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Financial and Environmental Analysis of Ground-Source Heat Pump Utilization in the Residential Sector in Iran

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ABSTRACT

A substantial part of global energy demand is the energy used to supply building cooling and heating loads. In order to prevent pollutant emissions caused by the use of fossil fuels in the building sector, renewable energies must be expanded. Among renewables, ground-source heat pumps are useful for supplying both heating and cooling. Iran has a wide range of different climates, and recent studies suggested that almost 8.8% of the country has the potential of geothermal energy.

This paper investigates different scenarios of supplying the energy demand for cooling and heating in buildings which will be constructed in Iran until 2030. In the first scenario, the required energy would be provided by using electricity which is generated by fossil fuel power plants. Natural gas would supply the building energy in the second scenario, and ground-source heat pumps will supply the last scenario, buildings' heating and cooling. It is observed that the overall air pollutant emissions for the first, second, and third scenarios are 167, 162 and 132 million tonnes, respectively. According to the calculations, the first scenario is financially the most favourable from the consumer point of view and the second scenario is the best for the government. However, considering all the costs for the country, the third scenario yields the best results. Therefore, if the government support heat pump installation costs by considering subside, it is the best option for the future.

1. INTRODUCTION

Conventional energy resources have been lowered drastically in today's world due to population growth as well as the development of industrial energy extraction methodologies. It is estimated that fossil fuel resources, such as oil, coal, and natural gas, will not be available for several decades from now[17]. This fact has caused increasing attention towards substituting conventional energy resources with renewables[1, 6, 13]. In Europe, energy sector development efforts have aimed for sustainable utilisation of renewable energy resources by trying to substitute current fossil fuel sources and consequently, lowering greenhouse gas emissions to the atmosphere[9]. One of the most available renewable energy sources is geothermal energy. Approximately 37% of the world's geothermal energy resource has been utilised for heating. Around 75% of this amount is dedicated to central heating of buildings, which saves 44772 TJ of energy, annually[8]. Furthermore, geothermal energy could be used as the energy source for heat pumps causing economic saving and lowering greenhouse gas emissions. Fig. 1 depicts the annual generated energy by ground-source heat pumps worldwide[7].

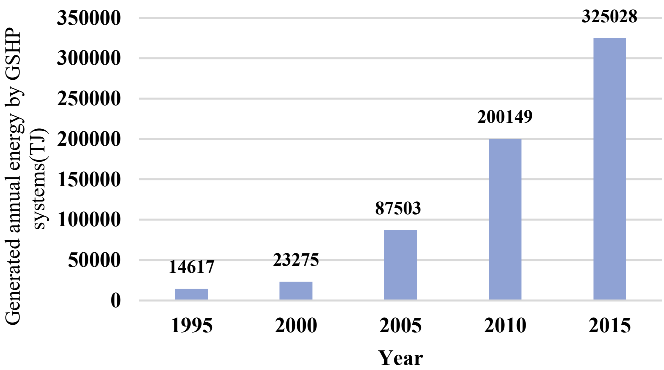

Figure 1: Annual energy production by ground-source heat pumps in 1995-2015[7]

Ground-source heat pumps consume electricity and exchange heat with the ground to produce energy for space heating, cooling, and water heating of buildings. In this regard, the ground is used as the heating source in wintertime and the cooling source in the summertime. In this system, the operating fluid within the pipes is flowed from the ground heat exchanger into the building transferring heat during Winter. Also, the hot air flow is pumped into the ground in order to be cooled during the Summer [12, 14].

The first employment of a ground source heat pump was implemented in Switzerland in 1912[3]. After that, it became popular in North America and Europe and specifically, after the first oil crisis in 1970, extensive efforts were focused on ground-source heat pumps in North America and Europe[5].

