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Renewable Energy Source (RES)-Based Polygeneration Systems for Multi-Family Houses

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Abstract: This research work synthetizes the energy, economic, and environmental aspects of a novel configurational analysis of four polygeneration schemes designed to fulfill the demands of a multi-family building that includes 12 dwellings. The design aims to meet the requirements (water, electricity, heat and cold air) from Renewable Energy Sources (RESs), in particular by selecting photovoltaic and photovoltaic-thermal panels, thermoelectric generators, and biomass as auxiliaries. Electricity is available from the grid, and no electrical storage is planned. Water and cooling may be produced by alternative technologies that configure the polygeneration alternatives. The case study is in Valencia, a coastal Mediterranean city in Spain. The Design Builder Clima estimated demand calculations, and the system performance was modeled in TRNSYS. Desalination was linked by using EES models. Results show that the suggested schemes offer substantial energy and CO_2 savings. The innovative life-cycle analysis applied further enhances the cumulative CO_2 savings across the four configurations if the impact of the installations is compared with the conventional external supply. The electric option (combining heat pump and reverse osmosis for cooling and desalination) emerged as the most appealing solution due to its reliability, lower investment cost, and environmental impact.

Keywords: multi-family houses; PVT panels; RES-based polygeneration

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1. Introduction

Structures in our close European context are responsible for forty percent of the consumed energy and about the same percentage of CO_2 released to the atmosphere; similar figures are found in similarly developed countries [1]. Achieving the ambitious goal of decarbonizing the construction sector over the next 35 years necessitates the implementation of energy transition strategies. Furthermore, regulatory changes must be made and investments in energy efficiency must be supported, particularly for existing buildings. Three forward-thinking Directives on Energy Performance of Buildings were authorized over the last two decades [2–4]. These directives have enhanced building enclosures to minimize energy waste and have been incorporated into national legal frameworks. Accordingly, starting in the last decade, constructions have been built aimed at meeting nearly zero-energy standards. In the future, regulations will aspire to achieve zero greenhouse gas emissions by 2050.

On the one hand, improving the thermal envelope is an effective strategy for reducing final energy consumption and improving thermal comfort, with potential significant cuts in demand [5]. In terms of primary energy, approximately one-half of the requirements in typical homes are associated with heating, ventilation, and air conditioning, making regulations crucial in decreasing buildings' energy consumption [6]. Unfortunately, the efficacy of building energy codes is heavily dependent on their mandatory and enforced nature [6], as demonstrated by analyses of these codes [7] in close areas with similar atmospheric scenarios [8].

The remaining energy demands must be met sustainably. One way to achieve this is by implementing a polygeneration scheme, which can provide a secure and sustainable solution for buildings by producing electricity, heating, cooling, and fresh water from one or several energy resources. While those systems have been employed in various industries, sometimes utilizing non-renewable energy sources or producing different products, they have shown promise as a sustainable option for buildings [9,10]. Other reviews on polygeneration focus on using biomass as a primary source [11,12], the use of solar energy [13], or optimizing its integration in buildings [14]. Sustainable solutions have been proposed for meeting diverse electricity, fresh water, heating, and cooling needs using only biomass [15] or solar energy [16,17]. Other studies have dealt with polygeneration schemes to solve the supply to islands by using solar energy alone [18–21] or in combination with biomass [22–25]. However, when considering electricity, air-conditioning, and water, specifically for buildings, the state of the art is somewhat reduced. Sometimes, the water is not provided by the scheme using solar energy [26] and helped by biomass [27], or the polygeneration supplies the demands of the building by using only biomass [28] or solar energy [29]. Simulations are usually conducted to optimize the design of the proposed plant, analyze its energy usage, environmental impact, and economic viability, and assess its sensitivity to external factors. Therefore, to the best of our humble knowledge, the configurational analysis described here using solar and biomass for a polygeneration scheme for the residential sector has not been described previously. Noteworthy is also the lack of experimental installations, even pilot-scale ones, given the complexity of the schemes, that would allow validation of the simulations performed in the previous studies.

In areas near the coast where water is scarce, a polygeneration scheme that relies primarily on heat provided by renewable technologies like hybrid solar panels and a biomass boiler is a viable option. Regardless, it is important to explore various options for producing cool and desalted water to determine the optimal integration. Many of the papers previously analyzed have only dealt with one configuration in a specific case study. Thus, the major contribution presented here is the examination of various structures of polygeneration schemes based on renewable thermal energy to meet the energy and water demands of a 12-dwelling building. Another innovative aspect is the analysis of the additional electricity contribution of Thermoelectric Generators (TEGs) to the system coupled to thermal devices.

The study conducted in Spain compared four configurations for the same type of building. Each configuration was designed depending on the choice for cooling of either a Heat Pump (HP) or Single-Effect Absorption Chiller (SEAC), and for desalination, Reverse Osmosis (RO) or Multi-effect Distillation (MED), resulting in unique combinations. The complete coverage, on a yearly basis, for electricity, fresh and hot water, and air conditioning was pursued for both configurations. The background for considerations under analysis is the primary energy saved ratio (PESR) with respect to the conventional supply of the building's scheduled demands. The study shows the obtained environmental benefits by comparing the CO_2 emissions throughout the entire life cycle, including the impact on construction, transport, and end-of-life disposal, in addition to the operational phase. This comprehensive approach, known as Life-Cycle Assessment (LCA), is also a novelty applied in the paper, to the best of our knowledge. This additional approach takes into account the environmental burdens associated with the materials used and the dismantling of the polygeneration scheme studied. In this way, a more complete vision of the best option in terms of sustainable performance is presented. The economic viability of the configurations was tested by using various well-known and rather simple metrics of the investment required, such as the Simple Payback Period (SPB), Net Present Value (NPV), and Internal Rate of Return (IRR). Levelized Costs (LC_x) of the five covered demands were also primarily assessed in order to determine, one by one, if the supplied demands are competitive concerning the alternative supply coming from external networks.

2. Methodology

Several software tools were consecutively used. The energy demands in the building were determined using the Design Builder v6 software. TRNSYS v18 was the main software to simulate the proposed four polygeneration configurations, coupled with EES v. 2020 for running certain complex desalination technologies. Then, output figures were collected, summarized, and analyzed in a spreadsheet. Afterward, SimaPro v9 was implemented for the environmental analysis.

2.1. Definition of the Required Flows

The multi-family dwelling is situated in Valencia, a city in Spain, with average official data [30]. It is a compact apartment building located between shared walls, representing a residential building from the 1970s typically found in medium or large cities. The general features of the building are summarized Table 1.

Table 1. Parameters of the multi-family dwelling.

Parameter	Value
Construction	Multi-family dwelling
Number of dwellings	12
Total people	48
Useful area per home (m^2)	100
Useful surface (m^2)	1200
Global surface (m^2)	1583
Volume (m^3)	4750.2
Number of above-ground floors	7 (6 + ground floor)
Number of below-ground floors	0
Overall height (m)	21
Number of bedrooms per dwelling	4
Orientation	North–South

Figure 1 presents the chosen building. Figure 2 shows the floor plan. The party walls facing east and west are deemed adiabatic, and all the dwellings' windows are on the north and south facades.

