Retrofitting of the HVAC plant of an elderly people residential care home

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About 14% of European population is over 65 years of age, and it is expected that this number will double by 2050. Care homes operate 24 hours a day, 365 days a year, with full occupancy. Some of the best available technologies were compared by an energy and economic analysis for a residential care home for elderly people in Vicenza (North East of Italy).

Keywords: Energy efficiency; HVAC plant; cogeneration; trigeneration; photovoltaic.

Introduction

Among the public (but not only) buildings, residential care homes for elderly people are ones of the potentially most important because of the increasing European population aging. Nowadays about 14% of European population is over 65 years of age, and it is expected that this number will double by 2050 [1]. These figures in Italy assume dramatic values, as actually we have 21.4% of population over 65 (13 million) and we will have 33.6% (18.7 million) by 2050 [2] [3]. Nowadays about 1.5 million elderly live in more than 24,000 care homes in Europe (300,000 elderly live in just less than 6,000 in Italy). These buildings operate 24 hours a day, 365 days a year, with full occupancy. For these reasons reducing energy consumption in residential care homes is important.

In this context, this paper focuses on the study of the energy performance of a quite new residential care home for elderly people in Vicenza (North East of Italy). A preliminary energy audit was carried out in order to obtain appropriate information about energy consumption of the building. Moving from the request of the managers responsible for running the care home, a Trnsys simulation model of the building and heating/cooling plant system was developed aiming at testing different solutions to retrofit the heating/cooling plant.

Building description and energy loads calculation

The considered building is a 29,889 m^3 residential care home for elderly people built during the 2002–2004 period and located in Vicenza (North Italy). The main data of the building are reported in **Table 1**. The model of this three floors building (about 2,800 m^2 each) was implemented using “Trnsys3d for SketchUp” (**Figure 1**) and “TRNbuild”.

An annual simulation of both heating and cooling loads was run with one-hour time step: annual heating and cooling energy use of the building were estimated to be 622,000 kWh and 529,000 kWh, with peak loads of 610 kW and 707 kW respectively. Concerning electric loads, there was availability of disaggregated data (on a quarter hourly basis) from local electric distributor for the years 2013 and 2014. Nevertheless, such data was subject to the different environment conditions (e.g. summer 2014 was extremely colder than usual in Italy) and building operating conditions. So, with some approximation based on information found by talks with technical personnel of the home, an hourly electric load profile was built taking into consideration monthly electric consumptions (deduced by electric bills), the actual installed electric power (400 kW) and the real data.

Table 1. Main data of the building.

Zone	Vicenza (North Italy)
Heating degree days	2479
Building destination	Residential care home
Internal volume (m^3)	29,889
Floors	3
External Surface / Heated Volume ratio (m^{-1})	0.35
Heating period	October 15th – April 15th
Cooling period	April 16th – October 14th
Typical temperature set-point, heating period (°C)	24.0
Typical relative humidity set-point, heating period (%)	–
Typical temperature set-point, cooling period (°C)	26.0
Typical relative humidity set-point, cooling period (%)	50%
Ventilation flow rate ($m^3 s^{-1}$)	4.09
External walls transmittance ($W m^{-2} K^{-1}$)	0.517
Floor transmittance ($W m^{-2} K^{-1}$)	0.433
Roof transmittance ($W m^{-2} K^{-1}$)	0.287
Windows transmittance ($W m^{-2} K^{-1}$)	3.155
Average internal heating gains ($W m^{-2}$)	4.0
Patients and staff	160

Heating/cooling plant description and primary energy consumption calculation

The existing heating, ventilation and cooling plant is mixed air/water; it is set up by:

- heating and cooling plant (vapour compression electric chiller and natural gas boilers);
- ventilation and air conditioning plant (many air handling units (AHU) to control relative humidity and for the necessary air changing inside the building; main units are set up by a rotary heat exchanger, pre-heating, cooling and dehumidification and post-heating sections). The common sites of the building (corridors, halls) are served by fan-coils and ventilation air, rooms and bathrooms are served by radiators and ventilation air, service and technical rooms by small AHUs or air heaters;
- air extraction plant (for service rooms).
- The object of the work is the energy and economic analysis of the retrofitting of the heating and cooling plant only. The main components are:
- one air/water vapour compression electric chiller (2 circuits – 4 oil free centrifugal compressors per

