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Energy, economic and environmental modelling for supporting strategic local planning

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Abstract

This study investigates the use of an evaluation model able to estimate the possibilities of reducing energy consumption and emissions of the building sector exploiting renewable energy sources. Specific attention is given to the use of ground source heat pumps in the urban context, proposing an ex-ante evaluation of different scenarios to identify the most balanced one in terms of energy, economic and environmental effects. The model is applied to a case study in Northern Italy to show how it can be used to support local administrations in energy urban planning, fitting economically and environmentally sustainable technologies. Moreover, it defines new boundaries in which the energy and environmental analyses should be carried out (spatial relocation), and the time span over which impacts have to be evaluated (temporal relocation).

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Keywords: Local energy planning; energy retrofit; economic feasibility; Ground Source Heat Pumps; CO_2 emissions

1. Introduction

In line with EU Roadmap 2050, it is fundamental to use renewable energy sources to mitigate environmental impacts of the energy sector [1]. The future energy system will be distributed, heavily relying on renewable energies,

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efficient use of energy, challenging all governance levels. At present, integrated low carbon policies and sustainable energy plans are affected by common challenges. At the local level, energy policies employ community and regional instruments limited to the energy performance of buildings. A proper transposition of the regulatory framework into municipal laws and plans is insufficient at the moment and the enforcement uneven. In particular, the current administrative organization shows to have poor knowledge and skills needed to perform updated planning.

Evaluation tools able to guide public administrations in low-carbon energy planning are essential. For this reason, a model for supporting local energy planning is developed with the objective of helping decision makers in defining energy policies at local level. In detail, the model aims to assess energy, economic and environmental impacts of alternative energy scenarios related to the use of low enthalpy geothermal heat pumps. The proposed model has been experimented on a real case study, the historical centre of Livorno Ferraris (Vercelli, Northern Italy). This case is particularly significant as the town that in the current state is never been regenerated from the point of view of energy, and represents the starting point to evaluate the maximum potential achievable by renewable sources for energy demand reduction. The EU Roadmap considers heat pumps as the main technology to achieve the objective of 100% renewable heating network. Heat pumps can use air or ground as heat sources. Heat pumps and, above all, Ground Source Heat Pumps (GSHPs) allow significant economic savings [2], which mostly depend on the ratio between the prices of gas and electricity [3]. GSHPs are divided into two main categories: closed-loop, based on the circulation of a heat carrier fluid in a closed pipe loop buried into the ground (Bore-hole Heat Exchanger, BHE), and open-loop, based on the thermal exchange on groundwater (Ground Water Heat Pump, GWHP). BHEs can be installed almost everywhere, since they do not require the presence of a productive aquifer. In addition, the design and authorisation of these plants is simpler. For these reasons, they are often used for small-size installations, i.e. up to 50 kW, while open-loop systems are more diffused for large-size plants up to some MWs of power [4], for which noticeable scale economies are achieved compared to the closed-loop solution. GWHPs efficiency is generally higher com-pared to BHEs, however they can only be installed where groundwater is present. Scale economies allow GWHPs to be used also for District Heating (DH) [5], for which closed-loop systems would hardly be viable. Individual heat pumps and DH are the core of the Heat Roadmap Europe [1] to achieve a 100% renewable heat production by 2050.

2. Methods

After having contextualized the potential of GSHPs in the section above, the goal of this second part is to study its application to the case study. This analysis considers the creation of a low-energy neighbourhood, for which a major share of the heating energy needs is covered by renewable energy production to reduce greenhouse gasses (GHGs) emissions. In particular, air- and groundwater heat pump systems are designed to achieve the objective. The case study is the historical town centre of Livorno Ferraris (Northern Italy). The neighbourhood extends over 7.6 hectares, and the total heating area of buildings is equal to 68,420 m². Most of the buildings located in this area were built before 1980, and then the thermal performances of envelopes are low. Also, some historical buildings, such as the old town hall and library built before 1800, are in this area. Different topologies and use purpose of buildings could be recognized. Nine building typologies distinguished by common features and characterized by comparable consumptions are identified, according to the TABULA database [6]. Once typified the neighbourhood buildings, the current annual thermal energy needs for heating were calculated (Table 1).

