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Technical-economic and financial feasibility of new technologies in the energy refurbishment of residential buildings

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Abstract. The revision of the Energy Performance of Building Directive (EPBD) provides for the construction of zero-emission buildings. The present work investigates possible solutions aimed at phasing out fossil fuel systems in buildings, in accordance with the EPBD requirements. An insulated residential building located in Rome is presented. The proposed refurbishment approach is based on the heating system replacement (heat pump, hydrogen fuel cell, hydrogen-ready boiler), and the use of renewable energy produced by a photovoltaic system. The results show that, although the energy optimal solution consists of the replacement of the heat plant with a heat pump coupled to both a PV and a fuel cell system, from the economic-financial point of view the proven solution of heat pump coupled with PV is still the only feasible one.

1 Introduction

Buildings account for more than 40% of European Union (EU) energy consumption and over half of EU gas consumption, contributing to 36% of energy-related greenhouse gas (GHG) emissions [1].

On December 7, 2023, the European Parliament and the Council reached a provisional agreement on the revised Energy Performance of Buildings Directive (EPBD), that will enter the formal adoption procedure in 2024 [1]. In line with the European Green Deal and the REPowerEU Plan, the revised EPBD is a key measure for reaching current EU goals of reducing GHG emissions and energy consumption by 2030, to achieve climate neutrality by 2050. Indeed, 85% of buildings in EU were built before 2000 and 75% of them exhibit poor energy performance [2].

In addition to various measures aimed at significantly improving the energy performance of existing buildings, the revised EPBD also introduces the concept of 'zero-emission buildings' (ZEB), a further step beyond the current Nearly Zero Energy Buildings (NZEB) standard for new buildings. A ZEB is defined as a building with a very high energy performance, in which the total annual primary energy consumption is below certain thresholds and is

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entirely covered by renewables generated or stored on-site, renewables generated nearby and supplied through the grid, a renewable energy community, or renewable energy and waste heat from an efficient district heating and cooling system [3]. All new public buildings must be ZEB from 2028, and all other new buildings from 2030, with some specific exceptions. Solar photovoltaic or thermal installations will be the norm for new buildings and will need to be gradually installed in existing public and non-residential buildings where feasible [1].

In addition, the revised EPBD will help the EU to gradually phase-out fossil fuels in heating and cooling, through different measures such as the ban on subsidies for the installation of stand-alone boilers powered by fossil fuels by 2025. Further, the draft revision of Commission Regulation (EU) No. 813/2013 on ecodesign requirements for space and combined heaters sets stringent standards. As a result, it will be impossible to introduce new fossil fuel boilers to the market starting from 2029.

To achieve these goals in existing buildings, various technologies are currently available on the market. These include insulating walls and roofs, replacing windows and doors, replacing air conditioning systems and heat generators with high-efficiency devices such as heat pumps, and installing renewable energy systems, usually roof-mounted solar photovoltaic (PV) and thermal systems.

Energy efficiency solutions, electrification of consumption and use of renewable energy can reach most of the mitigation targets by 2050; however, renewable gases such as green hydrogen will be needed for the decarbonisation of certain sectors where electrification of end-uses is not possible [4]. Therefore, the EU Strategy on Hydrogen [5] envisages introducing its application for long-distance heavy mobility, for some chemical and energy-intensive industrial sectors, and blended into the natural gas grid by 2030, and other applications by 2050, such as seasonal power storage or residential and commercial heating. Currently, The EU is trying to develop a supply chain using only renewable energy to produce sustainable, so-called green hydrogen through the electrolysis of water. However, by the end of 2021, only around 4% of the global hydrogen production came from electrolysis [4].

In a prior study [6], the techno-economic feasibility of potential solutions to achieve 'zero-emission buildings' performance in existing structures to meet their heating demands was evaluated. These solutions included thermal insulation of buildings, replacement of existing heat generators, and on-site renewable energy production.

