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EXECUTIVE SUMMARY OF THE THESIS

Optimization model of an energy community system with focus on the thermal sector electrification

TESI MAGISTRALE IN ENERGY ENGINEERING – INGEGNERIA ENERGETICA

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1. Introduction

The European Council endorses the objective of achieving climate-neutrality by 2050, integrating it in the 'Clean energy for all Europeans package', adopted in 2019. Italy, as a state member of the European Union, adopts the objectives related to climate action, within the 'National Energy and Climate Plan (PNIEC)'[1]. Two directives at European level enhance the spreading and promotion of energy communities: the 'Renewable Energy Directive' (RED II) [2] and the Directive (EU) 2019/944 (IEM) [3]. Italy integrates these ones through the combination of 'Legge 8/2020' [4], the regulation model identified by ARERA [5] and the incentive system defined by 'Ministero per lo Sviluppo Economico'[6]. One of the key elements considered in the documents cited above is the definition of renewable self-consumers and energy communities (EC) [7]. The EC is a group of final customers which produce electricity from renewable energy sources (RES) for self-consumption and can store or sell it. Within ECs, two categories can be identified: collective auto-consumption (AC), if participants are in the same building or renewable energy community (CER) if they are dislocated in single-family buildings. These schemes allow to obtain environmental, economic and social benefits at community level, and are also considered as an effective tool to increase public awareness and acceptance of new projects, mobilize private capital for the energy transition and increase the flexibility of the electricity system [8] [9]. In this work, both the AC and CER schemes can be modelled. For what concerns the approach for the EC constitution, the virtual one is considered, which consists in relying on the national electrical grid for the energy exchange between generation and consumption units [5]. Another useful element for the energy transition is the sector coupling, which can provide flexibility to the electrical grid. Several articles treat about the sector coupling, such as Gea-Bermúdez et al. [10], which analyzes its role in the energy system of northern-central Europe, or Hrvoje Dorotić et al. [11], that presents a novel approach to define the energy system of a carbon neutral island, only supplied with intermittent RES. Also, articles that treat about ECs have been analyzed, such as Bernadette et al.[12], which investigates the profitability and optimal installation capacities of photovoltaic (PV) systems in ECs with respect to

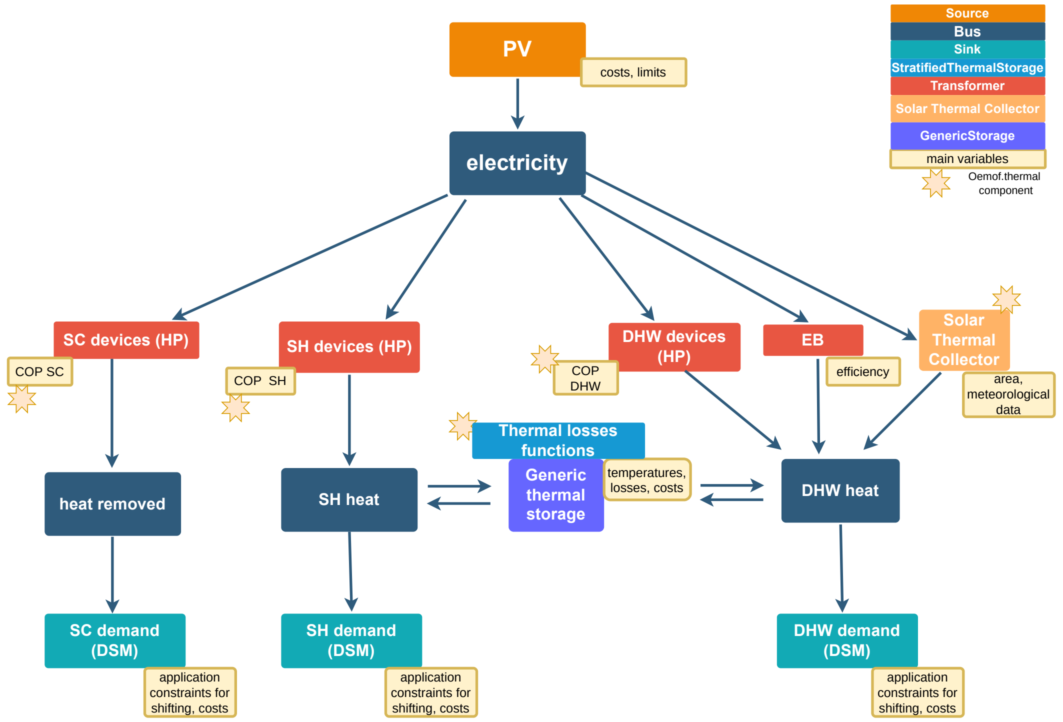

Figure 1: *Scheme of the single user's thermal items, represented by Oemof components.*

individual buildings, or Zatti et al. [13], who proposes a novel methodology to design and manage ECs. More details can be found in Table 9 (Appendix A). What emerges is a lack in the development of optimization models which integrates sector coupling in ECs. The study presented in this work aims at proposing a detailed and versatile optimization model of an EC, which focuses (i) on the thermal sector integration and electrification, (ii) on the detailed modelling of space heating (SH), cooling (SC) and domestic hot water (DHW) production devices (flexible setting options, technical temperatures, hourly COP), as well as of (iii) thermal storage, and (iv) on the attention to the single EC members characterization. Also, the demand side management (DSM) is implemented for all the demand profiles. This work presents a bottom-up optimization model characterized by hourly resolution and considering a time span of one year, which has been developed by using oemof [14] (Open Energy Modelling Framework), a Python toolbox for energy system modelling and optimization. An additional novelty is the use of an open source model, and in particular of both oemof solph [15] and oemof thermal [16] packages.

