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Hydraulic isothermal pressure reduction turbine: An efficient and low-cost electricity generation source

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ABSTRACT

There is currently a large amount of energy being wasted on pressure reduction valves across the world. This paper argues that this energy could be harnessed with isothermal depressurization by applying a hydraulic isothermal pressure reduction turbine. The hydraulic isothermal pressure reduction turbine consists of two tanks filled with water or an organic liquid. The pressurized gas enters the tank, displacing the liquid, which flows through a turbine, generating electricity. The proposed system has efficiencies surrounding 90%, which is higher than usual pressure reduction turbines. The estimated cost for the proposed technology is 1300 USD/kW. The proposed technology could be feasible to harness the potential for electricity generation wasted in pressure reduction valves. The need for this technology will increase significantly in a future hydrogen-based economy, given the low volumetric density of hydrogen and the significant energy losses when compressing and decompressing hydrogen.

1. Introduction

A large amount of energy is wasted in pressure reduction valves [1,2]. The oil and gas industry wastes a lot of energy with pressure reduction valves and is interested in increasing its operational efficiency [3]. The amount of energy loss with pressure reduction valves is set to increase significantly if a hydrogen economy is implemented in the future [4,5]. This is because hydrogen has a low volumetric energy density, and it is required to be stored at pressures of around 700 bar to be practical. At 700 bar, around 4% of the energy stored is within the pressure of the hydrogen [6]. If the energy generated during decompression is not harnessed, this energy would be lost.

There are several existing pressure reduction turbine types available on the market. These can be mainly divided into two categories: liquid and gases. The most common applications of such turbines in liquid form are in hydropower for electricity generation [7,8] and in hydraulic systems to generate electricity with the reduction in pressure of a water distribution network to increase the energy efficiency of the system [9,10]. In the case of gases, turbines are used in thermoelectric power plants for electricity generation [11,12] and also to reduce the pressure of steam in industrial processes to increase the energy efficiency of the system. Recently, there has been a high push to increase the efficiency of industrial processes, and pressure reduction turbines to decompress air and other gases such as natural gas, and hydrogen are gaining attention [13–19]. There are several types of turbines to implement this, such as axial [20], Tesla [21] and helix [22] turbines. An example of the operation of a conventional pressure reduction turbine is presented in Fig. 1.

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Nomenclature

CAPEX	Capital costs
HI-PRT	Hydraulic Isothermal Pressure Reduction Turbine
CAES	Compressed air energy storage
P	Power generated in the HI-PRT system
f	Flow of liquid through the turbine
ρ_g	Density of the gas at the given pressure
h	Generation head
g	Acceleration of gravity
e	Efficiency of the system

A problem with pressure reduction turbines operating with explosive gases is the gas that passes through the turbine rotation axis, which can cause loss of the gas or explosions. This can be solved with the use of magnetic bearings, but it also significantly increases the cost of the turbine [23].

Compressed air energy storage[1] (CAES) is one of the utility-scale electricity storage solutions, with a few operational plants already today. While the turbomachinery part of the technology is based on commercial, mature technologies, CAES has not received attention due to a few challenges in the storage process. The main drawbacks include the high energy losses in the turbines and the changes in temperature, which result in reduced efficiency and the need for additional fuel, usually natural gas, to increase the temperature and pressure of the air [24]. Hence, the technology has relatively low overall efficiency and is not emission-free if natural gas is used for supporting expansion. There are a few configurations of CAES to overcome these issues, including adiabatic CAES based on thermal energy storage [25]. Other challenges of CAES include being site-specific, i.e., the need for geological caverns for air storage, air leakage [26], the high cost of steel tanks if used for air storage, etc. [27]. Underwater compressed air storage has received little attention, with only a few commercial-scale systems developed. It consists of a fixed storage site in the sea or a lake and a compressor on the land that sends pressurized air to the storage site [28]. Several research projects have been investigating this technology [29–33]. An existing project has been implemented recently in Toronto, Canada [34]. Other energy storage technologies can be seen in [34–44].

Recently, a highly efficient isothermal air compression design has been proposed. The AirBattery is an innovative CAES solution that stores air isothermally with the displacement of air with water, with a round trip efficiency of 81% [45–48], as shown in Fig. 2. A pump pressurizes water that enters the isothermal compressor tank. As the tanks fill with water, the air pressure increases, and the air is pushed to one of the compressed air storage tanks. Electricity is then generated by using compressed air to push water into a hydropower turbine. The round-trip efficiency of the system is the highest so far for an operational CAES system. As a comparison, the energy losses in isothermal compression are around three times smaller than those in adiabatic processes. A similar ratio can be seen in decompression processes, as shown in Fig. 3 [49].