Various research attempts are conducted in the field of ground-source heat pumps in Iran and worldwide[11, 17, 15]. Yousefi et al. investigated the substitution of conventional HVAC systems with heat pumps for the under constriction buildings in Tehran in 2016[18]. The results demonstrated that annual value of 100568 tons of CO_2 could be prevented in case of employing ground-source heat pumps and as a result, an approximate economic saving of 641365 USD due to the consequent lowered annual expenses caused by environment protection from emissions could be achieved. Furthermore, 12931360 m^3 of natural gas could be saved annually in case of plan implementation.

In this paper, three scenarios are considered for supplying the required cooling and heating loads in the building. In the first method, the loads are provided by air-cooled split units(SP). In the second method, the loads are supplied by boilers and chillers (BCH), and finally, in the third scenario, ground-source heat pumps are employed (GSHP). The costs and incomes of each scenario are investigated.

2. MATERIALS AND METHODS

Heat pump operating systems are divided into three categories by ASHRAE, illustrated in Fig. 2[2]:

1- Ground-Water Heat Pump
2- Surface-Water Heat Pump
3- Ground-Connected Heat Pump

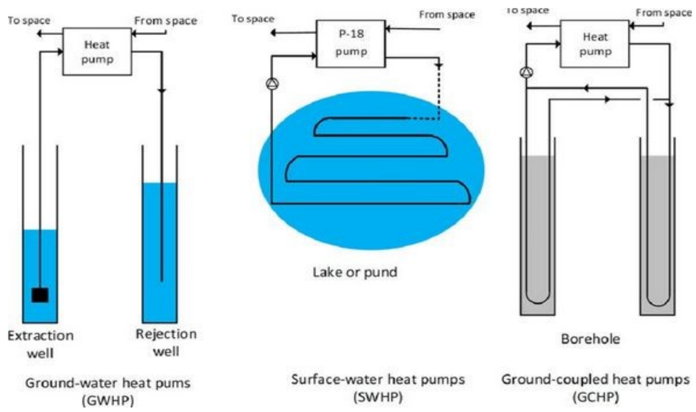

Figure 2: Operation categories of heat pumps

Fossil fuel consumption is relatively high in Iran due to great fossil fuel resources like oil and natural gas and low energy prices. In this regard, the highest consumption rate belongs to natural gas which consumed in several sectors. 56% of total Iran's natural gas consumption in 2016 was dedicated to the residential, commercial, and public sector. That 71% of the building energy is consumed to supply cooling and heating demands[4, 10].

The number of buildings to be constructed by 2030 was estimated based on the statistics of buildings constructed until 2016[4]. It is predicted that 609.8 million square meters will be granted construction license for building establishment, which can be considered as 4065900 of 150 m^2 apartment units and 508238 8-unit buildings. Considering the average heating and cooling loads of a 150 m^2 apartment unit as 50000 Btu/h (4.25 of refrigeration tons), it is estimated that a load equal to 203295 million Btu/h (59565.4 million watts), would be required by 2030 in the country. If 16-hour cooling/heating load requirement would be assumed for a typical building in Iran, 347862 million kWh of power is needed to supply.

In the first scenario, this load is assumed to be provided by air-cooled split units. In case the average cooling/heating efficiency (COP) of the split devices is assumed to be 3.88, the overall electricity consumed in this sector would be:

$$347862 \div 3.88 = 89655.1 (million\ kwh)$$

Considering an average of 15.5% of distribution network loss as well as an average efficiency of 41.4% for the country's power plants, the overall required power for supplying heating and cooling loads would be[4]:

$$89655.1 \times \frac{100}{84.5} \times \frac{100}{41.4} = 256282 (million\ kwh)$$

In the second scenario, the average chiller COP and boiler efficiency are assumed as 4.46 and 88% respectively. Since natural gas is directly supplied to chillers and boilers, the only loss corresponding to these devices would be the gas distribution network loss (5%) and electricity distribution network and power plant losses are only considered for electricity consumption of the fan coil units. In the case of having 173931 million kWh of cooling and heating loads, the power consumption of boiler and chiller devices would be:

$$\frac{173931}{0.88} = 197649 \quad (million\ kWh) \qquad \text{Boiler power consumption}$$

$$\frac{173931}{4.46} = 38998 \;(million\ kWh) \qquad \text{Chiller power consumption}$$

$$(197649 + 38998) \times \frac{100}{95} = 249102\ (million\ kWh)\ \text{Overall boiler and chiller power consumption}$$