Going further, this study proposes various strategies for replacing fossil fuel-based generation systems in accordance with EPBD requirements, to meet heating, cooling, electricity, and domestic hot water demands. Through a residential building located in Rome, where a thermal insulation has already been implemented in accordance with the previous study, a range of energy efficiency strategies aimed at reaching the ZEB target is evaluated. Available and cost-effective technologies, such as PV and heat pump (HP), are examined. Additionally, the use of green hydrogen through a fuel cell system operating as a co-generator is analysed. To ensure the economic sustainability, various scenarios combining different technologies and energy management options are examined. The goal of this research is to find a balance between technological advancements in energy and environmental efficiency with economic and financial sustainability.

2 Methodology

The methodology is based on the following steps:

1. Performing a dynamic energy simulation on annual basis, which considers the building and the heating/cooling systems, excluding generation.
2. Analyzing the hourly profile of thermal loads for heating and cooling, excluding generation, and of the electricity for end-users' appliances.
3. Domestic hot water (DHW) loads evaluation.

4. Dimensioning of the multi-energy generation system, considering the following technologies:
    a. heat pump (HP) combined with PV;
    b. hydrogen powered fuel cell;
    c. hydrogen-ready gas boiler.
5. Performing an energy and cost analysis to compare different options.

2.1 Energy analysis

Figure 1 illustrates a flow chart of the implemented methodology for the energy assessment.

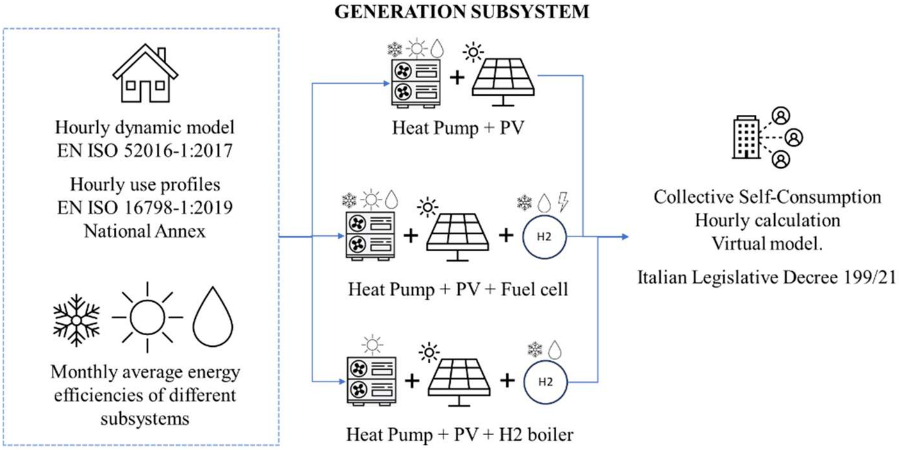

Fig. 1. Flow chart of the energy analysis process and system configurations.

The energy analysis is carried out according to the hourly dynamic method specified by EN ISO 52016-1:2017 [7] and adopting an hourly use profile according to EN 16798-1:2019 [8] National Annex for internal heat gains, natural ventilation and DHW. The Edilclima EC700 software [9] is used to perform the calculation.

Regarding the energy assessment in presence of HP combined with PV, the hourly thermal energy required by the building and the DHW production is related to the monthly average efficiencies of the various subsystems. Using this information, the hourly electricity demand of the HP was calculated.

The generation capacity of the PV system is determined on an hourly basis using PV-GIS software [10]. Once the generation profile of the PV system is known, the hourly fraction of the electricity self-consumed or fed into the grid is calculated, in compliance with the “dedicated withdrawal” procedure by the Italian energy services manager (GSE). It is assumed that only the centralized electrical loads can benefit from the self-consumption, namely the HP for heating and DHW production, and the condominium common services (lights, elevator). Appliances and autonomous cooling generators (i.e. splits) only concur to produce shared energy in the collective self-consumption contest, as explained below in the text.

The fuel cell operates as a co-generator. It is sized to meet the peak electrical load net of PV production. The recoverable heat from the fuel cell cooling circuit is used to reduce the thermal load for heating and DHW production, satisfied by means of the HP.

In all the system configurations (Figure 1) the cooling load is satisfied by means of individual split systems installed in the building apartments.

With reference to Legislative Decree 199/21 [11], it is also assumed the constitution of a group of collective self-consumption of renewable electricity (CSC), which includes all apartment buildings and the building itself, giving availability of their POD (Point of Delivered) in their name.