For the energy refurbishment of the historical centre, the substitution of the current conventional heating systems, which consist in high efficiency traditional boilers, with heat pumps was studied. Two different scenarios were evaluated: the first scenario (A) considers the installation of several geothermal and air-source heat pump systems, each one serving a cluster of buildings, while the second (B) investigates a district heating (DH) solution, requiring the installation of a heat pump station located outside of the town. Since a very productive aquifer underlies the analysed area, GWHPs were considered in this study rather than BHEs, due to their higher efficiency. In the scenario A, the buildings were divided into 27 clusters considering the different blocks of the town centre and the accessibility for drilling machines. Well locations were identified on the map and a GWHP well doublet was assigned to each cluster to meet its aggregated energy demand. Air-Source Heat Pumps (ASHPs) were considered for 10 clusters for which accessibility issues could arise for well drilling machines. However, only 17.4% of the total heat demand is covered by these 10 air-source heat pumps, while 82.6% is covered by GWHPs. In the scenario B, a

district heating power station with 3 groundwater heat pumps was considered, located SE with respect to the town of Livorno Ferraris. Wells location for both scenarios are depicted in Figure 1. In both scenarios, the existent high-temperature radiators were replaced with low-temperature ones for residential spaces and fan coils for commercial activities.

Table 1. Current energy need for space heating for each typology.

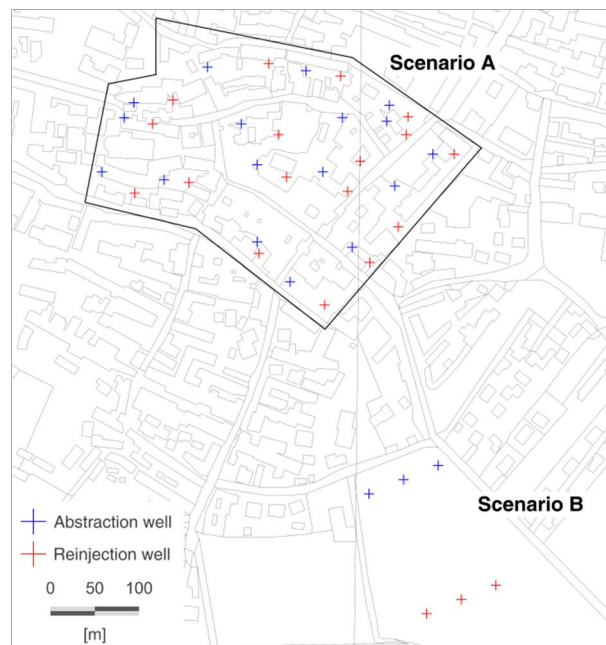| Typology	Buildings number [n]	Construction year class	Size classes	Energy need for heating [kWh/m²y]
1	22	< 1900	Terraced house	197
2	39	1901-1920	Terraced house	253
3	90	1946-1960	Terraced house	173
4	27	1961-1975	Terraced house	241
5	6	1976-1990	Terraced house	113
6	1	1991-2005	Terraced house	85
7	1	> 2005	Terraced house	65.8
8	1	< 1900	Town Hall	52
9	1	< 1900	Library	206

Fig. 1. GWHP abstraction and reinjection wells locations, for scenarios A and B.

The design thermal load P_{max} was calculated for each cluster, according to (1):

$$P_{max} = Q_H \frac{(20 - T_{min})}{24 \cdot HDD} \tag{1}$$

where Q_H is the annual energy demand of the cluster, including the energy losses in distribution system, T_{min} is the outdoor heating design temperature (-7 °C, according to Italian normative) and HDD are the heating degree days of the location (2549). Then, the thermal load profile of each cluster was derived considering the distribution of HDD on a fortnight basis, and well flow rates were derived considering a temperature difference of 3K between abstraction and injection. The technical feasibility and the underground thermal impact of the energy refurbishment scenarios were then assessed with a numerical flow and heat transport simulations with the finite element software FEFLOW. The 3-D model domain was developed according to the stratigraphy reported in the regional Water Protection Plan [7]. The unconfined aquifer is very thick (50 m) and has a shallow water table (depth of 2 m from ground surface). It is mainly composed of gravel with thin lenses of sand, and hence a hydraulic conductivity $K = 5 \cdot 10^{-3} \ m/s$ was hypothesized [8], while a much lower value ($10^{-8} \ m/s$) was assigned to the underlying aquiclude. The hydraulic gradient is of 3.9 m/km, and hydraulic boundary conditions were set consistently. The initial temperature was set to $T_0 = 12°C$ on the whole domain, i.e. equal to the yearly average outdoor air temperature, and the same value was imposed as a boundary condition at the upstream border. A simulation time of 10 years was adopted for both scenarios to assess the long-term sustainability of the system. Economic aspects of both scenarios were evaluated and compared, considering both costs and benefits related to the operation [9]. In particular, current market prices in Italy for installation and running costs of geothermal plants were considered (Table 2).

Table 2. Installation and running unit costs for GWHP and ASHP heat pumps.

Component	Investment costs	Unit
Heat pump	$5000 + (300 \cdot$ size) [kW]	€
Well doublet <5 l/s	18000	€
Well doublet <80 l/s	26000	€
Well doublet <150 l/s	32000	€
Existing heating system dismantling	1058	€
Existing radiators dismantling	37	€
Low-temperature radiator installation	465	€
Fan-coil installation	217	€
DH main pipe	748	€/m
DH secondary pipe	817	€/m
Technology	SPF	Unit
ASHP	3	-
GWHP	4.5	-
Source	Price	Unit
Natural gas	0.091	€/kWh
Electricity	0.243	€/kWh

Seasonal performance factors (SPFs) for GWHP and ASHP were assigned based on previous studies. SPF for district heating was slightly reduced considering that 10% of the produced heat is dissipated in the distribution grid. The environmental benefits of geothermal and air-source heat pumps compared to conventional heating systems (methane high efficiency traditional boiler) were evaluated in terms of CO_2 avoided emissions. Unit cost for natural gas and electricity in Italy were taken from EUROSTAT (Eurostat 2017), while emissions factors were derived from ARPA [10] and ISPRA [11]. The unit replacement cost of existing system and the installation one of new heating terminal devices were abstracted from Piedmont Region price-list [12]. For the scenario B, the investment costs related to DH grid realization were based on expenditure estimates from the technical and economic study carried out for a real neighbourhood located in Switzerland [13]. The costs of the district heating network elements include excavation works, materials and pipes installation.

3. Results and discussion

The results of flow and heat transport simulations confirmed the feasibility of replacing fossil fuel burners with groundwater heat pumps. The areas thermally affected by the GWHPs are shown in Figure 2 for the two scenarios A and B. Cold thermal plumes move towards Southeast in both cases, and the isotherm of -0.5 °C reaches a distance of 2 km downstream after 10 years, where neither drinking water wells nor GWHPs are present. The strong groundwater flow (>1.5 m/day) and the high transmissivity of the aquifer (0.25 m²/s) prevent the on-site accumulation of thermal plumes, thus avoiding the decay of systems performance during the years. However, in the scenario A, the GWHPs located in the SE part of the historical centre are thermally impacted by the upstream installations (Figure 3), thus inducing a maximum SPF reduction of 14% compared to the case of undisturbed groundwater at 12°C. Such issue does not affect scenario B since no GWHP is installed upstream, and no thermal recycling occurs [14]. On the other hand, the scenario A results in a smaller downstream thermal plume because of i) a better distributed thermal use of the aquifer and ii) 17.4% of the total heating need is covered by air-source heat pumps.

The investment cost and energy consumption of each heating system were calculated, and the payback period (PBP) [15] is estimated for the replacement of existing heating systems and, for the scenario B, of the district heating network. GWHPs turn out to be more profitable (PBP of 5-10 years) compared to ASHPs (9-18 years); the DH solution (scenario B) proves to be slightly less favourable (PBP of 9.3 years); moreover, about 1500 tons/year of CO_2 emissions are avoided for both scenarios, i.e. the equivalent of the total emissions of more than 200 inhabitants (Table 3). Scenario A, considering the average of all single installations, is slightly more economically convenient; however, strong differences exist between small and large installations, and between air-source and groundwater heat pumps (the latter being more convenient in both cases). On the other hand, scenario B provides a more homogeneous sharing of economic benefits among all the building clusters.
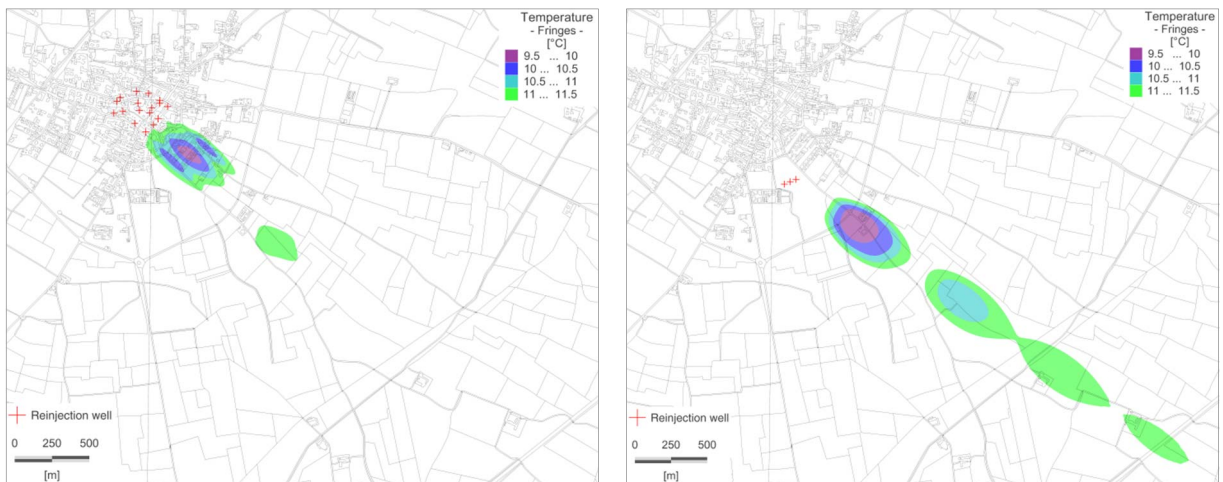

Fig. 2. Thermal plume induced by GWHP plants in scenario A (left) and B (right).
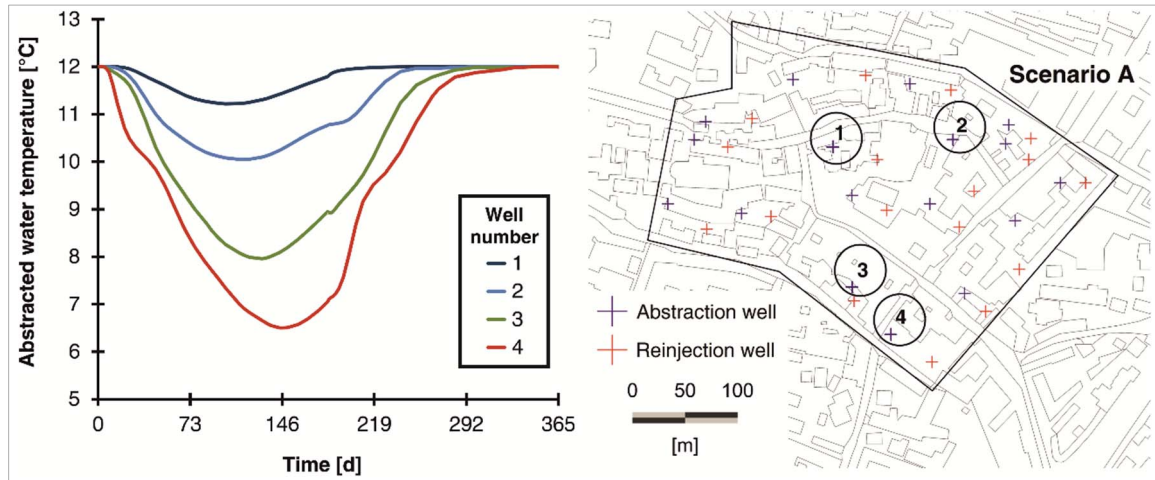
Fig. 3. Temperature evolution of abstracted water (left) for different wells locations (right) over each simulated year for A scenario.

Table 3. Economic and environmental analysis of scenarios A and B.

Cluster	Plant	Design power [kW]	Operating Hours [h/year]	Installation cost (HP+doublet) [€]	Dismantling [€]	Heating Terminals [€]	Yearly expense Heat Pump [€/y]	Yearly expense Methane Boiler [€/y]	Payback Period [y]	CO$_2$ avoided [ton/y]
1	GWHP	847	2265	283798	41364	225508	103615	205425	5.5	184.96
2	GWHP	631	2263	217160	33140	220758	77115	152886	6.3	137.65
3	GWHP	510	2265	179830	24459	171839	62385	123683	6.2	111.36
4	GWHP	174	2256	76170	8205	81500	21200	42031	8.0	37.84
5	ASHP	180	2257	59000	12766	67077	32908	43495	13.1	19.09
6	GWHP	469	2263	167181	32007	149728	57308	113617	6.3	102.30
7	GWHP	230	2265	93447	18251	158559	28129	55767	9.9	50.21
8	ASHP	35	2244	15500	2313	11568	6363	8410	14.4	3.69
9	GWHP	101	2263	53649	7882	40129	12340	24465	8.5	22.03
10	GWHP	101	2259	53649	6878	53578	12320	24424	9.5	21.99
11	ASHP	87	2261	31100	6117	30396	15936	21063	13.2	9.25
12	GWHP	321	2264	121521	12173	98134	39251	77817	6.1	70.06
13	ASHP	88	2264	31400	8939	53904	16138	21330	18.2	9.36
14	ASHP	343	2260	107900	21618	106068	62781	82978	11.7	36.43
15	ASHP	74	2264	27200	3408	21663	13569	17934	12.0	7.87