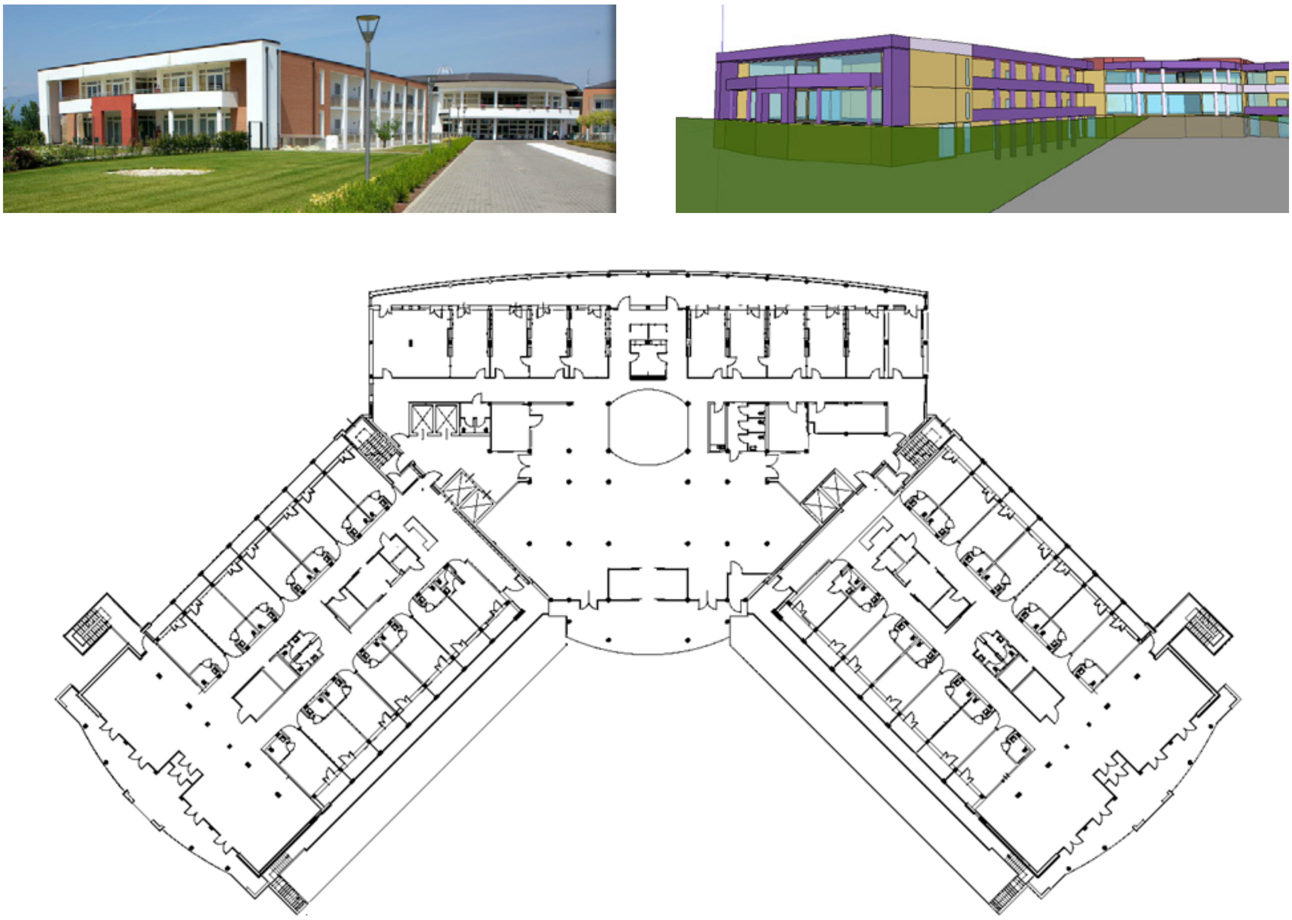

Figure 1. Photo, 3D model and layout (ground floor) of the considered residential care home.