In the above calculations, a fan coil unit with a cooling/heating capacity of 10200 Btu/h is considered, therefore, 14269000 of fan coil units would be needed for supplying the required load. If each fan coil unit consumes 100 W of power, the overall value of 1427 MW of electricity would be required for this purpose. With 16 hours of heating/cooling load requirement, 244.2 kWh of electricity is to be supplied. Taking into account the distribution network and power plant losses, the overall required power would be:

$$244 \times \frac{100}{84.5} \times \frac{100}{41.4} = 698\ (kwh)\ \text{The overall required power for fan coil units}$$

Since the power consumption of a fan coil unit is much lower than that of a boiler or chiller, its electricity consumption will be neglected in the environmental effect calculations.

In the third scenario, the load is provided by heat pumps. Considering the average COP of ground-source heat pumps the overall power consumption would be:

$$347862 \div 4.9 = 70992\ (million\ kwh)$$

If the distribution network and power plant losses are taken into account with values similar to the first scenario, the overall required power for supplying the required heating and cooling loads by ground-source heat pumps would be estimated as 202933 million kWh.

$$70992 \times \frac{100}{84.5} \times \frac{100}{41.4} = 202933$$

3. ENVIRONMENTAL ANALYSIS

The major concern around fossil fuel consumption is their pollution emissions, specifically carbon dioxide. Fig. 4 illustrates the fossil fuels share of CO_2 emission in Iran in 2015[4].

Despite being the cleaner energy as compared to other fossil fuel resources, natural gas is responsible for approximately 61% of the total greenhouse gas emissions in Iran.

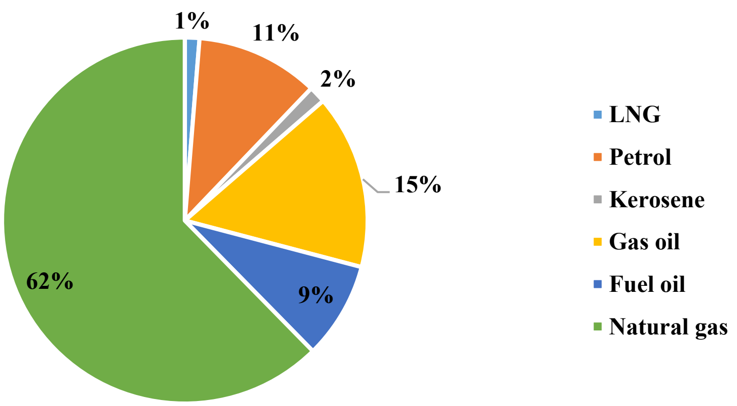

Figure 3: Fossil fuels share of CO_2 emission in Iran in 2015[4]

Tables 1, 2, and 3 present the emission prevention-related costs on the environment, followed by different discussed scenarios. It is observed that the overall cost of pollutant emissions for the first, second, and third scenarios equal 766.6, 745.2, and 607 million USD, respectively.

Table 1: Environmental cost reduction in SP[16]

Air pollutants and greenhouse gasses	Air pollutant emission index (gr per kWh)	Reduced air pollutant (million Ton)	External costs of Pollutants ($/Ton)	Amount of external costs reduction (million $)
$C0_2$	645.985	165.5543	2.86	473.4854
SPM	0.095	0.024347	1228.57	29.91174
CO	0.604	0.154794	53.57	8.292332
SO_2	1.113	0.285242	521.43	148.7337
CH_4	0.014	0.003588	60	0.215277
NO_X	2.413	0.618408	171.43	106.0138

Table 2: Environmental cost reduction in BCH[16]

