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Multi-Objective Optimization Applied to a Solar-Geothermal Multi-Generation System for Hydrogen Production, Desalination, and Energy Storage − Part II: Effect of Price Inflation

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Dear Editor

Please find enclosed paper entitled "*Multi-Objective Optimization Applied to a Solar-Geothermal Multi-Generation System for Hydrogen Production, Desalination, and Energy Storage – Part II: Effect of Price Inflation*" to be considered for possible publication in the Special Issue **(GCGW-2021)** of the International Journal of Hydrogen Energy.

This paper has not been published and is not under consideration for publication elsewhere.

We have no conflicts of interest to disclose.

Thank you for your consideration.

Best regards,

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Highlights

- Fresh water production declines by 15.00% when inflation reaches from 0.05 to 0.20
- The optimum solar area and H_2 production increase by 14.43 and 9.85%, respectively
- The ground water flow rate in the optimal condition goes down by 20.08%
- 12.24 and 11.96% decrease in the optimal annual power and heat generation is seen
- The payback period increases slightly from 6.11 to 7.39 years

Multi-Objective Optimization Applied to a Solar-Geothermal Multi-Generation System for Hydrogen Production, Desalination, and Energy Storage − Part II: Effect of Price Inflation

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Abstract

We investigate the effect of price inflation on the optimum design and techno-economic performance of a solar-geothermal system that can simultaneously produce hydrogen, power, fresh water, and heat. A total of seven parameters are considered. Two of them, the solar collector area and the mass flow rate of the extracted ground water, are chosen as the decision variables in a multi-objective optimization process. The remaining five parameters are the objective functions, consisting of the payback period and the annual production of hydrogen, power, fresh water, and

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heat. When inflation rises from 0.05 to 0.20, the optimization algorithm is found to increase the solar collector area by 14.4% and to decrease the extracted ground water mass flow rate by 20.1%. At the same time, hydrogen production rises by 9.85%, while the annual production of power, fresh water, and heat drops by 12.2%, 15.0%, and 12.0%, respectively. Finally, the payback period is found to increase from 6.11 to 7.39 years, demonstrating that the system is still economically viable, even in inflationary times.

Keywords: *hydrogen production; solar; geothermal; price inflation; optimal design; renewable energy*.

Nomenclature

Symbols

a	Pairwise matrix element
r	Normalized weight of the pairwise comparison matrix
s	Summation of the rows of the pairwise comparison matrix
w	Weight in the pairwise comparison of AHP
W	Final weight of an alternative in AHP

Subscripts

i	Pairwise matrix ith row
j	Pairwise matrix jth column

Abbreviations

AHP	Analytical hierarchy process
TOPSIS	Technique for order preferences based on the similarity to the ideal solution
TES	Thermal energy storage
MED	Multi-effect desalination
CSP	Concentrated solar power
NSGA-II	Non-dominated sorting genetic algorithm II
PTC	Parabolic trough collector

1. Introduction

For over a century, global energy demand has risen to support increased urbanization, enhanced quality of life, and socio-economic development [1-3]. Previously this demand has been met primarily through the combustion of fossil-based energy resources, but this is now known to be a major contributor to greenhouse gas emissions and climate change, posing serious threats to our ecosystem and human civilization [4]. According to the IEA, global energy demand is expected to rise by more than 4% in 2022, an increase that is to be partly met by fossil-based energy resources, especially in underdeveloped nations [5]. At the 2021 United Nations Climate Change Conference

(COP26) held in Scotland, the global community could only agree to “phase-down” (rather than “phase-out”) the use of coal, highlighting the need to develop more sustainable but economically viable alternatives for energy production and conversion [6-8].

Renewable energy systems are a promising alternative to fossil-based technologies [9-11]. Some systems of this sort can also produce heat, hydrogen and water to meet societal needs [12-14]. The efficient production and management of renewable energy would not only reduce our overall carbon intensity, but it would also reduce our reliance on fossil fuels, contributing to environmental sustainability while meeting the energy, security and water needs of our societies [15]. In this context, polygeneration technologies powered by renewable energy offer profound potential [16]. They can enhance the utilization of natural resources while promoting energy efficiency and reducing costs, both monetary and environmental [16].

In a polygeneration system, multiple objectives – such as the production of power, cooling, heating, hydrogen gas, and water – are simultaneously realized through integrated processes driven by various energy resources, including those with renewable credentials such as solar and geothermal [17]. There is a need to carefully analyze such integrated processes to estimate their energy efficiency and production performance. Sen et al. [18] have conducted thermodynamic modeling and analysis for electricity and hydrogen production from a multi-generation system powered by geothermal and solar resources. The exergy and energy efficiencies of the overall system were estimated to be 18.99% and 5.90%, respectively. Analysis based on exergy and energy perspectives was performed on a concentrated photovoltaic recuperator for a geothermal polygeneration system, where a noticeable performance improvement was found [19]. Siddiqui et al. analyzed an innovative multi-generation unit powered by solar and geothermal energy. The exergy and energy efficiencies were found to be up to 19.1% and 19.6%, respectively [20].