Isothermal compression and isothermal compressed air energy storage have been proposed in many studies in the literature [50] to provide highly efficient compression and energy storage services. Many studies investigate the use of pressure reduction turbine to generate electricity with the reduction in pressure of gases [21]. However, there is no research in the literature or products in the industry that propose the use of isothermal decompression of air, natural gas, hydrogen or any other gases for energy recovery. The main contribution of this paper is to apply isothermal decompression for electricity generation by replacing existing pressure reduction valves. This is the first time this innovative concept has been proposed for electricity generation, and it was named hydraulic isothermal pressure reduction turbine (HI-PRT). The paper analyses the techno-economic feasibility of such technology in comparison to other alternatives. The paper is divided into five sections. Section 2 details the methodology. Section 3 presents the results. Section 4 discusses the technology, and Section 5 concludes the paper.

2. Methodology

The methodology implemented in the paper is presented in Fig. 4. It is divided into three main steps. Step 1 consists of describing the HI-PRT system. It consists of detailing the components, such as the physical principles of the isothermal air decompression, and a detailed description of the operation of the HI-PRT system. Step 2 describes the power generation profile for a single HI-PRT system and proposes the combination of an energy storage solution to provide a constant amount of power. It then proposed four HI-PRT systems operating in synchrony to provide a constant amount of power. Step 3 estimates the costs of the components, the and CAPEX of the technology and analyses possible combinations of gases and liquids.

2.1. *Hydraulic isothermal pressure reduction turbine (HI-PRT)*

The hydraulic isothermal pressure reduction turbine electricity generation alternative proposed in this paper consists of the process described in Fig. 5 and is described as follows. The system consists of two pressurized tanks filled with liquid. The volume of the liquid is the same as half of the volume of the systems tanks, pipes, and turbine. In phase 1 “Displacement”, the pressurized gas enters Tank 1 at high pressure, for example, 50 bar, and displaces the liquid in the tank, which passes through a turbine and fills Tank 2 at a lower pressure, for example, 25 bar. The difference in pressure between Tank 1 and 2 is used to estimate the hydraulic generation head of the turbine, which in this case is 250 m. As the liquid enters Tank 2, the gas at 25 bar pressure outputs Tank 2. After Tank 1 is half emptied, phase 1 finishes and phase 2 starts. During phase 2 “Decompression”, the air input in Tank 1 stops and the gas is decompressed from 50 to 25 bar. The pressure in Tank 2 remains at 25 bar, and the gas continues to output Tank 2. This results in a reduction in the generation head of the hydraulic turbine. After the pressure in Tank 1 reaches 25 bar, phase 2 finishes and phase 3 starts. During phase 3 “Reversed-Displacement”, there is a rapid switch in gas supply, and the

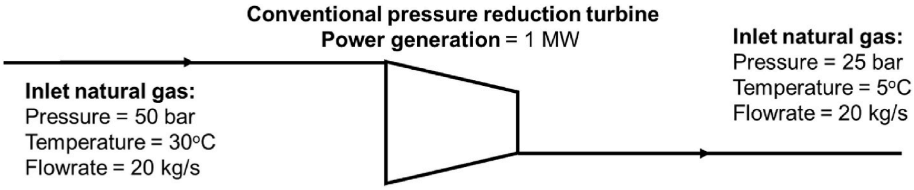

Fig. 1. Example of conventional pressure reduction turbine operation.

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[1] This technology works based on the concept of compressing air when electricity is cheap (charging), storing high-pressure air in a cavern or tank, and expanding air through a turbine to generate electricity (discharge).

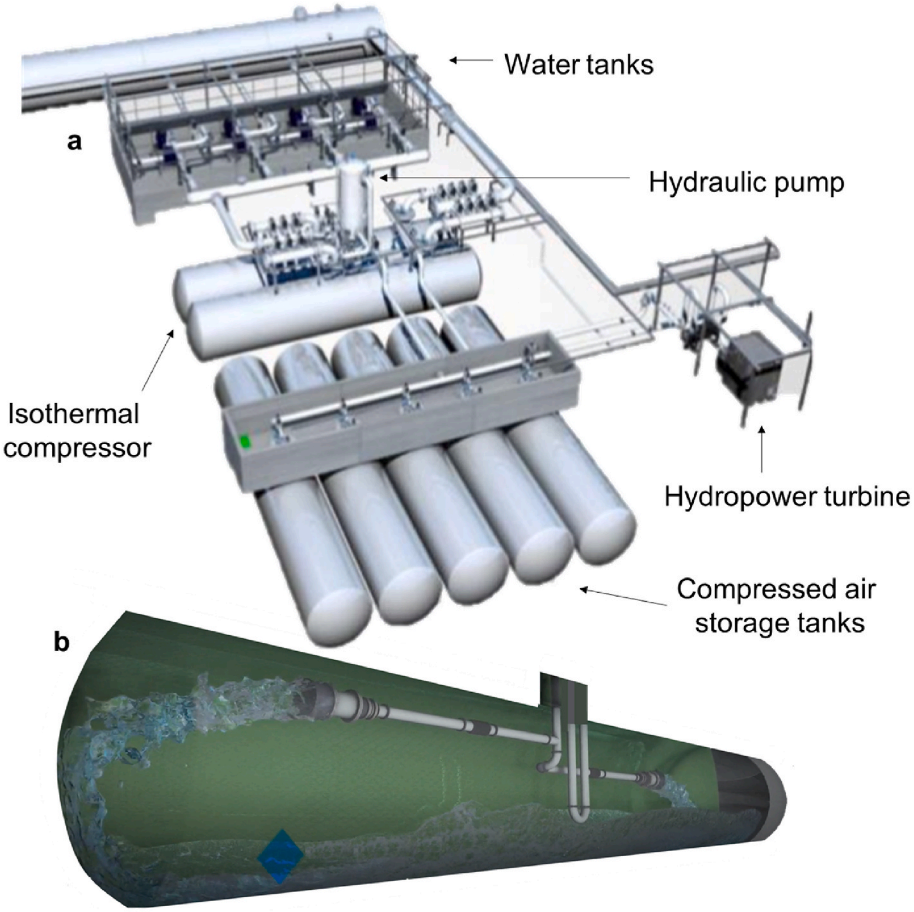

Fig. 2. AirBattery, an isothermal compressed air energy storage technology developed by Augwind.(a) System components, (b) isothermal air compressor.

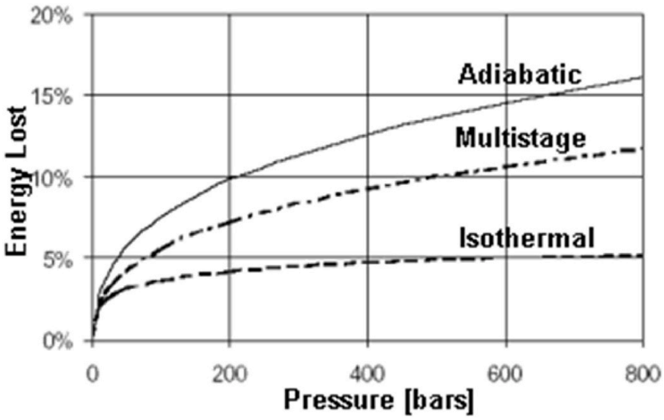

Fig. 3. Energy required for the compression of hydrogen compared to its higher heating value [49].

gas enters from Tank 2 at 50 bar and leaves the system from Tank 1 at 25 bar, and the process restarts on a reversed approach. One important challenge for this system is a result of the need to switch the gas intent from Tank 1 to Tank 2 and vise-versa, which can take a few seconds. To ensure that a constant flow of depressurized gas is supplied after the HI-PRT system, a bypass on the HI-PRT can be added with a valve that would open automatically with the reduction in pressure after the HI-PRT system. Regarding the disruption in power supply, surge tanks can be added to the turbine system. Alternatively, an ultracapacitor or flywheel can store energy and maintain a constant electricity supply during phase changes.

During decompression, the gas expansion happens with the proportion increase in volume, thus, the reduction in temperature is insignificant. Due to energy losses in the turbine and in decompression, the temperature of the gas leaving the system would be higher than the temperature of the gas entering the system. Thus, in practice, the system is not isothermal.

