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Thermal Energy Storage Materials, Media, and Systems

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TES Model for Hybrid Energy System Analysis

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Abstract. Long-duration energy storage (LDES) is essential for efficiently harnessing renewable energy. While electrochemical energy storage technologies have been increasingly deployed, they often face challenges due to high costs and limited mineral resources. Thermal Energy Storage (TES) offers a promising, cost-effective, and location-independent solution for LDES by storing energy as heat in inexpensive materials. A dynamic TES simulation tool within Flownex was developed to predict the TES outlet temperature for varying inlet conditions within a typical combined heat and power (CHP) system. The application of the dynamic TES model was demonstrated by successfully simulating the transient behaviour of a gas turbine cogeneration system for a 950°C gas turbine inlet temperature and ~18h TES energy storage duration. The model was used to evaluate the economic viability of a TES gas turbine cogeneration system compared to a lithium-ion (Li-ion) battery system for delivering the same output. An economic comparison over a 30-year project lifespan highlights the advantages of TES for LDES.

Keywords: Thermal Energy Storage, Long Duration Energy Storage, Hybrid Energy Systems, Cogeneration, Combined Heat and Power

1. Introduction

As the world transitions to low carbon energy, the need to accommodate variable renewable energy sources into electricity grids becomes crucial. Long duration energy storage (LDES) plays a crucial role in enabling the world to harness renewable energy efficiently, ensuring a sustainable and reliable power supply while minimizing our reliance on fossil fuels.

Electrochemical energy storage technologies have been deployed at ever greater capacities but is often hampered by high cost and limited mineral resources [1]. According to a recent report on the future of energy storage [1], Li-ion batteries will continue to be a leading technology for short duration storage (< 4 hours) and electric vehicles, but their high storage capacity costs will prevent their widespread deployment for long duration storage (>12 hours). The MIT study also recommended that alternative long duration storage technologies that rely on more earth-abundant materials be researched, developed and demonstrated.

Thermal Energy Storage (TES) has the potential to be an economical and location independent technology for LDES [2]. TES stores energy in the form of heat in low-cost materials and has the advantage of being scalable to utility scale capacities due to its low energy capacity cost. TES systems also boast a lifetime in the range of 30 years. TES systems have the unique ability to effectively tap into the large amounts curtailed renewable energy or industrial waste heat when utilised within an industrial setting. This study will focus on storing excess solar PV energy at high temperature in a TES system and explore the thermal and cost efficiencies of converting the heat to power via a gas turbine cogeneration system.

2. Dynamic TES model

The need to effectively address the intricate time-dependant complexities arising from widespread storage deployment and demand-side resources in future high-variable renewable energy electricity systems, requires modelling and software tools that accurately represent the dynamics of such systems.

Existing models involves significant computational load and does not consider nonuniform and nonlinear temperature distributions [2]. The development of TES models to simulate the transient behaviour of TES units integrated into hybrid energy systems is therefore critical to accurately size and predict the fluid outlet temperature discharged from a thermal energy storage tank. The optimal tank size should ensure minimal or no temperature degradation for the tank outlet stream during the required discharge period.

2.1 One-dimensional model for dual-media packed-bed sensible thermal storage

The principle of a dual-media thermocline thermal storage system is to deposit heat carried by the hot heat transfer fluid (HTF) into the packed-bed of the thermal storage material. The energy is recovered by passing the HTF through the packed bed thermal storage material. The two heat transfer mechanisms involved is convection within the HTF and conduction within the storage material. The convection and conduction happen simultaneously, which implies that this problem is a conjugate heat transfer problem. The two heat transfer processes are coupled by matching the temperature and heat flux at the interface between the HTF and storage medium.

The pioneering work of Schumann has been widely adopted in the analysis of forced convection heat transfer in randomly packed beds [3]. Unfortunately, Schumann's approach assumes a fixed inlet temperature at the inlet to the system, which is seldom the case in real thermal energy storage systems. The solution of the Schumann's governing equations has been solved by Li and Chan [2] using a different approach. They simplified the heat transfer between the solid packing material and HTF to be one dimensional in the z direction by assuming uniform radial distribution of the fluid flow and filler material throughout the storage tank, as illustrated in Figure 1. The main energy balance equations over the control volume for the analysis of a packed-bed thermal storage system was developed and have been reduced into their dimensionless forms. Due to their hyperbolic type, they are solved numerically by the method of characteristics. This method overcomes the numerical limitations of McMahan's work [4] and gives a direct solution to the discretized equations with no iterative calculations required; thereby eliminating any computational overhead. A grid-independent solution can be obtained at a small number of nodes and has been proven fast and efficient to solve Schumann's equations.