Multi-objective optimization can be used to find optimal solutions even with competing objectives. Chitgar et al. [21] proposed an integrated GT-SOFC system to produce electricity, fresh water, and hydrogen. The system was optimized using a genetic algorithm combined with multi-objective optimization, and the optimal solutions for various built-in scenarios were found. Ebrahimi–Moghadam et al. [22] presented optimal solutions for the simultaneous production of electricity, heating and cooling, and hydrogen from a multi-generation district heating system. Alirahmi et al. [23, 24] reported the simultaneous production of power, hydrogen, cooling and heating using thermodynamic modeling and multi-objective design optimization. Other studies have analyzed solar multi-generation systems using multi-objective optimization [25, 26].

Location selection is critical when installing a polygeneration system, because the availability of resources and energy potential varies around the world. Mostafaeipour et al. [27] performed an econometric analysis to produce electricity and hydrogen gas from the available wind potential in four Iranian cities. A minimum payback period of 5 years was found for a 100 kW wind turbine installed at Ardebil. Various decision-making and planning techniques were used to identify the best site location and to estimate the wind/solar potential to produce hydrogen and electricity [28-32].

Turning to techno-economic assessments, Li et al. [33] performed thermal modeling, economic analysis, and optimization on a geothermal tri-generation unit producing water, hydrogen and power. A payback period of up to 2.385 years was found when optimizing the three objectives. Shaofu et al. [34] conducted thermo-economic and optimization analyses for hydrogen production using waste heat from a steel plant.

A concentrated solar-geothermal poly-generation system − producing hydrogen, space heating, fresh water and electricity − was proposed by Temiz and Dincer [2]. The system featured a geothermal unit, a thermochemical Cu-Cl H_2 production unit, a trilateral ammonia Rankine cycle power generation unit, a desalination unit, a residential heat pump, and concentrated solar power assisted by thermal energy storage. Space heating, fresh water, and electricity requirements were met via geothermal energy. Sensitivity analysis at the component level, as well as energy, exergy and cost analyses for the whole unit and at the component level were performed. The cost of electricity and hydrogen production was estimated to be \$0.03/kWh and \$2.84/ kg, respectively. At ambient conditions, the exergy and energy efficiencies were found to be 17.3% and 27.4%, respectively.

From the above literature review, two research gaps can be identified in the optimization of multi-generation systems to produce hydrogen:

- In most studies, only a single rate of price inflation was assumed. In other words, the effect of rising inflation on multi-objective optimization of multi-generation systems has yet to be systematically investigated.
- The optimal solution was identified via TOPSIS or other decision-making approaches, in which the importance of all the objective functions is assumed to be the same. However, in real-world scenarios, some criteria are often more important than others. Advanced decision-making methods, such as those involving the analytical hierarchy process (AHP), which considers the relative importance of different criteria, have been used only to identify the ideal location at which to install such systems, not to optimize the system processes.

In the present study, we consider the combined production of hydrogen, power, fresh water, and heat via multi-objective optimization.

- The effects of price inflation on the multi-objective optimization are examined. For the solar-geothermal system under consideration, the effects of inflation on the optimal values of the solar collector area and the extracted ground water flow rate are examined. Also examined are the effects of inflation on the optimum values of the objective functions, namely the production of hydrogen, power, fresh water, and heat during a year, as well as the payback period. This is the primary novelty of this study.
- Here AHP is used instead of TOPSIS to converge to the final optimal solution. In this way, the relative importance of the objective functions is accounted for, providing more realistic conditions for multi-objective optimization. This is the secondary novelty of this study.

2. Methodology

The system under study is described first, followed by a presentation of the multi-objective optimization procedure and a representative case study.

2.1. The investigated multi-generation system

Location selection is important for the successful operation of a polygeneration system. It requires a high-grade heat source, possibly at around 550^{o}C, to ensure feasible and reliable Cu-Cl thermochemical H_2 production. For this, a parabolic trough solar collector is installed at the site. A temperature higher than 120^{o}C is needed for geothermal energy, and an annual global horizontal irradiation of greater than 1500 kWh.m^{-2} is needed for solar energy. The multi-generation unit combines a Cu-Cl cycle with renewable energy assisted technologies to produce power, heat, H_2 and fresh water. The subsystems consist of a PTC, a CSP, a TES, a geothermal system, a Cu-Cl thermochemical H_2 generation system, a trilateral ammonia Rankine cycle electricity production unit, an MED system and residential heat pump.

Geothermal energy is used for the auxiliary Cu-Cl system and useful products because this is a more reliable source of renewable energy than solar and wind, both of which are intermittent. The system is installed in a closed loop, with a reinjection system in place to avoid chemical and thermal pollution. The heat source comes from a trilateral ammonia Rankine cycle, which runs with geothermal power. The excess heat from this cycle is dissipated to a R-134a heat pump using heat exchanger 2. The required heat for space heating is supplied from heat exchanger 1 at 60^{o}C. Steam at 76^{o}C and 0.4 bar from separator 1 enters the MED system to produce fresh water from salty water. Heat exchanger 3 is fed by the separator remaining ground water for heating around the year. Geothermal water is discharged to the injection well after passing through a mixing chamber. The solar side of the polygeneration unit provides heat for a Cu-Cl thermochemical chamber to produce hydrogen gas in four steps: hydrolysis, thermolysis, electrolysis and drying. The hydrogen undergoes compression and other processes, becoming hydrogen fuel for vehicles. The electrical load is supplied by the geothermal side, whereas the heat load is supplied by the TES and CSP systems. The specifications of the system are listed in Ref. [2], and a schematic layout of the system is shown in Fig. 1.