circuit) which provides cold water for fan-coils and cold coils in AHUs. The nominal cooling power is 895 kW, 270 kW is the nominal electric power consumption, EER = 3.31. These performances are labelled for summer external air 35°C and evaporator input/output 12/7°C;

- two natural gas boilers with two-steps burners (nominal useful power 670 kW, minimum useful power 425 kW each) provide the thermal energy for heating, domestic hot water and pre and post-heating in AHUs.

The chiller and the boilers supply three hydraulic circuits. The "hot collector" supplies hot water to the radiators, air heaters, pre and post heating coils in the AHUs. It supplies also the domestic hot water plate heat exchanger that loads a 5,000 l tank. The "hot/cold collector" supplies hot (during heating season) or cold (during cooling season) water to the fan-coils. The "cold collector" supplies cold water to the cold coils of the AHUs (obviously during cooling season only). Reference [4] reports the temperature set points of the different energy uses and the schedules of the main equipment.

The first step was the simulation by Trnsys model of the just described existing plant ("As Is" solution). The validation of the model was carried out by analyzing flow rates and temperatures of the different circuits and by comparing simulated and real energy consumptions of the heating/cooling plant system. **Figure 2** reports the annual profiles of monthly electrical energy (EE) and natural gas (NG) consumptions, both simulated and real (referring to 2012, 2103 and 2014 available energy bills). Considering the variability of the environment and building operating conditions, the concordance between simulated and real data is quite good (the slight overestimate of electrical energy consumption during mid seasons is due to the wider cooling period in the simulations with respect to the reality).

Alternatives for the heating/cooling plant energy retrofitting

Different efficient technologies among the most common known were taken into consideration for the energy improvement of the heating/cooling plant, chosen referring to previous economic estimates in possession of the managers responsible for running the care home. Main technical data of all the equipment considered in the present analysis are reported in [4].