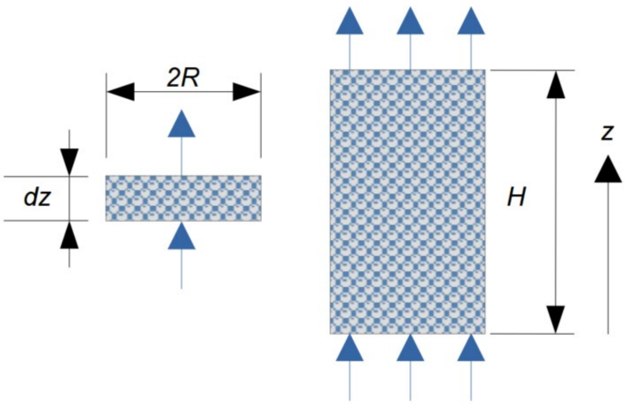

Figure 1. *Schematic of a packed-bed thermal storage system and a control volume for analysis*

The heat transfer model described above assumes no heat loss to its surroundings. This assumption holds true during both the energy charging and discharging processes, as well as during the intervals between these processes. For thermocline TES using solid filler materials for sensible heat storage, true thermal hysteresis (related to phase transitions with different heating/cooling temperatures) of the filler material itself is typically negligible or non-existent and not a primary factor affecting the thermocline. However, heat loss is unavoidable and should be considered for a TES; but would also be influenced by the dimensions of the tank. The model was developed from a design perspective and therefore aims to first determine the size of the tank required. A simple way of refining the design is to increase the tank size to compensate for the expected heat loss.

2.2 Flownex model for dual-media packed-bed sensible thermal storage

Although several approaches to analyse and solve the flow of a fluid through a packed bed have been developed in the past [5], they are often solved in isolation, which complicates the practical design analysis of a TES as part of an integrated energy system. Without proper design tools, it is difficult to quantify the potential benefit of integrating TES into an energy system or using it to recover industrial waste heat.

Flownex is a globally established, transient thermohydraulic process simulation software, which enables the design and analysis of flow and heat transfer systems [6]. Flownex is therefore an ideal platform in which to integrate TES models to study the operation and practical implications of incorporating TES systems into energy generation and heat-to-power conversion systems. For this purpose, a dynamic TES simulation tool within Flownex was developed, based on the method of Li & Chan [2] and successfully validated with literature data [7] as shown in Figure 2. Note that Flownex employs a transient solver governed by the progression of the simulation time according to the chosen time step size. To integrate this model into Flownex, the discretized grid of nodes, which is bound to intersections of dimensionless time and space, should be overlaid onto the Flownex solution time grid, to match the solution time exactly. This required that the non-dimensional TES outlet temperature profile be related to the simulation solution time for each time step.