As electricity in the HI-PRT is generated with a hydraulic turbine, Equation (1) is applied. To estimate the hydraulic generation head can be estimated with Equation (2).

$$P = f \times \rho_g \times h \times g \times e \quad (1)$$

where, P is the power generated by the HI-PRT system, f is the flow of liquid through the turbine in m^3/s, ρ_g is the density of the liquid at the given pressure, assumed to be 1000 kg/m^3, h generation head in meters, g is the acceleration of gravity m/s^2 and e is the efficiency of the system, which is assumed to be 90% [51,52]. The efficiency of the turbine is assumed to be 95% [53]. This is because the AirBattery has an efficiency of 80% for energy storage and electricity generation, while HI-PRT only generates electricity. It is very difficult to estimate the efficiency of the system in different operational configurations. A complex CFD model with many other assumptions would be required. As this is out of the scope of the paper, we took the estimated efficiency from a similar system from the industry.

$$h = (P_1 - P_2) \times 10.2 \quad (2)$$

Where, P_1 is the pressure in Tank 1 and P_2 is the pressure in Tank 2.

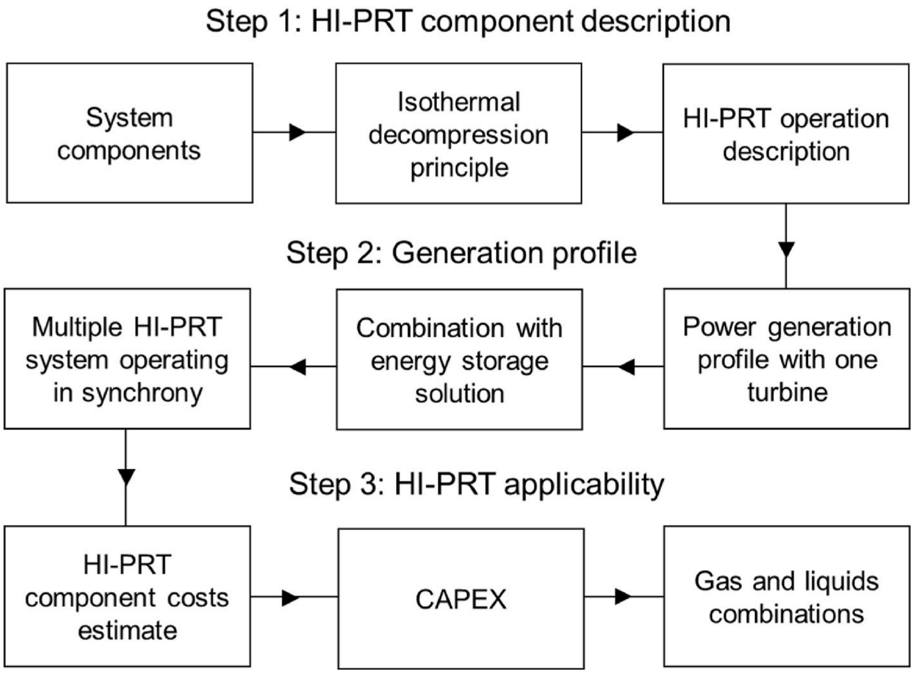

Fig. 4. Flow chart describing the methodology implemented in the paper.

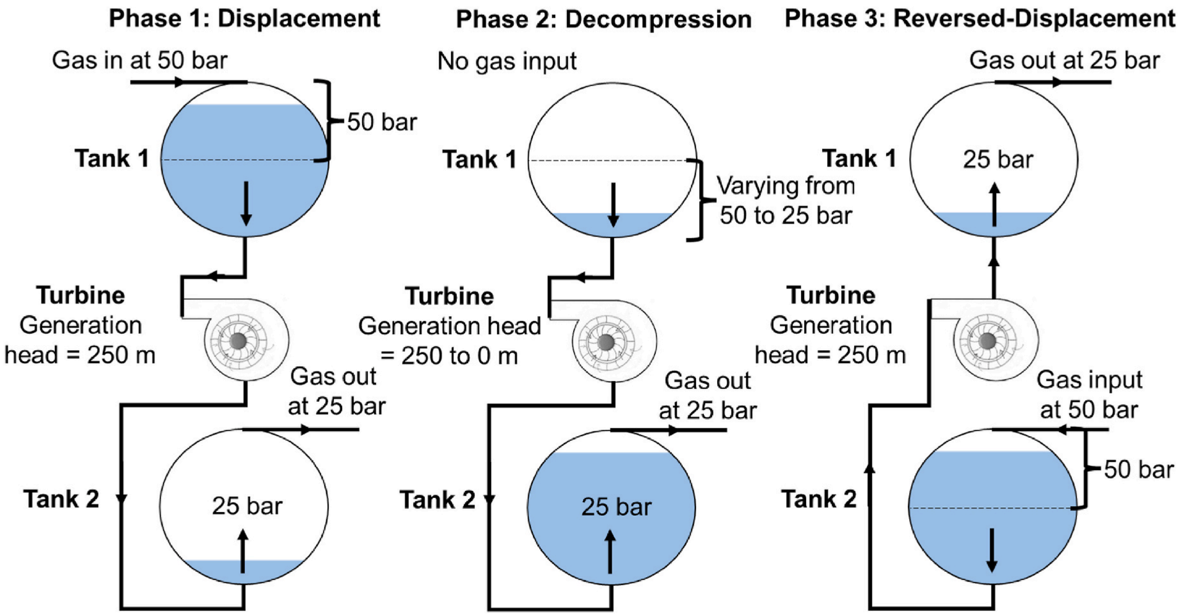

Fig. 5. Hydraulic isothermal pressure reduction turbine electricity generation system description.

3. Results

Assuming the equipment shown in Fig. 5 and the need to maintain a constant flow of depressurized gas after the HI-PRT system, the power generation profile of the system would look similar to the one presented in Fig. 6 (a), assuming that the turbine that maintains a high generation efficiency with a 100% head variation, which is not possible. A more realistic electricity generation potential is shown in Fig. 6 (b), where-after the head variation is higher than 50%, the turbine stops generating electricity. This electricity reduction results in a 6.5% energy loss. This energy loss is equivalent to the difference in power presented in Fig. 6 (a) and Fig. 6 (b). An approach that could be applied to transform the electricity generation described in Fig. 6 (b) would be to combine a battery, flying wheel or ultracapacitor to rectify the electricity generated in the turbines and provide a constant amount of power. Fig. 6 (c) shows the power produced by the turbine, storage solution and the final power supplied by the system, assuming an overall efficiency of 90%.

3.1. *HI-PRT in parallel*

Another approach to maintain a constant flow of gas after the HI-PRT turbine and not require implementing an energy storage alternative is to combine several HI-PRT operating in synchrony to supply a constant amount of energy. For example, if two HI-PRT systems are combined to complement each other, results in the power generation profile shown in Fig. 7 (a). As it can be seen, this conformation still does not allow for a