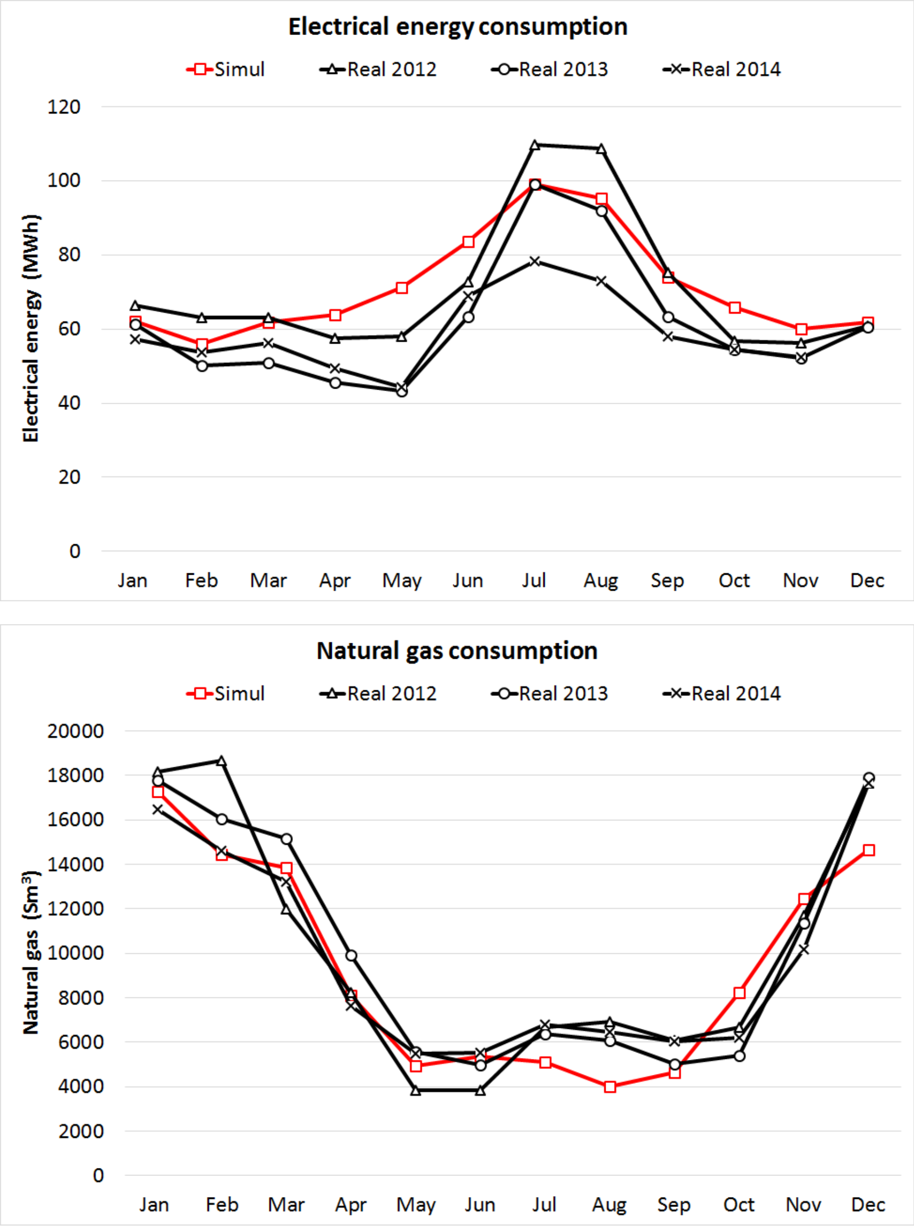

Figure 2. Annual profile of monthly electrical energy and NG consumptions.

For the sake of brevity, extremely concise information is here reported:

- photovoltaics, PV: different kinds of mono and policrystalline modules were considered, varying the peak power in the 230–315 W_p range (14-16.9% nominal efficiency), considering a fixed available area (two terraces of 108 m^2 each on the roof and three parking shelters for 1,022 m^2). In one alternative it was supposed to be able to install more PV modules on the roof (available area 350+350 m^2). A penalization factor of –0.60% per year was considered in order to take into account the annual decrease of useful power. All the other parameters and input in Trnsys model were set in order to suitably simulate the PV plant;
- combined heat and power, CHP (cogeneration): natural gas fueled internal combustion engines were considered with two different electrical nominal power (103 and 199 kW) and two different control strategies (electric load following and electric load following but during the 6.00 am-9.00 pm period only). A smaller size one was further considered (60 kW nominal power, electric - load following);
- combined cooling, heat and power, CCHP (trigeneration): in order to extend the operation hours of the cogeneration plants, three of the previous cases were implemented considering to use the heat produced by the engine also during cooling season by coupling suitable sized lithium bromide-water single effect absorption chiller;
- heat pumps: different sizes of vapour compression air/water heat pumps with both electric motor (EHP) and natural gas engine (GEHP) were considered. For the characterization of their performances the Authors referred to the UNI/TS 11300-4 and UNI EN 15316-4-2 method [5] [6] [7].

It was assumed to maintain the two actually present boilers with the double scope of both thermal integration and backup. Finally, primary energy consumptions were calculated taking into account thermal and electrical nominal efficiencies (on Lower Heating Value) for the cogenerators and nominal performances (COP) for the heat pumps, and considering their variations with the partial load (data derived by motors suppliers for the cogenerators – data derived implementing the UNI/TS 11300-4 and UNI EN 15316-4-2 calculation methods for quantifying energy loads and efficiencies of electrical HP-based heating plants).

Investment costs were determined by purchase, installation and first set up, besides costs of the existing plant adaptation [7] [8] [9] [10] (**Table 1**). The same table reports on the ordinary maintenance costs of the different solutions, while such costs for the existing plant are considered to be 5,000 € $year^{-1}$. Reference [4] reports on the costs of energy: natural gas and electricity purchased by the local distributors.