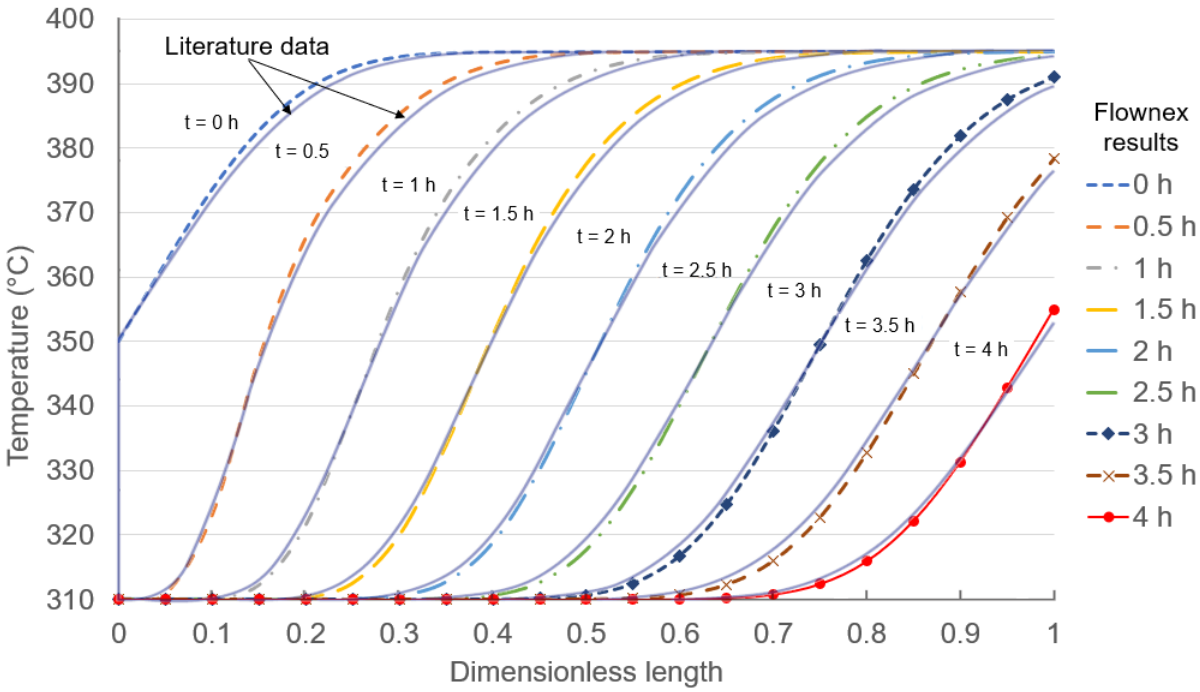

Figure 2. *Validation of Flownex model fluid temperature along z-axis during discharge cycle with refence case provided in literature [7]*

3. Transient System Analysis

Several gas turbine cogeneration concepts for the discharge of high temperature thermal energy storage units at atmospheric pressure were suggested by Holy et al. [8]. For the current study, a recuperated externally heated Brayton cycle with secondary heating cycle was chosen as shown in Figure 3. The separate heat transfer loops enable adjustment of the mass flow ratio of the fluid streams.

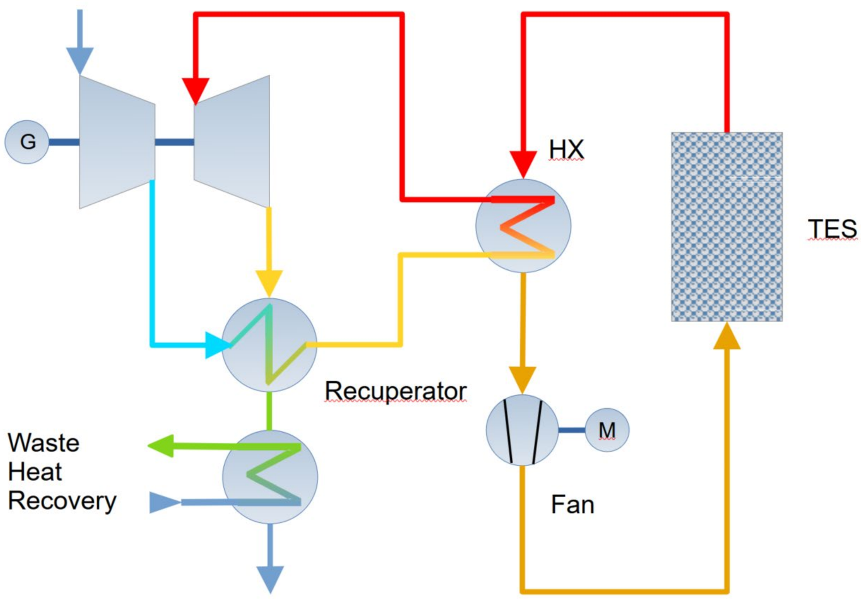

Figure 3. *Recuperated open externally heated Brayton cycle with secondary heating cycle*