The work is structured as follows. Section 2 describes the methodology used to develop the model. Section 3 describes different case studies, used to evaluate the thermal sector integration and electrification in ECs. Section 4 shows the main results and Section 5 draws the conclusions.

2. Methodology

A bottom-up Single-Objective optimization model of an EC with focus on thermal sector electrification was developed. Objective function and power balance are reported in equations (1) and (2), where i stands for input, o for output, n for node, vc are the flows variable costs, epc are the periodical costs, E stands for the electric or thermal energy, L for load, gen for generated, charge and disch for charged and discharged and sh for shortage, which can enter or exit the node.

$$Obj = \sum_{i,n} \sum_{o,n} \sum_{t} flow_{i,o,t} \cdot vc_{i,o,t} + \sum_{n} inv_n \cdot epc_n \quad (1)$$

$$L_{n,t} = \sum_{n} (E_{gen,n,t} - E_{charge,n,t} + E_{disch,n,t} - E_{excess,n,t} + E_{sh,in,n,t} - E_{sh,out,n,t}) \quad (2)$$

The EC is constituted by two or more households, each one modelled as a node, which main thermal components are represented in Figure 1. The variable parameters can be customized by the user, who sets them in the input excel file together with the number of households of the EC. This attributes to the model a high versatility. In the next sections the components of the EC model are described.

2.1. Demand Side Management

The DSM is an energy management technique that refers to a series of actions aimed to the optimal managing of energy consumptions [17]. DSM is considered in the model for all the demand profiles: the electrical one (EL) and the ones for space heating (SH), for space cooling (SC) and for domestic hot water (DHW). In this work the DSM is applied though the load shifting and shedding, techniques that make use of consumer demand elasticity, typically provided by thermal inertia, demand flexibility or physical storage. In the oemof model, DSM is implemented by using the SinkDSM component of the oemof solph package [15]. The 'DIW' approach, detailed in equations (3) and (4) and based on the model of Zerrahn et al. [18], is selected, being it the one that delivers best results in terms of demand curve representation, number of activations, optimal objective and time of execution [19].

$$\dot{E}_t = demand_t + DSM_t^{up} - \sum_{tt=t-L}^{t+L} DSM_{t,tt}^{do} \quad \forall t \in T \quad (3)$$

$$DSM_t^{up} + \sum_{tt=t-L}^{t+L} DSM_{t,tt}^{do} \leq max\{E_{tt}^{up}, E_{tt}^{do}\} \quad \forall tt \in T \quad (4)$$

DSM parameters have been investigated [20] for each demand profile and are reported in Table 1. Only load shifting is considered, according to Gils [20], which evidences the high costs and losses of comfort caused by load shedding, that make this approach mostly suitable for energy-intensive industrial processes.

Demand	Capacity up	Capacity down	Delay	Cost up	Cost down
SH	1	0.85	2	0.01	0.01
SC	1	0.3	2	0.01	0.01
DHW	0.9	1	12	0.01	0.01
EL	0.1	0.15	6	0.05	0.05

Table 1: *DSM parameters value.*

Due to the high impact on comfort and working routines caused by changes in the consumption pattern, the theoretical shift potential is reduced to a social potential [20], that reflect the load shifting impact a particular device has on user convenience (Table 1). The DSM application costs have been evaluated considering both investment costs, and O&M ones, which reflect the expenditures arising from the maintenance and utilization of the required ICT as well as compensation for losses in production output and comfort. The emerged values are represented in Table 2, which groups household devices in categories and attributes them costs.

Technology	O&M costs, var [€/MWh]
Heating AC-Res	10
Washing Equipment-Res	50
StorHeat-ResCom	10

Table 2: *Economic parameters of DSM technologies.*

2.2. Heat pumps and electric boiler

Heat pumps (HP) are becoming a key technology to enhance the renewable energy transition and to promote sector coupling. In this work, HP technologies are investigated and integrated in the model as one of the principal aspects to implement the electrification of the thermal sector in the EC. They are detailed and configured basing on different sources, domestic system typology, device functioning and operational options, sets by the user in the input file. Three types of sources are considered: air, ground source with ground heat exchanger and ground source which uses groundwater as source. The system can be based on air or water to air (AW/A) systems or air or water to water (AW/W) ones, furtherly divided in radiators, fan coils or floor heating systems. The HP categories are summarized in Figure 2.

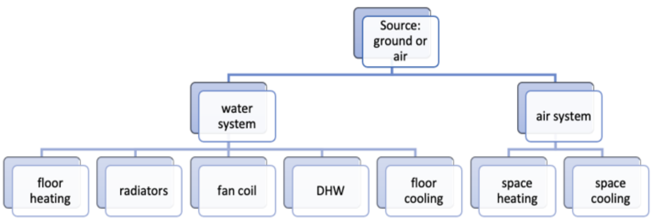

Figure 2: *HP categories considered in the model.*

The electric boiler (EB) is implemented in the system as an option for DHW production. HPs and EB are modelled though the 'Transformer' component of the oemof solph package that represents a node with multiple input and output flows (here electricity and heat flow respectively), converted through COP for HPs and through the efficiency for the EB. A precise evaluation of the hourly COP for each type of device is made by using the 'calc_cops' function of the oemof thermal package, which calculates it following equation (5). The COP^{Carnot} represents the ideal case COP (Carnot), corrected to consider the real case with the quality grade (φ), which values are reported by oemof documentation [14] and verified through Patteeuw et al [21]. Flow temperatures are defined in detail depending on the typology of HP implemented.

$$COP^{real} = \varphi \cdot COP^{Carnot} = \varphi \cdot \frac{T_{sink}}{T_{sink} - T_{source}} \quad (5)$$

Air system for heating/cooling

Comfort temperatures for domestic ambient in summer (25°C) and winter (21°C) season are reported in 'UNI EN ISO 7730:2006' [22], and integrated in the model. For summer season it is necessary to keep in consideration the contribution of radiation, which represents an additive heat gain inside the building, so a delta temperature of 3°C is set.