Concentrated solar radiation is incident on the receiver, increasing the temperature of the heat transfer fluid and storing thermal energy via the CSP and TES systems. TES is installed to provide a continuous heat supply when solar radiation is unavailable. The heated fluid from the CSP and TES systems is fed to the Cu-Cl unit for hydrogen production. Pressurized ammonia is evaporated in the evaporator in a trilateral Rankine cycle, in which ground water is used to meet the heat load. Ammonia at high pressure and temperature is made to expand in the expander to generate power. From here, ammonia (NH_3) is re-pressurized and then expanded in the second expander. Meanwhile, the heat dissipated from NH_3 is transmitted to the R-134 refrigerant, by heat exchanger

2, and then it is further directed for space heating. Excessive ground water is used in the MED system and direct heating unit of the greenhouse to produce fresh water and heat, respectively.

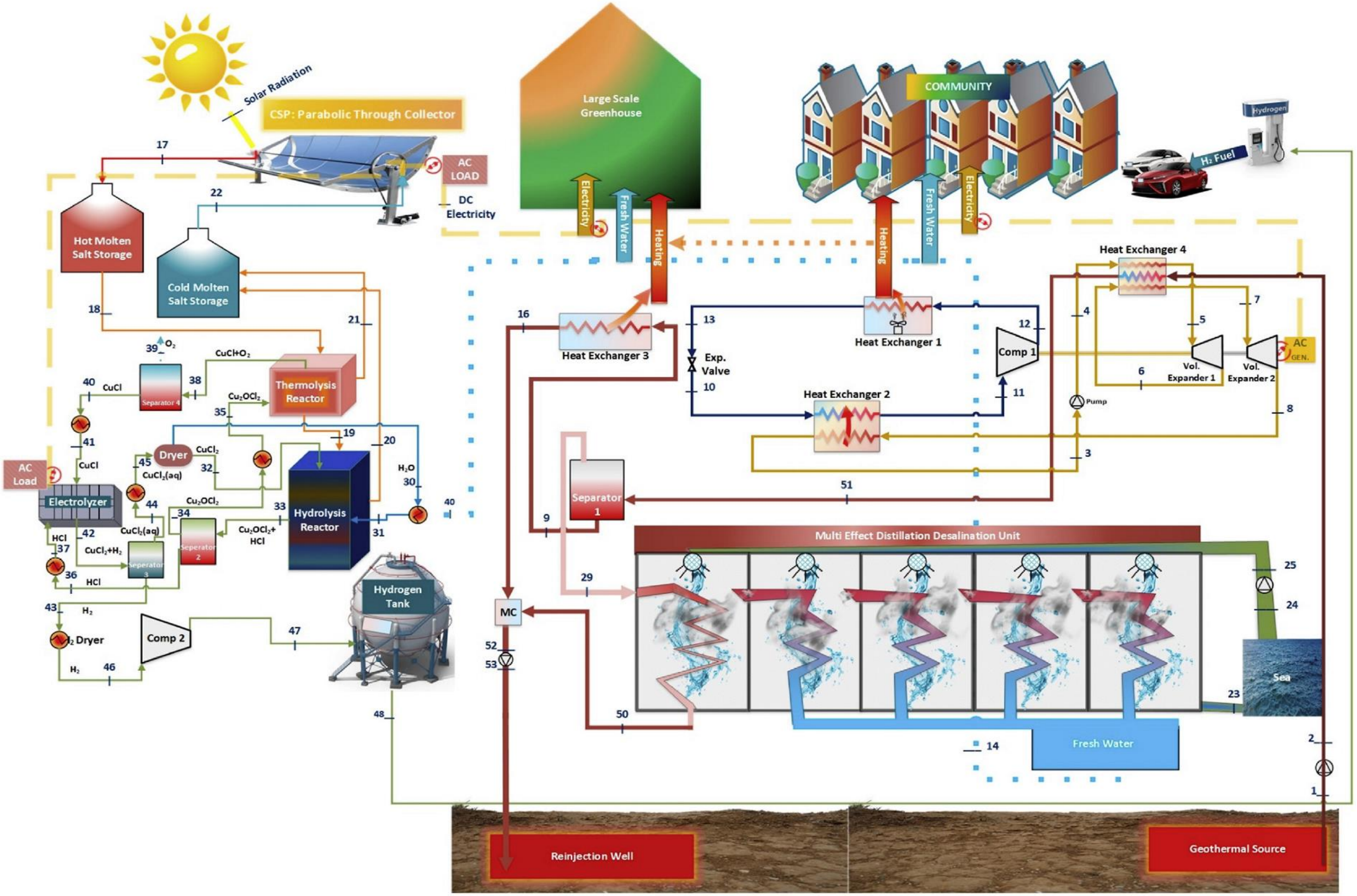

Figure 1. Schematic diagram of the investigated system, as per Ref. [2]

2.2. Multi-objective optimization

Here NSGA-II and AHP are combined for multi-objective optimization. Because the details of this procedure have been described previously (see Refs. [35] and [36]), only a brief overview is given here. The optimization is performed for the following parameters:

$$\begin{cases} \max & \textit{Annual } H_2 \textit{ production} \\ \max & \textit{Annual electricity production} \\ \max & \textit{Annual fresh water production} \\ \max & \textit{Annual heat production} \\ \min & \textit{Payback period} \end{cases} \tag{1}$$

The solar collector area and the extracted ground water mass flow rate are the decision variables, with no constraints imposed. As the modeling approach here is the same as that in Ref. [2], the reader is referred to that reference for details regarding the modeling.