A gas turbine cogeneration system was designed to deliver electrical power of ~100 kWe with 15 hours of thermal energy storage. Alumina spheres with 10 mm diameter was chosen as the thermal energy storage medium with air as heat transfer fluid. The TES stores heat at a temperature of 1300°C, which provides thermal energy via an intermediate heat exchanger to the gas turbine at 950°C. Initial sizing calculations yielded a TES tank with 4 m height and 2 m diameter with a capacity of 3.8 MWht, if it is assumed that 89% of the theoretical maximum thermal energy could be recovered at the required gas turbine inlet temperature (due to the thermocline shape in the TES), as suggested by Klein [9]. The process parameters and boundary conditions were chosen based on gas turbine technology in the power range below 2 MW_{el} [8]. All input values of the simulation are shown in Table 1.

Table 1. *Process parameters and results of gas turbine cogeneration system*

Input Parameters	**Value**	**Detail**
Ambient air conditions	20 °C @ 1 atm	Constant
Turbine isentropic efficiency	85 %	Steady state @ 62 000 rpm
Compressor isentropic efficiency	82 %	Steady state @ 62 000 rpm
Generator efficiency	95 %	Constant
Fan isentropic efficiency	84 %	Constant
TES outlet temperature	1300 °C	Steady state
Turbine inlet temperature	950 °C	Steady state
Recuperator thermal efficiency	96 %	Steady state
Waste Heat Exchanger thermal efficiency	98 %	Constant
System Results		
Electrical efficiency	40.1 %	Steady state
Thermal efficiency	92.8 %	Steady state
Thermal Energy Storage capacity	17.4 h	Turbine inlet > 900 °C

The system was simulated within Flownex (see Figure 4) and illustrates the capability of the TES model to predict the dynamic thermocline profile amidst varying cold gas inlet conditions. Uniform radial conditions in the TES were assumed, as explained in section 2.1. The transient simulation results are shown in Figure 5 and Figure 6. Note that the TES outlet temperature profile confirms that the TES capacity is sufficient to meet the delivery temperature of 1300°C for the required 15 h. However, the gas turbine inlet temperature could be maintained for 17.4 h before the temperature dropped below the cut-off point of 900°C since the TES outlet temperature was still high enough to deliver sufficient thermal energy to the Brayton cycle via the intermediate heat exchanger. Note that the gas turbine was shut down during the charging phase (hours 17-24).

Figure 5 illustrates a typical daily discharge and charge cycle, assuming that enough electrical heating from solar power is available to recharge the TES to full capacity. The thermal battery level is calculated with a 0% battery level at a reference temperature of 20°C. The TES will employ integrated electrical heating elements to perform recharging, which forms part of the TES capital cost. The concept enables permanent atmospheric pressure TES operation to reduce construction costs. As explained above, the separate heat transfer loops provide freedom to adjust the mass flow of each loop independently, which has the advantage that energy can be stored at higher temperatures in the TES, resulting in lower TES material cost per kWh of energy stored.

