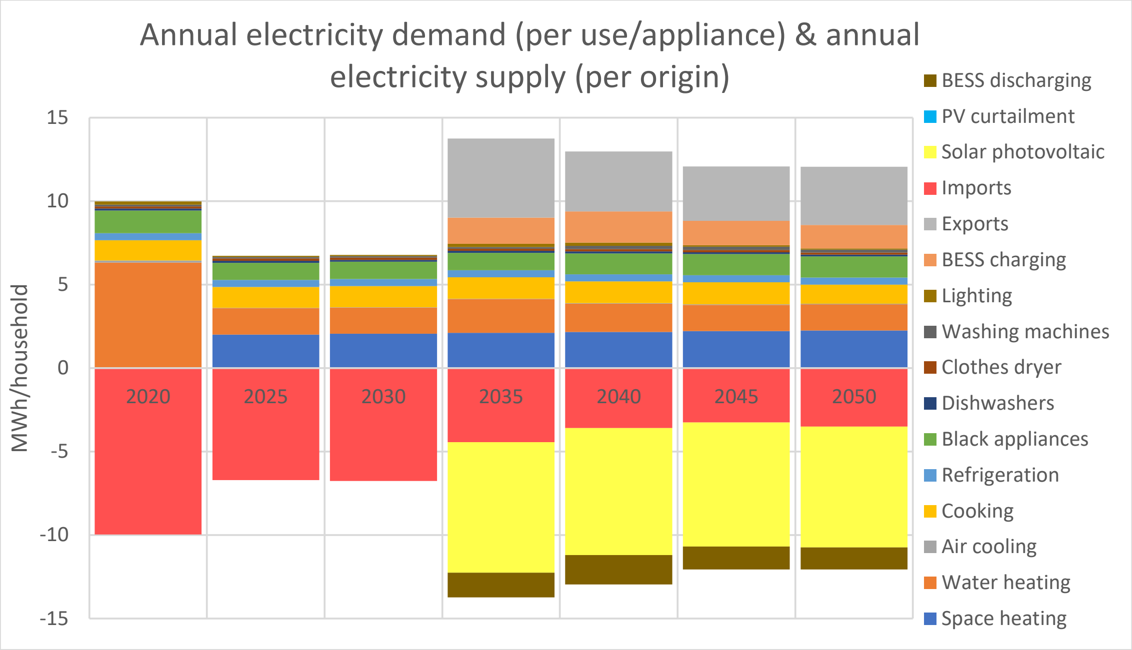
In 2035, the household invests in the rooftop PV and in the BESS. Using the locally available resource, the household reduces the needs for imported electricity from the distribution network by 35% in 2035 compared to 2030.

During the years 2035-2050, the household also injects electricity to the network that may come from two alternative sources:

- PV production that cannot be used in any other way (i.e., the electricity needs of the household are covered, achieving self-sufficiency, and the BESS is already fully charged) or

- proactively discharging the BESS during days of increased PV production in order to optimize the utilization of the available solar resource and to avoid spilling any surplus of PV energy (i.e., no curtailment of PV generation occurs).

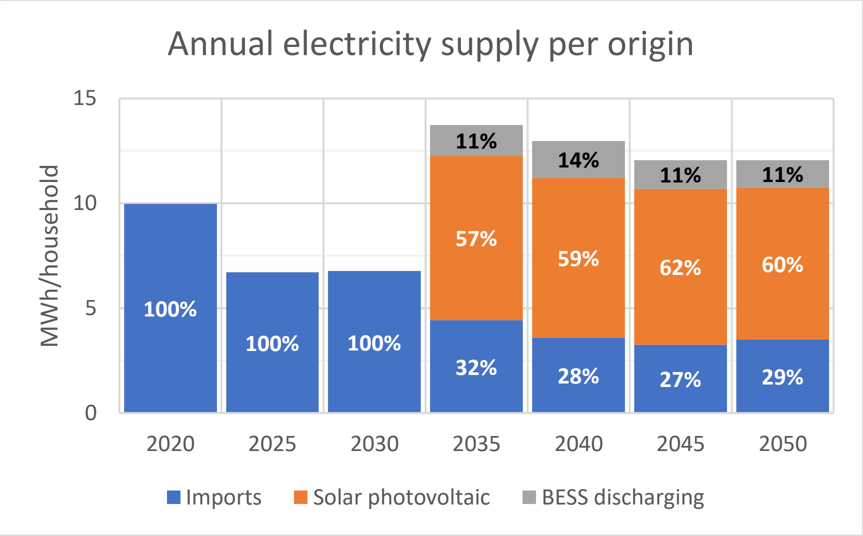
Figure 4 Annual electricity demand per use/appliance and annual electricity supply per origin for the historical year 2020 and for the projection period (2025-2050).