2.2.1. NSGA-II

NSGA-II is a method of determining a set of solutions that has the potential of being the optimal solution. Its working principle can be described as follows:

1. First, a set of answers is generated randomly, producing an initial population.
2. Each solution is compared with the others. If the optimization goal is to minimize all the objectives, answer ‘A’ dominates answer ‘B’ if:

   2.1. Each element of ‘A’ is smaller than or equal to the corresponding element of ‘B’.

   2.2. ‘B’ has at least one strictly larger element.

3. The dominancy degree, which is the number of answers dominating a solution, is calculated for each answer.

4. Answers are listed according to the dominancy degree, with solutions of the same dominancy degree forming a group.

5. The process to generate the next population begins. If the number of solutions in each group is lower than the number of the required answers, all of them are chosen. Otherwise, the answers in each group are listed according to a parameter called the crowding distance, and the solution with the larger crowding distance is selected until the required number of solutions is reached for the next generation.

6. Answers with the lowest dominancy degree are grouped together to form the Pareto optimal frontier (POF).

   6.1. If one of the stopping criteria is met, the POF is introduced as the output of NSGA-II.

   6.2.Otherwise, the next generation is formed, and the process is repeated via step 2.

2.2.2. Analytic hierarchy process

In engineering applications, decision making methods are often used to converge to the best answers on the POF. This is usually done via methods such as TOPSIS and LINMAP. However, as noted earlier, such methods do not account for any priority of the objective functions when identifying the optimal point, while the analytic hierarchy process (AHP) considers different degrees of importance for each objective function. Consequently, AHP is used here as the decision making method to achieve a more representative outcome from multi-objective optimization. This method, developed by Saaty [37], is based on pairwise comparisons of the criteria when choosing the final optimized solution. It contains several stages:

1. First, the important criteria for choosing the best alternative are introduced.

2. If there are any subcriteria, they are defined as well.

3. The degree of importance is specified, with three comparison levels [37]:

   3.1. Alternatives with respect to each subcriterion (if any). If there are no subcriteria for a criterion, comparing the alternatives is done directly with respect to that criterion.

   3.2. Subcriteria with respect to each criterion, if there are subcriteria for a criterion.

   3.3. Criteria with respect to the main goal of the decision making.

   The importance degree of C to D is represented by w_{CD} , and the importance degree of D to C is represented by w_{DC} , which is simply $\frac{1}{w_{CD}}$.

4. For each alternative, the preference index is computed. The final point is the one with the highest preference index. The pairwise comparison matrix is:

$$A = \begin{bmatrix} 1 & a_{12} & ... & a_{1n} \\ a_{21} & 1 & ... & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \quad (2)$$

To obtain the weight (*w*), the following steps are followed:

   4.1. Find the summation of each column:

$$s_i = \sum_{j=1}^{n} a_{ij} \quad i = 1, 2, ..., n \quad (3)$$

   4.2. Normalize the elements of the matrix A:

$$r_{ij}^{normal} = \frac{a_{ij}}{s_i} \quad (4)$$

4.3. Determine the weight of each element:

$$w_i = \frac{\sum_{i=1}^{n} r_{ij}^{normal}}{n} \tag{5}$$

4.4. The local weights are determined for each alternative, and then the preference index is determined:

$$W_i = \sum_{j=1}^{m} w_{ij} \times w_j \tag{6}$$

The weight of the ith solution with respect to the jth criterion is given by w_{ij}. w_j also represents the weight of the jth criterion.

2.3. A representative case study

Tehran, the capital and largest city in Iran, is selected as the focus of our case study. It has a population of over 10 million. Damavand, a region in the northeastern part of the city, is chosen as the site for system installation. This region is at a latitude of 35.70°N and a longitude of 52.06°E. It receives abundant solar radiation and has a high ground temperature.

Iran is facing severe water scarcity. Therefore, among the objective functions, the annual fresh water production is given the highest priority. After that, and because of persistent power shortages in the country, the annual electricity production is given the second highest priority. These two objective functions are followed by the payback period. Because the country has vast deposits of natural gas and oil, and because high subsidies are applied to vehicular fuels, the annual production of hydrogen and heat are prioritized fourth and fifth, respectively. Table (1) lists the priority in the form of a pairwise comparison matrix.

Table (1): Matrix of pairwise comparison for the objective functions, which are the decision criteria of AHP.