Concerning the management of the electricity produced by the cogenerators and photovoltaic plant besides own consumption, it was considered to be sold to the GSE (Energy Services Manager) at a constant price (fixed in 5.5 c€ kWh^{-1}). For the alternatives here considered, the incomes from the energy efficiency certificates resulted negligible because they did not, or only slightly, satisfy the minimum primary energy saving index provided by the 2004/8/EC directive [11]. Finally, for the primary energy calculations we considered the conversion factors reported in [12] [13], i.e. 1 kWh_{pr} kWh_{th}^{-1} and 2.17 kWh_{pr} kWh_{el}^{-1} respectively for natural gas and electricity.

Results and discussion

The solutions that maximize NG consumptions (even if minimizing the boilers consumption) are the ones with the installation of the 199 kW_{el} nominal power cogenerators, while the solutions minimizing the consumption in absolute terms concern installing the biggest sized electric heat pumps ("EHP_311 kWt" and "EHP_424 kWt"). The balance, in terms of electrical energy, takes into account the "self-produced" and the "sold to grid" electricity: the solutions that minimize the purchase from the grid (by more than 20 times with respect to the "As Is" plant) are the ones that maximize the self-production ("2, 199 kW – el. following" with and without trigeneration).

A more comprehensive comparison, carried out in terms of primary energy (PE), is reported in specific terms (per square meter of building surface) and in absolute terms as well in **Table 2**. Self-produced electrical energy accounts for a negative value in terms of consumption, so the best solutions foresee the installation of 199 kW_{el} cogenerator (coupling the absorption chiller allows a very slight improvement). These solutions allow to reduce by 63% the PE consumption. Anyway, if one looks at the benchmark for Italy suggested by [1] (234 kWh m^{-2} $year^{-1}$), all the CHP and CCHP alternatives and two PV solutions are performant. On the other hand, heat pumps, both electric and natural gas driven, are not advantageous at all and, in some cases, they lead to an increase of the PE consumption. This is due to the penalized operation of air/water heat pumps in the Vicenza winter

Table 1. Costs of the different heating/cooling plant retrofitting solutions (*Refer to the HP nominal thermal power at the condenser at A7/W45 conditions) (**Electric motor efficiency=0.95 – Internal combustion engine efficiency=0.3 [7]).

