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Economic rationalization of energy storage under low load diesel application

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Abstract

Globally diesel generator sets account for the majority of generation into remote and off-grid power systems. While diesel generation has proven to be a reliable and accessible technology, its downside involves the expense and environmentally emissions linked to diesel fuel consumption. In response diesel generation alternatives are becoming available and cost competitive, via the integration of renewable energy technology (RET). Hybrid power systems (HPS), those adopting both diesel and RET are increasingly employed to reduce cost and environmental emissions. As RET penetration increases within HPS a potential conflict arises, with diesel generation unable to lower output below minimum load set points. These load set points are predetermined to ensure engine efficiency and reliability. Under medium to high renewable penetration, diesel load set points compete with renewable generation to produce surplus energy. This surplus energy must be absorbed by the system. Various ancillary technologies, such as demand management, energy storage and dump loads can perform this role; however such technologies are expensive and complex. This paper introduces low load diesel (LLD) as one solution to minimising surplus generation within HPS. Economic and power modelling is used to explore removal of energy storage (ES) under LLD application. Model validation, undertaken against both kW and MW scale operational diesel generator data sets is referenced to support the conclusion, that LLD is cable of reducing both system establishment and operational costs for medium to high RET penetration HPS.

Keywords: Hybrid power systems; low load diesel; variable speed diesel; remote area power; energy storage systems.

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1. Introduction

Renewable energy technology (RET) is becoming increasingly relevant to off-grid communities as they seek to reconfigure their power supply away from reliance on conventional diesel generation (CDG) [1]. While CDG has served these communities for decades, escalating costs, and an awareness of the environmental and health issues resultant from diesel combustion justify change [2]. RET integration offers some relief to these communities. Firstly it offers relief from the high operating expense (OPEX) of CDG [3]. RET costs in contrast are principally linked to the initial RET purchase and integration, or capital expense (CAPEX). Development of RET projects can accordingly be characterised as high CAPEX, low OPEX activities. While CDG is a low CAPEX, high OPEX undertaking. Both have advantages, with CDG the more expensive option, yet able to defer much of its cost to future years. Indeed total lifetime costs (CAPEX plus OPEX) of CDG often exceed that of RET many times over [4]. Importantly, RET integration also offers immediate environmental and health benefits [5], with reduced diesel fuel consumption responsible for lower emissions and waste. While CDG remains the primary source of generation into remote communities globally, increasing awareness of both the total lifetime costs and environmental damage, increasingly promote the integration of RET's.

While HPS offer consumers many benefits over CDG, the stochastic nature of many RET's creates issues, the complexity of which increases with RET penetration [6]. For low levels of RET penetration (0-30%), few issues are observed. For medium and high levels of RET penetration (>30%), additional ancillary technology integration may be required. Energy storage (ES) integration is one common approach, with system requirements determined by the level of RET penetration. ES permits higher levels RET integration, albeit at the cost of additional system complexity and cost. Figure 1 illustrates the increasing costs associated with RET integration for a grid connected microgrid [7]. Initially RET integration is shown to lower the cost of generation (note the cost reduction is many times greater for off-grid systems given the higher base cost of CDG). While RET cost/benefit is optimal for medium and high levels of penetration, the majority of HPS restrict RET penetration to <20%, possibly to limit system complexity. Wholly RET supplied HPS would return maximum environmental benefit, eliminating the need for CDG entirely, however such "diesel off" systems are neither economical nor simple.

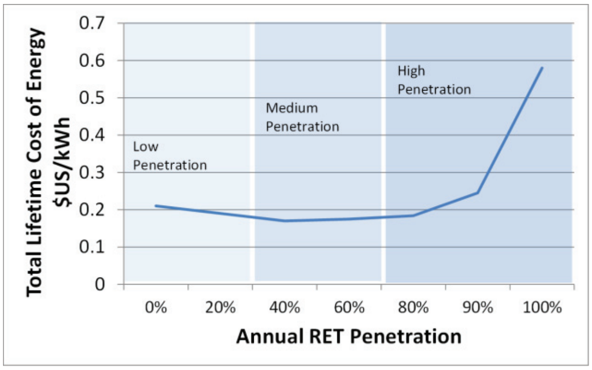


Fig. 1. RET in microgrids. [7]

Low Load Diesel (LLD) offers one solution [8], preserving the simple system architecture of low penetration HPS, yet permitting medium to high levels of RET penetration. The lower you can operate diesel generators, the greater RET penetration you can accept, and the lower your generation costs [9]. Historically, prolonged low load operation was ill advised, contributing to cylinder glazing, wet stacking and eventual engine damage [10], however a range of modern diesel technologies have silently eroded many of these barriers [11].