Water systems for space cooling

The approach of Karakoyun et al. [23] is integrated in the model. This studies the impact of different configurations of heat gains on the internal ambient temperature to define the supply cold water temperature in the system, in order to keep the floor one in the normative range [22].

Water systems for space heating

The typical hot water delivery temperature range for each water system has been identified [24] [25]: 30-45°C for underfloor heating systems, 35-55°C for fan coils systems, 45-60°C for radiators systems. The usual delta temperatures which occur during the transfer of heat to the internal ambient have been individuated [26] and are 10°C for fan coils systems, 15°C for radiators systems, 5°C for underfloor heating systems. Two possible regulations of the supply temperatures can be applied: the fixed-point regulation, in which the supply temperature of hot water in heating systems is constant, and the thermoregulation, where the supply temperature is adapted basing on the external ambient temperature. A function created from scratch ('climatic_regulation') builds a curve starting from minimum and maximum flow temperatures of water and ambient temperatures in the considered 'on' period for space heating [27], depending on the climatic zone of the EC. The chosen settings for heating systems are set by the user in the input file.

Domestic hot water production systems

To avoid Legionella risk [28], two types of thermal disinfection treatments can be applied: the continuous treatment, that consists in maintaining the water temperature above 50°C for all the hours of the day, or the periodic treatment, which keeps the water temperature at a lower value for all day (40°C) but then raise it to 65°C for at least 30 minutes per day. The choice on the treatment used is set by the user and then applied in the model through the created function 'periodic_treatment'.

2.3. Thermal storage

Thermal energy storage (TES) is considered in the model for both SH and DHW (separated for a more precise evaluation) and its installation is evaluated for each user. In the oemof thermal package, TES is modelled through the 'Stratified Thermal Storage' (STS) component, characterized by two perfectly separated bodies of water with temperatures 'high' and 'cold'[29]. The contribution of the STS is principally the evaluation of the thermal losses and the nominal storage capacity, however the component lacks in the possibility of using the 'NonConvex' option [15], useful to consider economies of scale and which objective function is detailed in equation (6), where E_{invest} is the invested capacity of the storage, $c_{invest,var}$ and $c_{invest,fix}$ are the variable and fix investment costs and b_{invest} is the binary variable for the status of the investment.

$$Obj = E_{invest} \cdot c_{invest,var} + b_{invest} \cdot c_{invest,fix} \quad (6)$$

Also, STS requires the definition of the diameter of the tank to evaluate losses and capacity. To overcome these issues, TES is implemented in the model by using the 'Generic Storage' component of the oemof solph package, integrated with the 'calculate_losses' function of the STS one, which evaluates relative and absolute thermal losses. The temperatures that characterize TES are the hot flow temperature of water for the hot side, and return/supply temperature of water for SH/DHW. For DHW, even if a supply temperatures of 6°C in summer and of 15°C in winter have been identified by [26], the cold temperature for TES is set to 20°C, according to [30] schemes and to the limits for Legionella survival [28]. To implement the investment mode considering economies of scale a curve is created, and it is represented in equation (8), where C is the installed TES capacity and y the total cost ([31][32]). The actualization is made through oemof tools [14] and represented by equation (7), where epc are the periodical costs, capex the investment costs, lifetime is the life expectancy and wacc is the weighted average cost of capital.

$$epc = capex \cdot (wacc \cdot (1 + wacc) \cdot \frac{lifetime}{(1 + wacc) \cdot lifetime - 1} \quad (7)$$

$$y = 23C + 305 \quad (8)$$

2.4. Solar thermal collector

The solar thermal collector (STC) is considered in this work as a support to other technologies for DHW production, according to IEA estimates [33], and articles [34] and [21]. The STC is integrated in the model through the 'SolarThermalCollector' component of the oemof thermal package [16], created to evaluate the usable heat of a flat plate collector based on temperatures and collector's location, tilt and azimuth. These parameters, together with the latitude and longitude in which the EC is located, are added by the user in the input file. The user will set the 'available' space left after a first optimization in which PV capacity is optimized, and this constitutes the limit for STC application (different for CER and AC). Data about the optical efficiency and thermal loss parameters are the ones of the 'Viessman vitosol 200-fm' [35]. The hourly irradiance data (horizontal, global and diffuse) are generated using the 'Photovoltaic Geographical Information System' (PVGIS [36]) software of the 'EU SCIENCE LAB'. The inlet water temperature is assumed to a value of 20°C [37], as it is extracted from the thermal storage cold side. The delta temperature due to the solar thermal collector is assumed to 10°C [38].

2.5. Photovoltaic system

The main RES of electricity considered in this work is the photovoltaic one, as it is becoming the cheapest source of power in many economies [39]. However, in the 'sources' sheet of the input file other sources could be implemented. The national electrical grid is also considered as a source. The normalized PV production profile can be set by the user in the input file depending on the EC location (the one used in this work is simulated through PVGIS [36]). The limit of PV capacity installed depends on the available surface, that differs in the cases of CER and AC, similarly than in the case of STC, and it is equal to the 50% of the house one (to consider the unusable north side of the roof and eventual shaping objects). The limit capacity is calculated as the ratio between the available surface and the surface occupied by 1 kWp of installed PV capacity (5.4 m^2/kWp [40]). Costs have been implemented by using the 'NonConvex' option of the oemof solph Investment mode, and the real turn-key costs on which the interpolation curve is based are the one proposed by Enel-x Store [41]. The cost curve is represented in equation (9), where P is the installed PV power and y the cost.

$$y = 1011.4P + 2041.1 \quad (9)$$

2.6. Electric storage

An electric storage is added in the model to allow a realistic optimization which also considers the aspects relative to the electric sector, besides the electrified thermal one. The input parameters are referred to the battery 'LG CHEM RESU SERIE' [42] and economies of scale are implemented by using the 'NonConvex' option in the 'Investment' mode. The cost curve is reported in equation (10), where C is the installed capacity and y the cost.

$$y = 620.83C + 2140 \quad (10)$$

2.7. Shared electricity

One of the principal characteristics of energy communities is the sharing of energy (in this case of electricity) between the community members.