Alternative	Cost per kW (Electric/Thermal/Cooling) installed	Electric/ Thermal/ Cooling installed power	Set up and adaptation	Total investment cost	Annual ordinary maintenance cost
As Is	Sunk cost	-	-	-	5000 €
1, Solon Black 220/16 mono (265 W$_p$)	On the roof: 1,300 € kW$_p^{-1}$ On the parking shelter: 1,700 € kW$_p^{-1}$	33.9 kW$_p^{-1}$ 156.9 kW$_p^{-1}$	-	310,792 €	3400 €
2, Solon Black 220/16 poli (230 W$_p$)	On the roof: 1,300 € kW$_p^{-1}$ On the parking shelter: 1,700 € kW$_p^{-1}$	29.4 kW$_p^{-1}$ 136.2 kW$_p^{-1}$	-	269,744 €	3400 €
3, Abba Solar ASP 60 245-250 poli Plus (250 W$_p$)	On the roof: 1,300 € kW$_p^{-1}$ On the parking shelter: 1,700 € kW$_p^{-1}$	32.0 kW$_p^{-1}$ 148.0 kW$_p^{-1}$	-	293,200 €	3400 €
4, Renesola 156 mono (275 W$_p$)	On the roof: 1300 € kW$_p^{-1}$ On the parking shelter: 1700 € kW$_p^{-1}$	35.2 kW$_p^{-1}$ 162.8 kW$_p^{-1}$	-	322,520 €	3400 €
5, Renesola Virtus II JC315M-24/Abs poli (315 W$_p$)	On the roof: 1300 € kW$_p^{-1}$ On the parking shelter: 1,700 € kW$_p^{-1}$	30.2 kW$_p^{-1}$ 156.2 kW$_p^{-1}$	-	304,920 €	3400 €
1, Solon Black 220/16 mono (265 W$_p$) _Plus	On the roof: 1,300 € kW$_p^{-1}$ On the parking shelter: 1,700 € kW$_p^{-1}$	110.2 kW$_p^{-1}$ 156.9 kW$_p^{-1}$	-	410,008 €	3400 €
1, 103 kW – el. following	1,800 € kW$_{el}^{-1}$	103 kW$_{el}$	10000 €	195,400 €	0.020 € kWh$_{el}^{-1}$
2, 199 kW – el. following	1,400 € kW$_{el}^{-1}$	199 kW$_{el}$	10000 €	288,600 €	0.020 € kWh$_{el}^{-1}$
3, 103 kW – el. following – day time only	1,800 € kW$_{el}^{-1}$	103 kW$_{el}$	10000 €	195,400 €	0.020 € kWh$_{el}^{-1}$
4, 199 kW – el. following – day time only	1,400 € kW$_{el}^{-1}$	199 kW$_{el}$	10000 €	288,600 €	0.020 € kWh$_{el}^{-1}$
5, 60 kW – el. following	2,000 € kW$_{el}^{-1}$	60 kW$_{el}$	8000 €	128,000 €	0.020 € kWh$_{el}^{-1}$
2, 199 kW – el. following – trigeneration	Cogenerator: 1,400 € kW$_{el}^{-1}$ Abs. chiller: 500 € kW$_c^{-1}$	Cogenerator: 199 kW$_{el}$ Abs. chiller: 147 kW$_c$	30000 €	382,100 €	0.020 € kWh$_{el}^{-1}$
3, 103 kW – el. following – day time only – trigeneration	Cogenerator: 1,800 € kW$_{el}^{-1}$ Abs. chiller: 600 € kW$_c^{-1}$	Cogenerator: 103 kW$_{el}$ Abs. chiller: 70 kW$_c$	25000 €	252,400 €	0.020 € kWh$_{el}^{-1}$
5, 60 kW – el. following – trigeneration	Cogenerator: 2,000 € kW$_{el}^{-1}$ Abs. chiller: 625 € kW$_c^{-1}$	Cogenerator: 60 kW$_{el}$ Abs. chiller: 50 kW$_c$	20000 €	171,250 €	0.020 € kWh$_{el}^{-1}$
EHP_99 kWt*	500 € kW$_{el}^{-1}$	29 kW$_{el}$	20000 €	34,600 €	10 € kW$_{el}^{-1}$
GEHP_99 kWt* **	250 € kW$_{th}^{-1}$	153 kW$_{th}$	30000 €	68,239 €	5 € kW$_{th}^{-1}$
EHP_209 kWt*	500 € kW$_{el}^{-1}$	58 kW$_{el}$	20000 €	48,900 €	10 € kW$_{el}^{-1}$
GEHP_209 kWt* **	250 € kW$_{th}^{-1}$	300 kW$_{th}$	30000 €	105,042 €	5 € kW$_{th}^{-1}$
EHP_311 kWt*	500 € kW$_{el}^{-1}$	86 kW$_{el}$	20000 €	63,000 €	10 € kW$_{el}^{-1}$
GEHP_311 kWt* **	250 € kW$_{th}^{-1}$	458 kW$_{th}$	30000 €	144,479 €	5 € kW$_{th}^{-1}$
EHP_424 kWt*	500 € kW$_{el}^{-1}$	116 kW$_{el}$	20000 €	78,000 €	10 € kW$_{el}^{-1}$
GEHP_424 kWt* **	250 € kW$_{th}^{-1}$	618 kW$_{th}$	30000 €	184,438 €	5 € kW$_{th}^{-1}$

Table 2. Annual Primary Energy consumption of the different solutions, both absolute (MWh) and specific (kWh m^{-2}).

