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Do the Dam Project—Evaluating floating solar photovoltaic and energy storage at Inanda Dam within eThekwini Municipality, South Africa

Leshan Moodliar[a,*], Innocent Ewean Davidson[b]

[a] Durban University of Technology, 41/43 M L Sultan Rd, Greyville, Durban, 4001, South Africa
[b] Cape Peninsula University of Technology, PO Box 1906, Bellville, Cape Town 7535, South Africa

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Abstract

South Africa's electricity generation plant portfolio includes several aged units, resulting in frequent breakdowns, electricity shortages and load shedding. This study evaluates the feasibility of generating electricity at the Inanda Dam located within eThekwini Municipality of South Africa by installing a floating photovoltaic (FPV) system. The Inanda Dam provides water for many local communities, and load shedding affects pumping operations and disrupts the continuity of water supply. Therefore, the study further evaluates the plausibility of coupling energy storage/alternate generation with the FPV system to provide enough electricity for pumping operations during an outage. In addition, this study evaluates the financial benefits to the municipality resulting from the project implementation. The Hybrid Optimization Model for Multiple Energy Resources (HOMER) software tool was utilised to conduct techno-economic analysis and optimise the size of system components to meet the load requirements while minimising the overall net present costs (NPC). Without limiting the dam usage space for FPV, the optimal FPV system size was 10 MWp to maintain the least NPC. However, with the generation system size larger than the water pumping demand, the excess solar energy generated can be exported back into the grid resulting in the municipality gaining $1 015 473 in the first year of operation. Incorporating battery energy storage or a diesel generator can mitigate load shedding at the pumping site. However, battery energy storage requires significantly more capital upfront and produces a nil financial investment return compared to the diesel generator option, making it the least preferred option to implement.

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Keywords: Floating PV (FPV); Solar photovoltaics; Techno-economic modelling; Renewable energy sources

1. Introduction

The traditional electricity value chain commenced with fossil fuel-fired power stations being far from urban nodes as they had to be closer to the fuel source. With decentralised solar generating systems gaining momentum

* Corresponding author.
E-mail address: 22289297@dut4life.ac.za (L. Moodliar).

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due to technological advancements and falling prices, the opportunity to generate electricity within urban zones has become a reality. However, a large-scale solar-powered system requires considerable space. Unfortunately, due to competing land priorities, urbanised areas do not have much land for electricity generation. Therefore, taking advantage of existing water bodies in the form of dams and reservoirs to install solar systems and generate electricity presents an ideal opportunity [1].

By 2018, global installations of FPV were estimated at 500 GWp, with projections to exceed 1000 GWp by 2023 [2]. According to Ramasamy [3], China has the most installed FPV equivalent to 52% of the global total, followed by the Taiwan Region and Japan with 12% and 10%, respectively. While Durban is on the lower end of solar irradiation (4.7 kWh/kWp) in South Africa, it is considerably higher than most European countries. For example, Germany's average solar irradiation is 3.5 kWh/kWp [4]. However, Germany has an installed solar capacity greater than the current available generation capacity in South Africa. Thus, Durban's solar irradiation is reasonable, and solar generation opportunities should not be ignored as South Africa is experiencing an electricity shortage. In 2021, 1136 h of load shedding resulted in a total load reduction of 2455 GWh [5]. Therefore, any plausible generation potential to alleviate the constrained electricity grid and strengthen the security of supply should be explored.

The Inanda Dam provides water for various suburbs within eThekwini. However, water is reticulated from the dam through pumping operations that rely on electricity [6]. When load shedding is implemented, pumping operations are interrupted, leading to water supply outages. The dilemma of not having electricity is also compounded by not having a supply of water. While this is disruptive to communities, there is also a loss of revenue to the municipality. As illustrated in Fig. 1, the Albert Falls Dam fed from the Midmar Dam releases water to the Nagle Dam, which flows by gravity to the Durban Heights Water Treatment Plant. However, when Nagle or Albert Falls Dams are below full supply capacity and are unlikely to reach full supply capacity throughout the season, the water supply to the treatment plant is maximised by pumping from the Inanda dam and supplemented by gravity supply from the Nagle dam [6]. A stable electricity supply to the pumping operations is therefore of paramount importance.