	Annual fresh water	Annual power	Annual H_2 production	Annual heat	Payback period
Annual fresh water	1	2	6	5	3
Annual power	$\frac{1}{2}$	1	3	4	2
Annual H_2 production	$\frac{1}{6}$	$\frac{1}{3}$	1	$\frac{1}{2}$	$\frac{1}{2}$
Annual heat	$\frac{1}{5}$	$\frac{1}{4}$	2	1	$\frac{1}{3}$
Payback period	$\frac{1}{3}$	$\frac{1}{2}$	2	3	1

The ranges of the two decision variables are as follows:

- 0 to 200,000 m^2 for the solar collector area.
- 0 to 5,000 $kg.s^{-1}$ for the extracted ground water mass flow rate.

3. Results and discussion

This section presents the results from the numerical simulations. The results are first validated, and then the effect of price inflation on the optimal design and performance of the system is examined.

3.1. Validation of the modeling framework

The results of Ref. [2] are used for system validation. Figure 2 shows that there are only minor differences between the data of Ref. [2] and the simulation data of the present study. For example, errors of 1.301% and 0.81% are found in January and July, respectively. The mean and maximum errors are 1.16% and 1.72%, respectively, demonstrating the reliability of the present numerical framework. It is worth noting that as the data from Ref. [2] is for the city Geysers, California, USA, the simulation data shown here is for this region as well, ensuring consistency.

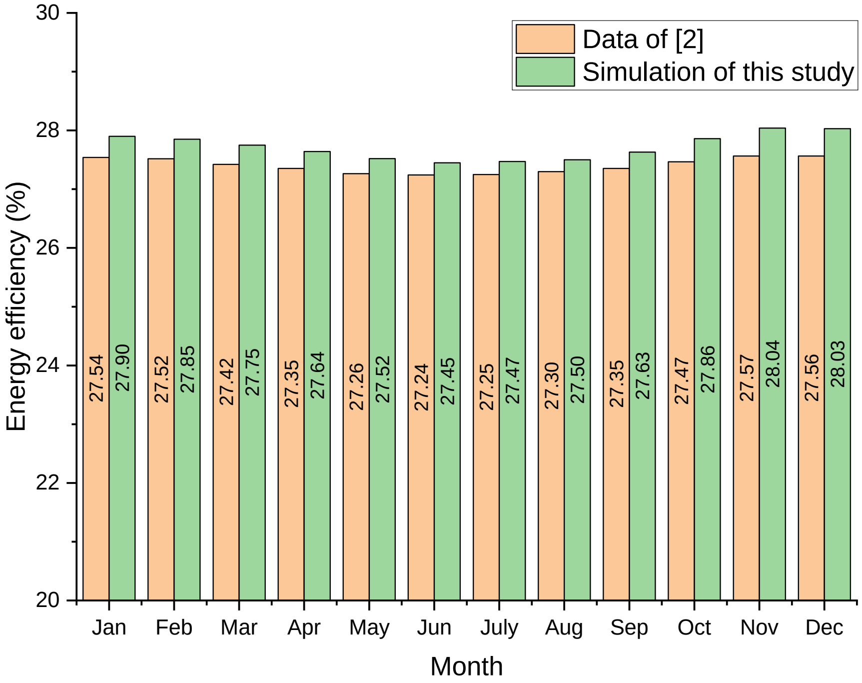

Figure 2. Validation of the present simulation framework against the data of Ref. [2].

3.2. Effect of price inflation on the optimal design

We first consider the effect of inflation on the decision variables, namely the solar collector area and the mass flow rate of the extracted ground water.

3.2.1. Solar collector area

As Figure 3 shows, as inflation rises, the required solar collector area for the optimal design rises as well. For example, an inflation of 0.05 gives a solar collector area of 19815m^{2,} but this increases by 8.42% to 21484.5m^2 when inflation doubles to 0.10. A further rise in inflation to 0.15 leads to a further increase of 3.64% in the solar collector area. Therefore, the rate of change of the optimum solar collector area decreases with rising inflation. The solar collector area itself seems to follow a power-law relationship with rising inflation.

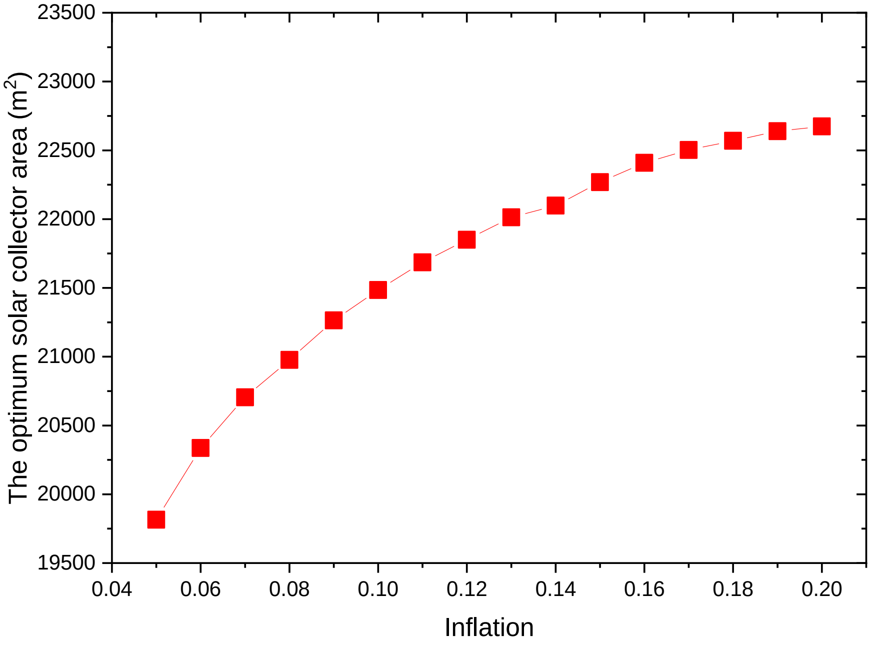

Figure 3. Effect of inflation on the optimum solar collector area.