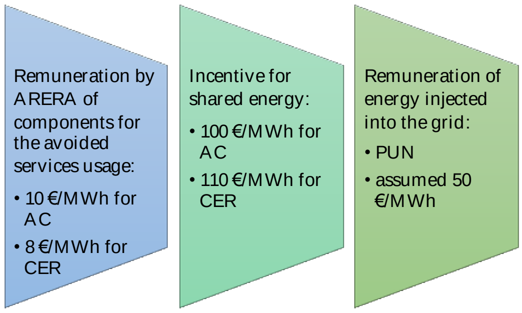

Figure 3: *contributes of the economic support scheme for Ecs*

Shared electricity flows can be modelled in oemof solph thanks to the 'Link' class [15], that takes as input the two buses between the energy is shared (in both directions) and a conversion coefficient which is in this model considered equal to one, being it a 'virtual' sharing. The shared and injected into the grid electricity valorization values defined in support schemes have been implemented in the model (Figure 3). The shortage is considered for all the flows, and its cost is deepened in a sensitivity analysis to evaluate the effective advantage of the thermal sector electrification.

2.8. Demand Profiles

Demand profiles of EL, SH, SC and DHW are made with the aim of proposing values which can reflect the Italian situation. From 'Istituto Nazionale di

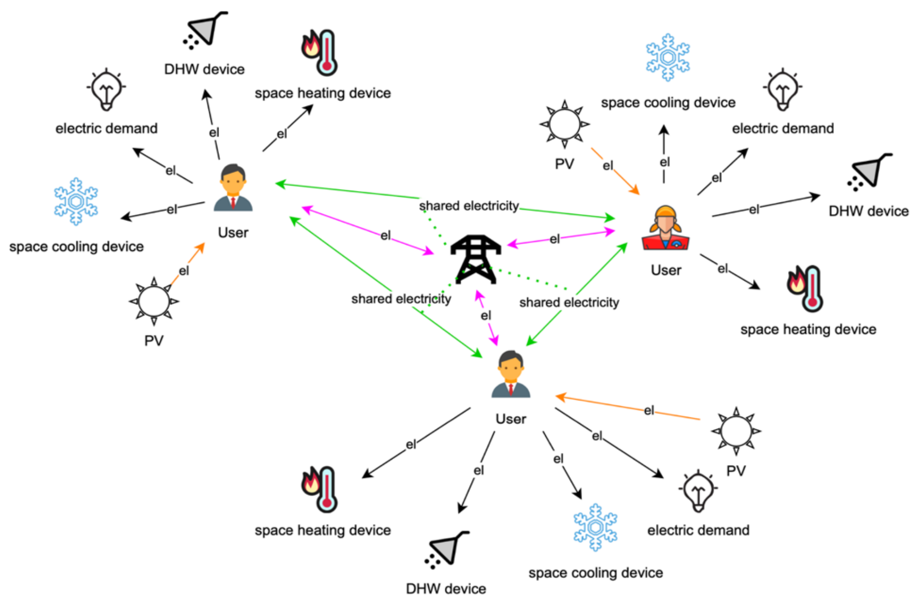

Figure 4: *EC scheme with electricity flows.*

Statistica' (ISTAT) data about families' number of components and about families' typologies have been selected. Percentages relative to these classes have been crossed and associated to categories of 'Load Profile Generator' (LPG), a tool used to generate demand profiles depending on several factors. The resulting composition of the model population is obtained by the combination of the two set of data and is reported in Table 3.

Combined categories		
ISTAT	LPG	%
alone persons	CHR10	33.63
couples without children (over 65)	CHR16	6.57
couples without children	CHR01	21.75
couples with children, 3	CHR03	14.56
one parent with children, 3	CHR08	4.86
couples with children, 4	CHS01	11.72
couples with children, 5	CHR05	2.99
one parent with children, 4	CHR50	3.92

Table 3: *Italian population categories with data obtained from ISTAT and LPG.*

Then, for each one of the categories described, an hourly EL demand profile expressed in kWh and an hourly DHW demand profile expressed in liters have been generated by using the LPG tool, and the DHW demand is converted in kWh by means of the created function 'DhwDemand_Lh_KWh'. For the calculation, a hot water temperature of 48°C is considered [43]. The cold temperature is equal to the supply one described in section 2.3. A function was created from scratch to generate SH profiles ('Thermal_Profiles') following the instructions of the 'EN 15316-4-2:2018' regulation [44], based on the bin-method, which allows to obtain the yearly SH and SC profiles considering the trend of the ambient temperature and the energy label of the building. Details are reported in equations (11) and (12). The same procedure with different values is followed in the 'Cooling_Profiles' function, created to generate SC profiles for each user.

$$Q_{SH,i} = Q_{max} \cdot \delta_i \cdot \frac{T_{bil} - T_{amb,i}}{T_{bil} - T_{design}} \qquad (11)$$

$$Q_{max} = \frac{Q_{annual}}{\sum_i^{year} \delta_i \cdot \frac{T_{bil} - T_{amb,i}}{T_{bil} - T_{design}}} \qquad (12)$$

Q_{max}: *maximum energy required in the coldest condition*
T_{design}: *minimum ambient temperature*
δ_i : 1 *when system is ON*, 0 *when system is OFF* [45]
Q_{annual}: *yearly energy demand for the house*
T_{bil}: *balancing temperature*

2.9. EC model details

All the components and the demand profiles described in the previous sections have been integrated in a generic EC model, which can be fitted to the considered case. The scheme of the EC with electricity flows details is reported in Figure 4. In the model, a dictionary called 'Users' is created to collect all the data about the EC members, defined through the created function 'users_statistics', which applies the evaluations made in section 2.8. Surfaces and energy classes are assigned considering the Italian situation. The energy class is uniquely set and imported from the input file if the EC is an AC, otherwise it is assigned through the created 'EnergyClass_assignment' function, which considers ENEA [46] statistics. The annual consumption for SH and SC for each energy class have been evaluated considering the relative weight of these components on the overall one, reported in the legislation [47], based on the case studies proposed by ENEA [48]. Another dictionary ('devices') is created to collect all the imported or elaborated data about devices.

3. Case studies

The EC considered is composed by five members, which characteristic reflect the Italian situation. For each case study different configurations concerning water treatments, space heating and cooling technical settings, electricity prices, sources and other aspects are considered. The characteristics assigned to the users, constant for each configuration, and based on 2.8 and 2.9, are summarized in Table 4.

User	LPG class	Energy class	SH consumption [kWh/y·m^2]	SC consumption [kWh/y·m^2]	House surface [m^2]	EL demand [kWh]
A	CHR10	A1	30.4	0.8	74	4122.84
B	CHR10	E	197.6	5.2	74	4122.84
C	CHR01	F	266.0	7.0	74	5198.25
D	CHR03	G	304.0	8.0	74	4854.90
E	CHS01	G	304.0	8.0	124	6290.95

Table 4: *EC users characteristics.*

In Figure 5 it is possible to appreciate differences in total electricity consumptions (comprehensive of electrified SC, SH, DHW and EL) for the EC users.

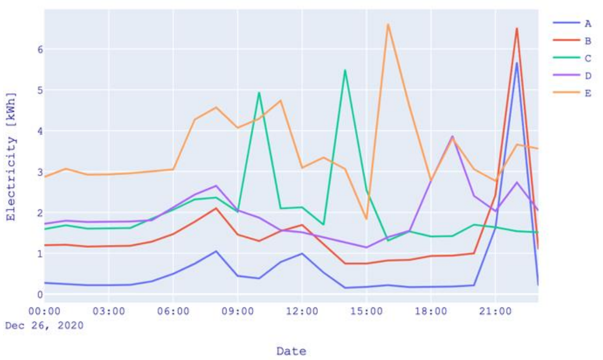

Figure 5: *Total electricity consumptions for EC users, 26th December.*

Details about analyzed configurations are reported in Table 7. Electricity dispatch, economic and emissions results are explained in section 4 (Table 5, Table 6 and Table 8).

3.1. Case study n.1

Location: Milan.

Configuration n.1 (reference):

- CER
- Meteorological data: Milan, 2020
- Climatic zone: E
- Electricity price: 200 €/MWh
- PUN: 50 €/MWh
- Thermoregulation for space heating
- Periodic treatment for DHW
- Air source heat pumps
- STC not activated

In Figure 6 the electricity entering/exiting each node is represented. PV are installed only for three out of five members, while the other two benefit from the electricity sharing. All the users still rely on the national grid, used to cover the periods of low electricity production from PV. In Figure 7 the COP variation in time is represented for each type of SH device, while in Figure 8 the related temperature variation for floor heating HP systems is evidenced.

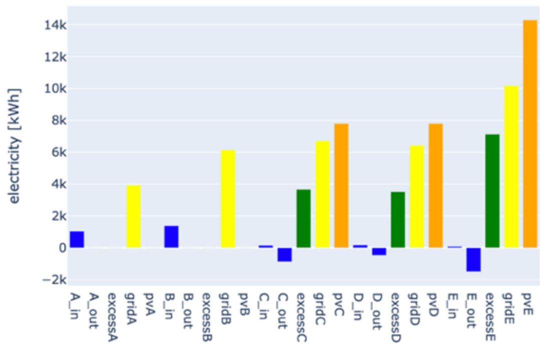

Figure 6: *Cumulated electricity entering/exiting each node.*

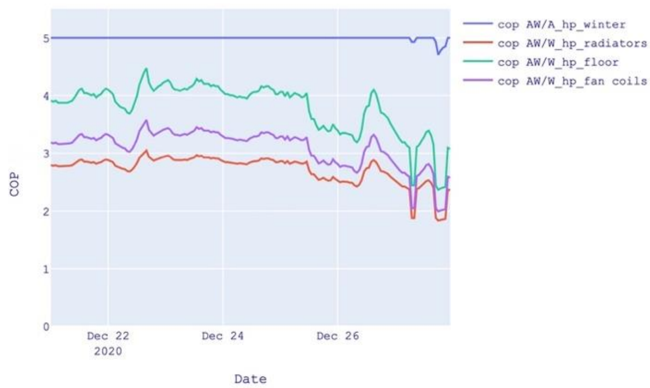

Figure 7: *COP variation in time for SH HPs, winter week.*

Figure 8: *Temperature variation in time, winter week.*

In Figure 9 electricity flows for user 'C' are reported, to evidence the functioning of energy sharing. The total annual electricity produced by PV and self-consumed by the EC, imported from the grid, and consumed by different loads is represented in Figure 10.

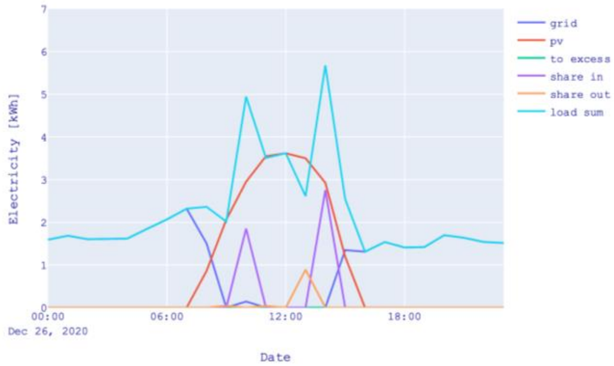

Figure 9: *Electricity flows analysis for user C, 26th December.*

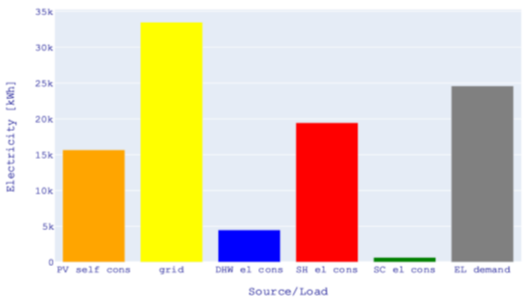

Figure 10: *Annual electricity production/consumption of the EC per source/load.*

3.2. Case study n.2

Location: Brindisi.

Configuration n.1 (reference):

- CER
- Meteorological data: Brindisi, 2020
- Climatic zone: C
- Electricity price: 200 €/MWh
- PUN: 50 €/MWh
- Thermoregulation for space heating
- Periodic treatment for DHW
- Air source heat pumps
- STC not activated

In Figure 11 the COP variation in time for SH HPs can be appreciated and compared with the one proposed for Case study 1. The other configurations referred to these case studies are described in Table 7, where differences with respect to Configuration n.1 are evidenced. Electricity dispatch, economic and emissions results are reported in section 3 (Table 5, Table 6 and Table 8).

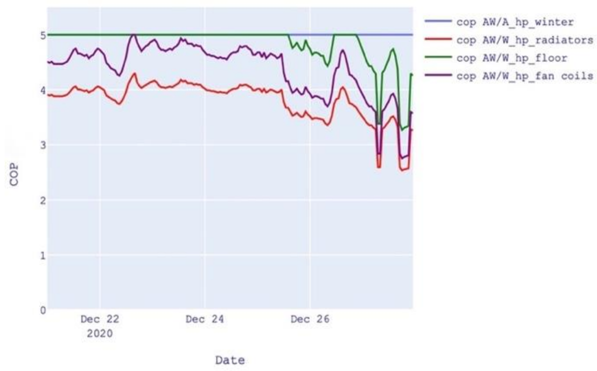

Figure 11: *COP variation in time for SH HPs, winter week.*

4. Results

It is possible to notice the influence that flexible setting options, location, technical temperatures, sector coupling, and in particular thermal sector electrification have on results (Table 5, Table 6 and Table 8).

First, the reference configuration shows a positive net present value (NPV), which makes the investment profitable. PV cover nearly the 32% of the overall electric demand, comprehensive of the electrical and thermal ones. 18% of the EC self-consumed energy is shared but also nearly half of the one produced is injected in the national grid. In Configuration n.2 (2/1 vs 1/1) the electricity consumption for SH is increased by the 34%, due to the different type of devices implemented, which are characterized by lower COPs. A lower Internal Rate of Return (IRR) and a higher Pay Back Period (PBP) show that the Investment is less convenient. Lower performances of thermal devices lead to higher excess electricity (50.31% vs 47.7%). In this case the TES installed capacity is equal to 156 kWh, while in the reference case only 31 kWh are implemented.

	Configuration / Case study							
	1 C1	2 C1	3b C1	4 C1	6 C1	8 C1	1 C2	2 C2
NPV	27519.78	27876.93	27714.18	29985.82	27282.11	19817.22	30095.61	29384.95
IRR	0.14	0.12	0.14	0.12	0.14	0.21	0.15	0.15
PBP	8	10	8	9	8	6	8	8

Table 5: *Economic results in 20 years.*

Configuration	CO2 emissions [ton/year]
1 C1	9
7 C1	13.63
8 C1	120.64

Table 6: *Emissions results.*

Configuration / Case study	Location	SH settings	DHW settings	Heat/cool source	PV	A/A HP	A/W HP	Solar Thermal Collectors
1 / 1 (ref)	Milano	Thermoregulation	Periodic treatment	Air	yes	yes	no	no
2 / 1	Milano	Thermoregulation	Periodic treatment	Air	yes	no	yes	no
3 / 1	Milano	Thermoregulation	Periodic treatment	Ground with hex	yes	yes	no	no
3b/ 1	Milano	Thermoregulation	Periodic treatment	Ground with hex	yes	no	yes	no
4 / 1	Milano	Fixed point regulation	Continous treatment	Air	yes	no	yes	no
6 / 1	Milano	Thermoregulation	Periodic treatment	Air	yes	yes	no	yes
8 / 1	Milano	-	-	-	yes	no	no	no
1 / 2	Brindisi	Thermoregulation	Periodic treatment	Air	yes	yes	no	no
2 / 2	Brindisi	Thermoregulation	Periodic treatment	Air	yes	yes	no	yes

Table 7: *Configuration characteristics with respect to the reference one.*

Configuration/ Case study	PV [kW]	SH storage [kWh]	DHW storage [kWh]	PV [kWh]	Grid [kWh]	HP cons SH [kWh]	HP cons SC [kWh]	HP cons DHW [kWh]	EL demand [kWh]	Self-sufficiency [%]	Shared [%]	Excess [%]
1 / 1	23	31	0	29839.40	33490.86	19447.7	636.5	4477.48	24589.79	31.86	18.28	47.70
2 / 1	29	35	121	37691.69	37051.49	26056.44	636.5	4498.72	24589.79	33.58	12.08	50.31
3 / 1	23	30	0	29893.4	33270	19349.6	636.5	4024.42	24589.79	31.54	18.96	48.72
3b / 1	23	26	60	29893.4	33663.8	20630.4	636.5	4014.36	24589.79	32.50	17.94	45.78
4 / 1	29	42	69	37691.69	41178,98	29124.07	636.5	5895.45	24589.79	31.65	11.75	49.41
6 / 1	23	26	60	29893.4	33361	19447.7	636.5	3982.11	24589.79	33.26	13.87	45.87
8 / 1	11	0	0	14296.84	16509.35	0	0	0	24589.79	32.86	64.04	43.48
1 / 2	23	39	0	29893.4	31274.35	15276	2127.92	4036.79	24589.79	36.42	18.34	43.92
2 / 2	23	40	0	29893.4	31088.84	15276	2013.87	3539.54	24589.79	36.33	17.01	44.80

Table 8: *Electricity dispatch results for different case studies and configurations.*

Due to optimized installed capacities of PV and TES, which lead to a better match between production/storage and demand profiles, the shared electricity percentage is lower. The impact of continuous treatment for DHW and fixed-point regulation for SH, instead of periodic treatment and thermoregulation, is evidenced in Configuration n. 4 (4/1 vs 1/1), in which the electricity consumptions for SH increase by nearly the 50%, and the ones for DHW by nearly the 32%, due to worst HP performances. In this case, the payback period (PBP) increases and the IRR decreases, making the investment less advantageous. The percentage of shared electricity decreases, due to the high TES installed capacity. The influence of the heat/cool source change, which leads to higher COP for HPs, is evident in Configuration n.3b (3b/1 vs 2/1), where the electricity consumption for SH is lowered by the 20.82%, and the one of DHW by the 10.77% with respect to Configuration 2. N. 3b emerges within Case study 1 as the best configuration, both for economic and energy aspect, allowing an NPV of 27714 € and a self-sufficiency of 32.5% The contribution of the solar thermal collectors installation for DHW production is investigated in Configuration n.6 (6/1 vs 1/1). This does not result profitable from an economic point of view and leads to limited electricity consumption savings. Traditional energy sources (methane for DHW and SH, electricity from grid for SC with the usage of a HP with fixed COP) are not selected as optimal ones nor in the first configuration nor in the one without the PV installation option, in which the choice is still to electrify the thermal sector and feed it through the electricity from the grid. In Configuration n.8 (8/1 vs 1/1) the impact of sector coupling is explored. The installed PV capacity decreases because it only must cover the EL demand, and emissions drastically increase due to the usage of methane to supply SH and DHW. The IRR seems to make the investment the most advantageous one, however the thermal demand is not covered and higher costs for each thermal kWh (0.11 €/kWh th) than in the electrified configuration (0.2 €/kWh el /COP) must be considered. The sharing increases due to economies of scale, which make the PV installation for only one user the optimal solution. An additional case is considered, which consists in Configuration n.8 with the introduction of sector coupling (with thermal sector electrification and PV constant capacity).

This shows a deep increase in the electricity self-consumption by the EC (excess from 43% to 21%) and a decrease in the sharing (64% to 51%) due to a better fit between demand and production profiles. The NPV increases together with IRR, which is now equal to 26%, and the PBP decreases to 5 years. However, the NPV is still higher in Configuration n.1, in which capacities are optimized for both electrical and thermal demands. These considerations show the advantages of thermal sector coupling and electrification in ECs. Economies of scale enhance the sharing between the EC members; however, their application is limited in configurations in which PV capacity is not fixed and the limit to PV installation (available surface) for different users is reached due to the higher demand related to sector coupling. The influence of the geographical location has been investigated in Case Study 2 (1/2 vs 1/1), where significative decreases in SH and DHW demands, but also an increase of SC one can be noticed. In this case, even if the installed PV capacity is the same than in the first configuration of Case study 1, dispatch differences are present. Higher PV production due to major values of irradiance, and lower thermal demands lead to an increase of the self-sufficiency of the EC, and so lower energy injected into the grid. The EC investment in Brindisi is more profitable than in Milan, due to more favorable conditions. However, the impact of solar thermal collector installation is still limited.

5. Conclusions

ECs are emerging as key elements of the renewable energy transition, however, in the literature overview, lacks in their modelling emerged. This work aimed at developing a versatile bottom-up Single-Objective model for an EC system focused on the thermal sector integration and electrification. At this scope oemof, an open-source modelling framework, was used. Attention was given to many aspects. First, DSM was integrated in a precise way in the model to optimize energy consumptions for all the demand profiles. Then, the single user model was developed, analyzing in detail all the components. In a second step, this was integrated into the EC model, in which each member was represented as a node. HPs were configured basing on different sources, domestic system typology, device functioning and flexible operating options, aspects which lead to different COPs. Thermal energy storage was considered and integrated with thermal losses calculation and economies of scale. Electric storage too is present. The main RES implemented is the PV one, whose limits are detailed for each scheme (CER or AC). As a sensitivity analysis to be conducted after a first optimization process, STCs were added for the support of DHW production. Electricity fluxes have been valorized considering incentives, remunerations and incomes deriving from the electricity injection into the grid. Also, CO_2 emissions were calculated to provide a complete overview of the described cases. The focus in this work was also on the characterization of EC users, made to reflect the Italian situation. Two case studies were developed to explore the potentialities of the model and to investigate the impact of thermal sector electrification and integration in ECs, together with the one of technical and flexible operation choices. The first case study was in Milan, while the second one in Brindisi, to underline the impact of the geographical location. For both cases different configurations were characterized. Results show the impact of the technical settings, which lead to different COP of HPs. This causes different electrical consumptions, different optimal capacities for PV and TES, and differences in the electricity dispatch, which in some cases valorizes the sharing while in others the self-consumption. Investments on ECs with thermal sector electrification resulted to be profitable. The electrification of the thermal sector emerges as the optimal solution too in the case PV are not activated. Relevant advantages of the electrified thermal sector integration in the EC were demonstrated, both in economic, emissions and energy dispatch terms. At the contrary, STCs have not been evaluated as a profitable investment, and their contribution for DHW production was limited. Future developments of the work could be related to the development of a Multi-Objective optimization model, also focused on emissions optimization. It could be interesting to evaluate the district heating option and the introduction of the electrified transport sector in the EC model.

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Appendix A

Reference	Sector	Optimisation	Objective function/Simulation	Software/Solver	Temporal/Spatial resolution	Zone	Source	Implemented aspects
Gea-Bermúdez [10]	Electric, Thermal (space heating, dhw), Transport	capacity and operation	minimise discounted system costs/-	Balmorel	hourly/bidding zones	United Kingdom, Belgium, Netherlands, Germany, Poland, Finland, Sweden, Norway, and Denmark	wind & PV	• Factors impacting sector coupling
Hrvoje Dorotić [11]	Electric, Thermal (space heating and cooling, dhw), Transport	supply capacities with constraints	minimization of investment costs and total electricity import/ energy demand	LEAP and EnergyPLAN	hourly/ island	Croatian Island of Korčula	wind & PV	• Import/export balance • CO2 emissions
Gils [20]	Electric, Thermal (space heating, dhw), Transport	capacities and operation of the infrastructures for energy conversion, storage and transport of power, heat, hydrogen, and methane	cost minimisation /-	REMix	hourly/ region	Germany	wind, hydro, PV, hydrogen	• Hydrogen penetration
Rinaldi [49]	Electric, Thermal (space heating, dhw)	optimal capacity and schedule of power assets	cost minimisation /-	GRIMSEL-AH / CPLEX	hourly (electricity) and daily (heat)/country	Switzerland	PV	• Future energy mix scenarios
Calise [50]	Electric, Thermal (space heating and cooling, dhw)	-	_/polygeneration system	TRNSYS	daily, monthly, yearly/ island	Pantelleria	solar and geothermal	• Desalinated water production • Heat dissipation
Maruf [51]	Electric, Thermal (space heating, dhw)	energy mix and capacity investment	cost minimisation /-	OSeEM-DE from Oemof	hourly/country	Germany	wind, solar, hydro, biomass	-
Bernath [52]	Electric, Thermal (space heating, dhw), Transport	capacity expansion and hourly dispatch	cost minimisation /-	Enertile	hourly/continent	Europe	PV, CSP, wind	• EU energy market • Future energy mix scenarios
Jimenez-Navarro [53]	Electric, Thermal (space heating and cooling, dhw)	power dispatch	cost minimisation /-	Dispa-SET	hourly/continent	Europe	CHP	• CO2 emissions
Østergaard [54]	Thermal (space heating and cooling, dhw)	-	_/energy system	energyPRO	hourly/region	Denmark	CHP, Heat sources	• Energy efficiency • Hourly varying factors
Bernadette [12]	Electric, Thermal (space heating and cooling, dhw)	NPV, capacities, energy flows	maximize net present value/-	Yalmip / Gurobi	hourly /EC	fictitious	PV	• Building typology impact
Zatti [13]	Electric, Thermal (space heating and cooling, dhw)	capacities, energy flows	best cash flow for community/-	-	typical day/EC	Italy	PV	• Shapley value to distribute benefits
Martorana [55]	Thermal (space heating, dhw)	-	_/plant operation	TRNSYS	hourly/ micro EC	South of Italy	PV & PVT	-
Di Lorenzo [56]	Electric, Thermal (space heating, dhw)	-	_/energy sharing	Matlab/Simulink	hourly/building	Italy	PV	• Unidirectional electricity sharing • Optimal control strategies for energy sharing
Moncecchi [57]	Electric	capacity of generators and storage	maximize economical value of investment/-	Python / Gurobi	hourly /EC	Italy	PV & hydro	• Shapley value to allocate costs and benefits
Fouladvand [58]	Thermal (space heating, cooling, dhw)	-	_/community formation	PAW	daily /EC	Netherlands	renewable thermal energy sources	• Technical and institutional factors influence on EC formation • ABM approach
Casalicchio [59]	Electric	capacity and dispatch	cost minimisation /-	Oemof / Gurobi	hourly /EC	Italy	PV	• BM schemes • DSM strategy • TOU tariffs • Regulatory framework • Clustering • Composition analysis
Liu [60]	Electric, Thermal (space heating, cooling, dhw)	equipment capacity	multi-objective: emission reduction rate, annual cost minimisation, energy saving rate/-	Python / NSGA II	hourly /EC	Beijing	PV, ICE	• CO2 emissions
This Work	Electric, Thermal (space heating and cooling, dhw)	capacity and dispatch	cost minimisation/-	Oemof / Gurobi	hourly /EC	Italy	PV, solar	• DSM strategy • Hourly COP • Italian regulatory framework • Italian population composition • Flexible setting options • Economies of scale • Technical temperatures

Table 9: *Literature overview.*