Cluster	Plant	Design power [kW]	Operating Hours [h/year]	Installation cost (HP+doublet) [€]	Dismantling [€]	Heating Terminals [€]	Yearly expense Heat Pump [€/y]	Yearly expense Methane Boiler [€/y]	Payback Period [y]	CO$_2$ avoided [ton/y]
16	ASHP	168	2264	55400	8509	51336	30804	40714	11.6	17.87
17	ASHP	165	2264	54500	7357	48437	30255	39989	11.3	17.56
18	GWHP	228	2263	92830	7752	51873	27859	55232	5.6	49.73
19	ASHP	58	2248	22400	2807	10259	10561	13959	10.4	6.13
20	GWHP	690	2263	235362	29986	213094	84304	167138	5.8	150.49
21	GWHP	392	2263	143426	20994	129054	47894	94954	6.3	85.49
22	GWHP	381	2262	140032	19168	129553	46545	92280	6.4	83.09
23	GWHP	463	2262	165330	28903	182986	56557	112128	6.9	100.96
24	GWHP	462	2262	165021	24300	155088	56423	111864	6.3	100.72
25	ASHP	156	2259	51800	15616	74209	28546	37730	15.4	16.56
26	GWHP	215	2256	88819	14364	75982	26188	51919	7.0	46.75
27	GWHP	186	2263	79872	13071	75160	22726	45056	7.6	40.57
TOTAL SCENARIO A		7755		2813296	432349	2687442	1030020	1878287	7.1	1540

Well doublet	Plant	Design power [kW]	Operating Hours [h/year]	Installation cost (HP+doublet) [€]	Dismantling [€]	Heating Terminals [€]	Yearly expense Heat Pump [€/y]	Yearly expense Methane Boiler [€/y]	Payback Period [y]	CO$_2$ avoided [ton/y]
1	GWHP	2585	2262	818388	144116	1569932	354168	626096	9.3	497.69
2	GWHP	2585	2262	818388	144116	1569932	354168	626096	9.3	497.69
3	GWHP	2585	2262	818388	144116	1569932	354168	626096	9.3	497.69
TOTAL SCENARIO B		7755	6787	2455163	432349	4709796	1062505	1878287	9.3	1493

4. Conclusions

The main challenge of this paper was to demonstrate how can the EU roadmap for 100% renewable heating be implemented in a real case study. A scenario analysis is performed considering heat pumps (air-source and groundwater) for the heating systems of the historical town centre of Livorno Ferraris (Italy). The scenario A applied a combination of GWHP and ASHP in 27 building clusters, while scenario B implements a district heating network fed by GWHPs. For both scenarios, the thermal impact on the aquifer proved to be sustainable, although some

interference between neighbouring plants occurs for scenario A. The economic and environmental benefits of the proposed solutions were assessed, respectively estimating the PBP and the avoided CO_2 emissions achieved by replacing existing methane heating systems with heat pumps. While scenario A proves to be slightly more economically convenient, the scenario B introduces two main advantages from a planning point of view, i.e. i) a more homogeneous sharing of economic benefits among all dwellings and ii) the elimination of interference issues among neighbouring installations. A stronger thermal alteration of the aquifer was observed for scenario B, however no downstream target has been identified for such impact. Significant CO_2 emissions savings (about 1500 tons/year) were found for both solutions, which is the equivalent of the yearly emissions of more than 200 inhabitants.

The paper shows how a more comprehensive decision support system, able to consider the different aspects involved in energy decision problems, could become a useful tool to assist the public administrations at the local level. Starting from a real case, this study provided an estimation of the efficiency measures at the urban scale. The results obtained by applying the proposed procedure to the Livorno Ferraris area highlight the great potential achievable in the wider context of sustainable urban planning in terms of reduction of CO_2 emissions, in-creasing use of natural and renewable energy sources. To provide a comprehensive overview and analysis of the energy investments, initiatives for networking and cooperation between different experts are needed. The program optimization of these energy systems should be applicable with the aim of creating configuration systems regarding energy, environment, and economy.

Concerning future research, more precise environmental impacts estimates must be made by re-defining the environmental boundaries. The present work did not consider the retrofit of the buildings envelope, which would be highly advisable in order to reduce the heating demand, before considering its coverage with renewable energy sources.

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