3.2.2. Mass flow rate of the extracted ground water

Figure 4 shows that there is a downward trend in the extracted ground water flow rate as inflation rises. When inflation is 0.05, the system extracts 103.24 kg.s^{-1} of ground water, but this drops to 82.51 kg.s^{-1} when inflation rises to 0.20. The rate of change of extracted ground water starts at 2.82% but eventually reaches 0.83% at high inflation.

The costs of solar collectors are incurred only at the beginning, as an initial investment. The costs of using the ground water and its driving force, however, are distributed throughout the overall lifespan of the system. These costs, therefore, increase with rising inflation. As a result, the optimization algorithm prefers to cover more of the energy required to run the system via solar collectors, so that it is less exposed to the costs of rising inflation. This explains the opposing trends found in Figure 3 and Figure 4.

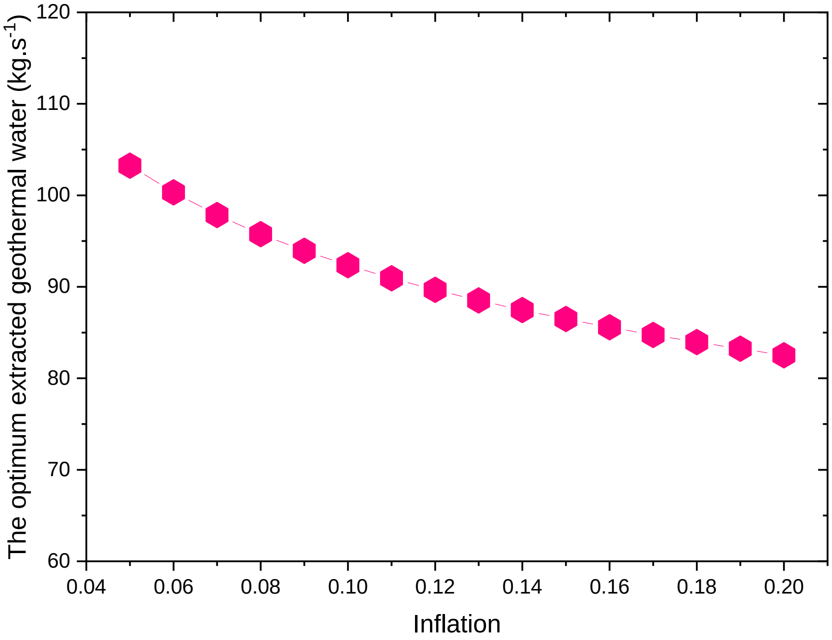

Figure 4. Effect of inflation on the optimum extracted ground water flow rate.

3.3. Effect of price inflation on the optimal performance

We now examine the effect of inflation on the objective functions, namely the annual production of H_2, water, power and heat.

3.3.1. Annual H_2 production

The more solar radiation the system receives, the more hydrogen it can produce. Therefore, in the hotter months of the year, when the solar radiation is high, the system produces more hydrogen. Figure 5 shows that the annual H_2 production starts at 211.8 ton when inflation is 0.05, but then increases to 232.7 ton when inflation climbs to 0.20, a jump of nearly 10%. The H_2 production curve seems to follow a power-law scaling.

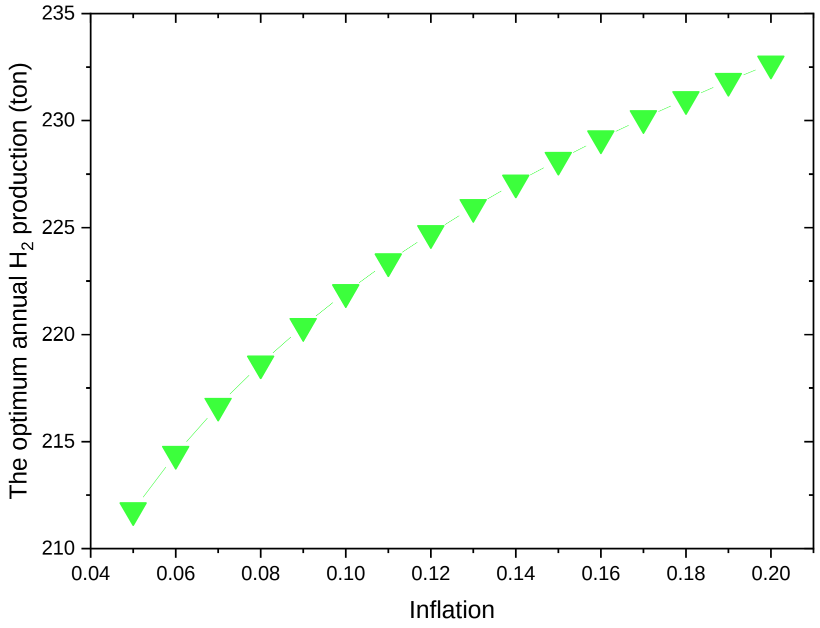

Figure 5. Effect of inflation on the optimum annual H_2 production.