Air pollutants and greenhouse gasses	Air pollutant emission index (gr per kWh)	Reduced air pollutant (million Ton)	External costs of Pollutants ($/Ton)	Amount of external costs reduction (million $)
$C0_2$	645.985	160.9162	2.86	460.2202
SPM	0.095	0.023665	1228.57	29.07373
CO	0.604	0.150458	53.57	8.060014
SO_2	1.113	0.277251	521.43	144.5667
CH_4	0.014	0.003487	60	0.209246
NO_X	2.413	0.601083	171.43	103.0437

Table 3: Environmental cost reduction in GSHP[16]

Air pollutants and greenhouse gasses	Air pollutant emission index (gr per kWh)	Reduced air pollutant (million Ton)	External costs of Pollutants ($/Ton)	Amount of external costs Reduction (million $)
$C0_2$	645.985	131.0917	2.86	374.9222
SPM	0.095	0.019279	1228.57	23.68515
CO	0.604	0.122572	53.57	6.566157
SO_2	1.113	0.225864	521.43	117.7725
CH_4	0.014	0.002841	60	0.170464
NO_X	2.413	0.489677	171.43	83.94538

4. ECONOMIC ANALYSIS

As mentioned before, the required power for supplying the heating and cooling loads by air-cooled split units equals 256282 million kWh. Considering an average requirement of 16 h for heating and cooling loads supplying in Iran, power plants with a total capacity of 43.8 GW (149738 million Btu/h) would be required. According to Table 4, the average price of establishing a power plant equals 6 cents per kWh of capacity. Therefore, the overall price for establishing a power plant capable of supplying the required heating and cooling loads of the country equals 15377 million USD.

Table 4: Establishment and maintenance costs of various power plant types

type	Establishment cost (cent/kWh)	Maintenance cost (cent/kWh)	Fuel cost (cent/kWh)	Overall cost (cent/kWh)
Natural gas consuming power plant	1.2	0.05	5.9	7.2
Combine cycle power plant	1.1	0.1	3.5	4.7

Taking into account that an air-cooled split unit would cost 0.041 USD for each Btu/h of capacity, the overall price for providing this system for the country would be:

$$0.41 \times 149738 \ = 6140(\text{million } \$)$$

Therefore, the overall price of the first scenario, including power plant establishment, preventing emissions, and supplying split devices would be:

$$6140 + 15377 + 706.6 = 22233 \ (\text{million } \$)$$

In the second scenario, the required power is assumed to be supplied via fan coil units using chillers and boilers. Each chiller and boiler devices must provide 72771 million Btu/h, i.e. 21327 MW, of power. The overall cost of this scenario consists of the cost of providing fan coils, chiller and boiler devices, environmental cost, and natural gas utility cost. If a 0.059 and 0.041 USD price is considered for each Btu/h capacity for the chiller and air conditioner devices, respectively, and the boiler cost is assumed to be 3.5 USD/kW, the overall price of systems is :

$$(72771 \times 0.09) + (21327 \times 0.0035) + (145542.3 \times 0.041) = 12737.4 \ (\text{million } \$)$$

Considering the heating value of natural gas in the second scenario, 23778 m^3 of natural gas would be required to supply the heating and cooling loads. Considering 0.35 USD/m^3 of natural gas price, the overall fuel price is:

$$23778 \times 0.35 = 8322.3(\text{million } \$)$$

If the first scenario is considered as the base scenario, 7180 million kWh of power (685.4 million m^3 of natural gas) is saved in the second scenario. This amount of natural gas could be exported to neighbouring countries and make an income worth 240 million USD for the country. In this case, the overall price for the second scenario equals:

$$12737.4 + 8322.3 + 745.2 - 240 \ = 21565 \ (\text{million } \$)$$

In the third scenario, the required power for supplying the considered loads by GSHP equals 202933 million kWh. Similar to the first scenario, the heating and cooling requirement is considered to be 16 h on average during the day across the country. Therefore, an overall power plant capacity of 34749 MW (9.8 million refrigeration tons) is needed to be supplied. In order to supply this load, a power plant with 34.7 GW of capacity is required. The establishment cost of this power plant capacity equals 12176 million USD.