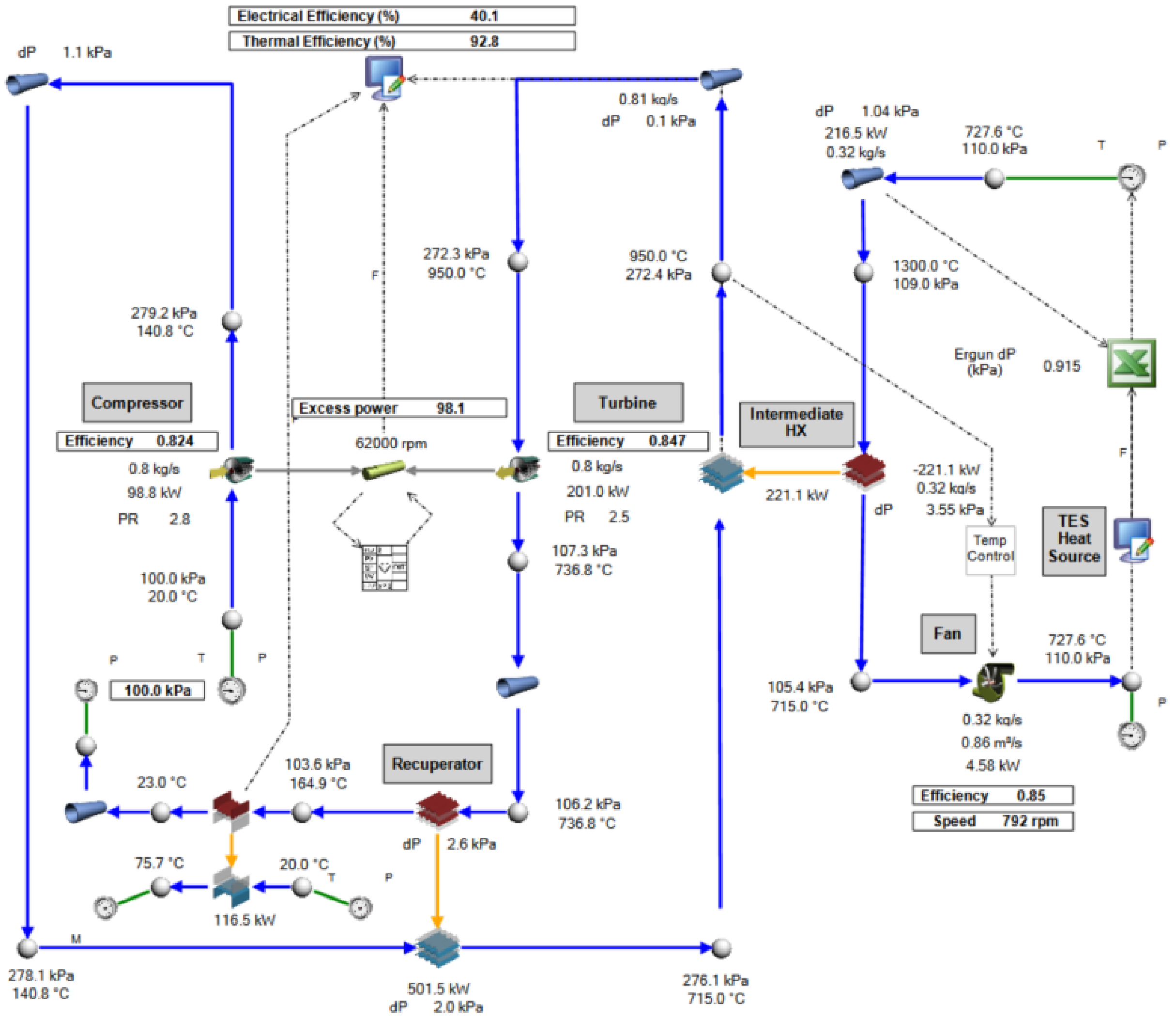

Figure 4. *Flownex network of recuperated open externally heated Brayton cycle with TES heat source via secondary heating cycle*