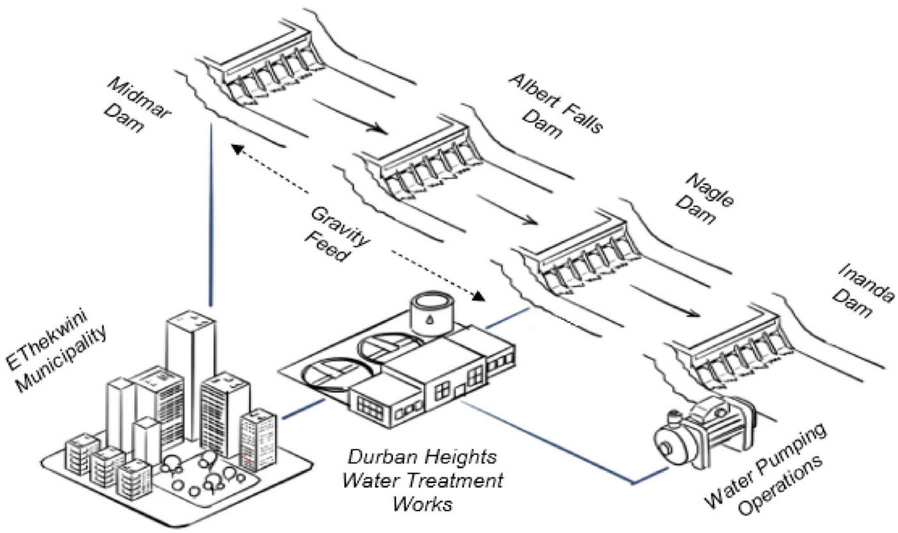


Fig. 1. Extract of Mgeni System indicating water flow to Durban – Own elaboration referencing [6].

FPV was 346% more expensive than ground-mounted systems in 2017. However, the pricing differential started to rapidly converge over the past four years as the costs of the floating system versus the ground mount system in 2021 deviated by only 19%. Currently, FPV systems are priced at $511 551/ MWp. [7]. Within eThekwini, 40% of all carbon emissions are due to electricity usage. As a result, the city has adopted the Durban Climate Action Plan (DCAP), which seeks to migrate away from traditional energy generation sources and towards 40% renewable energy by 2030 and 100% renewable energy by 2050 [8]. In support of these ambitious goals, exploring FPV on existing water bodies within eThekwini is welcomed. The purpose of this study is to evaluate FPV's role

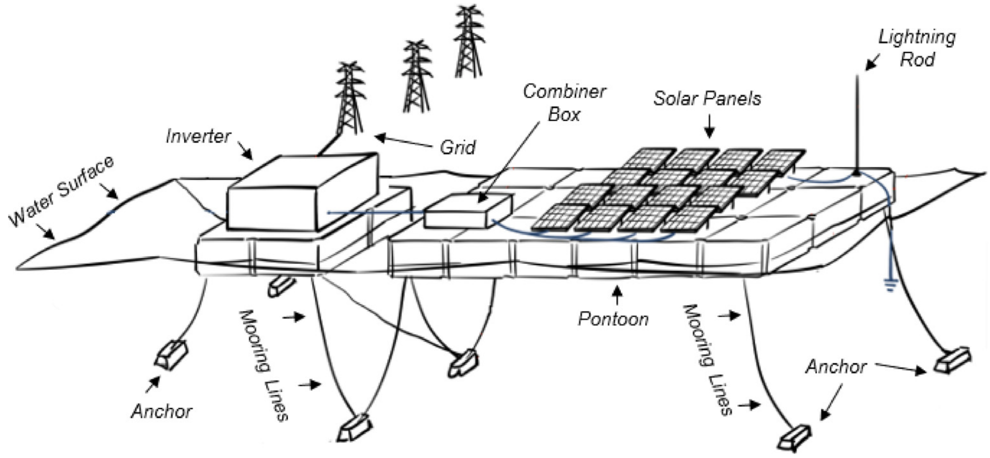


Fig. 2. Floating solar configuration. Own elaboration referencing [9,10,12].