3.3.2. Annual fresh water production

Unlike hydrogen production, the other system products are proportional to the change in the extracted ground water. Regarding the annual fresh water production, Figure 6 shows that the amount of water produced decreases with rising inflation in accordance with a polynomial function. When inflation is 0.05, the system generates 107387.5 tons of fresh water, but this drops by 15.00% to 91270.3 ton when inflation rises fourfold to 0.20. This decrease is due to the part of the system that utilizes ground water to produce fresh water.

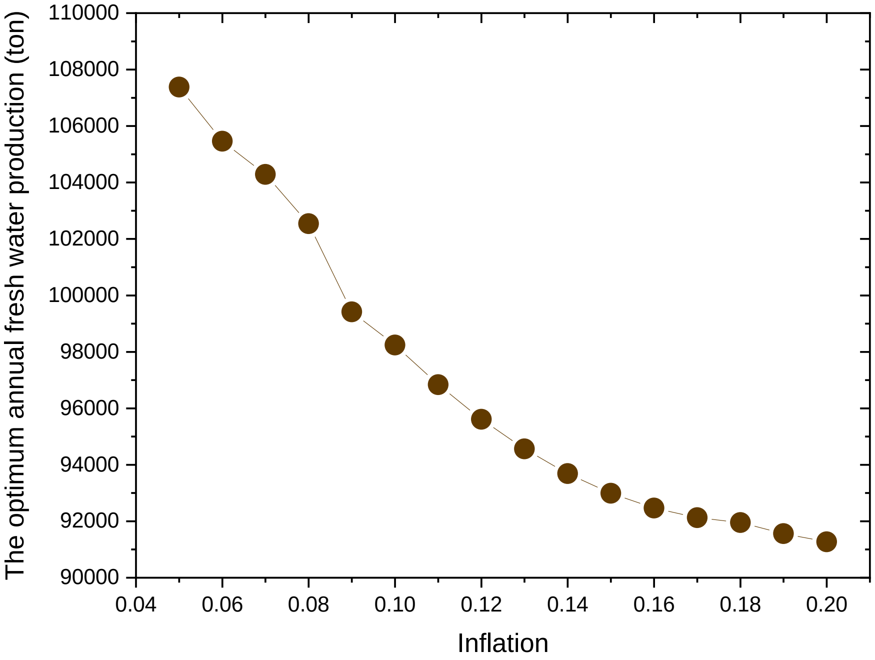

Figure 6. Effect of inflation on the optimum annual fresh water production.

3.3.3. Annual power production

Figure 7 shows that the optimum annual power production decreases with rising inflation. For initial inflation of 0.05, the system produces 304.3 MWh of power, but this drops by 37.3 MWh (or 12.25%) when inflation rises to 0.2. The rate of change of the power decreases with rising inflation, causing the power production itself to converge to 267 MWh. This trend is also due to the amount of extracted ground water, because the power is mainly produced by geothermal sources. The optimum annual power production seems to follow a polynomial function of degree 2.

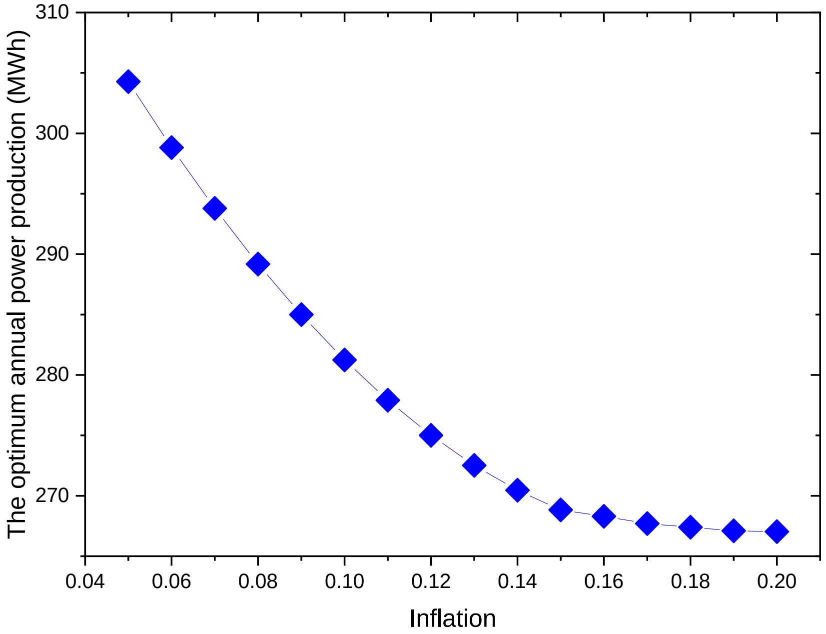

Figure 7. Effect of inflation on the optimum annual power production.