Source: newTRENDs – own calculation

Focusing on the supply of the electricity (Figure 8), the entire amount of electricity is imported from the electricity distribution network up to 2030. As soon as the combination of the solar PV with the BESS is available, the locally available resources are utilized to cover almost 70% of the household’s energy needs and, thus, significantly reduce the import dependency of the household.

Figure 5 Annual electricity supply per origin for the historical year 2020 and for the projection period (2025-2050).



Source: newTRENDs – own calculation

4.2.2 Hourly operation

The hourly operation of the equipment and appliances using electricity and lighting per typical day and hour is presented in Figure 6 for the year 2025. Since no on-site generation is installed, the total energy needs of the household are covered by electricity imported from the electricity distribution network. The energy needs of the various energy uses depend on the occupancy of the household, which is different during the working days and the holidays.

The electrified space heating presents its highest energy needs during days of low temperature, while, on an hourly basis, its operation is negatively correlated to the variations of the external temperature.

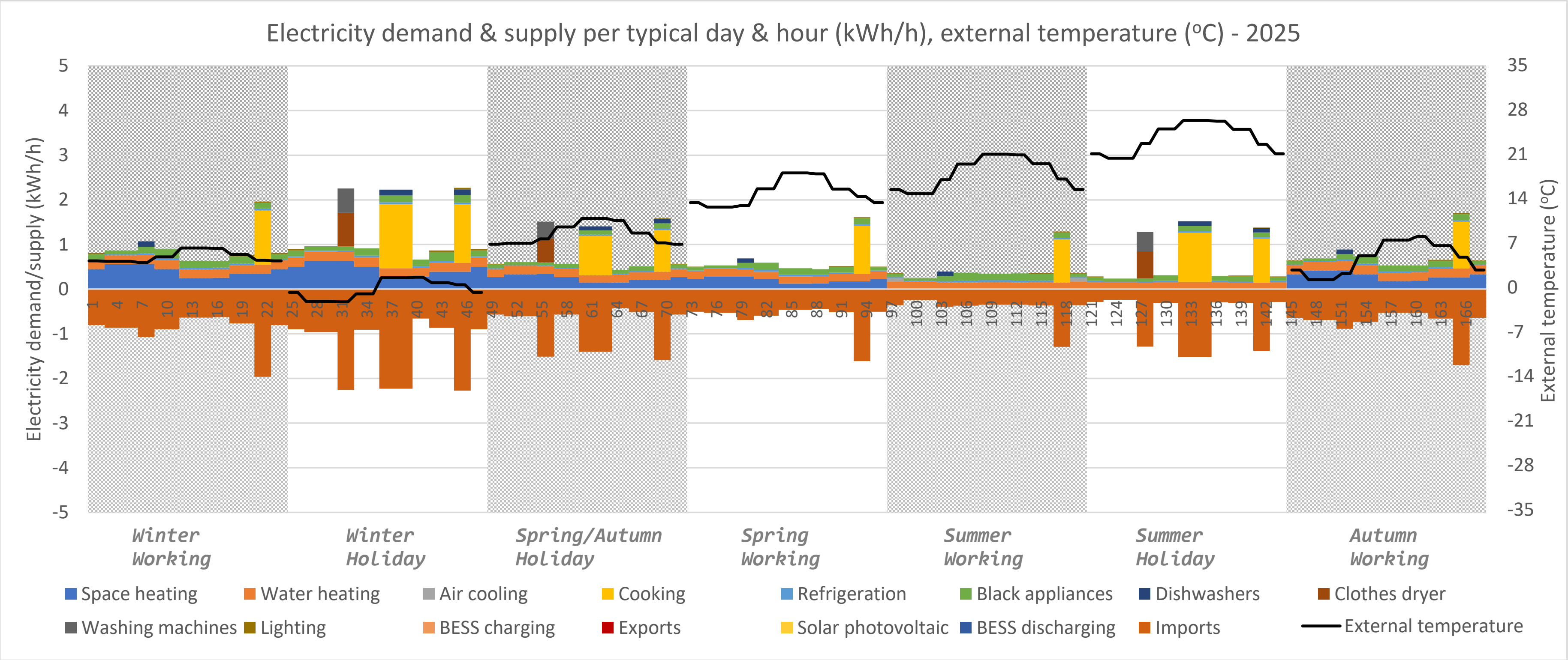
In the year 2045 (Figure 7), the household may cover part of its electricity needs using the on-site generation. This happens during all typical days. Particularly evident during the typical days of highest solar resource availability is the elimination of electricity imports for certain hours of the day, leading to lower electricity imports annually. Furthermore, during hours of peak solar PV generation, the energy surplus is injected into the network (exported quantities), since the limit of the power line connecting the household to the utility grid is not reached.