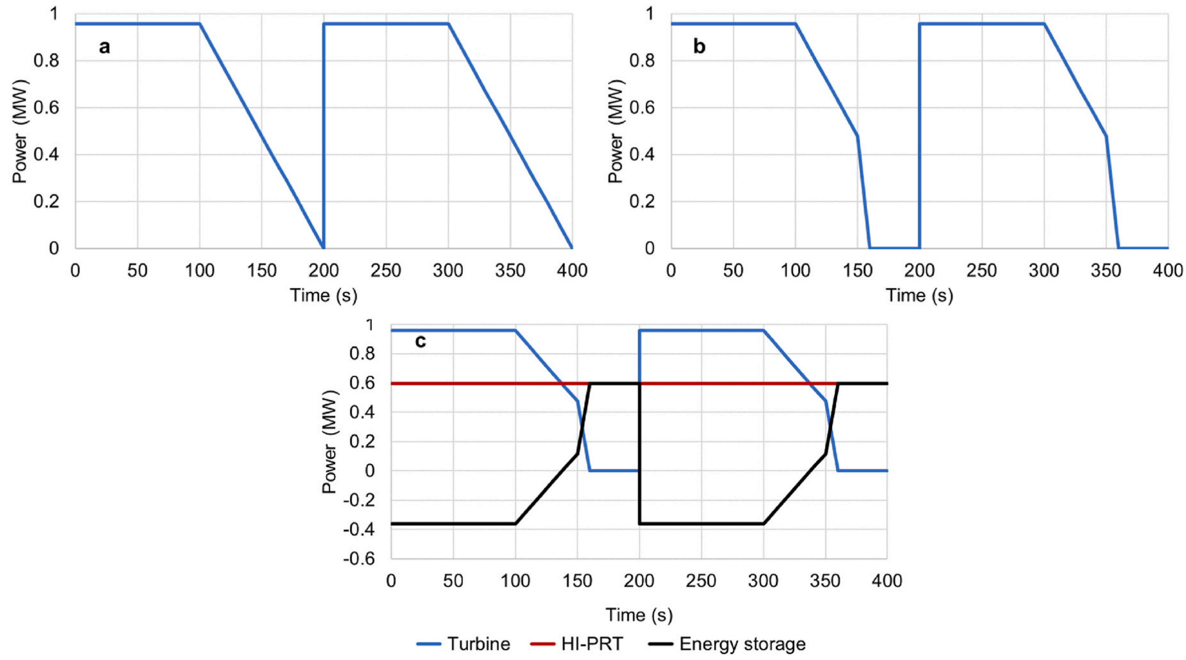

Fig. 6. Power generation profile with (a) theoretical turbine, (b) real turbine and (c) HI-PRT with energy storage solution.

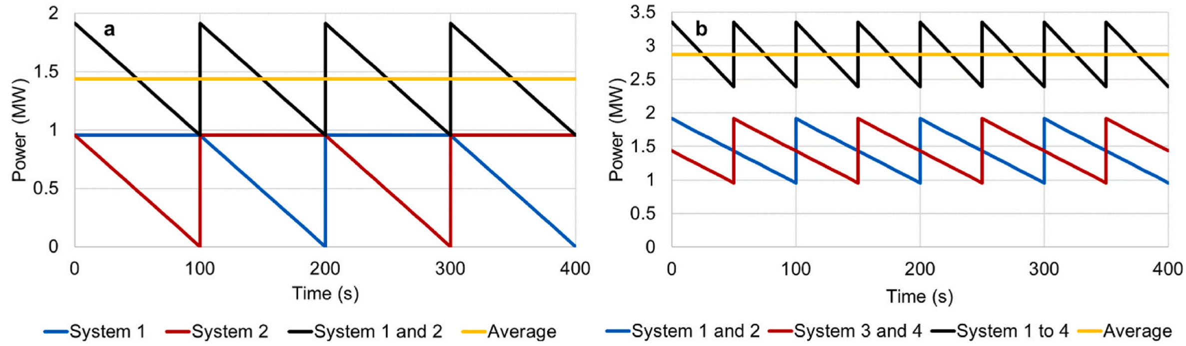

Fig. 7. Power generation (a) two and (b) four HI-PRT systems operating in synchrony.

constant supply of energy as there are moments in which one turbine will not generate electricity, and it is not possible to main the system's average electricity generation. The only option that the authors thought would provide a constant amount of power and gas flow after the system, without an energy storage solution, is to have four HI-PRT systems, as shown in Fig. 7 (a). To generate a constant amount of energy, however, the outlet gas flow of each system will have to vary synchronously to provide a constant electricity generation and overall outlet gas flow. This might be the reason why the AirBattery system showcases four systems in parellel, each with two tanks [45–48]. To use only one turbine to generate electricity, a surge tank would be required to equalize the changes in head and low so that the turbine can supply a constant amount of energy.

3.2. HI-PRT in series

The example where the pressure varies from 50 to 25 bar works well with a two tanks system, as shown in Fig. 5. This is because the volume of gas at 25 bar is only two times larger than the gas at 50 bar. If the system is designed to reduce the pressure from 90 bar to 1 bar, it would be interesting to increase the number of systems in parallel to reduce the overall volume of the high-pressure tanks, which are expensive. Table 1 presents an example of HI-PRT in series. The proposed plant consists of three systems in series with two tanks each. System 1 tanks vary in pressure from 1 to 4 bar, which results in a pressure reduction of 3 bar. The tanks in System 1 have a volume 20 times higher than the volume of System 3. This is because the same mass of gas passes through both systems. However, the minimum pressure of System 3 is 20 times higher than in System 1. The constant pressure volume section consists of the volume of gas displaced in phase 1 (Fig. 5). In the HI-PRT design in Fig. 5 the constant pressure, volume section is 50%. For systems 1 to 3 in the HI-PRT in series, we propose 20% to lower investment costs. The lower the constant pressure, volume section, the lower the investment costs in the tanks. However, the higher the turbine's generation head variation, the lower the isothermal decompression efficiency of the process. The ideal constant pressure, and volume section will vary with the equipment costs, the head variation flexibility of the turbine, the isothermal

Table 1
HI-PRT in series design description.

System	Pressure (bar)	Pressure reduction (bar)	Relative tank volume	Constant gas pressure volume section (%)
1	1–4	3	20	20
2	4–20	16	5	20
3	20–90	70	1	20

decompression efficiency, the control systems, the energy storage solution to control the electric supply, the gas and the liquid implemented in the system.

Fig. 8 presents the HI-PRT in series power description, including the hydraulic head variation in the three tanks arrangement proposal. As can be seen, System 1 has the very highest volume (77%) but a small generation head (30.6 m–0 m), System 2 has a medium volume (19%), and generation head (163.2 m–0 m), System 3 has a small volume (4%) but a high generation head (714 m–0 m), as shown in Fig. 8 (a). The resulting electricity generation potential shares between the three systems is similar, as shown in Fig. 8 (b).

3.3. HI-PRT cost estimation

Table 2 presents a cost estimate for a HI-PRT arrangement that operates from 50 bars to 25 bars with natural gas. We believe that the arrangement combining only one HI-PRT system and an energy storage solution will be the most cost-effective because of the gains in scale in the storage tanks and the reduction in the cost of energy storage solutions in the coming years. Flywheel energy storage was selected for this task due to the short energy storage cycles of 100 s, small energy storage requirement (in kWh) and the high installed capacity requirement (in MW). The estimated cost of the HI-PRT system is 1300 USD/kW, which is similar to the cost of wind power. If the system operates with a capacity factor higher than 30%, then the levelized cost of generation for HPTR would be cheaper than wind power. Another advantage is that the electricity is generated close to the demand, reducing transmission costs. The lifetime of some of the components, such as the tanks and the hydropower turbine, is assumed to be 30 years. The energy storage alternative would vary according to the selected solution. For example, the flywheel might have to be replaced after 10–15 years of operation.

4. Discussion

Table 3 compares the cost of solar and wind power with HI-PRT. This shows that the installed capacity cost for solar and wind is comparable to HI-PRT. However, HI-PRT has a higher capacity factor, and it can be a baseload source of electricity or provide electricity when other renewable sources are not generating.

Table 2
Cost estimate for HI-PRT system components with 1 MW installed capacity.

Component	Cost description	Cost
Storage tanks	Two storage tanks with 100 m^3 each and a maximum pressure of 50 bar, each storage tank at $80,000 [54].	160,000 USD
Turbine	1 MW turbine with a head that varies from 250 to 125 m and auxiliary equipment for 200,000 USD [55].	200,000 USD
Generator	1 MW generator and auxiliary electrical equipment for 360,000 USD [55].	360,000 USD
Energy storage solution	Assuming is required 22 kWh of energy storage is to provide a constant amount of electricity for 12,000 USD/kWh with a flywheel solution [56].	264,000 USD
Construction	30% of the equipment costs.	295,200 USD
Total project cost	–	1,279,200 USD
Installed capacity cost	The estimated cost of the system is 1300 USD/kW.	1300 USD/kW

Table 3
Cost comparison between HI-PRT and other electricity generation sources.

Technologies	Power costs (USD/kW)	Capacity factor	Flexibility
HI-PRT	1300	80% or higher	Base load or controllable
Solar power	900 [57]	15–30%	Variable
Wind power	1325 [57]	20–60%	Variable

Table 4
HI-PRT liquid selection challenges.

Gas	Liquid	
	Water	Diesel
Air	Could work	Could work
Steam	Some of the water can evaporate, which can reduce the pressure from the steam.	Could work
Natural gas	Could occur the formation of methane-hydrates.	Could work
Hydrogen	Could work	Could work

The selection of the liquid applied in the system is significant and will depend on the inlet gas and the application of the gas in the downstream process. The ideal liquid is inert and does not dissolve or react with the pressurized gas. Table 4 presents an analysis of different gases and liquids that can be considered in a HI-PRT plant. “Could work” means that there is no major impeditive to the combination. However, it is important to analyze the impact on the process downstream of the HI-PRT system. One advantage of HI-PRT when decompressing explosive gases, such as methane or H_2, is that the gas does not flow through the hydraulic turbine. Thus, there is no gas leakage, which increases the