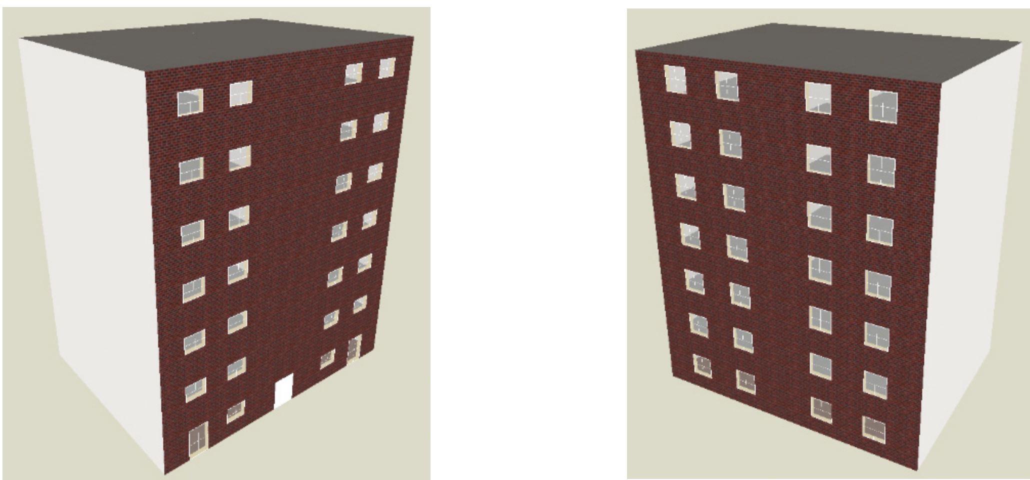

Figure 1. Building (north and south side, respectively).

The surface of all the windows on the south façade is 2 m^2, while on the north façade, their surface is 1.3 m^2. The entrance doors' surface is 1.6 m^2. The ground floor is slightly different from the floor plant shown in Figure 2, as it has two shops with a main 3 m^2 door and two additional entrances (2.6 m^2) for the two premises. The building does not meet the best energy efficiency standard, since it was selected as a typical construction from the 1970s.

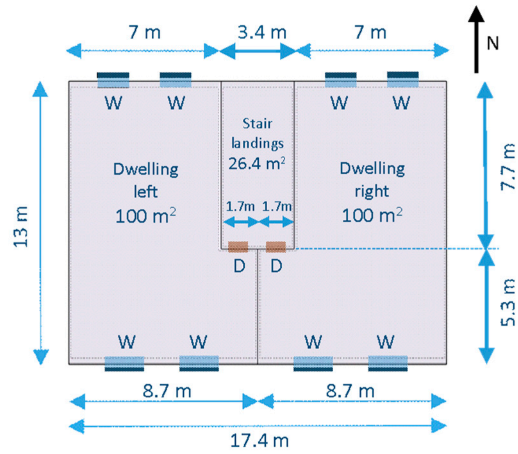

Figure 2. Scheme of the construction (W = window; D = entrance door). Source: adapted from [31].

It is located in Valencia, on the Mediterranean coast. It is coded in the Spanish regulation [32] as B3, with B corresponding to the winter climate severity (coded A–E) and 3 to the summer climate severity (coded 1–14). This climate can also be coded as Csa according to the Köppen-Geiger classification. Table 2 summarizes the main features of the place.

Table 2. Main data of the location (Valencia). Source: [32–34].

Zone	
Location	Valencia
Spanish/Köppen Geiger climate zone	B3/Csa
Latitude	39°28′ N
Altitude above sea level (m)	8
Yearly mean temperature (°C)	17.6
Solar irradiation (kWh/y)	1615
Average yearly wind (m/s)	3.1
Average yearly temperature of network water (°C)	14.6

The energy simulation tool in Design Builder provided the hourly acclimatization profiles. The electricity requirement was estimated according to the standard electric equipment and lighting loads set in the regulation [32].

The building energy model required the geometric definition, the thermal envelope characterization (U-values and thermal bridges), the flow demand performance, the cleaning of the air, and the climate data.

Considering the building practice of the 1970s [26], different U-values were taken: 2.5 W/(m^2·K) for the external walls, roof, party walls, and internal partitions; 2.35 W/(m^2·K) for the ground floor; and 5.7 W/(m^2·K) for windows. The usage profile followed the legal specifications in Spain [32]: the heating setpoint is 20 °C (day) or 17 °C (night) from October to May, while the cooling setpoint is 25 °C (afternoon) or 27 °C (night) from June to September. For internal loads, it is assumed that 3.51 W/m^2 is from occupants and 4.4 W/m^2 is from both lighting and equipment, assuming a typical hourly distribution [32].

Fresh water and domestic hot water (DHW) demands on an hourly basis were established from real records [35]. The monthly tap water temperature obtained from the national data sources [32] was considered to estimate the energy required for DHW.

Table 3 displays the yearly demands derived from the hourly simulations.

Table 3. Yearly demand for the case study, in kWh/y.

Location	Valencia
Heating (kWh/y)	60,625
Cooling (kWh/y)	13,882
Electricity (kWh/y)	33,455
Fresh Water (m^3/y)	1532
Hot Water (kWh/y)	24,060

2.2. Description of the Energy Configuration

The primary energy source commences with a solar field comprising PVTs (Photovoltaic-Thermal panels), a reservoir, and a cooling system to avert excessive heat buildup. Electricity demand is also facilitated by photovoltaic panels (PVs), complemented with TEGs installed on one-half of the PVT surface. The installation is equipped with an appropriate inverter to match the absolute power output, enabling energy exchange with the grid in response to demand and real-time production levels.

The domestic hot water demand and the heating are met by the tanks, ensuring adequate flow rates at 45 °C and 35 °C, respectively. The heated water is then returned at 25 °C, taking into account the presence of underfloor heating in the building.

For cooling purposes, there are two options available: an SEAC or an HP linked to a deep water body (about 15 °C). Regarding seawater desalination, two methods are proposed: using membranes (RO) or distillation (MED). A biomass boiler (BB) is utilized to maintain the setpoint temperatures for final uses. Additionally, TEGs are incorporated at the top of the BB to increase the power provided.

A 50 m^3 freshwater tank (FWT) controls desalinated water production in response to freshwater demand (FWD). The chosen cooling technology also includes an additional tank to prevent frequent on/off cycling of the HP.

The configurational analysis considers four different combinations, depending on the cooling and desalination technology adopted. The flows related to cold supply and fresh water are indicated as dotted lines in the configuration in Figure 3. Table 4 illustrates these four combinations.

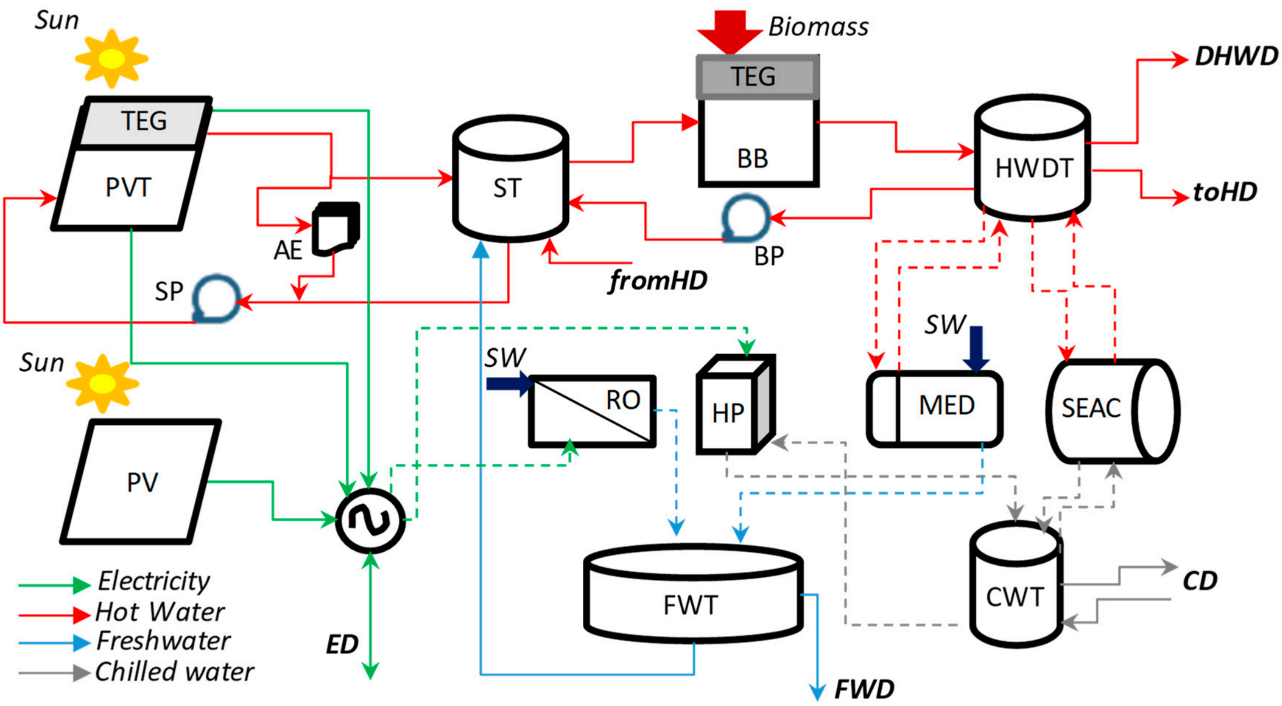

Figure 3. Global scheme for the configurational analysis. Source: [36].

Table 4. Details of the four available configurations.

Service	A	B	C	D
Electricity	PV + PVT + TEG			
Heating and DHW	PVT + (AE) + SP + ST + BB + BP + HWDT			
Cooling (CWT+)	HP	HP	SEAC	SEAC
Freshwater (FWT+)	MED	RO	RO	MED

Regardless of the specific combination chosen, each option's final design will exhibit variations concerning several aspects:

- The number of PV/PVTs utilized for electricity and heat generation.
- The heating nominal power of the biomass boiler.
- The cooling nominal power of the HP/SEAC.
- The storage volume to meet demand requirements.

The operating temperatures of some technologies were adapted according to the final configuration of the system.

2.3. Simulation Steps

The TRNSYSv18 software was implemented to model the configurations based on its type library. Normalized data in the existing HP and SEAC types were first adapted to meet the requirements of our building with variable load profiles. Secondly, the lack of a dedicated type for desalination was incorporated to complete the scheme. As a result, intricate models were initially created for RO and MED in the EES software and then linked to TRNSYS. Unfortunately, the solution was not fully operative for long simulation periods, and simpler models for RO and MED were included in TRNSYS. Regarding TEGs, a basic EES model was developed and subsequently integrated into the types related to PVTs and BB, with additional equations in a calculator. A summary of the basic data for the implemented types is presented in Table 5. Note that VP means that it is a parameter that affects any global system design but must be adapted to any configuration.

Table 5. Key elements of the TRNSYS model.

Element	Number	Parameter	Figure	Unit
Climate	15-6	Inclination	37	°
Tap water	14-a	Temperature	VP	°C
Photovoltaics	103-b	Area (of module)	1.93	m^2
		I_{sc} at RC	9.38	A
		V_{oc} at RC	46.2	V
Hybrid solar panel	50-a	Surface	1.63	m^2
Aerotherm (AE)	5-g	Cooling airflow	285,600	kg/h
TEG	--	ZT	0.72	
Inverter	48-a	Efficiency	95	%
Solar loop pipes	31	Overall loss coefficient	0.3	$W/m^2 \cdot K$
Solar controller	113	Cooling setpoint	90	°C
Solar pump (SP)	3b	Power	VP	W
		Flow	VP	L/h
Solar tank (ST)	156	Volume	VP	m^3
		Nodes	10	-
		Loss rate	0.35	$W/m^2 \cdot K$
Demands (5.txt files)	9-c	Periodicity	VP	h

Table 5. *Cont.*

Element	Number	Parameter	Figure	Unit
Hot water demands tank (HWDT)	534	Capacity Number of ports Loss coefficient	VP VP 0.35	m^3 - $W/m^2 \cdot K$
Biomass boiler (BB)	122	Output power Efficiency Minimum load	VP 80 5	kW_{th} % %
Boiler pump (BP)	3b	Power Flowrate	VP $50 \cdot A_{PVT}(m^2)$	W L/h
Demand controller	106	Heating setpoint	VP	°C
Pumping unit	927	T in T out	15 12	°C °C
SEAC unit	107	Cooling capacity T out Cooling temp. Hot Water temp. Range of operation	VP 12 20 VP 70–85	kW_{cl} °C °C °C °C
Cold water storage	156	Capacity Nodes Losses	VP 10 0.35	m^3 - $W/m^2 \cdot K$
MED unit	--	Desalting production Recovery factor Operation temperature	1309 20.65 60–82	L/h % °C
RO unit	--	Desalting production Recovery factor Rejection factor	500 45 99.31	L/h % %
Freshwater tank (FWT)	39	Maximum capacity Minimum volume Off desalt level	50 5 35	m^3 m^3 m^3

The simulation was run yearly using a 5 min time step. From the results obtained with TRNSYS, several key performance indicators (KPIs) were derived to comprehensively determine the optimum configuration. These KPIs are outlined in the following section for a thorough assessment of each option's performance.

2.4. Energy Analysis

The chosen KPI is the PESR. This ratio balances the energy consumed with respect to a reference system (RS). The proposed system (PS) takes into account the non-fulfilled power demand from the grid. In contrast, the RS assumes that conventional technologies based on fossil fuels will supply the demands with diverse conversion efficiencies (refer to Table 6 for specific details). The calculation of Primary Energy Saving (PES) and its further ratio (PESR) is carried out using Equations (1) and (2), respectively:

$$PES = PES_{RS} - PES_{PS} \tag{1}$$

$$PESR = \frac{PES}{PE_{RS}} \tag{2}$$

$$PE_{RS} = \frac{E_D}{\eta_E} + \frac{Q_{SH}}{\eta_Q} + \frac{Q_{DHW}}{\eta_Q} + \frac{Q_{CL}}{COP_R \cdot \eta_E} + \frac{W_D}{SEC_R \cdot \eta_E} \tag{3}$$

$$PE_{PS} = \frac{E_{FG}}{\eta_E} \tag{4}$$

Table 6. Background data for the analysis.

Device	Parameter	Figure	Unit(s)	Source
PV	Inv. and OM	1000, 1	€/kW_p, %/y	[37]
PVT	Inv. and OM	200, 2	€/m^2, %/y	[38]
Water tanks	Inv.	495 + 808·V(m^3)	€	[39]
Inverter	Inv.	180	€/kW	[40]
Pumps	Inv. and OM	419 + 0.03·Q − 2.16·10^{-8}·Q^2, 0.5	€, %/y	[41]
BB	Inv. and OM	282, 1	€/kW_{th},%/y	[42]
Heat Pump	Inv. and OM	350, 0.5	€/kW_{cl}, %/y	[37]
SEAC	Inv. and OM	600, 0.2	€/kW_{cl}, %/y	[38]
MED	Inv. and OM	1500, 0.5	€/(m^3/d), %/y	[43]
RO	Inv. and OM	800, 1.5	€/(m^3/d), %/y	[44]
$p_{E,p}$	Price	0.2	€/kWh	
$p_{E,s}$	Price	0.08	€/kWh	
p_{NG}	Price	0.07	€/kWh	
p_b	Price	0.052	€/kWh	
p_W	Price	2.0	€/m^3	[45]
$f_{CO2,E}$	Emission rate	0.19	$kgCO_2$/kWh	[46]
$f_{CO2,NG}$	Emission rate	0.204	$kgCO_2$/kWh	[47]
r	Interest rate	2	%	
COP_R	Cool. efficiency	2.6	--	[48]
η_E	Elect. efficiency	0.42	--	[49]
η_Q	Thermal eff	0.92	--	[48]
SEC_R	Spec. consump.	4	kWh/m^3	[50]

In Equations (3) and (4), PE_{RS} and PE_{PS} are, correspondingly, the energy consumption in the RS and PS. E_D is the building electricity demand; Q_{SH}, Q_{DWH}, and Q_{CL} are heating, domestic hot water, and cooling requirements; and W_D is the needed fresh water. Regarding efficiencies, η_E is the electric performance of the Spanish grid system, η_Q is the thermal performance of the extra boiler. For cooling, COP_R is the coefficient of performance, and SEC_R accounts for the energy consumption of one cubic meter of desalted water. E_{FG} is the electricity from the grid.

2.5. Economic Analysis

The Simple Payback (SPB) was chosen as the key metric. The SPB is calculated by dividing the total capital cost of the PS by the savings (AS) obtained by the PS compared to the RS. The lifetime is considered to be 25 years. This metric helps to preliminarily know the time to recover the investment through the achieved energy savings over the RS.

$$SPB = \frac{TI_{PS}}{AS_{PS}} \tag{5}$$

$$AS_{PS} = OC_{RS} - OC_{PS} \tag{6}$$

where TI_{PS} is the total investment and AS_{PS} is the annual saving in the PS, and OC_{RS} and OC_{PS} are the operating cost in the RS and in the PS. The AS considers that in the RS, electricity is sourced exclusively from the national grid. On the contrary, the PS achieves an overall yearly balance by combining PV, PVT, and TEG to match the electric user load. This self-sufficiency in generating electricity from RES significantly reduces the reliance on the grid. Nonetheless, there are occasions when the system may require the grid to complete load demand. Different prices are observed for electricity purchased from or sold to the grid. To precisely evaluate the annual cost of the RS, the charges due to natural gas, biomass pellets (with a defined LHV—Lower Heating Value), and water from the municipality are compulsory (see Table 6 for details). Indeed, the annual operating costs (OCs) also encompass the investment and installation necessary. Those costs were gathered from analogous studies in the literature and are detailed in Table 6. They significantly influence the overall economic feasibility of the PS when compared to the RS.

$$TI_{PS} = C_{PV} + C_{PVT} + C_{INV} + C_{ST,DHT,CWT} + C_{SP,BP} + C_{BB} + C_{HP/SEAC} + C_{RO/MED} \quad (7)$$

$$OC_{RS} = E_D \cdot p_{E,p} + \left(\frac{Q_{SH}}{\eta_Q} + \frac{Q_{DHW}}{\eta_Q}\right) \cdot p_{NG} + \frac{Q_{CL}}{COP_R \cdot \eta_E} \cdot p_{E,p} + W_D \cdot p_W \quad (8)$$

$$OC_{PS} = E_{FG} \cdot p_{E,p} - E_{TG} \cdot p_{E,s} + E_B \cdot p_b + OM_{PV,PVT,BB,HP/SEAC,RO/MED} \quad (9)$$

Equation (7) considers the investment expenses related to various components comprising the overall system. Nonetheless, to concentrate the analysis on the evaluation of the different generation possibilities, the distribution system's cost to dwellings and any other common arrangement for the four configurations is neglected here. In Equations (8) and (9), the terms $p_{E,p}$, $p_{NG,}$ and p_W represent costs of electricity, natural gas, and water from the corresponding network. Furthermore, $p_{E,s}$ denotes the price of excess electricity, E_B stands for the energy provided by the biomass boiler, and p_b is the procurement cost of biomass pellets. Here, OM_x gathers the operating and maintenance costs associated with a technology.

In this line, the Levelized Costs of the different outputs (LCO_x) were calculated. To account for the fact that certain driving technologies supply heat and electricity to meet the demands, sharing factors ($f_{E,x}$ and $f_{Q,x}$) are introduced. These factors are determined depending on the proportion of the (electrical or thermal) energy required for any specific demand in relation to the total energy produced. For example (see Equation (10)), in the estimation of the Levelized Cost of Water (LCO_W), the total cost encompasses both operation and maintenance (O&M) expenses, and the energy needed for the desalination plant accounts for the proportional costs of the upstream equipment. The leveled costs of each demand can be determined accurately, providing valuable insights into the economic viability and cost–benefit analysis of the proposed system, particularly with the value for each provided request.

$$LCO_W = \frac{\left[C_w + \sum_{n=1}^{25} OM_w \cdot (1+r)^{-n}\right]}{\sum_{n=1}^{25} E_w \cdot (1+r)^{-n}} \quad (10)$$

where C_W is the investment cost of desalting technology, OM_W accounts for the complete costs related to water O&M, r is the return rate, and E_W is the globally demanded energy for the defined water supplies, which varies according to the desalting technology selected.

Lastly, the Internal Rate of Return (IRR) and the Net Present Value (NPV) are considered. The IRR determines the rate at which the project's net present value becomes zero. On the other hand, the NPV takes into account the present value of all projected cash flows. By considering the IRR and NPV, decision makers can evaluate the financial merits of implementing the proposed system and make informed choices based on economic factors.

2.6. Emissions (During Operation)

The performance of the environmental study was carried out by taking the avoided CO_2 (ΔCO_2) and its relation (CO_{2R}) as KPIs. These are calculated in Equations (11) and (12):

$$\Delta CO_2 = CO_{2,RS} - CO_{2,PS} \quad (11)$$

$$CO_{2R} = \frac{\Delta CO_2}{CO_{2,RS}} \quad (12)$$

$$CO_{2,RS} = E_D \cdot f_{CO_2,E} + (Q_{SH} + Q_{DHW}) \cdot f_{CO_2,NG} + \frac{Q_{CL}}{COP_R \cdot \eta_E} \cdot f_{CO_2,E} + W_D \cdot SEC_R \cdot f_{CO_2,E} \quad (13)$$

$$CO_{2,PS} = E_G \cdot f_{CO_2,E} \quad (14)$$

The main features of the reference and proposed systems ($CO_{2,RS}$ and $CO_{2,PS}$) are detailed in Table 6. The carbon dioxide tax for electricity generation in Spain ($f_{CO2,E}$) and the CO_2 emission rate for heat provided from natural gas (RS, $f_{CO2,NG}$) are also included.

2.7. Lifecycle Environmental Performance

The previously mentioned environmental Key Performance Indicators (KPIs) do not take into account the CO_2 emissions throughout the whole life cycle of the proposed schemes. Moreover, their values closely resemble those observed with the Primary Energy Savings (PES) approach, especially when the carbon dioxide (CO_2) emissions for electricity and combustion of natural gas exhibit similar data, as is the case in Spain. To address this limitation, a thorough Life-Cycle Assessment (LCA) was undertaken for both the PS and the alternative RS designed to meet building demands. This meticulous analysis enables a comprehensive comparison of the environmental impacts of the PS, determining the entire life cycle of the alternatives. It encompasses the effects related to the construction and transportation of materials utilized for a technology, extending to the post-installation phase when the system is disassembled. These factors are combined with the impact generated during the operation of the systems, which is typically easier to estimate (as explained in the previous section). This approach offers a broader perspective on the environmental burdens linked to each solution.

Though this method is complex, it is being gradually incorporated as an additional analysis for experimental solutions based on Renewable Energy Sources (RESs) to account for environmental assessment [51–53]. Notably, it has never been employed for a polygeneration scheme that simultaneously provides five different services, making this study a significant contribution to the field.

In this specific case, the first step of an LCA (defining the functional unit) presents some complexity. Considering that the installation generates five demands, the functional unit is the entire installation itself, encompassing all the energy and flow requirements. This approach allows for a detailed assessment of the impact linked to each individual demand within the polygeneration system, expressed as a percentage of the overall total and single-unit basis (kWh, m^3).

In this study, the Life-Cycle Inventory (LCI) (i.e., the second step of an LCA) of the PS was meticulously compiled for each option (A to D), since they incorporate different sets of PVs, PVTs, and other equipment units. By conducting the inventory separately for each unit, it becomes straightforward to aggregate the complete inventory for the alternatives; here, the software SimaPro v9.0 was used. Both the Ecoinvent database (EIDB [54]) and other European standards databases (ELCD [55]) were employed, as well as some published studies or previous works (see Table 7). Some data were then extrapolated to represent the resulting capacity in every configuration. The transportation needed for the devices is contingent on the distance from the supplier, and data sources showing similar equipment performance were utilized when available. Regarding the end-of-life phase, the most conservative approach (landfilling the entire facility) was adopted, aligning with similar research works [51]. The global inventory for the four alternatives is summarized in the table, categorized by the different equipment used. In contrast, the LCI of the RS only accounts for a natural gas boiler as well as the impacts of electricity (low voltage, LV) and water from the abovementioned databases for the supply of 1 kWh and 1 m^3, respectively.

We chose a simple yet widely recognized LCIA method in the more generalist domain when selecting an impact assessment method (third step of an LCA). The IPCC 100-year GWP (Global Warming Potential) method quantifies environmental impacts in terms of kilograms of CO_2 equivalent and provides a single indicator to assess the overall environmental impact. In the analysis, we considered the installation's life cycle for a period of 25 years. After this timeframe, all components are expected to be replaced. By evaluating the environmental impact over this extended period, which also includes the impact on materials comprising the installation, we can comprehensively understand the system's sustainability and its contribution to mitigating greenhouse gas emissions when compared with the RS.

Table 7. Relevant data and references to perform the LCI of the four options (PS) and the RS.

Item	Reference	Capacity	Unit	km Truck	km Ship
PV	[51]	320	W_p	300	16,500
PVT	[51]	320	W_p	20	--
Aerotherm	[56]	24	kW_{th}	150	--
Inverter	[51]	2.5	kW_e	1892	--
Water tanks	[54]	2000	L	100	--
Water pumps	[56]	40	W	20	--
Heat Pump	[54]	10	kW_{cl}	1500	--
SEAC	[56]	19	kW_{cl}	2500	200
MED	[57]	2.8	m^3/d	50	--
RO	[50]	35	L/h	500	1000
Piping	[51]	5	kW_p	300	--
Wiring	[56]	3	kW_p	1500	--
Expansion vessel	[54]	80	L	150	--
Foundations (solar field)	[50]	260	W_p	80	--
Biomass boiler	[54]	50	kW_{th}	50	--
Natural gas boiler	[54]	300	kW_{th}	900	--
LV power, Spanish grid	[55]	1	kWh_e	--	--
Heat demand (to DH)	[54]	1	MJ	--	--
Deionized water (RO)	[55]	1	L	--	--

3. Results

3.1. Final Configuration of the Alternative Systems

Table 8 provides a summary of the final designs needed for each case, with the objective of fully covering the demands. However, when it comes to electricity, achieving 100% coverage is accomplished through an approximate yearly grid net balance. Similarly, for cooling, the buffer tank avoids a precise 100% coverage of the demand.

Table 8. Layout for each suggested configuration (A–D).

Item	A	B	C	D
Set of PV panels	30	60	40	30
Set of PVT panels	90	40	70	75
TEG power (kW_p)	0.60	0.24	0.54	0.55
BB nominal power (kW_{th})	150	50	150	150
BB setpoint temp. (°C)	75	55	80	82
Solar tank volume (m^3)	5	3	5	6
Hot water demand volume (m^3)	5	2	5	6
HP/SEAC power (kW_{CL})	30	25	35	48
Cold water tank volume (m^3)	2	2	2	3
Coverage of Electricity annual demand (%)	104.49	104.21	103.82	103.29
Coverage of Cooling annual demand (%)	104.36	99.61	98.74	103.27

When comparing the options, it can be observed that a significantly larger solar field incorporating PVT technology, a higher boiler, and hot water tanks are essential when utilizing the MED technology, and, to a somewhat lesser extent, when cooling is achieved by the SEAC. Specifically, the choices A and D demand a greater thermal supply-side dimension compared to the other options. In these scenarios, the proportion of PV decreases, and PVT increases to meet the demands. In alternative A (HP and MED), the defined PVT capacity is higher than the theoretically highest capacity (configuration D). This discrepancy is primarily attributed to the lower BB set-point temperature, which is configured to activate the MED process.

In certain cases, thermal demand may necessitate upsizing the biomass boiler (BB). Nevertheless, it is important to note that the BB has modulating capacity, and its equivalent number of operating hours can vary greatly, even when it has the same capacity. This is particularly evident during the spring and autumn seasons, when cooling is unnecessary, leading to the underutilization of the BB. Therefore, it is crucial to carefully consider the specific requirements and demands of the thermal system to avoid oversizing the biomass boiler unnecessarily. Proper planning and system design can help optimize the utilization of the BB and ensure that it efficiently meets the thermal demands without excessive capacity or underutilization. Additionally, exploring the possibility of integrating thermal storage solutions or other renewable energy sources can further enhance the overall performance and energy efficiency of the system. By taking these factors into account, it becomes possible to strike a balance and achieve an optimal and sustainable thermal supply solution.

The SEAC's heat demand better harmonizes with the abundant solar resources in summer. Consequently, opting for the SEAC option does not result in a representative increment in the resulting scheme, specifically the PVT panels required to satisfy the cooling demand. Thus, an efficient cooling without requiring a significant expansion of the overall system could be found.

Thermally activated technologies offer improved control, preventing overheating and the need for a dissipative device (AE). In scenarios where only low temperatures are necessary (case B) to meet the scarce heating and DHW requests, a large excess of heat was observed even when the boiler's setting was adjusted to 55 °C.

- Based on its technical characteristics, the SEAC exhibits a slower response to cold demand compared to the HP (Heat Pump). Thus, higher capacities and linked CWTs (Chilled Water Tanks) are demanded by the SEAC to meet the demand in a manner similar to the HP.
- The electricity supplied by the TEGs is almost negligible. The installed capacity in each configuration, as shown in Table 8, relies on the design capacity of the PVT and the boiler. Experimental tests conducted by the authors revealed that the available reduced temperature difference (ΔT) in the PVTs is insufficient to achieve appropriate energy efficiencies. Consequently, the contribution of TEGs in PVTs amounts to less than 1.0% of the overall electricity generated by both PV and PVT. For BB, tests already conducted by the authors incorporating TEGs demonstrate that the hot side operating temperature remains at 300 °C, while the cold face depends on the end-use temperature. This increased electrical generation with improved efficiencies, reaching up to 1.3% of the total demand, is shown in Table 9.

Table 9. Production of electricity of each device per system.

Current Provider	A	B	C	D
PV	43.78	78.92	57.78	48.30
PVT	62.31	25.84	47.06	56.39
TEG in PVT	0.93	0.79	0.71	0.87
TEG in BB	0.82	0.29	0.47	1.26

3.2. Performance Analysis

Table 10 summarizes the performance of the four proposed configurations. The calculated KPIs and the LCO_x of each demand are shown and analyzed.

From the perspective of PESR, all configurations exhibit similar values, ranging from 0.71 to 0.75. The slight variation in the results is mainly attributed to the mismatch between the demands not covered at 100%. Minor differences observed among the configurations arose with the management of electricity surplus or deficits during specific demand periods. Overall, the PESR analysis highlights the energy efficiency of the proposed configurations compared to the RS. This value could be enlarged if power storage was analyzed. A similar pattern is observed with CO_2 savings, but they exhibit a slightly higher value, ranging from

0.83 to 0.85. This difference is primarily due to the emission factors of natural gas, which exceed the CO_2 factor associated with electricity generated by the Spanish grid (as indicated in Table 6). The CO_2 savings demonstrate the significant environmental advantage of the PS in their operation, especially considering the higher emissions associated with natural gas compared to grid electricity in the Spanish context.

Table 10. Performance comparison.

KPI Parameter	A	B	C	D
Primary energy saving ratio (PESR)	0.707	0.745	0.753	0.750
CO_2 emiss. saving ratio ($CO_{2,R}$)	0.835	0.848	0.856	0.854
Total investment (TI_{PS}, €)	157,849	79,609	127,630	172,925
Annual saving (AS_{PS}, €/y)	3862.1	12,034.8	9514.7	2248.7
Simple payback (SPB, years)	40.87	6.61	13.41	70.62
Levelized cost of power (LCO_E, €/kWh_E)	0.035	0.034	0.037	0.040
Levelized cost of heating (LCO_{SH}, €/kWh_H)	0.022	0.023	0.040	0.019
Levelized cost of DHW (LCO_{DHW}, €/kWh_H)	0.022	0.023	0.040	0.019
Levelized cost of cooling (LCO_{CL}, €/kWh_C)	0.058	0.054	0.155	0.149
Levelized cost of water (LCO_W, €/m^3)	3.557	0.523	0.522	3.295

Attending to the economic figures, it is observed that Option D necessitates the highest investment compared to the other configurations. This is primarily because it involves the installation of a large solar field and the costs associated with both SEAC and MED technologies. On the other hand, option B requires the minimum investment among all the alternatives. This is mainly due to the combination of HP and RO technologies, which have lower associated costs compared to the other configurations. Indeed, electrically activated technologies such as HP and RO exhibit better energy performance compared to their thermally activated counterparts. When thermal energy is displaced from PV to PVTs, there is an electrical penalty, which affects the overall system efficiency.

Moreover, the demand for fuel pellets increased to maintain the necessary temperature for both MED along the year and SEAC during summer. As a result, biomass becomes the predominant expenditure in the system, which consequently reduces the overall savings achieved by the system. These factors highlight the complexities and trade-offs involved in optimizing the polygeneration system's economic performance while considering the varying demands and technologies used.

To summarize, based on the analysis of both the investment costs and annual savings, the order of configurations in terms of feasibility is as follows:

1. Option B: HP + RO (Heat Pump and Reverse Osmosis). This configuration yields the highest annual savings among all the options.
2. Option C: SEAC + RO (Single-Effect Absorption Chiller and Reverse Osmosis).
3. Option A: HP + MED (Heat Pump and Multi-Effect Distillation).
4. Option D: SEAC + MED.

The internalized costs in the configurations analyzed (electricity production from both PV and PVT fields) were found to be similar and attractive at less than 0.04 €/kWh. Similar expenses were observed for heating and DHW demands, as they draw heat from the hot water storage. However, reduced heating expenses result from the link with thermally activated technologies such as MED and SEAC in the configuration. When it comes to cooling, using HP for the same purpose is approximately one-third cheaper than employing SEAC. This difference can be attributed to the respective Coefficient of Performance (COP) values of the technologies despite the higher cost of electricity compared to heat. For providing fresh water, RO is found to be one-sixth cheaper than the distillate produced by MED, considering the Specific Energy Consumption (SEC) of both alternatives. In spite of this, the lower costs observed for heating and DHW do not fully compensate for the costs associated with the remaining services. Overall, configuration B (HP + RO) proves to be the most profitable solution, as it offers the best combination for cost-effectiveness.

3.3. Sensitivity to Externalities

In the base scenario, the economic figures considered for the analysis were derived from Spanish regulations or the scientific literature. Nevertheless, it is essential to acknowledge that the impact of externalities on the viability of polygeneration can be significant. Externalities refer to factors related to the investment and prices of electricity, natural gas, and biomass, which are influenced by market dynamics and policies. While these external factors play a crucial role in determining the overall profitability of the polygeneration plant, interestingly, the interest rate did not become a critical parameter affecting the SPB. This underscores the importance of considering a comprehensive range of economic variables and external factors when assessing the economic viability of polygeneration systems, as they can significantly impact the overall profitability and sustainability of such installations.

The investment required for the solar field or the biomass boiler shows an important influence on the liability of the proposed scheme. The main sensitivity energy factors are represented in Figure 4. Note that annual savings did not consider the potential income from CO_2 avoidance. Given the current global emphasis on decarbonization and the importance of mitigating greenhouse gas emissions, these values should be considered in the economic balance. Moreover, certain details that were not explicitly considered in the study, such as the operation and maintenance (O&M) costs of specific equipment and piping, which can also have an impact on the economic balance. Including these additional factors can provide a more accurate representation of the overall economic feasibility of the polygeneration system. However, in some manner, both impacts are compensated for.

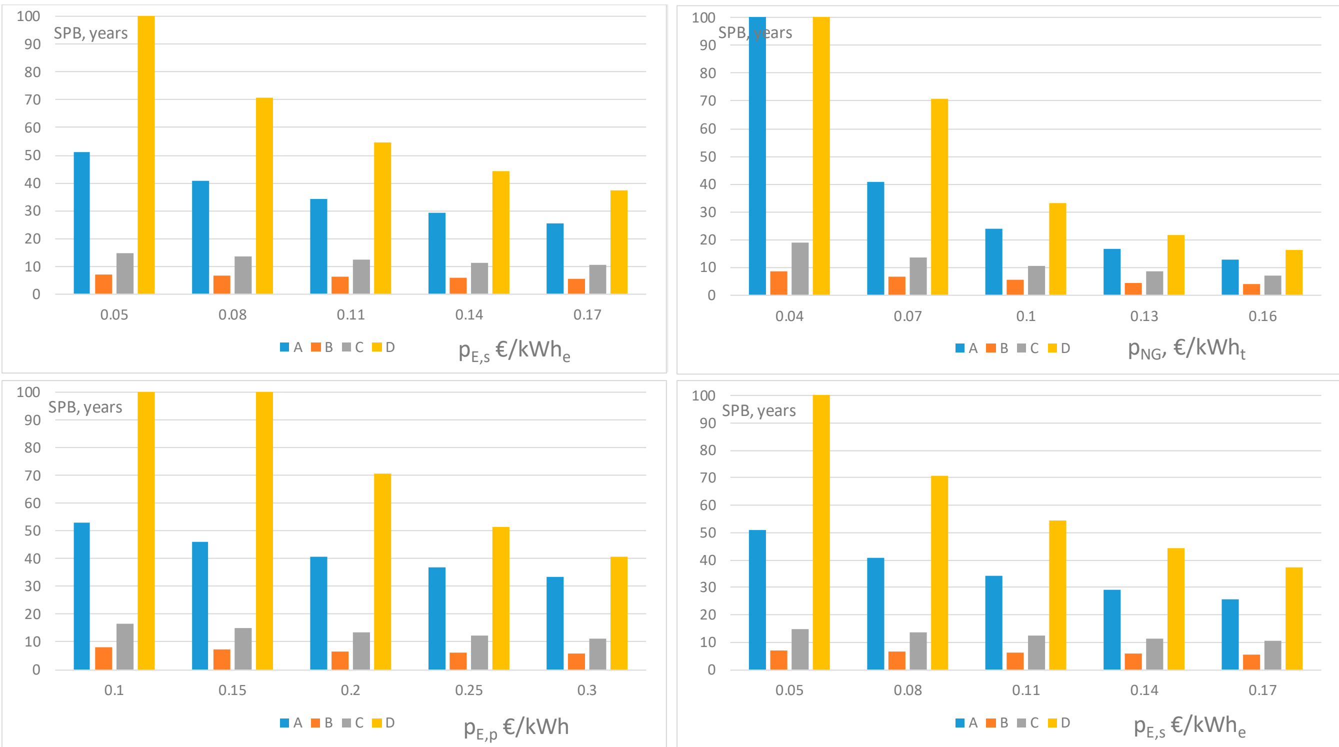

Figure 4. Sensitivity SPB analysis as a function of the biomass p_b, electricity purchase and selling prices ($p_{E,p}$ and $p_{E,s}$), and natural gas price p_{NG} in EUR/kWh.

3.4. LCA

As a complement to the emissions avoided during the operation of the PS with respect to the RS every year, an LCA of the polygeneration facility was conducted to complement the results shown in Table 10, which focused on the main energy, economic, and environmental KPIs. Table 11 presents the noteworthy findings from the LCA, specifically focusing on the emissions along the entire life cycle of the installation devices for the four configurations.

Table 11. Released $kgCO_{2eq}$ for the different configurations (grouped by device).

Items	Conventional	A	B	C	D
PV field	--	6534.1	13,068.2	8712.1	6534.1
PVT field	--	24,320.2	10,809.0	18,915.7	20,266.8
Aerotherms (AEs)	--	10,933.3	4859.2	8503.6	9111.1
Inverters	--	974.6	1949.3	1299.5	974.6
Water tanks	--	11,640	6790.0	11,640.0	14,550.0
Water pumps	--	485.8	117.3	268.1	460.6
Heat Pump	--	5430.0	4525.0	--	--
SEAC	--	--	--	2247.4	3082.1
MED	--	57,571.4	--	--	57,571.4
RO	--	--	5285.7	5285.7	--
Piping	--	707.7	230.0	408.8	589.6
Wiring	--	475.5	951.0	634.0	475.5
Expansion vessels	--	297.3	137.4	206.1	247.7
Foundations (solar field)	--	7272.4	5153.3	7730.0	6343.2
Biomass boiler	--	20,190.0	6730.0	20,190.0	20,190.0
Total polygeneration	--	146,832.1	60,647.9	86,040.9	140,396.8
(% construction)		95.26	93.22	92.60	94.47
(% operation)		0.64	1.37	1.28	0.90
(% dismantling)		4.11	5.41	6.12	4.63
Electricity (from the grid)	--	35,900	36,100	33,600	34,100
NG boiler	22,485	--	--	--	--
LV Electricity, Spanish network	165,000	--	--	--	--
Heat from DH net	528,540	--	--	--	--
Deionized water by RO	329,425	--	--	--	--
$kgCO_{2,eq}/m^3$	1.567	2.383	0.294	0.302	2.284
$kgCO_{2eq}/m^3_{DHW}$	9.251	0.384	0.412	0.699	0.641
$kgCO_{2eq}/kWh_H$	0.251	0.010	0.011	0.019	0.009
$kgCO_{2eq}/kWh_C$	0.224	0.032	0.028	0.037	0.024
$kgCO_{2eq}/kWh_E$	0.447	0.069	0.062	0.065	0.070

The LCA results are striking, revealing the minimal environmental impact (ranging from 9% to 17%) of the RES-based scenarios when compared with the RS, which considers the environmental impact of the external supply of the five demands. Although a net electricity balance requires an important input of electricity from the network, the impact associated with the PS operation is only about 1% of the total impact, with about 94% of the impact due to materials. This emphasizes the effectiveness of the polygeneration systems in reducing overall environmental burdens, despite the need for grid electricity. Finally, the displacement of equipment and its disassembly at the end of its useful life (25 years) contribute less than 5% to the total environmental impact, indicating that these aspects have a relatively minor effect on the system's overall sustainability.

Examining the unit emissions for the different required demands, similar trends to those found for the Levelized Costs (LCO_x) emerge. Note that the impact assessed for each demand was weighted by the energy and units required upstream in the scheme. The MED technology presents a higher environmental impact in the integration, as does the application of SEAC for cold production compared to using HP. Heat production demonstrates a lower impact than other demands, since it is based on solar power. Nevertheless, the unit values for all four schemes are, on average, one order of magnitude lower than the impact associated with the RS. These findings underscore the environmental benefits of utilizing polygeneration systems with RES, as they offer more sustainable and eco-friendly solutions along their life cycle compared to conventional alternatives, thereby contributing to the global efforts towards decarbonization and environmental preservation.

4. Discussion

The configurational analysis highlights the significance of carefully selecting the set of PVs or PVTs to compose the solar field to cover the established requirements. While PVT technology generally offers superior performance by producing electricity and heat simultaneously, it may not always be the most suitable solution. The optimal choice depends on the specific downstream demand and the existence of alternative technologies with lower energy consumption and investment costs. For instance, if the heat produced by PVTs can be efficiently substituted by an electrical technology with lower investment costs, a purely thermal integration in a polygeneration scheme, especially involving desalinated water, may not be justified. This becomes evident in the comparative analysis of configurations A to D, where using HP and RO for cooling and water production with electrical technologies proves to be a more favorable option than thermal integration. The case of using MED for water demand, in particular, leads to a considerable increase in the required solar field compared to having RO; in the Gulf countries, where distillation is still preferred, this combination cannot be ignored. SEAC technology, on the other hand, is better suited for major solar inputs (i.e., in summer), and its impact on HP usage is less significant compared to desalination. It is essential to emphasize that this four-option analysis specifically applies to regions facing freshwater restrictions and similar cooling and heating demands in the housing sector, since the choice of desalination and cooling technologies plays a crucial role in determining the optimal configuration.

The analysis of polygeneration setups equipped to generate thermal energy also included the integration with TEG for concurrent electricity generation. However, the TEG devices make a modest contribution to electricity generation, accounting for approximately 2.1% of the overall electricity generation derived from PV and PVT. Consequently, these integrated TEG devices could be considered optional features in the proposed configurations.

The case study presented focuses on a specific coastal location in Spain, where air-conditioning demands and building standards significantly influence the results. The replicability in the building sector was considered by applying the same configurational analysis to an 80-dwelling building with the best construction standards in three different locations in Spain (Valencia, Almería, and Zaragoza) [36]. The KPI values obtained for these locations are similar and align with those obtained in the current study. The order of best integrations in terms of viability remains consistent, as B-C-A-D. While the analysis did not include a 100% RES solution (without the grid-net energy balance and energy storage systems), the authors studied the influence of using or not using batteries for an isolated domestic dwelling in separate analyses [58]. In these cases, the polygeneration only included PVT panels and RO for desalination and the inclusion of a solid desiccant wheel (SDW) to cool the house, which was also thermally activated. These analyses also highlight the importance of the economy of scale, as the required configurations were less viable than those obtained in this study, resulting in higher unit installation costs and a worse SPB.

The economic analysis considered a defined energy price framework in Spain, which may significantly change. While the trend anticipates a rise in biomass expenses, other parameters, such as natural gas prices, buying and selling electricity prices, and unit investment costs of solar panels and biomass boilers, favor the viability of the schemes compared to the initial estimates in Table 6. Additionally, if avoided CO_2 is included as income due to the different working mode of the schemes compared to conventional grid supply, the results are considered conservative. This pattern strongly supports the viability of integrated schemes based on renewable energy sources and efficient energy management, enhancing the favorable environmental effects but also the energy KPIs firstly identified here.

It is important to remember that the estimation of the unit costs of each demand, both economic and environmental, are based on the required primary energy captured from the integrated facility. Still, another criterion, such as exergy could give another cost distribution, which would certainly be less favorable for thermal energy in this case.

Regarding the reliability of the results, while direct comparison with other references is challenging due to the different configurations analyzed and varying external input parameters, the authors are confident in the reliability of the simulations performed. The complexity and accuracy of the simulations, along with the verification of internal temperature profiles, lead to a reasonable reliability of the results obtained. In any case, the adoption of fixed values for certain equipment parameters, as well as energy and water prices, investment costs, and financial fees, make the values a first approximation that must be adapted to each location and technological state of the art if we want to have an accurate picture of the feasibility of the polygeneration project.

It is valuable to highlight the significance of the LCA implemented in the facilities shown. It contributes to improving the analyzed results, particularly in terms of CO_2 avoidance along its life cycle. This reinforces the notion that decentralized power and water generation near users is a preferable and sustainable long-term option. The better results than those obtained for $CO_{2,R}$ indicate that the impact of supply infrastructure is very important with respect to the impact of energy savings from integration.

Although the research was focused on a given type of building, and thus the specific results are not general, some general trends can be identified that can help policymakers obtain conclusions that are useful. First of all, it can be seen that renewable energy-based polygeneration schemes providing electricity, heat, cold, and fresh water to buildings have advantages, taking into account primary energy consumption and CO_2 emissions in the life cycle. For this reason, this should be supported by removing barriers related to installation of these small-scale facilities in buildings. Furthermore, the payback of the better examples is close to what is expected by a company for investing; accordingly, some economic support can boost the installation of these type of schemes. Last but not least, dissemination and training of people to be in charge of these technologies is also required.

5. Conclusions

The study conducted a comprehensive 3E analysis (energy, environmental, and economic) for a series of innovative polygeneration setups structured around thermal technology, including PVTs, TEGs, and BBs. Each configuration could produce cold and desalinated water either from heat or electricity, resulting in four distinct polygeneration schemes relying on solar and biomass energy. The study was developed in a site on the Mediterranean coast in Spain and also incorporated Life-Cycle Assessment (LCA) to account for environmental impacts linked to the installation, construction, and end phases, in addition to CO_2 savings during the operation and compared to a conventional supply based on conventional grids. Specific software was appropriately used for each step of this sequential procedure (Design Builder–EES–TRNSYS–SimaPro–Excel).

The results revealed that all four schemes demonstrated favorable values for PESR (Primary Energy Saving Ratio) and CO_2 Reduction Ratio, of around 0.72 and 0.85, respectively. However, these values were influenced by forcing a yearly zero net balance without batteries, which could improve installation viability.

Among the four schemes, the "electric" alternative (B) stood out as the most economical option, involving a combined set of PVs, PVTs, TEGs, and BBs, with HP and RO as the preferred technique to integrate the scheme for cooling and desalination. This configuration exhibited an SPB of approximately 6 years, which was significantly better than the other configurations. The main reason is the lower investment required with electrically activated technologies.

Furthermore, the levelized costs of the five considered required flows supplied by the polygeneration systems were lower than those of conventional commodity-based supplies. For instance, power costs of less than EUR 0.04 can be found in all configurations. However, the financial results were heavily influenced by the prevailing prices of electricity and fuels, and it is expected that forthcoming markets will further enhance the economic performance of the studied integrations.

The LCA study provided more positive figures than $CO_{2,R}$ when comparing the scheme with the infrastructure needed for conventional supply from local networks, thus indicating the superior sustainability of the polygeneration RES-based schemes. In the best option (case C), the total impact of the plant is only 9% with respect to the conventional case, and most of the 9% comes from the materials required for the installation.

In conclusion, this study emphasized the significant potential of these innovative polygeneration configurations in the urban sector. While the research provided promising outcomes, further investigations focused on integrating alternative technologies or Energy Storage Systems (ESSs) for power, heat, and fresh water could contribute to even more sustainable urban energy management. A further step will then be the plant optimization of the finally selected configuration, with the help of the TRNEDIT or TRNOPT modules available in the TRNSYS environment. Demonstration projects have to be developed in order to test the applicability and limitations of the schemes as well as to serve as examples to show their advantages to stakeholders.

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Nomenclature

AE	Aerotherm
AS	Annual saving
BB	Biomass Boiler
BP	Biomass Pump
CD	Cooling Demand
$CO_{2,R}$	CO_2 Saving Ratio
COP	Coefficient Of Performance
CWT	Cooling/Chilled Water Tank
DH	District Heating
DHW	Domestic Hot Water
DHWD	Domestic Hot Water Demand
ED	Electricity Demand
EES	Engineering Equation Solver
ESS	Energy Storage System
FWD	Freshwater Demand
FWT	Freshwater Tank
GWP	Global Warming Potential
HD	Heating Demand
HP	Heat Pump
HSW	Hot Sanitary Water
HWT	Hot Water Tank
HWDT	Hot Water Demand Tank

IRR	Internal Rate of Return
KPI	Key Performance Indicators
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
LCOx	Levelized Cost Of x
LV	Low Voltage
LHV	Light Heating Value
MED	Multi-effect Distillation
NG	Natural Gas
NPV	Net Present Value
OC	Operating Cost
O&M	Operation and Maintenance (Cost)
PESR	Primary Energy Saving Ratio
PS	Proposed System
PV	Photovoltaic
PVT	PhotoVoltaic-Thermal panel
RES	Renewable Energy Source
RO	Reverse Osmosis
RS	Referenced System
SDW	Solar Desiccant Wheel
SEAC	Single-Effect Absorption Cycle
SP	Solar Pump
SPB	Simple Payback Period
ST	Solar Tank
SW	Sea Water
TEG	Thermo-Electric Generator
TI	Total Investment
TRNSYS	TRaNsient SYstem Simulation program

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