Alternative	**Total PE**		**Saving**
	(MWh)	**(kWh m^{-2})**	
As Is	2,944	351	–
1, Solon Black 220/16 mono (265 W_p)	2,015	240	32%
2, Solon Black 220/16 poli (230 W_p)	2,058	245	30%
3, Abba Solar ASP 60 245-250 poli Plus (250 W_p)	2,058	245	30%
4, Renesola 156 mono (275 W_p)	1,942	231	34%
5, Renesola Virtus II JC315M-24/Abs poli (315 W_p)	2,138	255	27%
1, Solon Black 220/16 mono (265 W_p)__Plus	1,694	202	42%
1, 103 kW – el. following	1,236	147	58%
2, 199 kW – el. following	1,101	131	63%
3, 103 kW – el. following – day time only	1,524	181	48%
4, 199 kW – el. following – day time only	1,317	157	55%
5, 60 kW - el. following	1,689	201	43%
2, 199 kW – el. following – trigeneration	1,092	130	63%
3, 103 kW – el. following – day time only – trigeneration	1,581	188	46%
5, 60 kW – el. following – trigeneration	1,720	205	42%
EHP_99 kWt	2,999	357	–2%
GEHP_99 kWt	3,067	365	–4%
EHP_209 kWt	2,911	347	1%
GEHP_209 kWt	3,064	365	–4%
EHP_311 kWt	2,916	347	1%
GEHP_311 kWt	3,111	370	–6%
EHP_424 kWt	2,931	349	0%
GEHP_424 kWt	3,135	373	–6%

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climate with frequent defrosting necessity ([9] [10] [14]) and especially due to the high temperature of water to be produced at the condenser (70°C) serving the radiators and the pre and post heating coils of AHUs.

The interest rate, the inflation rate and the period of the economic analysis were fixed at 4%, 1.8% and 20 years respectively. From the economic point of view, the comparison between the different alternatives did not consider the investment cost of substituting the existing plant, as it was considered to be a sunk cost (**Table 1**). The best solutions in terms of trade-off between maximum differential (investment alternative versus "As Is" solution) net present worth (NPW) and minimum discounted pay-back period (DPB) are the CHP/CCHP ones with installed electrical power around or less than 100 kW$_{el}$. In these cases, NPW is around 630–670 k€ and DPB is between 3 and 4 years (**Figure 3**); these are very interesting results, also considering that we are talking about the plant of a public building stock (so payback periods can be quite longer than in industry sector). These are also the solutions that allow the minimization of thermal energy dissipation by the cogenerator. From this point of view, it is interesting to observe that a further increase of the economic viability of such alternatives would be obtained by operating the cogenerator with the thermal load following logic.

Concerning the "2, 199 kW" solution it is worth to stress that coupling the absorption chiller can improve the economic viability, but even more advantageous is the operation during the day only (respectively NPW increases from 195 to 332 to 423 k€ and DPB decreases from 10.9 to 9.6 to 7.1 years). Photovoltaics is also interesting, even if it allows smaller NPWs (200-300 k€) and longer DPBs (9-11 years). Should be possible to use more surface on the roofs ("1, Solon Black 220/16 mono (265 W$_p$)__Plus" solution) the economic viability would increase (NPW=440 k€, DPB=8.6 years). It is interesting to observe that heat pump solutions are not advantageous at all as they present a greater than "As Is" solution annual cash flow for the reasons explained before.

In reference [4] these conclusions are completed by a sensitivity analysis in order to compensate for the uncertainty of some of the parameters here considered, such as natural gas and electrical energy costs.

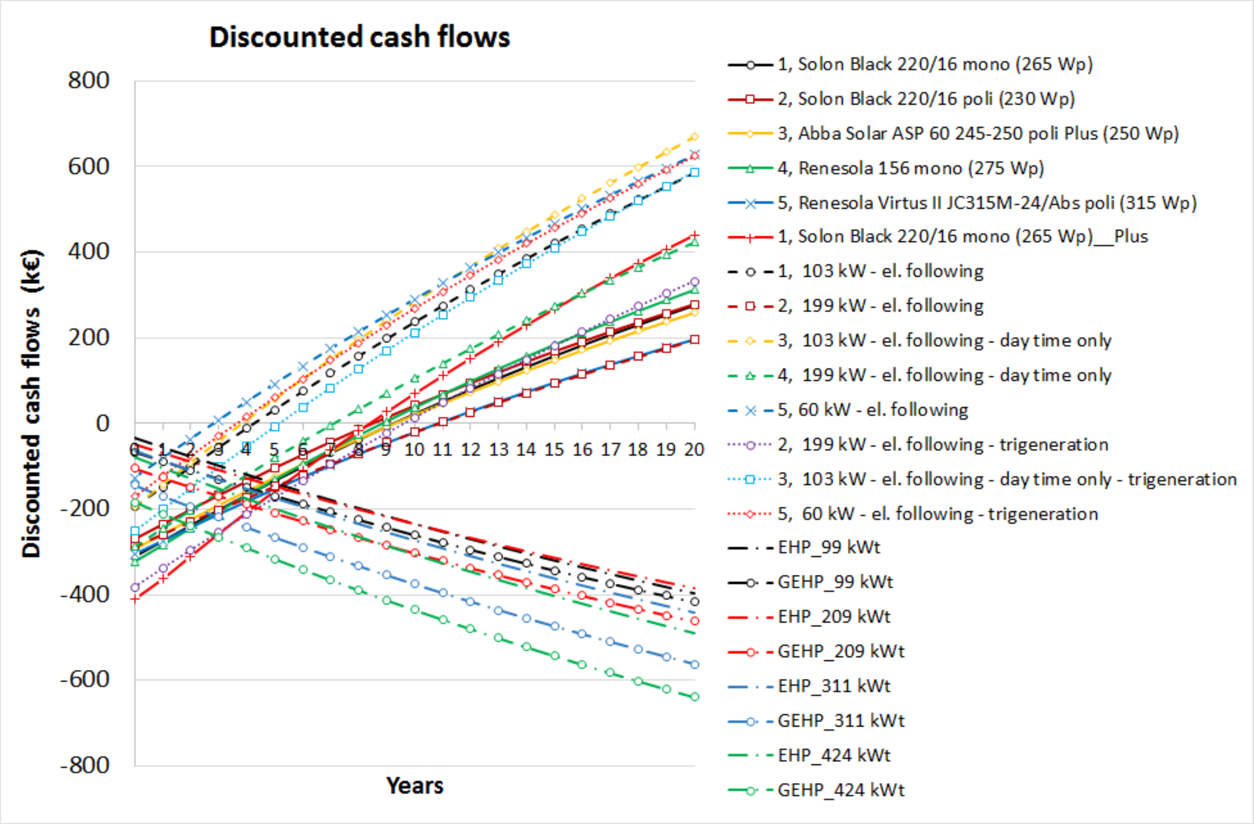

Figure 3. Discounted differential (between the alternatives and the "As Is" solution) cash flows of the different solutions. NPWs can be read at the end of the period of analysis (20 years), DPBs by the interceptions of the curves with the x-axis.

Conclusions

Many energy efficiency interventions can be thought to be implemented in residential care homes for elderly people as the greatest part of them are old buildings, i.e. built before regulations on buildings energy performance and economic incentives. In this sense, interventions on the building (e.g. retrofitting of the opaque and transparent surfaces by thermal insulation and windows substituting) are the first ones that should be implemented; installing a solar thermal plant and substituting the old lighting appliances by more efficient ones should be the second ones. In more recent (and so more energy performant) buildings some retrofitting interventions in heating/cooling plant can be analyze. Photovoltaics, cogeneration, trigeneration, electric and gas engine heat pumps were considered in this study and the energy and economic viability were evaluated. Cogeneration with small size engines (with respect to the installed electric power by local distributor) result the most advantageous solutions, whereas coupling a single-effect absorption chiller do not significantly improve the advantage. Photovoltaics as well allows an interesting energy saving with respect to the existing plant, even if with longer payback periods. Air/water heat pumps (the most economic and widespread diffused ones) are not advantageous at all in this case because of the high temperature at condenser and because of the cold and humid winter climate typical of the Po Valley (that implies frequent defrosting of the evaporator coil). The main conclusions of this study will be delivered to the managers responsible for running the residential care home in order to make energy efficient informed decisions. ■

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