By contrast, during typical days of limited availability of the solar resource but of high energy needs (especially during winter) the household depends mainly on imported electricity.

The electricity demand for space heating in 2045 follows a similar pattern to the one of 2025.

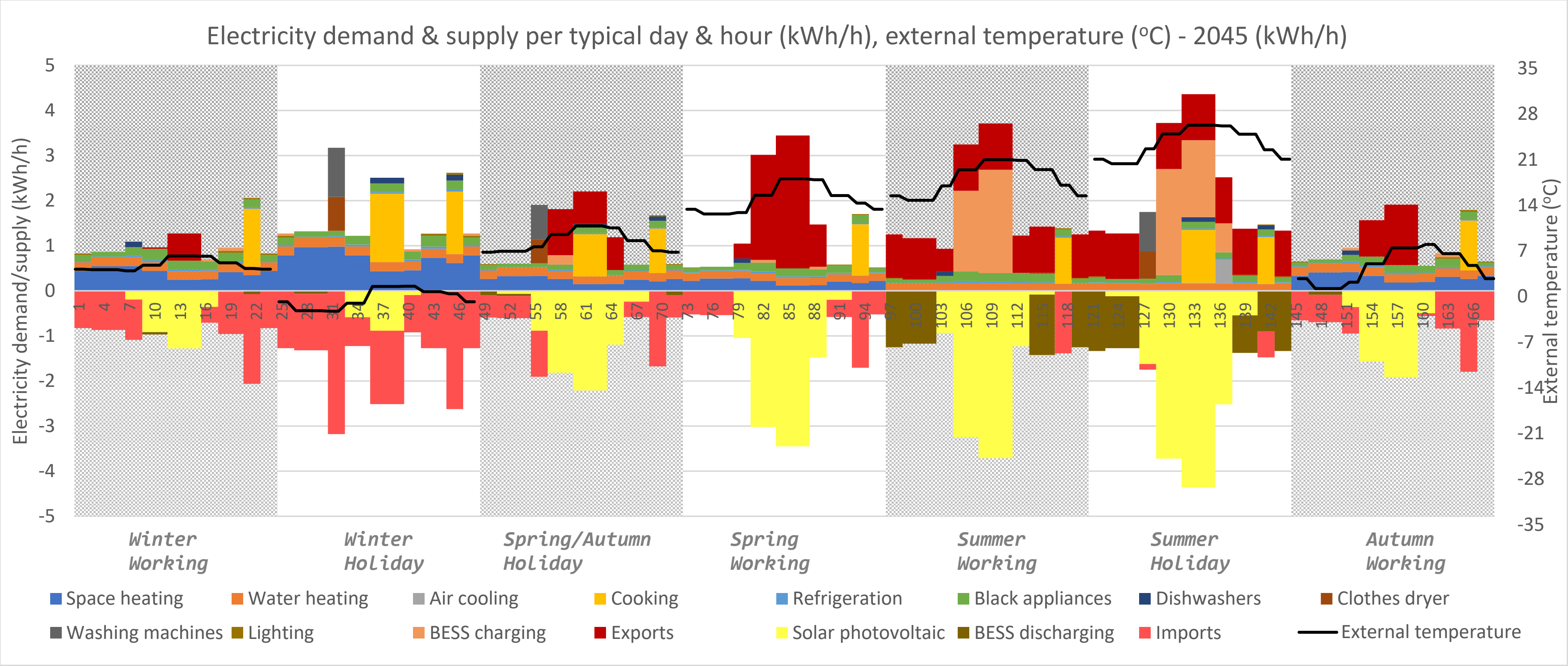
The BESS is mainly used to store the electricity surplus of the solar PV that cannot be used locally (i.e., the electricity load is low) and cannot be injected into the network in the form of exports, as this is not allowed by the capacity of the power line connecting the household to the utility grid. During those typical days characterized by a highly available solar resource, the BESS is proactively discharged – its energy used first for covering the electricity needs of the household and any additional amount injected into the electricity distribution network – to make room for subsequently storing the energy surplus of the solar PV.

Figure 6 Electricity demand per use/appliance and electricity supply per origin per typical day and hour (kWh/h); external temperature per typical day and hour (°C) – year 2025.



Source: newTRENDs – own calculation

Figure 7 Electricity demand per use/appliance and electricity supply per origin per typical day and hour (kWh/h); external temperature per typical day and hour (ºC) – year 2045.



Source: newTRENDs – own calculation

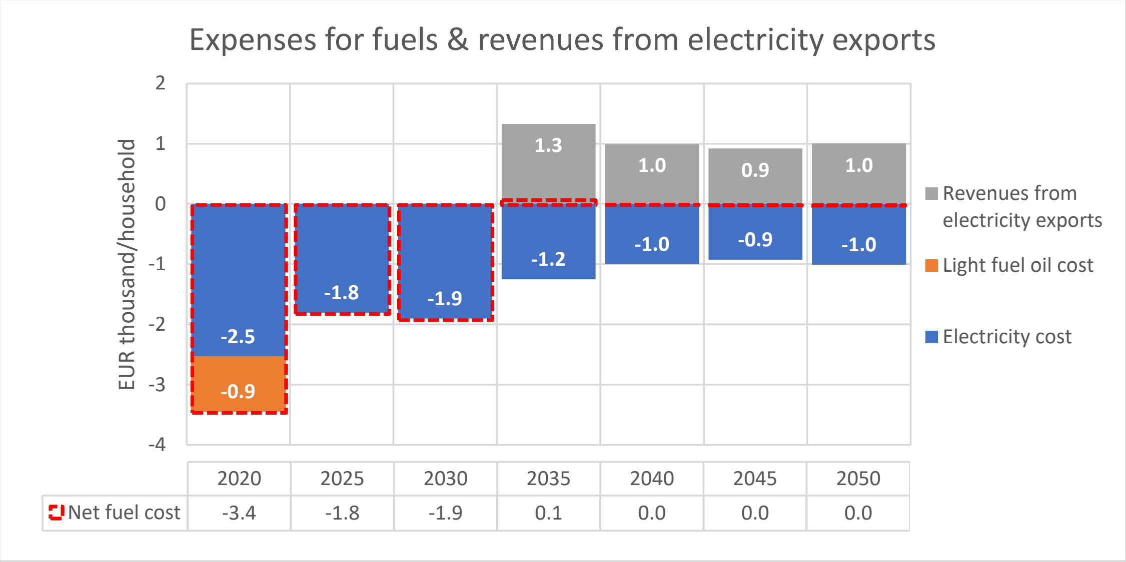
4.3 Costs

The shift in the behavior of the household is reflected in its expenses for energy products and the revenue streams that appear when on-site generation is available (Figure 8). The cost of purchasing light fuel oil is eliminated in 2025 thanks to the electrification of the space heating energy use. During the same year, the implementation of the renovation intervention and the selection of more efficient equipment in certain uses reduce the needs for electricity and the associated costs.

By design, the prosumager is a price-taker and remains a net importer of electricity on an annual basis even though on-site generation is available from 2035 onwards. Exports to the electricity distribution network are allowed and observed. Thus, a significant revenue stream appears as soon as the investment in on-site generation and BESS is implemented.

As the exports form an income to the prosumager, their optimal level is selected to be the maximum one that does not violate the previously mentioned design principle. As such, the total amount of imports is marginally higher that the total amount of exports. With the electricity price for energy injected to and extracted from the grid being the same (i.e., net-metering applies), the net cost for electricity from 2035 onwards is virtually eliminated.

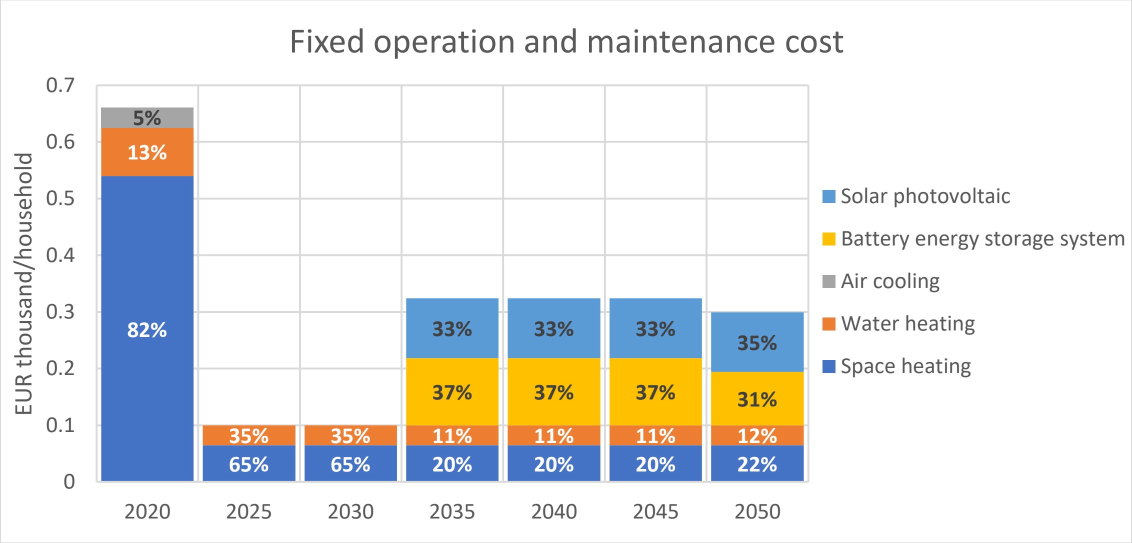
Figure 8 Expenses for fuels, revenues from electricity sales and net fuel cost for the historical year 2020 and the projection period (2025-2050) (EUR thousand/household).



Source: newTRENDs – own calculation

The technology shift that occurs in the space heating use and the investment in renovation of the building envelope results in lower fixed operation and maintenance costs compared to 2020 (Figure 9), since the energy needs are lower and the equipment is of lower capacity. However, from 2035 onwards, the operation and maintenance cost increases again, due to the investment in rooftop PV and in BESS.

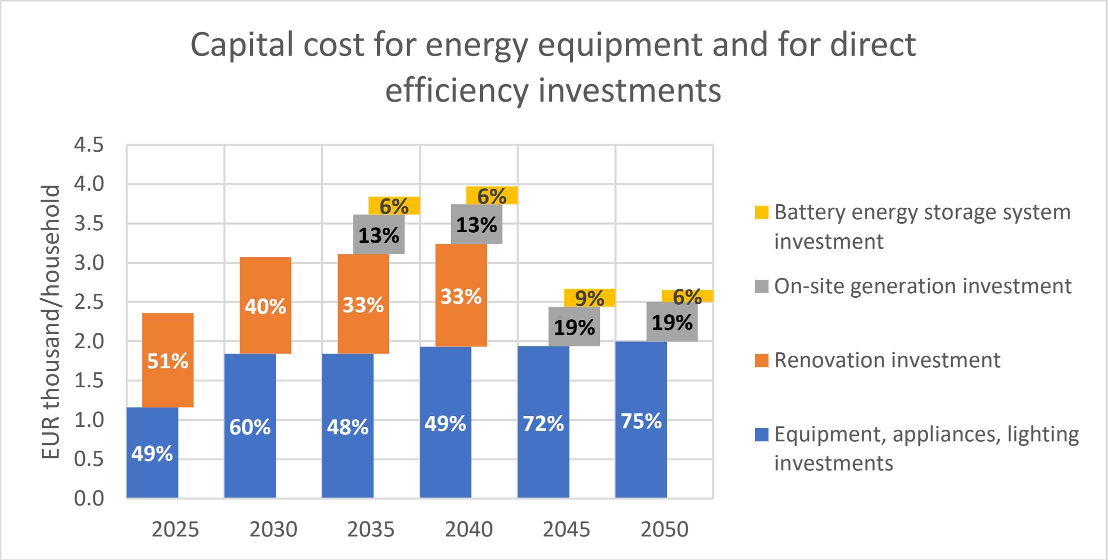
Figure 9 Fixed operation and maintenance cost for equipment used for space heating, water heating, air cooling, for BESS and for solar PV (historical year 2020 and projection horizon 2025-2050) (cost figures correspond to annual expenses for each year of the five-year period) (EUR thousand/household).



Source: newTRENDs – own calculation

Implementing the various investments implies annuity capital payments during the economic lifetime of each choice (10% discount rate applies) (Figure 10).

Figure 10 Capital cost for energy equipment and for direct efficiency investments for the projection period (2025-2050) (EUR thousand/household).



Source: newTRENDs – own calculation

Even though the fixed operation and maintenance costs during the first years of the projection period drop, they rise again to almost half of the 2020 levels after the implementation of the investment in local generation and BESS. In addition, the improved situation (cost-wise) for purchasing energy products cannot compensate for the high capital costs associated with increased energy efficiency and high penetration of renewable on-site generation. The framework within which the prosumager operates, however, offers incentives for investing in energy efficiency and deploying renewables despite their high cost, allowing for the market uptake of more expensive consumer choices that help meet the climate targets.

4.4 Variation – stepwise electricity prices

This section presents the most significant results of the studied variation. In this case, the pricing regime for the electricity exchanged with the electricity distribution network is differentiated: for every extra amount of energy that the household imports from the electricity grid, the charge price is higher; by contrast, when the household is exporting surplus electricity to the grid, the remuneration is performed at a unit price that is lower as the volume of exports increases.

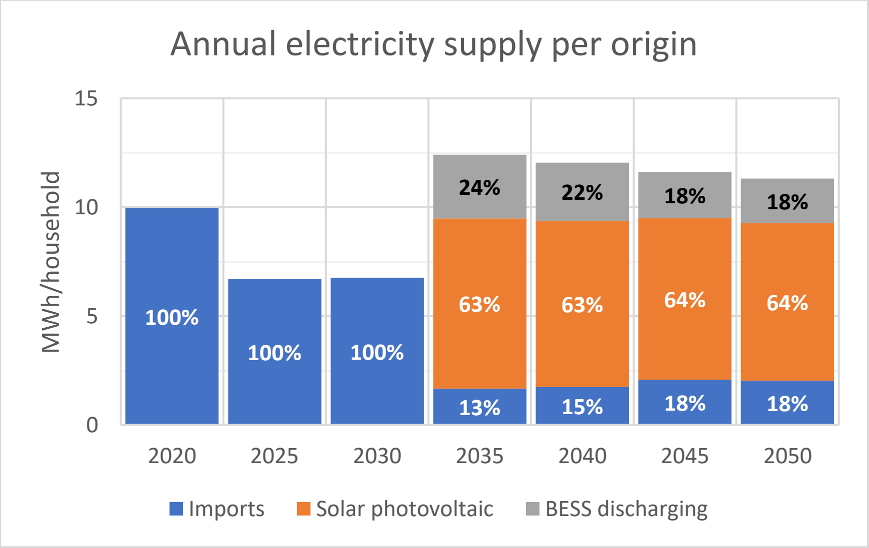
In terms of investments for the various pieces of equipment, appliances, lighting and on-site generation, the variation does not present differences from the case studied thus far.

However, the household invests in a BESS of higher capacity (5.0 kW in 2035 and 4.5 kW in 2050). This result is attributed to the new operational regime: the household experiences a different pricing policy that functions as a disincentive for demanding high levels of electricity from the grid. At the same time, with the price for exports reducing for higher volumes, the household is expected to be more reluctant to inject electricity into the grid. As a result, by investing in a BESS of higher capacity, the prosumager attempts to increase his self-sufficiency and reduce his exposure to the increasing charge prices. In parallel, the higher capacity BESS allows storing higher amounts of produced electricity from the rooftop PV to be used for covering the local needs.

This is reflected in the annual results: the total electricity supply is covered by 82-87% by local resources and only 13-18% of electricity imported from the grid (Figure 11). By contrast, the import dependency of the household in the base case examined in the previous paragraphs was 27-32%.

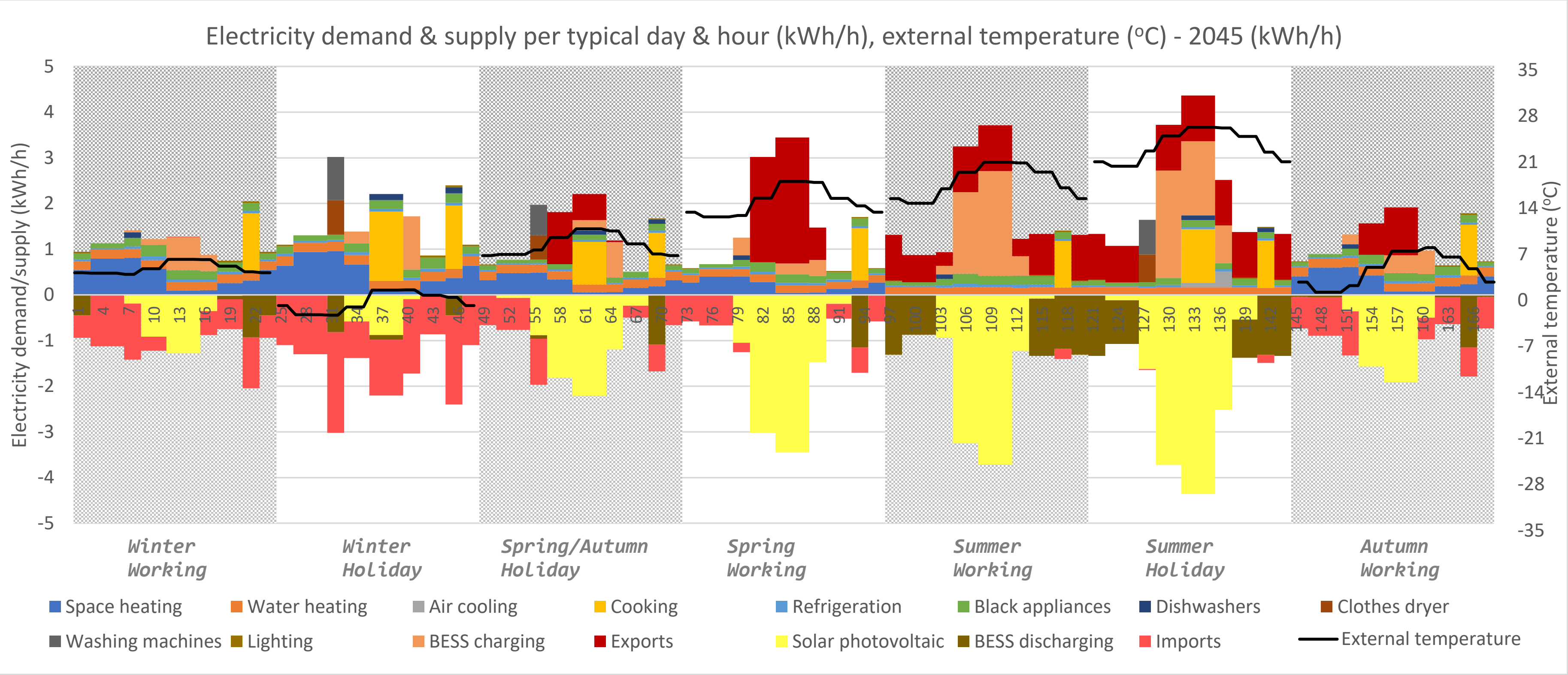
At the level of the hourly operation (Figure 12), now the electricity imports occur less frequently and are of lower volume. Where possible, they are replaced by operating the BESS. This is made possible by charging the BESS during hours of high PV availability instead of exporting the surplus amount of energy to the grid (this is particularly evident in the winter working day).

Figure 11 Annual electricity supply per origin for the historical year 2020 and for the projection period (2025-2050) – case with stepwise electricity grid price.



Source: newTRENDs – own calculation

Figure 12 Electricity demand per use/appliance and electricity supply per origin per typical day and hour (kWh/h); external temperature per typical day and hour (˚C) – year 2045 – case with stepwise electricity grid price.



Source: newTRENDs – own calculation

5. Concluding remarks – discussion

5.1 The prosumager model within newTRENDs

The prosumager model developed within Task 5.3 of newTRENDs is designed as an enhanced demand modeling option both for covering new trends in energy consumption and for assessing the impacts of policies on energy demand. The core features of the model are designed in such a way as to take advantage of the analysis performed in the other Work Packages (WP) of the project.

More specifically, the gap analysis of WP 3 (Yu, et al., 2021) indicates the new features that are needed to cover the various trend clusters as identified in WP 2 (Rosa, Mikova, & Brugger, 2022):

- The hourly simulation performed within the prosumager model allows to test the implementation of electricity pricing schemes that trigger behavioral changes in the electricity consumption of households (e.g., load shifting, load curtailment), thus covering the ‘digitalization’ and ‘smart metering’ trends.
- The incorporation of decision in local generation to meet household needs (or part of them), while considering the possibility of bidirectional electricity flows, covers the ‘electrification’ and ‘green transition’ trends, by tapping the potential for emissions-free resources.

At the same time, features of the PRIMES-BuiMo included also in the prosumager model help cover several other trends:

- ‘Increased urbanization’ is covered through a modified number of building types per location - urban, semi-urban, rural.
- ‘Decentralized work’, ‘increased awareness of citizens’, ‘energy and climate policies’ are covered through adjusting useful energy demand to account for behavioral changes due to trends and policies on working from home.
- ‘Alternative means for green finance’ and ‘increasing investment expenditure in energy efficiency’ are covered though the existing feature of investment subsidies and perceived costs.

The policy assessment, on the other hand, as performed within WP 4 (Kochanski, et al., 2022), indicates that almost all existing and emerging EU-level energy demand-side policies and instruments, other than those specifically related to the transition towards prosumaging, are either directly or indirectly considered within PRIMES-BuiMo. The design of the prosumager model makes it possible to consider most of the remaining policy instruments, namely:

- The features of local RES generation and BESS investment options may reflect relevant regulations regarding on-site energy generation, such as product standards for PV systems and batteries.
- Investment subsidies and perceived costs of RES generation and BESS may reflect economic and financial instruments promoting self-consumption.

- Efficiency class of local RES generation included in the prosumager model may reflect emerging soft instruments such as Energy Labels and Eco-Design.

The output of the prosumager model, on the other hand, allows to quantify several indicators that are of interest to policy making and are identified in the screening of demand-side policy needs. Applying the model on a variety of households per country with different characteristics (income class, location, type of dwelling, etc.), the following indicators can be potentially calculated:

- share of energy consumers in the residential sector that are self-consumers of renewables per category of consumer;
- share of energy consumers equipped with electricity storage facilities;
- share of energy consumers in the residential sector equipped with a gas boiler, heat pump;
- amount of energy stored, self-consumed, and injected into the national power grid;
- amounts of energy sold under TOU tariffs;
- share of building energy demand to be covered by RES.

Within WP 5, the smart meter data analysis performed in Task 5.1 may serve as part of ex-post analysis of the prosumager model results, either through comparison of consumption patterns, where possible, or as a data source of more accurate consumption profiles.

Throughout the rest of the modelling WPs, some initial linkages may be identified mainly with PRIMES/GEM-E3 (household consumption, disposable income may inform the prosumager model), and FORECAST/TERTIARY (shared assumption regarding the impact of the ‘home office’ trend on the floor space demand and on the energy demand shift from the tertiary sector to the residential sector), without excluding potential linkages to other models such as FORECAST/INDUSTRY and PRIMES/TREMOVE.

While the proposed approach is designed to describe in as much detail as possible the elements that affect the decision-making of a prosumager regarding the investment and operational options available, it comes with its own limitations. The application of the prosumager model for studying various policy frameworks described in this report should consider the following: while the simultaneous optimization of investment and operational decisions results in more informed investment decisions, there is a trade-off between the detailed representation of the hourly operation and the need to have a model that reaches its outcome within a reasonable amount of time. Simulating typical days and typical hours ensures tractability of the model but limits the ability to have a perfect representation of the hourly and sub-hourly operation of the household energy system.

Moreover, the model assumes a decision-maker that is rational and makes choices in a cost-optimal manner. However, other qualities may be present making the prosumager a hard-to-predict actor regarding the selection of equipment, appliances, and renovation interventions and resulting in counterintuitive decisions (even if this is rare).

5.2 The prosumager model within PRIMES

The prosumager model developed as an add-on option to PRIMES-BuiMo is formulated mathematically as a mixed-integer optimization programming problem. The decision-maker is the individual household, assuming rational behavior. Thus follows a different approach compared to PRIMES-BuiMo and its nested hierarchical choices that co-exist, each one assigned with its frequency through Weibull distribution.

Additionally, the core of the prosumager model differs from PRIMES-BuiMo in several aspects. More specifically, the prosumager model:

1. Does not perform the useful demand projection and the buildings stock projection. Instead, useful demand per use is an input to the prosumager model, as extracted from PRIMES BuiMo.
2. Features the investment decision on local generation units and BESS.
3. Applies optimization of the hourly operation of the equipment considering bidirectional energy exchange with the electricity network.
4. Allows differentiating the electricity pricing scheme to test demand response options.
5. Performs the optimization of the decisions considering the entire horizon under study. PRIMES-BuiMo performs also an intertemporal optimization but with oscillating horizons.

However, the model shares common ground with PRIMES-BuiMo in the following aspects:

- endogenous decision of the timing and depth of renovation;
- equipment and appliance choice;
- input data for shared features;
- energy policy drivers.

Therefore, a combination of both approaches offers several options for modeling new demand trends, existing, emerging policies as well as foreseen policy needs.

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