The average cost of installing GSHP in Iran is 1100 USD per refrigeration ton on average. Therefore, the overall price of installing heat pumps across the country for supplying the required loads is calculated as follows:

$$9.8 \times 1050 = 10290 \ \ (\text{million } \$)$$

In addition, 5092 million m^3 of natural gas is saved, which could result in an income of 1782.2 million USD for the country in case of export.

Accordingly, the overall price of the third scenario, including the heat pump installation, emission prevention, and the income from the natural gas export is estimated as follows:

$$10290 + 12176 + 607 - (1782.2) = 21291(\ million\ \$)$$

In Table 5 the costs for air-cooled split units, chillers, boilers, ground source heat pumps, and fuel consumption is considered as public costs, while the costs of power plant establishment and environmental costs, as well as the export income, are considered as the governmental costs. As is illustrated, the first scenario leads to the lowest cost for the consumer, while the second scenario leads to the lowest cost for the government. However, the third scenario is proven to be the best one regarding the overall cost. Therefore, if governmental support is guaranteed for the prices of heat pump installation, ground-source heat pump scenario is the best possible outcome.

Table 5: Detail costs for the consumer and the government for each discussed scenario (million USD)

Scenario	Public cost	Governmental cost	Total cost
ES	18185	4048	22233
BCH	21060	505	21565
GSHP	19828	1463	21291

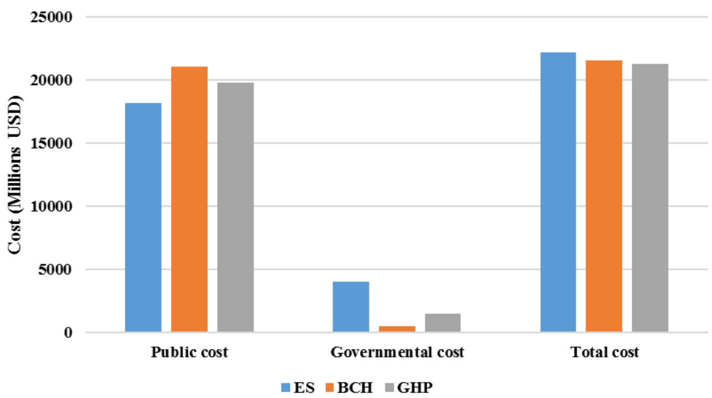

Figure 4: Detail costs for the consumer and the government for each discussed scenario

It should be mentioned that health-related costs are not accounted for in this paper. Increasing rates of pollutant emissions would be a considerable potential threat to human health, causing both long-term and short-term harming impacts on society's health by spreading heart as well as respiratory diseases. In this regard, increasing pollutant gas emission rates strongly correlate to significantly higher values of health sector expenses. Since the amount of emitted greenhouse gases are higher in the first and second scenarios, as compared to the third scenario, implementing the third scenario could substantially decrease the overall expenses in the long run in comparison.

5. CONCLUSIONS

Since Iran has acceptable potential in renewable energy resources, including geothermal energy, a significant share of the required heating/cooling loads of the buildings sector could be supplied by this source. This paper compared three methods of supplying the required heating and cooling loads for constructed buildings between 2015-2030 in Iran. In the first scenario, the loads are assumed to be supplied by air-cooled split units. The second scenario used chillers, boilers, and fan coils to supply the energy demand, and finally, in the third scenario, the required loads are considered to be supplied by geothermal heat pumps. It is observed that the overall cost of pollutant emissions for the first, second, and third scenarios are 766.6, 745.2, and 607 million USD, respectively. According to the calculations, the first scenario is the most favourable from the consumer point of view and the second scenario is the best for the government. However, considering all the costs for the country, the third scenario yields the best results. Therefore, if the government support heat pump installation costs by considering subside, it is the best option for the future.

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