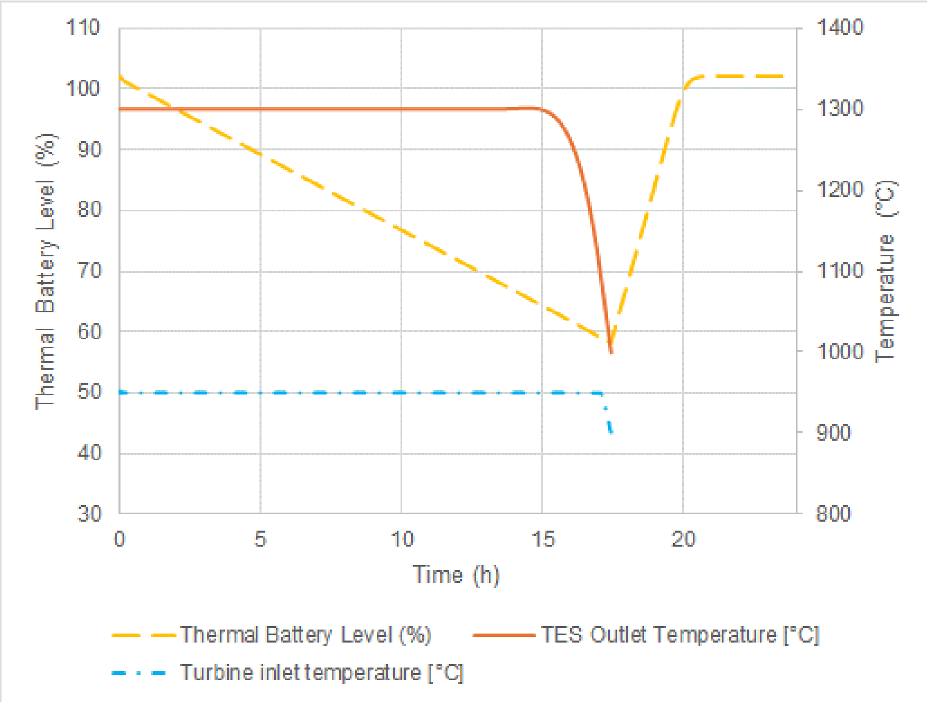

Figure 5. *Transient simulation results showing thermal battery cycling*

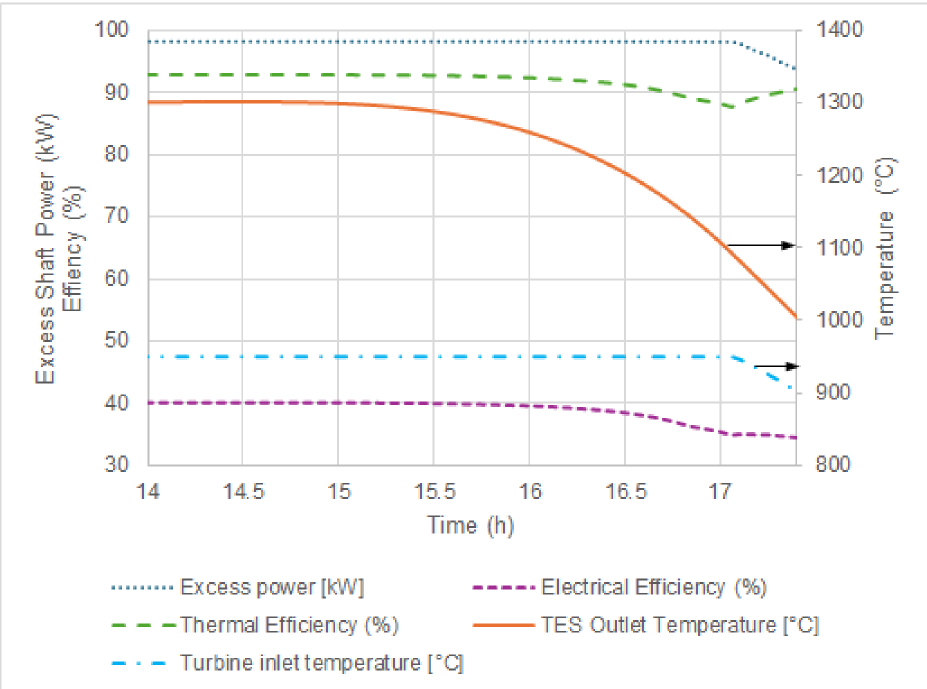

Figure 6. *Transient simulation results showing TES outlet temperature and turbine outlet temperature decline at the end of the TES discharge cycle*

4. Economic Comparison

The expected economic viability of a TES gas turbine cogeneration system with 18 h energy storage was compared to a lithium-ion (Li-ion) battery system to deliver the same output. Both systems use solar PV as energy source, but the former converts all excess electrical power to heat for storage in the TES. Capital cost estimates for the TES ranges between 10 – 30 $/kWh, confirming initial estimates by Stack [10]. The capital cost of utility scale batteries were assumed to be 413 $/kWh in 2024 [11] and 200 $/kWh in 2040 [12] with a 15 year lifespan [12]. All economic model assumptions were based on realistic literature values as listed in Table 2.

Table 2. *Assumed economic model parameters for cost comparison of utility scale battery vs TES gas turbine cogeneration system*

Economic model parameters		
TES and gas turbine lifespan	30	years
Project lifespan	30	years
Tax rate	35	%
WACC	10	%
Discount Rate	13	%
Gas Turbine cost parameters	**Electrical Efficiency (%)**	**Capital cost ($/kW)** [13]
100 kW, 950°C	40 %	2390
100 kW, 1200°C	46 %	2390
30 MW, 1200°C	52 %	768

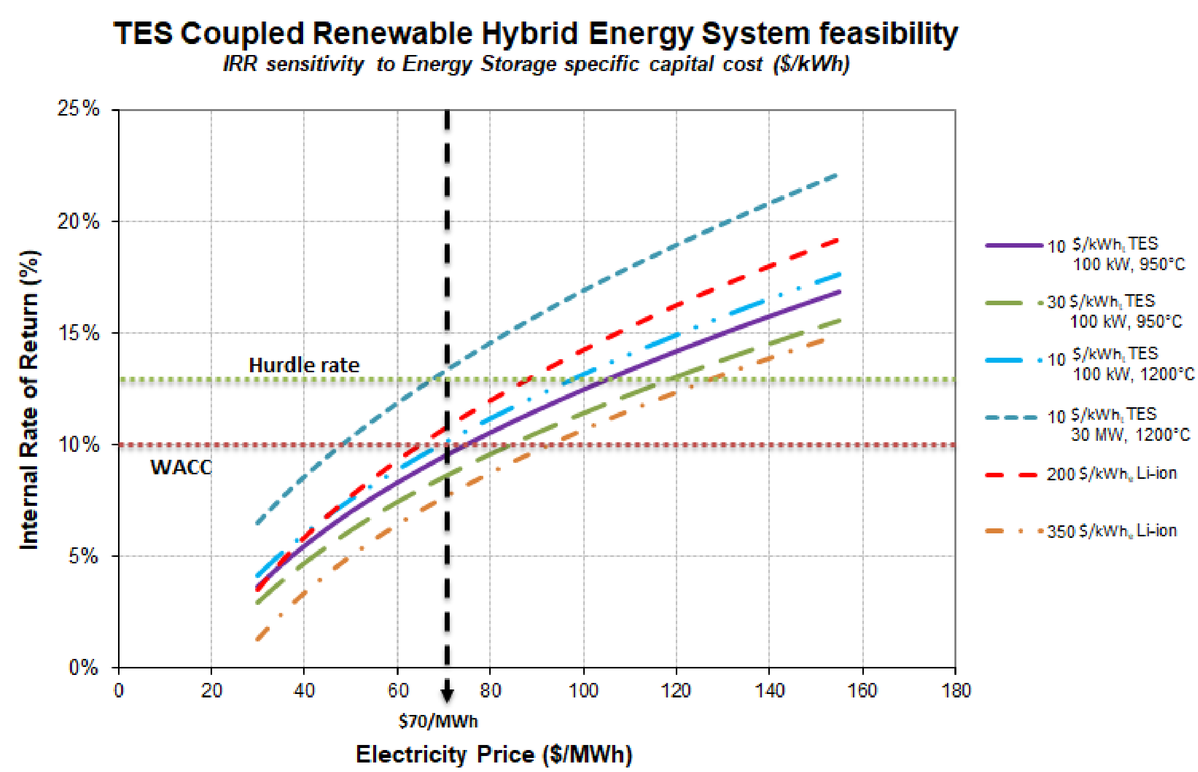

Figure 7. *Internal Rate of Return (IRR) sensitivity to energy storage specific capital cost. Assume Weighted Average Cost of Capital (WACC) rate of 10% and project hurdle rate of 13%.*

The comparison of the predicted IRR for both systems over a 30-year project life is shown in Figure 7, confirming the benefit of TES for LDES. The analysis results also illustrate the sensitivity of gas turbine size and inlet temperature to the IRR, which implies that large scale gas turbines with their higher efficiency will be more cost effective than low-cost utility scale Li-ion batteries. Note that the current economic comparison does not take the potential benefit of waste heat recovery (e.g. hot water production) from the recuperator outlet of a TES gas turbine cogeneration system into account and was only done on an electrical-to-electrical basis. Practical systems might adapt battery energy storage system (BESS) in combination with TES systems to enhance system performance.

Author contributions

Frikkie Botha: Investigation, Methodology, Resources, Software, Simulation, Validation, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Willem le Roux**: Funding acquisition, Project administration, Supervision, Writing – review.

Competing interests

The authors declare that they have no competing interests.

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