By means of the virtual model, the shared electricity is calculated on an hourly basis, equal to the minimum value between the renewable electricity by the PV (after deduction of the HP) or by the fuel cell and fed into the grid, and the electricity withdrawn from the grid by the PODs participating the CSC. The electrical load profile per building unit is defined by benchmark data.

2.2 Economic analysis

The economic feasibility of the proposed solutions was evaluated according to EN 15459-1:2017 [12] and a previous study [6]. Accordingly, the Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Time (PBT) were assessed. Considering a micro-economic approach and a direct investor, a calculation period of 20 years and a discount rate of 5% were assumed [13].

The investment costs, including the expenses for works, materials and equipment, and ancillary costs were estimated through a metric estimate computation (CME) using the DEI Price List, with few exceptions. The cost of the fuel cell and the PV system were derived from market prices and integrated into the CME. The tax deductions currently in force for PV system, heat pump, and fuel cell were also considered [6].

Energy costs include electricity, natural gas, and hydrogen. The costs of electricity and natural gas were estimated according to a previous study [6]. For the PV system, ordinary and extraordinary maintenance, insurance policy and AUC management fee were also included. In addition, the substitution of the fuel cell's stack was considered as an operating cost, where its useful life was calculated according to Marocco et al. (2021) [14].

In the case of electricity production from PV and fuel cell systems, revenues consist of the feed-in of the electricity produced and the incentive for shared electricity. The remuneration is calculated equal to the average PUN for each time band, calculated in the period between December 2022 and December 2023. In addition, the natural gas savings from the grid due to heat generator replacement were considered. Finally, the waste heat from the fuel cell system is supposed to be sold to the public district heating system.

3 Application

3.1 Case study

The case study [6, 15], is a residential building located in Rome (Figure 2, Figure 3). The building comprises 7 floors above ground level, for a total of 18 apartments. The ground floor houses commercial activities, and it is not subject to study.

Fig. 2. Building facades prior to thermal insulation interventions: south-east (A), north-east (B), north-west (C). From [15].

Fig. 3. Floor plans. Adapted from [15].

The building was subjected to an energy refurbishment according to both the Ministerial Decree of 26 June 2015 'Requisiti Minimi' [16] and the Ministerial Decree 'Requisiti' [17] prescriptions, consisting in building envelope thermal insulation and windows replacement. Table 1 summarizes the technical solutions adopted and the thermal transmittance average values (thermal bridges included) obtained for the main retrofitted building components; further data are available in previous works [6, 15].

Table 1. Thermophysical characteristics of building components subjected to energy refurbishment. Adapted from [6].

Building component	**Thermal insulation solution**	**Thermal transmittance U [W/(m^2 K)]**	
		Mean value	**Limit value [17]**
External wall	Graphite-sintered expanded polystyrene, thickness 10 cm, $\lambda = 0.032$ W/(m K)	0.23	0.26
Roof	Phenolic foam panel, thickness 7 cm, $\lambda = 0.020$ W/(m K)	0.24	0.22
Windows	PVC frame with three hollow chambers ($U_f = 2$ W/(m^2 K)). Low-e double-glazing with argon 4-16-4 ($U_g = 1.2$ W/(m^2 K))	1.38-1.77	1.67

The residential units are equipped with a centralized system for heating and DHW production; common areas are unheated. The combined heat generator is located into the technical room and consists of a natural gas boiler characterized by a nominal thermal power of 152.5 kW. The distribution subsystem is composed of risers running in the external walls; the emitters are radiators equipped with thermostatic valves.

3.2 Energy efficiency measures

The building system is designed to provide heating (H), cooling (C) and domestic hot water (DHW) services (Figure 1). Three different plant options are considered and described below:

1) Replacement of the existing gas boiler with an electric air/water heat pump combined with a PV system + individual split systems for cooling.
2) Scenario 1 + hydrogen powered fuel cell.
3) Replacement of the existing gas boiler with a hydrogen-ready boiler + PV system + individual split systems for cooling.

Table 2 summarizes the efficiencies of the subsystems for the current state and energy refurbishment scenarios.

Scenario 1 considers the replacement of the current gas boiler with an air-to-water heat pump characterized by a useful power of 40.40 kW and COP of 4.16 at full load in nominal conditions.

In Scenario 2 the HP is coupled to a pure hydrogen fuel cell equipped with a proton exchange membrane (PEMFC). This is an electrochemical device designed to produce electricity by combining hydrogen and oxygen present in the air molecule. Collaterally, the cell produces heat, which can be recovered to partially meet the building thermal load for heating and DHW production. The cell has an overall efficiency of 85%, with maximus values of specific efficiencies equal to 57.9% for electricity and 41.4% for thermal production respectively. Due to the combined operation of several devices, the generation efficiency of the second scenario is lower than that of a heat pump.

In Scenario 3 the current gas boiler is replaced with a hydrogen-ready boiler for heating and DHW production (useful thermal power of 36 kW and 94% efficiency).

Table 2. Efficiency subsystems.

Average seasonal efficiency	Emission + Control + Distribution			Generation		
	H	C	DHW	H	C	DHW
Current state	91%	-	93%	90%	-	92%
Scenario 1	92%	89%	93%	COP 3.26	EER 7.87	COP 3.33
Scenario 2	92%	89%	93%	1.4	EER 7.10	1.28
Scenario 3	92%	89%	93%	94%	EER 7.87	94%

In all the Scenarios the split system for cooling consists of one condensing unit and two internal unit each apartment, characterized by a useful power of 3.00 kW and EER 5.45 at full load in nominal conditions.

PV system consists of 23 panels installed on the flat roof of the building, considering an Azimuth of 0° and an inclination of 39°. The panel characteristics are shown in Table 3. The annual electricity production of the PV system is estimated at 15.54 MWh; a performance decay of 0.6% per year was also considered.

Table 3. Technical data of the photovoltaic system.

Parameter	**Unit of Measurement**	**Value**
Panel peak power	[W]	415
Panel efficiency	[-]	21.3%
Panel width	[mm]	1,134
Panel height	[mm]	1,722
Plant peak power	[kW]	9.6
Efficiency of electrical cables	[-]	90
Inverter efficiency	[-]	98%

3.3 Modelling assumptions

The main assumptions for H, C and DHW production evaluation are summarized below:

- Climatic conditions: city of Rome, climate zone D.
- Heating system switch-on period from 1 November to 15 April.
- Solar shading schedule considered according to UNI/TS 11300-1:2014 [18], by existing shutter system.
- Weekly average internal heat gains of 5 W/m^2, for both hourly and monthly method.
- Weekly average air change rate of 0.3 h^{-1}, for both the hourly and the monthly method.
- Subsystem efficiencies according to UNI/TS 11300-2:2019 [19].
- Annual electricity consumption per single apartment of 3000 kWh.

- Primary energy conversion factors for various energy sources according to DM 26 June 2015 [16]; for hydrogen 1 is used, totally renewable.
- CO_2 emission factors: natural gas 0.211 $kgCO_2/kWh$ for the reference year 2021 (58.504 tCO_2/TJ, LHV 8190 $kcal/stdm^3$) [20], Italian electricity mix 0.255 kg CO_{2e}/kWh for the reference year 2020 [21], green hydrogen from renewables 0 $kgCO_{2e}/kgH_2$ [22].

The economic analysis was carried out considering the condominium as investor, assuming a discount rate of 5% for the investment [13]. Table 4 shows the main parameters and assumptions adopted to estimate investment costs, operating costs, and revenues.

Extraordinary maintenance of the fuel cell consists of replacing the stack at the end of its service life. This is equal to 6 years in scenario 2), given 86,400 annual operating hours and 1 annual switch-on and switch-off cycles, after which it will be necessary to replace it. Concerning the cost of green hydrogen from the grid, an annual cost reduction of 0.25 €/kgH_2 is assumed over the timeframe of 20 years, starting at 7 €/kgH_2 in 2023 [23] and reaching 2 €/kgH_2 in 2043, consistently with different scenario analysis [24, 25], due to the sharp decrease of capital costs of electrolysers and cost of renewable electricity used to power the electrolysers in the next years.

Table 4. Cost and revenue parameters for the economic analysis. Adapted from [6].

Item	**Component**	**Cost/revenue**	**Reference/notes**
Investment costs			
PV system		11,500 € (1,200 €/kW_p)	Market price
Smart-meter PV		200 € each	Market price
Disposal PV system		10% investment costs	
Cooling system		53,500 €	CME, DEI price list
Heating system, Scenario 1		61,000 €	CME, DEI price list
Heating system, Scenario 2		122,000 € (FC 62,000 €, HP 13,500 €)	CME, DEI price list Fuel cell producer
Heating system, Scenario 3		25,000 €	CME, DEI price list H_2 boiler producer
Operating, maintenance, energy, replacement costs			
PV system	Insurance	40 €/kW	Market price
	Ordinary maintenance	2% investment costs	Market price
	Extraordinary maintenance	5% investment costs	Market price
	AUC operator fee	2% shared energy	Market price
Electricity, energy purchase	Total cost (electricity 54%, transport and meter costs 10%, network loss avoided 3.8%, system charges 22%, taxes 10%, VAT 22%)	F1: 344.89 €/MWh (153.22 €/MWh el.) - F2: 349.98 €/MWh (155.48 €/MWh el.) - F3: 287.78 €/MWh (127.85 €/MWh el.)	PUN, annual average per each time slot, December 2022 -November 2023 [26]
Natural gas, energy purchase	Total cost	122.50 €/MWh (42.17 €/MWh natural gas market price)	Market price Annual average December 2022 -November 2023 [26]
Green hydrogen, energy purchase	Total cost	7 €/kgH_2	Second quarter, 2023 [23]
	Annual cost reduction	-0.25 €/kgH_2	Annual cost reduction 2023-2043
FC	Extraordinary maintenance	26.7% CAPEX	Stack substitution [14]

Revenues			
Electricity, shared energy	Shared energy incentive	124 €/MWh	[27, 28]
	System charges, refund	8.37 €/MWh	
Electricity, grid feed-in	Feed-in tariff	F1: 123.77 €/MWh F2: 112.50 €/MWh F3: 101.20 €/MWh	Ritiro dedicato, Zonal price South-Centre Italy (Lazio), annual average per each time slot, January 2023 - November 2023 [29]
	Annual management	- 0.7 €/kW (maximum 10,000 €)	Power bracket 1-20 kW, provided to GSE [30]
	IRAP	- 23%	Taxation on income from grid feed-in
Heat, district heating network feed-in	Feed-in tariff (assumed as natural gas)	42.17 €/MWh natural gas market price	Market price Annual average December 2022 -November 2023 [26]

4 Results and discussion

4.1 Energy analysis

Figure 4 shows the main results of the energy assessments for the current building compared to the retrofit scenarios. The thermal energy indices were calculated using the hourly model; results are the same for all the cases as the building envelope and the use profiles are fixed. The non-renewable performance indices were evaluated using the monthly model.

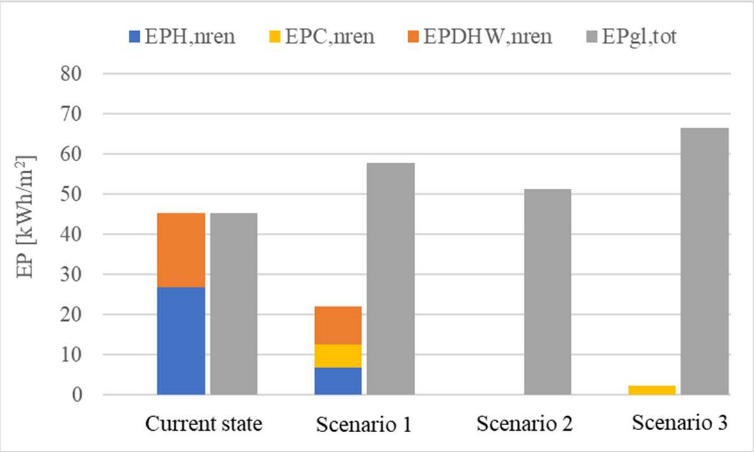

Fig. 4. Energy performance indices.

The primary energy needs for heating and DHW production of the current state of the building is totally non-renewable. Scenario 1 drastically reduces the global non-renewable primary energy need despite the presence of the cooling service in addition; nevertheless, the total global primary energy is higher because it also considers the renewable energy from the air and from the electricity by PV and the grid.

Scenario 2 reduces to zero the non-renewable energy needs thanks to the combined use of solar energy and hydrogen. In addition, the total global energy need is also reduced compared to Scenario 2 because of the lower electricity from the grid thanks to the FC.

In Scenario 3 the only non-renewable primary energy need refers to the cooling service, as the PV system is not able to cover all the request. Nevertheless, the total global energy need results the highest of all the scenarios; compared to the current state, that is due to added cooling service.

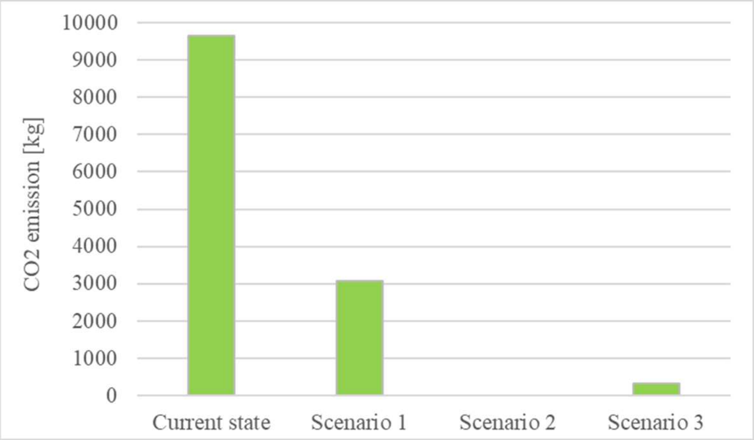

Fig. 5. Energy performance indices.

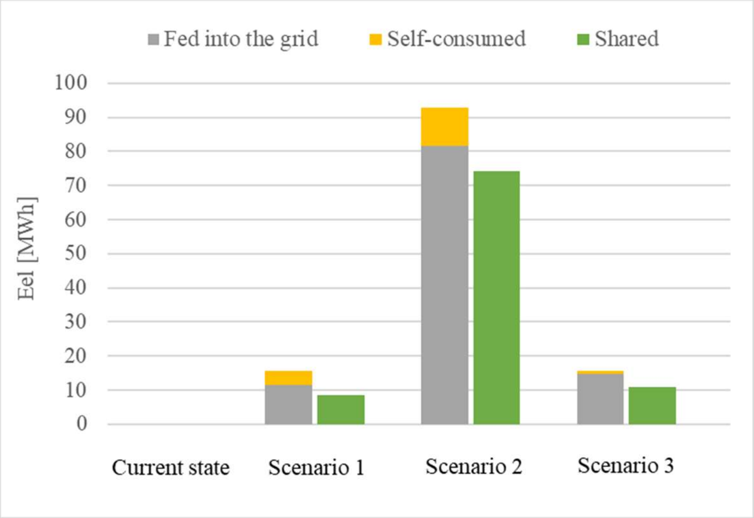

Fig. 6. Renewable electricity.

Figure 5 shows the yearly CO2 emission and highlights the deep reduction due to the use of renewables. Compared to the current state, the HP + PV (Scenario 1) reduces the CO2 emission of 68%, while the H2-ready gas boiler + PV (Scenario 3) of 97%. Nevertheless, only Scenario 2 is totally NZEB.

As regards the electricity production from renewable sources and the possibility to self-consume, feed into the grid and finally share that last one by means of the CSC group, Figure 6 shows that most of the produced electricity is fed into the grid, and more than 75% is then shared. As to increase the self-consumption, the use of electricity storage may be considered.

4.2 Economic analysis

In Table 5, the results of the economic analysis are presented. The main investment and operating costs, deductions and average annual revenues are also shown. None of the scenarios is economically feasible. This is due to the high investment costs on the one hand and the operational costs due to electricity and hydrogen of the other (see Table 4). The cooling service involves an additional investment cost of 53,500 € and an operating cost for electricity of 1,046 €/year that are not repaid by the revenues associated with the sale and the share of electricity. Indeed, further calculations show that Scenario 1 would have a SPBT of 9 years if the cooling system was not considered in addition.