Prior research has investigated many of the problems caused by high RET penetration in HPS [12, 13]. The opportunity to replace CDG with wind generation has also been widely discussed [14]. Isolated power system control strategy, which can be categorized by control technique, and energy management strategy represents another body of existing research [15-17], with much of this research directed to optimal ES sizing. In [18] a power sharing approach is proposed to reduce the required ES capacity, while in [19, 20] demand management is adopted to the same end. Unfortunately these approaches all increase the complexity of the HPS, a criticism identified in [21-23], with these papers focusing on the capabilities and efficiencies of modern diesel generators. This paper considers a new approach to facilitating high RET penetration within a minimalist HPS architecture. Case studies are presented to compare CDG operation to LLD. Economic and power system models are developed to explore the system response, with LLD investigated as a low cost, low complexity pathway to high RET penetration. LLD application is the ability to run diesel infrastructure below manufacturer load limits for the acceptance of additional RET contribution.

2. Economic Modelling

Economic modeling for LLD application is undertaken using Homer, an optimisation model developed by the U.S. National Renewable Energy Laboratory (NREL). Diurnal and monthly profiles for both consumer load and renewable energy (RE) resource are used to define the variability of each respective parameter[†]. The economic model iteratively develops an annual, hourly time series simulation of all compliant generation sources to determine the lowest cost generation portfolio able to satisfy the load plus reserve (10%). Possible system configurations are ranked according to net present cost (NPC), equation 1 [24].

$$NPC(i,n)=\sum_{n=0}^{N}\frac{C_n}{(1+i)^n} \tag{1}$$

Where N is the total number of years n, C_n is the annualized cost, and i is the interest rate (8% assumed). Net present cost (NPC) represents a negative NPV, as incurred for RET system investment.

Wind generator output is represented by the turbine hub height mean wind speed, electrical efficiency and density corrected power curve [25]. ES interaction is represented by a capacity curve, lifetime curve, efficiency and minimum state of charge [26]. Diesel generator performance is represented by a rated capacity, low load limit, fuel consumption curve and total operable life [27]. Additionally all components include capital, replacement, generation and maintenance cost profiles. For CDG the generation costs include a fixed and marginal cost, as calculated from equations 2 and 3 respectively [28].

$$C_{fixed}=C_{om}+\frac{C_r}{N}+F_oRC_f \tag{2}$$

$$C_{marginal}=MC_f \tag{3}$$

The fixed cost (C_{fixed}) represent the cost of running the generators, while the marginal costs (C_{marginal}) represent an additional cost of energy generation, where;

C_{om} represents operations and maintenance costs,
C_r replacement cost, (noramlised to CDG: multiplier of 3x for wind and 4x for ES per MW/MWh) [26,29]
N is the generator life time, (30,000 hours CDG, 20 years wind, 6,000 full cycle equivalence ES) [26,29]
F_o is the fuel curve intercept coefficient, [30]
R is the rated generator capacity,
C_f is the fuel cost (a diesel fuel price of $1/litre is assumed) [27], and
M is the gradient of the fuel consumption curve.

[†] Data for King Island Renewable Energy Integration Project is adopted within the model configuration. http://www.kingislandrenewableenergy.com.au

3. Power System Simulation

Detailed power system simulation, inclusive of validated wind, diesel, battery and dump load models is presented in literature [8], as used to validate the presented economic modelling. Results confirm the projected fuel savings and support the case for ES removal. All power system studies in-turn consider a 50% step load increase (t=6s), variable RET output, and a 50% step load decrease (t=16s). The control approach targets uninterrupted operation of the system via co-ordination of both generation and demand, maximising RET utilisation. The diesel generation is tasked with reactive and active power control coordination. The wind turbine receives priority dispatch. During high wind periods the wind generation may exceed the load, with maximum wind utilisation achieved via throttling back any diesel contribution to its low load limit. Excess generation is dissipated to either the ES (where present) or resistive dump load, subject to SoC. Should no wind generation exist, the diesel generator is exclusively used to supply the required load, with all other elements inactive. Under all operating scenarios the diesel generator remains on. Compliance to the Tasmanian electricity code over frequency and under frequency thresholds defines the acceptable system security.

4. Results

Case studies are presented, initially considering HPS of increasing RET penetration, Figure 2(a), from which a cost optimised RET penetration can be determined. Representative of a cost optimised configuration, a medium RET penetration system is then selected to consider performance under either LLD, ES or both.

4.1. Economic Modelling

System NPC was assessed against increasing RET penetration, Figure 2(a). Results of the economic analysis confirm the optimal level of RET penetration, after which costs escalate rapidly, in support of Figure 1. Importantly LLD is shown to reduce NPC across medium to high levels of RET utilisation, while also deferring the introduction of ES. Sensitivity analysis was subsequently used for a medium level RET penetration system, to estimate the fuel savings associated with LLD application, Figure 2(b). Fuel savings of up to 15.3% at no load (0% load limit) are observed (A to B). For comparison a fuel reduction of 16% was returned when assessing this scenario within the associated Simulink model [8]. Of note CDG ES pairing returns a similar benefit (14.6% fuel reduction A to C), supportive of the recommendation to consider LLD as a precursor to ES.