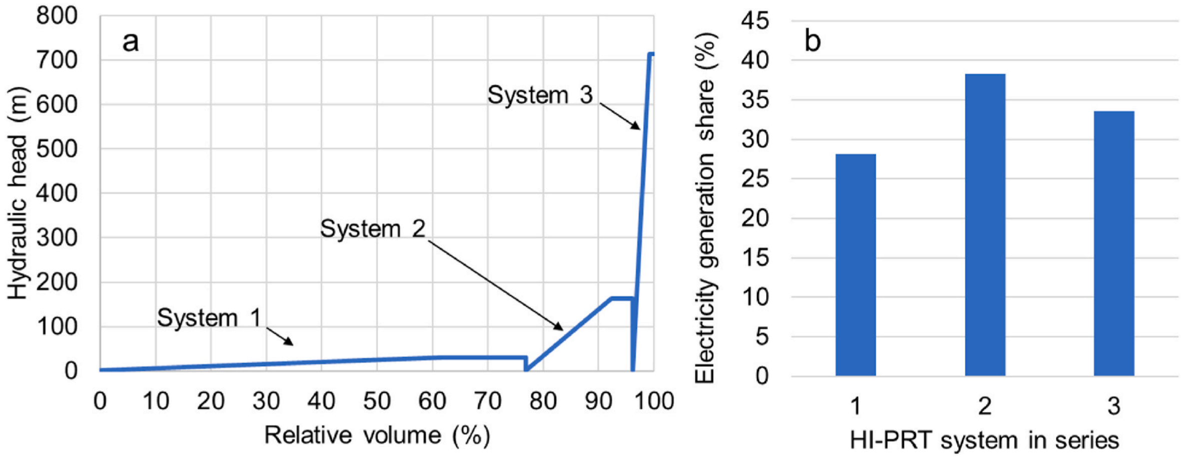

Fig. 8. HI-PRT with three systems in series operation, (a) hydraulic head variation, (b) power supply share between the three systems.

safety of the system.

Suppose there is a heating source to increase the temperature of the liquid in the storage tanks. The thermal energy would contribute to increasing the temperature of the gas as the gas passes through the liquid entering the bottom of the tank. The gas warmer gas would expand, reducing the required inflow of gas to generate 1 MW. This would allow the system to be built with an increased installed capacity and generate more electricity. In other words, the additional heat source to the system would be transformed into electricity with a small increment cost. This could also the impacted by the temperature of the gases in the distribution pipeline [58].

If the gas being decompressed is air and the liquid applied in water, after the water passes through the turbine, its solubility of CO_2 will reduce significantly, resulting in some of the CO_2 dissolved in water changing to the gaseous phase. This water can be directed to another tank to extract the CO_2 before it is reutilized in the HI-PRT system. In other words, the proposed technology can also be used as a technology for “Direct Air Capture” of CO_2, with very little added cost. The captured CO_2 can then be turned into synthetic fuels using H_2 and electricity. In this way, HI-PRT can generate electricity and produce e-synthetic fuels.

5. Conclusions

This paper proposes a novel electricity generation alternative making use of the energy wasted in pressure reduction valves. Usually, pressure reduction turbines are used to extract energy from the depressurization of gases. However, these turbines are expensive and significantly reduce the temperature of the gas after the turbine.

The recent development of an isothermal solution for CAES has opened a new alternative to transform the energy within a gas into electricity with a low CAPEX and efficiencies of around 80%. This paper proposed two different hydraulic isothermal pressure reduction turbines, one with one isothermal decompression system coupled with an energy storage alternative and another with four systems operating in synchrony. As the costs for energy storage are reducing rapidly, the first solution was proposed. The cost of HI-PRT is estimated at 1300 USD/kW, which is competitive with wind regeneration, but as the electricity is generated close to the demand, it does not require investment in new transmission lines.

Hydraulic isothermal pressure reduction turbines have a large potential for electricity generation replacing existing pressure reduction valves that do not generate electricity. In the future, with the development of a hydrogen economy, HI-PRT’s role will further increase in importance due to the low volumetric energy density of hydrogen and the need to recuperate some of the energy lost in hydrogen compression and decompression. Future work will focus on improving the description of the system efficiency with a real file case study, the description of the system in a temperature-entropy diagram, the creation of isothermal decompression evaluation indicators and estimating the role and potential for hydraulic isothermal pressure reduction turbines in a future hydrogen economy.

Declaration of competing interest

All authors have participated in conception and design, or analysis and interpretation of the data, or drafting the article, or revising it critically for important intellectual content, and approved of the final version.

Data availability

Data will be made available on request.

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