The annual revenues of Scenario 2 (24,075 €) are the highest, thanks to the electricity sold and shared by FC in addition to PV. Currently, the cost of technology and green hydrogen are not sustainable for civil applications, although development forecasts predict a drastic reduction of both cost items.

Table 5. Economic and financial analysis results and main investment costs.

	Scenario		
	1	2	3
Total investment cost [€]	**126,154**	**187,154**	**90,154**
Heating system [€]	61,000	122,000	25,000
Cooling system [€]	53,500	53,500	53,500
PV system [€]	11,654	11,654	11,654
Annual average operating costs [€]	**8,214**	**26,144**	**10,652**
Annual average electricity cost [€]	5,176	0	675
Annual average hydrogen cost [€]	-	19,983	7,659
Annual average maintenance cost [€]	3,038	6,161	2,318
Annual average extraordinary costs [€]	**57**	**752**	**57**
Average annual tax reductions [€]	**4,012**	**5,995**	**2,843**
Average annual tax payment [€]	8,025	11,990	5,685
Annual average total revenues [€]	**10,303**	**24,075**	**10,874**
Annual electricity self-consumption savings [€]	973	973	973
Annual electricity feed-in [€]	1,055	7,214	1,338
Annual shared electricity [€]	1,117	9,630	1,405
Annual natural gas savings [€]	7,158	7,158	7,158
Simple payback time PBT [years]	**>20**	**>20**	**>20**
Net present value NPV [€] (	**-38,566**	**-146,601**	**-82,170**
Internal rate of return IRR [%]	**-5%**	**-11%**	**-18%**

Figure 7 shows the simple and discounted cash flows of Scenario 1. Despite the improvement trend, the retrofit does not achieve a positive net present value overall.

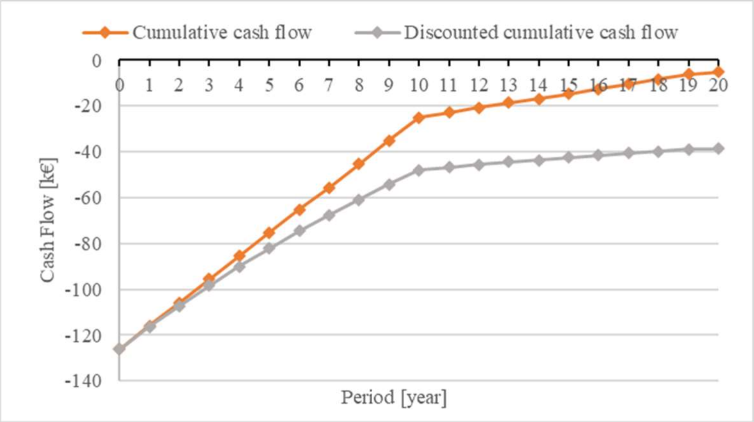

Fig. 7. Simple and discounted cumulative cash flows for intervention 1) concerning the installation of the photovoltaic system and the replacement of the heat generator with a heat pump.

5 Conclusions

This paper explores possible solutions for the phasing out of fossil fuel systems in buildings, through innovative generation systems, renewable energy production and energy sharing. The use of renewable source always available, such as hydrogen (Scenario 2 and 3) is necessary to achieve the performance of zero-emission buildings but is not economically feasible, even against the tax deductions currently in force in Italy, because of the high costs of the energy source. The plant retrofit by means of HP coupled with PV system is not economically feasible too (Scenario 1) if the refurbishment also considers the addition of the cooling service (individual split systems). On the contrary, in case of only H and DHW production services, Scenario 1 would have a SPBT of 9 years.

As to make the energy retrofit economically feasible, it would also be appropriate to optimize energy revenues and costs, by means of electricity self-consumption, feeding into the grid and sharing. To optimize self-consumption, it is possible to insert a storage - thermal or electric - to avoid the temporal mismatch between thermal load and PV production. Likewise, to optimise energy sharing, it is necessary to have electricity input profiles as contemporary as possible to the occupant usage profiles. This is again possible by entering a storage, or by changing the habits of end users. However, some evaluations show that the increase in total annual revenues is still not sufficient to make the intervention profitable.

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