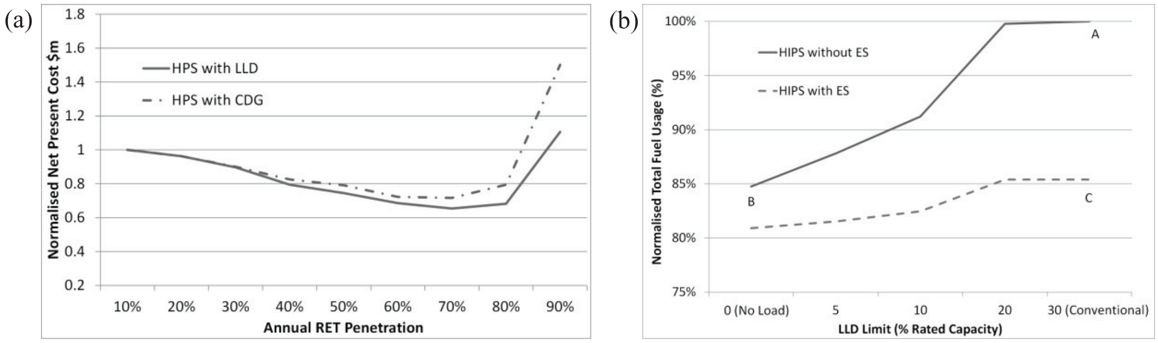
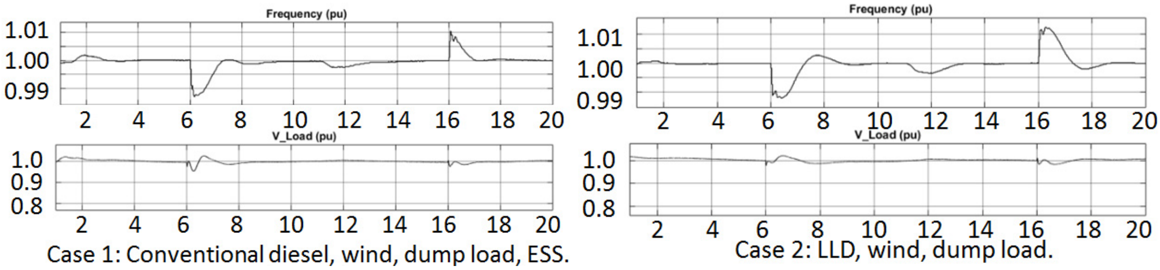


Fig. 2. Economic analysis of LLD (a) Net Present Cost for increasing RET Penetration, (b) Fuel Usage for increasing LLD limit.

4.2. Power System Modelling

Power system modeling (PSM) can be used to assess the security implications of ES removal, as proposed under the presented economic model. PSM can also assist to further describe the role of each component, with the dump load and battery observed to maintain network frequency under high RET penetration. The diesel responds to meet consumer demand with ramped output at t=6s, and throttled output at t=16s, limiting frequency rise. At both of these events the dump load and battery response is event on the network frequency, Figure 3. The plots of the system frequency and voltage demonstrate acceptable performance standards throughout, with and without ES integration.

PSM results in a 16% reduction in the observed diesel fuel consumption, a finding validating the prior economic analysis [8]. Of note the frequency and voltage profiles remain similar across case studies, despite ES removal. ES removal significantly reduces the system complexity and cost, another key advantage of LLD application within high RET penetrations. Given high RET penetration, the diesel generators ability to throttle back to low load allows for a significant increase in the RET utilisation, and a proportional decrease in the diesel fuel consumption.



Case 1: Conventional diesel, wind, dump load, ESS.

Case 2: LLD, wind, dump load.

Fig. 3. Frequency and voltage (p.u.) plots for simulation cases [8].

5. Conclusions

One solution available to HPS looking to maximise RET penetration involves the integration of ES. While ES costs are broadly anticipated to reduce over time, they are, unfortunately prohibitive to the majority of HPS. This paper identifies another opportunity, one accessible to the majority of isolated consumers, in redefining the role given to CDG's. Historically diesel generation has been run as base load, in opposition to greater than low levels of RET penetration (hence the need for ES). With the advancememt of LLD, diesel generation can perform a role more characteristic of ES than of base load. This paper assesses the economic benefit for LLD application, demonstrating improved RET penetration, and reduced energy costs. Importantly this approach additionally simplifies HPS architecture, with PSM confirming the ability of LLD application to permit removal of ancillary ES, under medium levels of RET penetration. LLD is presented as an affordable and accessible transitional technology able to provide an immediate pathway to improve RET penetration.

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