in lowering carbon emissions and reducing the municipal costs of supplying the water pumping operations at the Inanda dam. Further, the study aims to find the optimum generation supply configuration to improve the water pumping operations' reliability and resiliency during load shedding.

1.1. Floating PV technology

FPV systems are very similar to ground-mounted systems. In the floating system, the entire generating system is mounted on suspended platforms that float on the water's surface, as shown in Fig. 2. The design of the floatation system and anchoring is of extreme importance as the generating system must remain stable under varying tidal and weather conditions [9,10]. Multiple pontoons make up the floatation platform. The pontoons are usually manufactured out of high-density polyethylene with high tensile strength, maintenance-free, and UV stable [10]. The floating platform is held in position with an anchoring system interconnected with mooring lines. The anchor system is usually concrete blocks set on the floor or a series of piles drilled into the floor. The mooring lines are manufactured from nylon or a similar material [7]. The mooring and anchoring system design is complex and dependent on various factors. These factors include the system's weight, the water's depth, tides, wind speeds and ground soil composition [11]. Cables connecting the floating generation system to the electrical grid must consider movement and allow for slack. The FPV panels are connected and terminated at the combiner box and, after that, into the inverter. The inverter is then connected to the electricity grid. A lightning rod is incorporated within the system design and connected to all metal frames and structures that are firmly bonded to the earthing system [7].

1.2. Literature review

FPV projects were initially at a small scale and mainly for research and demonstration purposes. However, the FPV sector turned a corner and started gaining traction in 2015 when Japan's first larger FPV plant of 7.55 MW was installed [13]. Since 2021, the world's largest floating solar PV plant is in China, with an installed capacity of 320 MW [14]. There is growing interest and advancement in FPV technology. However, researchers have varying views about technical performance and environmental impacts.

Considering the reviewed literature, researchers have agreed that FPV saves space and welcomed installing FPV; however, some, including Kumar et al. [7], had reservations about its impact on the marine ecosystem. In addition, the researchers unanimously agreed that the FPV system would be more efficient than the traditional system; Akole et al. [10] believe that the output could increase by 16%. However, Apribowo and Habibie [15] claim that the output could be as much as 30.54% more. Kumar et al. [7] and Liu et al. [16] also claimed that energy production output would increase; however, they conservatively claimed a 10% increase. Whilst researchers vary in their energy output projections, they all agreed that efficiency is gained as the water is believed to cool down the surface reducing the cell temperature and allowing for better performance. Such agreement is based on the premise that as the temperature of a crystalline silicon photovoltaic (PV) module drops, its conversion efficiency rises [17]. Akole et al. [10] and Gurfude et al. [18] believe that the FPV system can reduce water evaporation and benefit the dam. However, their estimates on the level of evaporation varied between 20% and 70%, subject to surface coverage. Whilst Kumar et al. [7] also agreed that FPV would reduce evaporation, they further claimed that the system would also reduce the amount of sunlight entering the water and, thus, the dissolved oxygen levels, which could impact the natural food chain. Song et al. [19] acknowledged the various advantages of FPV; however, they raised concerns that FPV could adversely affect the fishing activity and visitation of birds to the water bodies mainly due to the glare effects of the panels floating on the water surface. Due to the immaturity of the FPV sector, there are limited standards and guidelines in place. As a result, funders and insurers may be reluctant to finance and insure such projects. Therefore, this is viewed as a risk. However, the researchers of [20] concur that synergies can be derived from more mature industries, such as offshore wind. FPVs have proved their operability and workability, but their impact on aquatic life is not fully understood, and the sector lacks coordinated standards. It would therefore be prudent to roll out FPVs in a phased manner.

2. Research method

To adequately understand and evaluate FPV systems, techno-economic assessments were carried out. Fig. 3 illustrates the analysis process, considering the inputs and outputs, respectively. The technical inputs were site-specific and included, amongst others, the technology choice, the load profile and the solar irradiation. Important financial inputs included technology system costs and electricity prices, while the modelling inputs included discount and inflation rates. The key outputs included the simple payback period (SPP), internal rate of return (IRR), the levelized cost of electricity (LCOE) and the net present cost (NPC). The optimisation and design were implemented using the HOMER software. HOMER simulates a variety of technology integrations and generates optimised results ranked in ascending order of the NPC. The NPC and the LCOE are widely accepted means of evaluating project feasibility and are used in various studies. For example, the researchers of [21], [22], [23] and [24] utilised either NPC or LCOE as key outputs when evaluating projects.

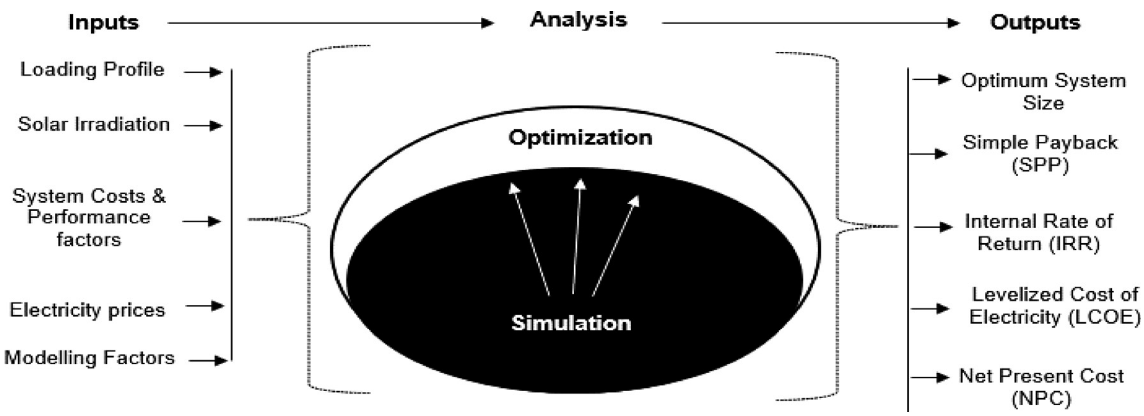


Fig. 3. Research methodology - Own elaboration referencing [25].

3. The generation potential at Inanda Dam

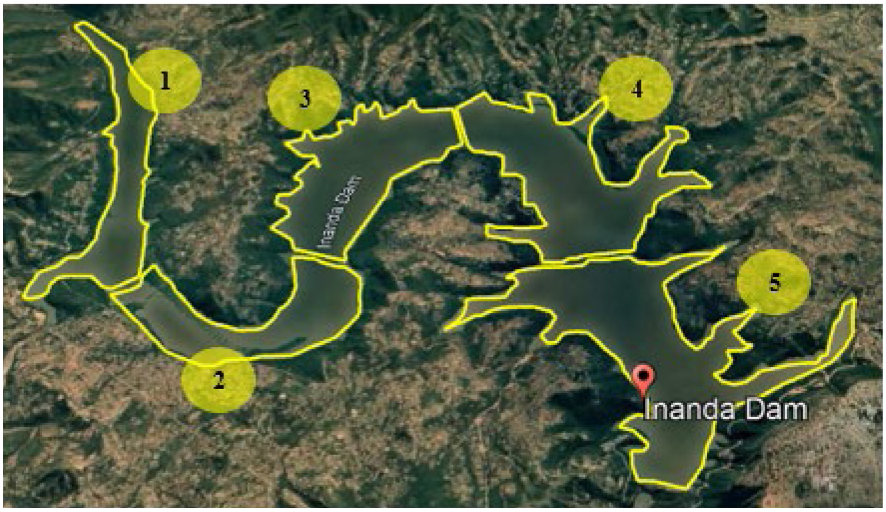
The Inanda dam, located 42 km north of Durban in the Valley of a Thousand Hills, was completed in 1989 and took two years to fill with water. Table 1 summarises key facts related to the Inanda Dam [26].

Utilising the PVsyst software, it was determined that a 1 MWp solar installation would require an area of 5700 m^2. Separating the dam into five sections using aerial footage and estimating the area per segment allowed for a proportional allocation of generation potential per segment, which is presented in Fig. 4.

EThekwini Municipality's peak load averages between 1600 MW and 1850 MW per annum [28]. Should the entire dam be covered with FPV, the potential exists to generate more electricity than the needs of eThekwini

Table 1. Key facts pertaining to Inanda Dam [26].

Deepest point (m)	Height of dam wall (m)	Length of the dam wall (m)	Length of the spillway (m)	± Length of the dam (km)	± Width of the dam (km)	Shoreline length at full dam capacity (km)
50	57	610	140	29	1.5	100



No.	Area (m^2)	MWp
1	1 612 088	283
2	1 624 095	285
3	2 324 122	408
4	3 029 654	532
5	3 322 241	583
Total	11 912 200	2091

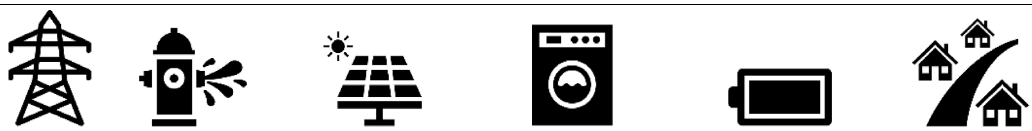
Fig. 4. Satellite view of Inanda Dam [27], separated into five segments.

Municipality. The Inanda Dam Resource Management Plan highlights that the dam is earmarked to allow for various activities around the water. Activities include the creation of a marina, water sport training and a yacht club. However, the plan does not indicate the intent to install FPV [26]. Considering the existing pre-approved plans, installing FPV on the entire dam may be impractical. For realistic modelling, it was assumed that a small section of the dam (0.05%) could be used to generate electricity up to 1 MWp without adversely affecting the existing plans.

4. Modelling analysis

The scenarios are shown in Table 2. Scenario 1 represents the base case and calculates the municipal energy costs in supplying the pumping operations. Scenario 2 illustrates an FPV system in conjunction with the grid to meet the demands of the water-pumping operations and maximises exporting energy back to the grid. In scenario 3, the FPV system was limited to 1 MWp, and the diesel generator size was optimised to meet 48 random loading shedding events of 2 h each. Scenario 4 limits the FPV system to 1 MWp, optimises the battery capacity to meet 48 random load-shedding events and maximises exporting energy back to the grid.

Table 2. Modelling configurations for scenarios 1, 2, 3, and 4.



Description	The Grid	Water Pumping	Floating Solar PV	Diesel Generator	Battery Storage	Inanda Community
Scenario 1	•	•				
Scenario 2	•	•	•			•
Scenario 3	•	•	•	•		•
Scenario 4	•	•	•		•	•

Table 3. Input parameters applicable to the modelling scenarios.

PV system		Battery energy storage	
Total PV installed cost	$550/kW	Battery Storage Type	Lithium Ion
Replacement inverter cost	$275/kW	Battery Storage Costs (4 h)	$1 100 110/MW
Replacement inverter year	Every 10 years	Replacement battery year	Every 10 years
PV degradation per annum	0.8%	Round trip efficiency	90%
Improved energy output factor due to the cooling effect of the floating system on the water surface.			10%
Diesel generator			
Generator installed costs	$413/kW	Fuel Curve Intercept	52.8 L/h
Generator lifespan	15 000 h	Fuel Curve Slop	0.236 L/h/kW
Minimum generator load	25%		
Diesel price	$1.10/Per Litre	Diesel price escalation	8% per annum
General modelling inputs		Electricity price	
Modelling period	25 Years	Energy price (2021)	Eskom Megaflex Distance: 0–300 km Voltage: >132 kV
Inflation Rate	5%	Yearly electricity price escalation	8%

The input settings strongly influence the simulation results. Table 3 shows the key input parameters used in the simulations. Each generation and storage technology had to be defined through its operating parameters. The solar PV system's installation costs, replacement costs, and degradation performance were defined. The battery energy storage parameters included the battery type, costs, and efficiency characteristics. The diesel generator was also defined through installed costs, diesel costs, lifespan, and load ratios. The general modelling inputs were the project lifespan, discount factors, and inflation rates. Other parameters that affected the project included the electricity prices and annual escalations.

5. Discussion of results

A summary of the results for the scenarios are contained in Table 4. Scenario 1 represents the base case for the municipality supplying the water pumping operations. The municipal cost amounts to $1 153 059 per annum, while the overall LCOE under this scenario is $0.138/kWh. The carbon emissions are at 12 056 029 kg/year. The NPC over 25 years was $31 511 457.

Table 4. Key results for scenarios 1, 2, 3, and 4.

Scenario	Levelized cost of cnergy (LCOE)	Carbon emissions	Net present cost (NPC)	Internal rate of return (IRR)	Simple payback period (SPP)
	($/kWh)	(kg/year)	$	%	year
Scenario 1	0.138	12 056 029	31 511 457	–	–
Scenario 2	0.035	7 715 954	11 935 577	24.6	4.71
Scenario 3	0.137	11 300 656	32 052 799	25.7	4.48
Scenario 4	0.135	29 046 606	66 962 211	Nil	24.98

Scenario 2 represents the case where the available space for FPV installation was not restricted. The optimum FPV size was 10 MWp with an NPC of $11 935 577 over the project lifespan. Compared to scenario 1, this is a savings of 62%. The initial investment required was $5 500 550, and the project delivered an IRR of 24.6% with an SPP of 4.71 years compared to the grid-only scenario. As a result, the municipality could supply the pumping operations and generate $1 015 473 in the first year of operation by implementing this project and would be able to provide 57% of the water pumping operations with renewable energy and reduce the carbon emissions by 4 340 075 kg/year. As illustrated in Fig. 5, the FPV system is larger than the load requirements. Excess electricity generated is exported into the grid. The municipality uses exported energy to supply surrounding customers, generating revenue. The FPV system can fully meet the loading requirements during grid sales. Accordingly, grid purchases are zero. Without batteries, grid sales cannot be controlled and will occur anytime excess energy is available. As

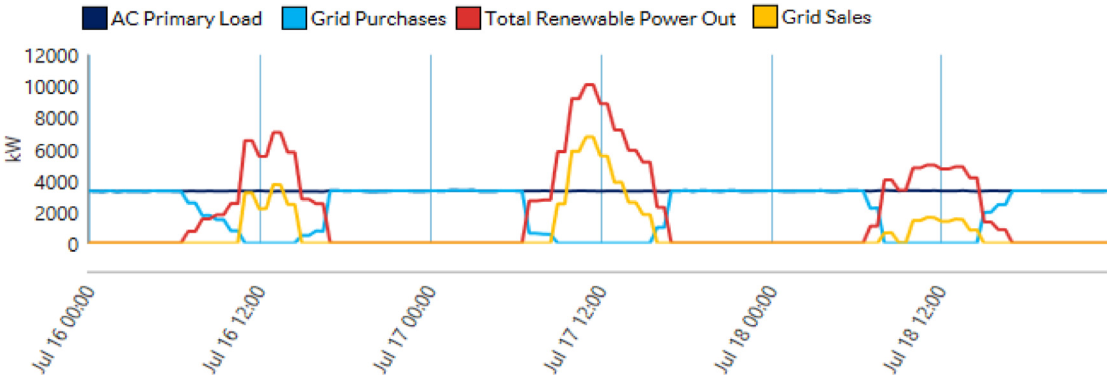


Fig. 5. Time series plot highlighting scenario 2 energy usage analysis.

a result, energy arbitrage cannot be specifically exploited. The overall LCOE of the project over its lifespan was $0.035/kWh representing a 75% reduction compared to scenario 1.

Scenario 3 represents the case where the space for FPV installation was restricted and only allowed for a 1 MWp installation. Further, a 3.6 MW diesel generator was incorporated within the supply system to mitigate loading shedding. Finally, 48 random load-shedding events have been modelled, with each event having an outage time of 2 h.

The project NPC was $32 052 799 over the project lifespan. The total investment required was $2 035 203, with the generator costing $1 485 148 and $550 055 for the initial FPV investment. The project delivered an IRR of 25.7% with an SPP of 4.48 years compared to the grid and diesel generator. The load supplied through renewable energy is only 8.28%, and the yearly carbon emissions were 11 300 656 kg. The LCOE was $0.137/kWh. The municipality only makes a savings of $100 236 by implementing this supply configuration; however, it can provide a reliable service to the water pumping operations. The reliability service provision entails using 47 701 litres of diesel costing $52 476. There is an opportunity for the municipality to charge for such services and augment its income stream. An option for the tariff charge could be based on the relevant cost of unserved energy (COUE) or the equivalent. Implementing the tariff charge would depend on the willingness of the customer to enter into an arrangement for such a service.

Scenario 4 reveals the impact of incorporating 40 MW of battery energy storage (instead of the diesel generator) in conjunction with the 1 MWp FPV plant to mitigate load shedding. The scenario delivered an NPC of $66 962 211 over the project lifespan. The initial investment required was $44 554 455, and the project offered a nil IRR with an SPP of 24.98 years compared to the grid and diesel generator. As illustrated in Fig. 6, energy arbitrage and grid sales have been exploited with the incorporation of ample battery storage. The discharge of the battery

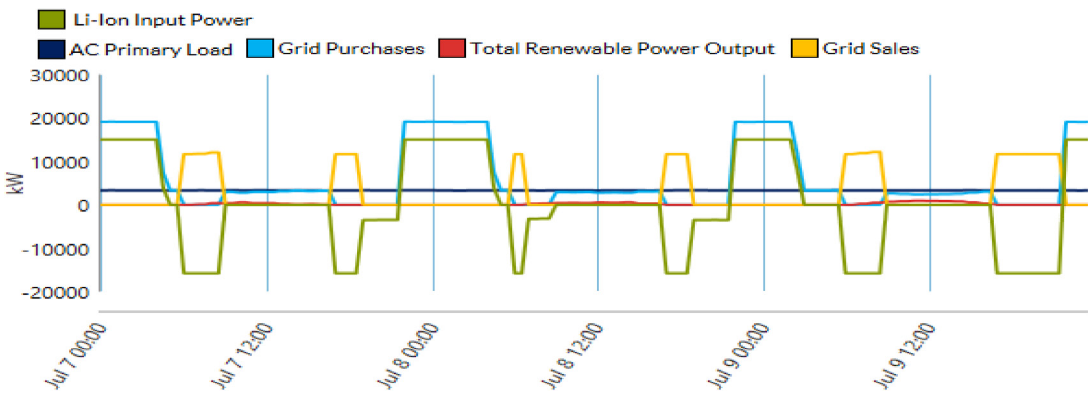


Fig. 6. Time series plot highlighting scenario 4 energy usage analysis.

occurs during the peak periods, whilst the charging occurs outside the peak periods. As a result, the municipality generated \$1 471 021 in the first year of operation. However, the emissions increased to 29 046 606 kg/year as the battery charging was predominately grid-based as the FPV system was limited in size. Increasing the FPV size would assist battery charging through renewable energy, reducing carbon emissions. The LCOE under this scenario is \$0.135/kWh representing minimal improvement when compared to scenario 3.

6. Conclusion

South Africa is experiencing a shortage of electricity and currently implementing rotational load shedding. The Inanda Dam pumping operations are currently grid-connected and subject to electricity outages. The idea of installing FPV coupled with battery energy storage and diesel generators was evaluated from a supplier perspective, i.e., the municipal perspective, to lower carbon emissions, reduce costs and improve the resiliency and reliability of the electricity supply to the pumping operations and the surrounding area.

A literature review of existing FPV projects for inland water was carried out and presented in this paper. It is concluded that FPV is a viable means of generating electricity. FPV is commonly used in areas where space is a constraint. Due to the floating nature, the water beneath creates a cooling effect on the panels, increasing their production efficiency. Whilst site conditions and individual circumstances dictate overall efficiency gains, studies have reported an average energy increase of 10% with FPV compared to ground-mounted systems. Despite the advantages, there is a lack of understanding of how FPV will impact aquatic and marine life. In 2017, FPV was 346% more costly than ground-mounted systems; however, the price differential rapidly narrowed to 19% in 2021.

Considering an area of 11 912 200 m^2 on the dam's surface results in an estimated theoretical FPV generation of 2091 MWp, which exceeds the total loading of eThekwini. According to the Resource Management Plan for the Inanda Dam precinct, there are intentions to advance the sport, recreational and tourism-related developments. Unfortunately, the provision for energy generation through FPV is not included in the plan. As a result, the practicality of rolling out large-scale FPV at the dam would be subject to further deliberation with key stakeholders. However, a techno-economic analysis reveals that a 10 MWp FPV system would be an optimally sized system to implement at the dam. With a 10 MWp installation, 57% of the pumping operations could be supplied with renewable energy.

Furthermore, when allowing for the feed-in of excess electricity back to the grid, the project produced an NPC of \$11 935 577 over the project lifespan, with an IRR of 24.6% and a simple payback period of 4.71 years when compared to the grid only scenario. With the understanding that FPV was not initially included within the resource management planning, the FPV installation at the Dam was limited to 1 MWp for other scenarios, requiring a reduced space availability of approximately 5700 m^2, i.e., 0.05% of the total dam area.

The option of including a diesel generator and battery energy storage was considered to improve the resilience and reliability of the electricity supply. A 3.6 MW diesel generator coupled with a 1 MWp FPV system and the grid were sufficient to meet the onsite pumping operations and mitigate 48 load-shedding events, each for two hours. However, realising the project would cost \$2 035 203 with an NPC of \$32 052 799.

Another means of improving resilience and reliability was to incorporate battery energy storage with the 1 MWp FPV system and the grid. The modelled battery size was 40 MW. Such a configuration required an investment of \$44 554 455. At the significantly higher investment costs, the LCOE did not improve significantly when compared to the use of the diesel generator. The project produced an NPC of \$66 962 211 with a nil IRR and a simple payback of 24.98 years when compared to the grid and diesel generator. The advantage of incorporating the battery energy storage was leveraging energy arbitrage. The control of the battery dispatch allowed for discharging the battery during peak periods and charging outside peak periods. With this controllable dispatch, the excess energy generated was fed back into the grid generating \$1 471 021 for the municipality in the first year. Despite the ability to generate revenue and mitigate load shedding, the considerably high investment required without an investment return makes the incorporation of battery energy storage unfeasible.

EThekwini Municipality is experiencing negative sales growth with an increasing cost structure. Should this trend continue, the electricity prices would rise above inflationary norms and could result in the municipality triggering a downward spiral. It is, therefore, imperative that the city seeks innovative revenue-generation methods. The municipality can generate additional revenue by implementing FPV. The additional revenue generated could be viewed as artificial growth strengthening the municipal financial position. FPV at the Inanda Dam presents an innovative opportunity for the municipality to strengthen the security of supply and generate revenue.

Declaration of competing interest

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.

Data availability

Data will be made available on request.

Acknowledgement

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