3.3.4. Annual heat production

The annual heat production follows a similar trend to that of the annual power production, as shown in Figure 8. This is because, like power generation, heat production is largely dependent on the geothermal part of the system and the extracted ground water. Furthermore, the change in heat production with rising inflation seems to exhibit polynomial behavior of degree 2. The system generates 2805.2 MWh of heat when inflation is 0.05, but this decreases by 11.95% to 2469.7 MWh when inflation rises to 0.20.

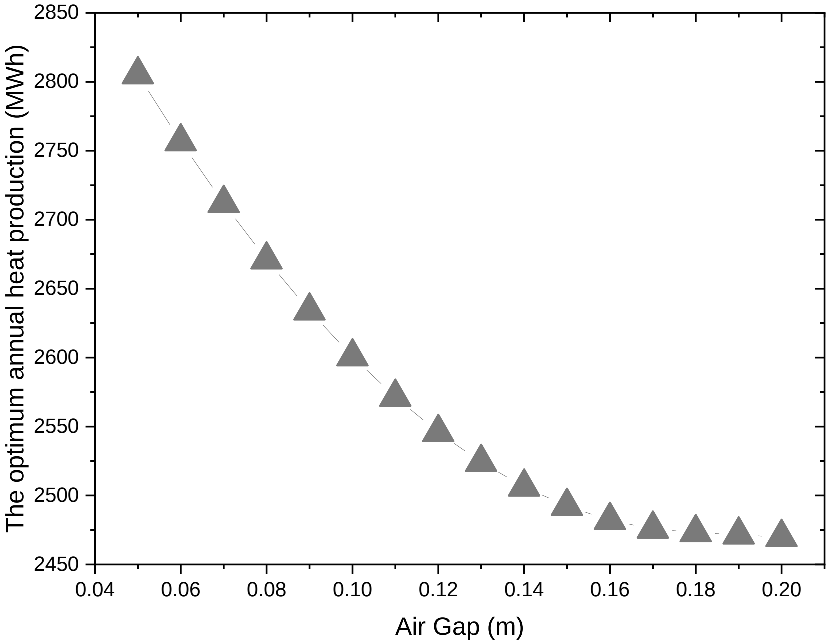

Figure 8. Effect of inflation on the optimum annual heat production.

3.4. Payback period

Figure 9 shows that the payback period increases with rising inflation, producing what seems to be a logarithmic trend. When inflation is 0.05, the payback period is 6.11 years, but this increases by 20.94% to 7.39 years when inflation rises to 0.20. This trend occurs because the diminishing effect of water, power and heat production counterbalances the incremental effect of hydrogen production. Nevertheless, even when inflation is relatively high (0.20), the payback period is still reasonable, demonstrating the economic feasibility of the system design.

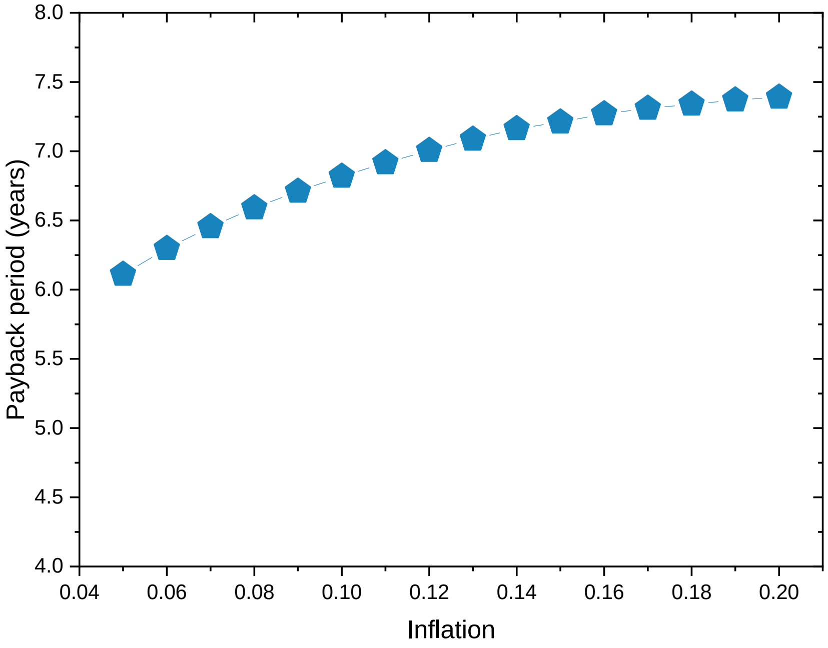

Figure 9. Effect of inflation on the optimum payback period.

4. Conclusions

We have shown that when inflation rises, an optimization algorithm combining NSGA-II and AHP tends to prefer balancing the system performance by increasing and decreasing the solar collector area and the extracted mass flow rate of ground water, respectively. This preference arises because the solar collector area is paid for up front as an initial investment, so that it is not exposed to the effect of rising inflation, whereas the ground water flow rate becomes more expensive owing to payments distributed over the lifespan of the system.

The annual hydrogen production was found to be a function of the available solar collector area, so it increased with rising inflation, whereas the other products (namely power, fresh water, and heat) decreased. Even at relative high inflation of 0.20, the payback period stayed within an acceptable range. This demonstrates the economic viability of simultaneously producing hydrogen, power, fresh water and heat, even in times of rising inflation.

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Declaration of Interest Statement (use official Word Template)

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: