Economics of Renewable Energy Integration and Energy Storage via Low Load Diesel Application

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Abstract: One-quarter of the world's population lives without access to electricity. Unfortunately, the generation technology most commonly employed to advance rural electrification, diesel generation, carries considerable commercial and ecological risks. One approach used to address both the cost and pollution of diesel generation is renewable energy (RE) integration. However, to successfully integrate RE, both the stochastic nature of the RE resource and the operating characteristics of diesel generation require careful consideration. Typically, diesel generation is configured to run heavily loaded, achieving peak efficiencies within 70–80% of rated capacity. Diesel generation is also commonly sized to peak demand. These characteristics serve to constrain the possible RE penetration. While energy storage can relieve the constraint, this adds cost and complexity to the system. This paper identifies an alternative approach, redefining the low load capability of diesel generation. Low load diesel (LLD) allows a diesel engine to operate across its full capacity in support of improved RE utilization. LLD uses existing diesel assets, resulting in a reduced-cost, low-complexity substitute. This paper presents an economic analysis of LLD, with results compared to conventional energy storage applications. The results identify a novel pathway for consumers to transition from low to medium levels of RE penetration, without additional cost or system complexity.

Keywords: isolated power system; microgrid; off-grid solutions; renewable energy; low load diesel

1. Introduction

Isolated and remote power systems cannot rely upon traditional grid connection, which becomes economically unviable over large distances [1]. For these communities, diesel generation represents the mainstay of their power supply infrastructure [2]. Historically, diesel has offered available, affordable, reliable, and well-supported generation solutions [3]. Unfortunately, volatile pricing and diesel's environmental impact have motivated the search for alternative generation sources [4,5]. At the same time, renewable energy (RE) technologies have established themselves as clean and cost-competitive alternatives to diesel [6,7].

In contrast to diesel generation, RE generation is stochastic, unable to supply a power system without the support scheduled generation [8]. In response, communities are increasingly pairing RE with their existing diesel generation, creating hybrid diesel architectures. While a range of enabling technologies exist to support RE penetrations within hybrid systems, the cost and complexity of these solutions can be significant [3,9]. Prior research has identified multiple barriers to medium- and high-penetration RE integration, with system cost, complexity and flexibility as common issues [10,11]. In general, high RE penetrations add complexity, with increased demand placed upon the control and energy management strategies [1,12–15]. From the perspective of the diesel generation, these strategies tend to restrict diesel contribution to one of two extremes, standby operation [16,17] or continuous operation [6,18]. Enabling technologies are required for standby operation, with energy storage system

(ESS) integration the state-of-the-art approach [10,19,20]. ESSs improve system flexibility yet add to the expense and complexity of the system [21]. Given their high cost, significant research has been devoted to determining the optimal ESS sizing [22–26]. In contrast, this paper identifies a novel alternative, one independent of ESS integration, yet able to provide comparable system flexibility without the associated costs or complexity [27]. The research contributions of this paper include a definition of a technology alternative to ESS integration, validation of a low load diesel economic modeling approach, development of a LLD hybrid diesel control strategy, and simulation of low load diesel transient response.

Low Load Diesel (LLD) is the name assigned to modified engine application, allowing an engine's full capacity to be employed. LLD is implemented via removal of an engine's low load limit, as set within the station sequencer or controller. LLD is applicable to all diesel engine makes and models, irrespective of age or capacity [21,27,28]. The ability to exploit existing diesel assets results in a very low capital cost and minimal hardware or software disruption. Conventionally, load limits are set between 30% and 40% of an engine's rated capacity, prohibiting operation below this level. Engine manufacturers stipulate compliance with load limits as part of their standard warranty terms and conditions. Subsequently, most power system operators adopt the practice across an engine's lifetime [3]. Unfortunately, as the available renewable generation increases, load limits serve to restrict the balance of generation offered to any renewable technologies (Figure 1a). LLD allows for improved engine response, permitting engine operation across its full range, opening up an additional 30–40% of engine capacity for renewable pairing Figure 1b. All three scenarios presented in Figure 1a–c assume an identical twin peak load profile and RE resource. In all cases the consumer load is met by diesel and/or renewable generation. If no renewable generation is available, the load is met entirely via diesel generation. If renewable generation is available, the load is met by the renewable generation plus diesel generation, with the diesel generation able to reduce to the specified low load limit. In this manner, the lower the diesel load limit, the greater share of renewable generation can be utilized. If the available renewable generation exceeds the consumer load, this generation is spilt from the system. High renewable spillage can be addressed via the integration of energy storage (Figure 1c).
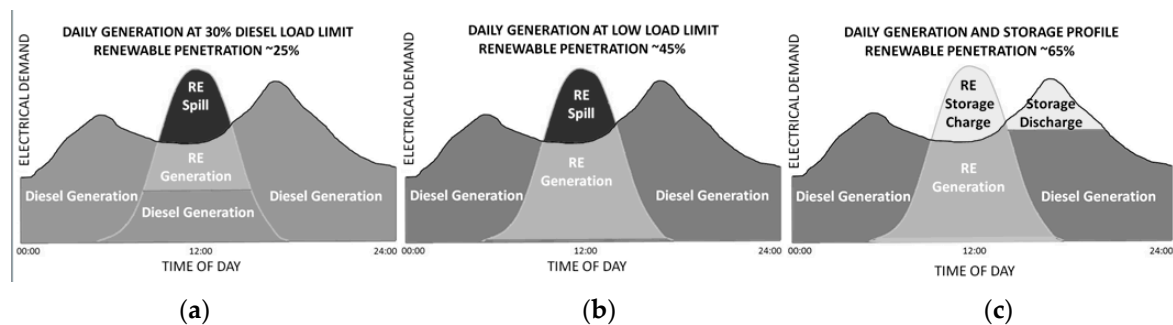

(a)　　　　　　　　　　　　(b)　　　　　　　　　　　　(c)

Figure 1. Typical electrical demand [black line], diesel generation [dark grey area], renewable generation [grey area], energy storage [light grey area] and renewable spill [black] for cases (**a**) to (**c**). Case (**a**) represents a standard 30% diesel load limit, Case (**b**) low load diesel, and Case (**c**) low load diesel plus energy storage applications. Note the increasing share of renewable penetration across (**a**) to (**c**). A solar PV RE resource is shown for illustrative purposes above.

While LLD is not a new technology, prolonged low load operation was historically ill advised. Low load operation typically resulted from incorrect engine sizing, when an engine was oversized in regard to a load. Under such an application the reduced torque demand requires less fuel, resulting in reduced cylinder temperature and pressure. Both are strong drivers of combustion efficiency. To compound reduced cylinder pressure, exhaust volumes drop, restricting turbocharger performance, further constraining air charge density. Engine impacts included reduced efficiency, cylinder glazing, wet stacking and eventual engine damage [29]. Cylinder glazing results from incomplete fuel

combustion, with carbon accumulation impacting correct cylinder function. Wet stacking results when there is unburnt fuel in the exhaust stream. The solution to both issues was traditionally to correctly size the engine. In contrast, this paper identifies opportunity for low load diesel application, in partnership with renewable generation.

More recently, low load specific purge routines have been developed, which permit sustained low load application without risk to engine condition or breach of warranty provisions [30,31]. Purge routines exhaust engine carbon, exposing the engine to elevated loading at sufficient frequency to prevent any adverse performance. Elevated loading sufficiently increases the thermal inertia of the engine to restore engine condition in much the same way as a particulate filter regenerates under elevated temperatures [32]. While purge requirements are engine- and load-specific, one hour of purge, every eight to 12 h of continuous low load operation is typical [30,31,33]. For hybrid diesel systems, the improved low load function offers an opportunity to accept significantly greater renewable content without an increase in system cost or complexity. This paper presents both economic and system considerations for LLD application. The paper details model validation and results (Section 2), with the model used to evaluate a number of LLD case studies. Discussion of the challenges and opportunities of LLD application are presented in Section 3, ahead of the modeling methodology (Section 4) and conclusions (Section 5).

2. Results

2.1. Economic Modeling

Economic simulation allows for rapid evaluation across a range of system architectures, component sizes and RE penetrations. Prior to assessment of low load application, simulation results for increasing renewable energy penetration were validated against the performance of the King Island power system (Figure 2) [34]. King Island is located in North West Tasmania, approximately 200 km south of Melbourne, Victoria. Generators supplying King Island include five diesel generator sets (6.0 MW), one low load diesel (1.2 MW), five wind turbines (2.45 MW), a 3 MW 1.5 MWh advanced lead-acid battery, a 1.5 MW resistor bank, a dual axis solar array (100 kW) and two Hitzinger Diesel-UPS (1.0 MVA) units. King Island was selected for the ability to validate simulation results to observed system performance, specifically the system's ability to utilize high RE penetrations, and the recent integration of a LLD generator set.
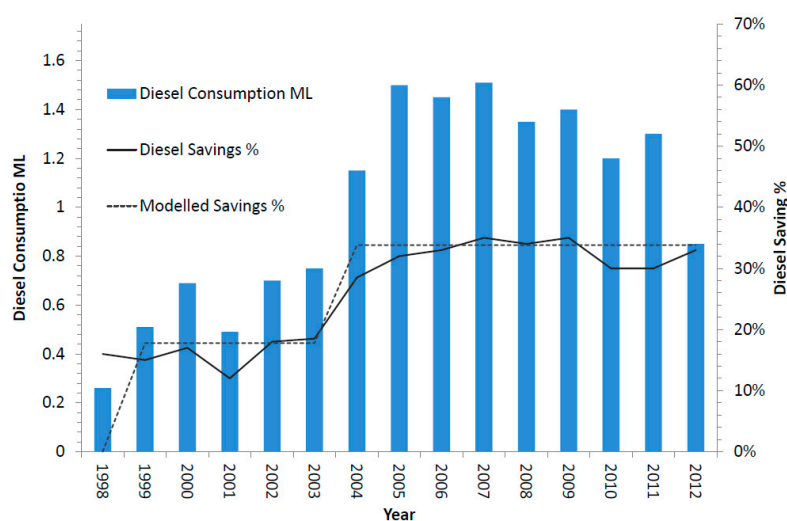

Figure 2. Annual diesel consumption (megaliters) and the associated fuel savings under increasing RE integration, observed and modeled for King Island power system, 1998–2012, [34]. Diesel savings represents the annual fuel savings returned within a year, in comparison to a 100% diesel-reliant system.

Renewable integration can be observed to reduce the diesel consumption required to meet the King Island load. Modeling results for the system are also presented in Figure 2, in validation of the developed modeling methodology. In interpreting the system performance integration milestones include, two Nordex N29 (500 kW) wind turbines installed in 1998, followed by two Vestas V52 (1.7 MW) wind turbines in 2004. Simulation results accurately represent the system performance following each milestone. Despite the annual resource variation evident between modeled and measured performance, the root mean square error is within 3% across the measurement period. The model was subsequently extended to low load application via revision to the diesel engine low load limit and low load fuel consumption.

In assessing the performance of the hybrid diesel systems, it is useful to define low (<30%), medium (30% to 60%) and high (>60%) RE penetrations. The level of RE penetration represents the renewable energy contribution, as a percentage of the total annual system load. Adopting this classification the reader can appreciate the divide between low RE penetration, where the majority of isolated power systems reside, and high RE penetration systems, those offering the lowest cost of energy (Figure 3). With reference to King Island, the configuration of the system from 2004 to 2012 approaches the cost optimized RE penetration level for a conventional diesel system (Figure 3a). Post 2012, enabling technologies, including a battery ESS, were installed on King Island. RE utilization increased to 65%, the cost optimized RE penetration level for diesel plus ESS (Figure 3a) [34]. In realizing high RE penetrations, King Island has addressed many technical barriers; however, commercial obstacles remain, with the system capital cost exceeding $20 million [35]. A significant contributor to this cost is ESS integration, yet without such enabling technologies, increasing the level of RE integration is not possible. The challenge for hybrid diesel systems seeking to emulate King Island remains to minimize the capital cost and complexity of such enablers. As an enabling technology, LLD achieves this. LLD performs as a conventional diesel system at low RE penetrations, while offering benefits comparable to ESS integration, at higher levels. LLD accordingly finds application bridging the two approaches, with the ability to offer many of the benefits of storage without the high capital cost or complexity. Conceptually it bridges the divide evident between low and high RE penetrations (Figure 3a), offering systems a transitional pathway to improved RE utilization. Such a strategy holds additional benefit as battery ESS pricing discounts over time.
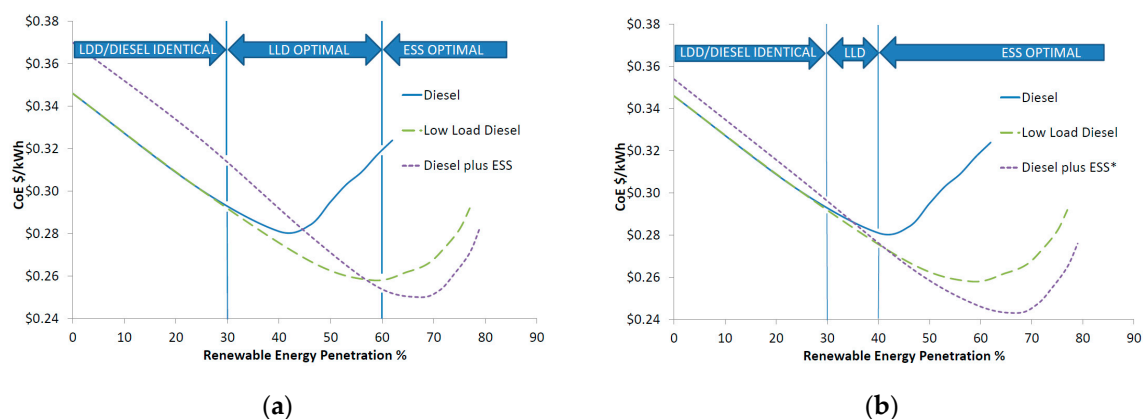

(a)   (b)

Figure 3. (**a**) CoE as a function of RE penetration for diesel, LLD and diesel plus ESS; (**b**) CoE for reduced ESS pricing, as a function of RE penetration for diesel, low load diesel and diesel plus energy storage architectures. At sufficient (>50%) ESS discount LLD benefit becomes marginal.

Sensitivity analysis for the presented CoE modeling, to both ESS pricing (Figure 3b) and strength of renewable resource (Figure 4a), identifies the influence of these parameters on the case for LLD adoption. A range of values were modeled to represent the possible future position of each parameter. ESS pricing was assessed within the range of $1 million/MW to $3 million/MW, while a wind

resource of between 7 m/s to 9 m/s was assessed. The assessment was designed to identify values for both renewable resource and ESS price at which LLD application was not recommended. Figure 3b demonstrates the diminishing role for LLD assuming reduced ESS pricing. Given a 50% ESS price discount (Figure 3b), justification for prior LLD adoption is significantly diminished. However, under reduced ESS pricing, we should consider a fourth architecture, that of a paired LLD and ESS application. Partnered, the two produces a cost curve below that for standalone ESS integration. Paired with an ESS, LLD can reduce the required ESS capacity, providing system benefit during unfavorable battery states of charge (when the battery is flat). Alternatively, Figure 4a considers reduction to the average site wind resource. Weakening RE resource is shown to lessen both the CoE gradient and cost optimized RE penetration. Subject to reduced RE resource, diminished benefit is observed for RE integration, and accordingly also enabling technologies, such as LLD or ESS. Resource variation is similar to the impacts of fuel price variation, with reducing fuel pricing also moderating the CoE gradient (the gradient determined by the ratio of diesel to RE energy costs). Of distinction, fuel price movement exhibits bias for diesel reliant systems (left hand side of the graph), while resource variation impacts renewable reliant systems (right hand side of the graph). The greatest risk to the proposed LLD methodology remains declining ESS pricing. However, the astute reader will appreciate the need for diesel generation under all ESS approaches [21]. ESS pricing accordingly affects the staging approach between LLD and ESS adoption, rather than displacing LLD application.
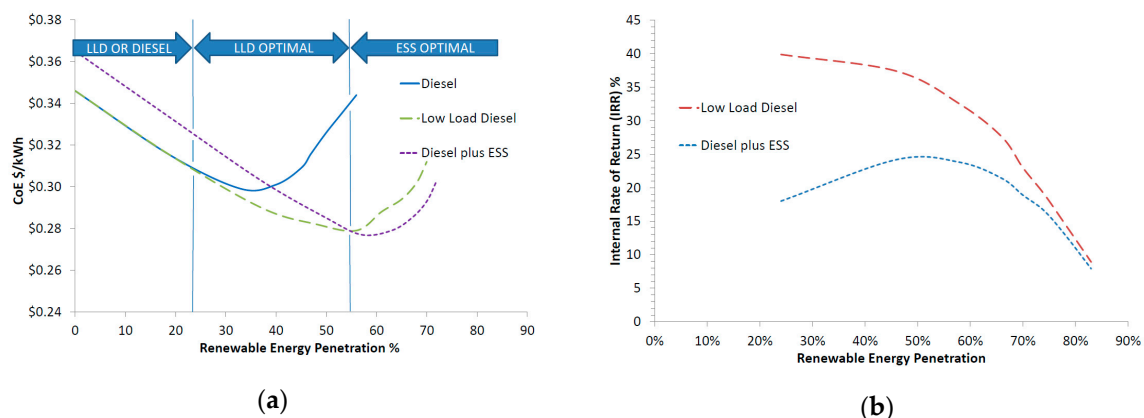

(a)   (b)

Figure 4. (**a**) CoE for a reduced RE resource, as a function of RE penetration for diesel, low load diesel and diesel plus energy storage architectures. Weaker RE resource is observed to reduce optimized RE penetrations across all cases; (**b**) IRR as a function of RE penetration for diesel and low load diesel.

In further exploring the barriers to hybrid diesel RE progression, discussion of the investment return, not just the capital cost, is relevant. Figure 4b defines the reducing internal rate of return observed for increasing RE penetration across both ESS and LLD applications. The inputs to the IRR analysis are detailed in Table 1. Internal rate of return (IRR), represents the discount rate applicable to the annual fuel savings, as required to align the system costs with a 100% diesel base case. With consideration for IRR across high RE penetrations, we observe diminishing returns for every dollar invested, despite reducing energy costs. Of the two approaches, lower total system costs and improved return are achieved under LLD. Under LLD application, low RE penetration systems are permitted to transition into medium penetrations without the economic and technical barriers associated with ESS integration. In doing so LLD represents a transitional pathway for hybrid systems looking to increase RE penetration.

As evident in Figure 4b, LLD allows owners to more efficiently allocate capital across medium RE penetrations, promoting increased RE capacity while permitting delay to ESS integration. In general decreasing returns are driven by the reduced return for additional RE investment, with increasing returns prompted via increasing utilization of available storage capacity. It is also relevant to note

that ESS investment is not directly able to contribute generation, with ESS sizing critical to efficient investment. Given the interdependence of the two approaches, LLD application is recommended as a precursor to ESS integration. Projected diesel fuel savings across the range of medium RE penetration are between 8–18% for LLD, and 10–26% for ESS integration, as compared to a conventional hybrid diesel reference case.

Table 1. Economic model inputs.

Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
Discount Rate	8%	Fuel Curve Slope	0.24	Wind CAPEX	$1700/kW	ESS CAPEX	$1900/kWh
Project Life	20 years	Diesel Fuel Cost	$1/L	Wind Maintenance Cost	$30,000 per annum	ESS Replacement Cost	$600/kWh
Diesel CAPEX	$500/kW	Diesel Heating Value	43.2 MJ/kg	Wind Turbine Losses	18%	ESS Maintenance Cost	$20,000 per annum
Diesel Maintenance Costs	$2/h	Diesel Density	820 kg/m^3	Wind Turbine Lifetime	20 years	ESS Roundtrip Losses	15%
Diesel Lifetime	20,000 h	Diesel Low Load Limit	0%	Hub Height	60 m	System Fixed Capital Cost	$5million
Fuel Intercept Coefficient	0.0134	-	-	Rotor Diameter	52 m	-	-

2.2. Transient Response Simulation

LLD offers remote and isolated power systems the ability to increase RE penetration without substantial change to the configuration or control of the system. Unfortunately, economic analysis is unable to comment on the power security implications of the proposed approach. This is because the economic model considers a time scale resolution of hours, while transient events within a power system occur on a time scale of milliseconds. For this reason assessment of LLD application must consider both power security and economic performance. To address system security, the transient response of three medium RE penetration case studies are presented, with simulations undertaken in Matlab. Medium penetration RE case studies were selected given the greatest role for LLD across this range. The three cases were selected to represent a range of possible technology configurations, including conventional hybrid diesel system design (Case 1), state of the art design (Case 2), and a LLD design (Case 3). Case 1 introduces a conventional wind diesel system architecture, specifically to explore the limitations of conventional approaches to achieve medium level RE penetrations. A common response to these limitations, Case 2 introduces a battery ESS to enable higher RE penetration. In contrast, Case 3 introduces LLD as an alternative to ESS integration. All case studies consider the diesel generator subject to a rated capacity step load increase of 60%, followed by a 60% step load decrease. The system load and generator response for Case 2 are presented in Figure 5.

The loading is intended to simulate the connection or disconnection of a major load/generator. Typically this would involve a system fault, which occurs a handful of times a year. The control approach targets uninterrupted operation of the system via co-ordination of the available generation to meet demand. At all times wind generation receives a priority dispatch to maximize the RE utilization. As part of the system security thresholds, a 2 Hz frequency variation is adopted for the presented analysis [36]. Frequency dip typically follows load acceptance given a decline in the systems spinning reserve as the generators respond to the increased demand. In all cases the diesel generator remains the systems primary means of frequency regulation, with a large load variability observed.
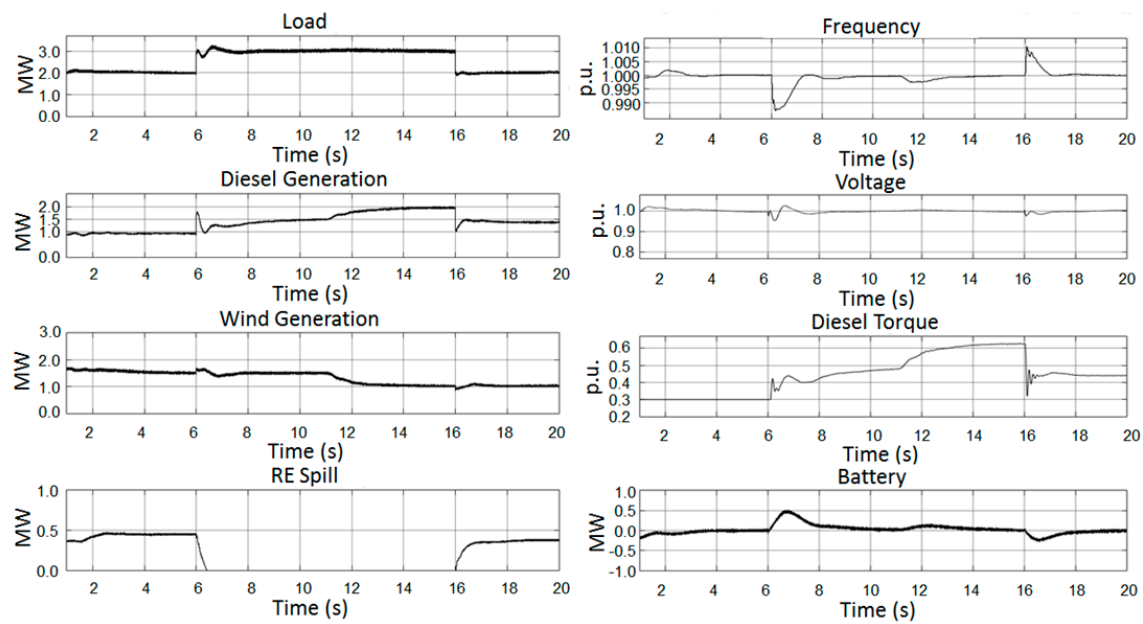
Figure 5. Operation of the diesel plus ESS system (Case 2) under wind speed deviation and 60% load perturbation, Top left going clockwise: Load (MW), Frequency (p.u.), Voltage (p.u.), Diesel Torque (p.u.), Battery (MW), Dump Load (MW), Wind Generation (MW), Diesel Generation(MW).

2.2.1. Case 1—Conventional Diesel and Wind System

Case 1 consists of diesel generation (1 p.u.), a renewable resource (1 p.u.), a consumer load and a resistive dump load (1 p.u.). The purpose of the resistive dump load is to spill excess RE generation as heat. The dump load offers the system improved frequency response, with the resistive element able to switch at a faster rate than the pitch response typically available from a wind turbine generator. The generators are sized to be of equal capacity. The diesel generation is tasked with reactive and active power coordination. The wind turbine receives priority dispatch, exporting power to the system, as available. During high wind periods the available generation may exceed the load. Available generation consists of the wind generation, plus the diesel generation operating at its low load limit (30%). Excess generation is spilt from the system via the resistive load. The wind turbine control allows for pitch regulated wind spill; however, dump load frequency control is preferable, offering improved system inertia. Unless a substantial heat load exists, all renewable energy spilt in this way is lost from the system and should be minimized. During low wind periods the wind generation may not satisfy the load, with diesel generation used to maintain the power balance. Should no wind generation exist, the diesel generator is exclusively used to supply the required load. Under all operating scenarios the diesel generator remains on. Case 1 performance is used to benchmark Case 2 and 3 results, as representative of conventional system performance.

2.2.2. Case 2—Conventional Diesel, Wind, Plus Energy Storage System (ESS)

Energy storage (0.5 p.u.) is subsequently added to the Case 1 system model, with the integration of an ESS permitting excess RE generation to be directed to the ESS. Subject to the state of charge (SoC) of the battery, it can acts either as a source or a sink, serving to reducing RE spill, the number of diesel starts and promoting diesel efficiency. Typical SoC is within the range of 40% to 90%, with the battery permitted to drain to a 30% SoC under extreme operating conditions. The capacity and operation of the ESS has been selected to represent the King Island system performance.

2.2.3. Case 3—Low Load Diesel and Wind System

Case 3 is analogous to Case 1, with a low load functionality introduced (0% load limit). This case is used to assess the performance of low load diesel application in comparison to an ESS approach.

A summary of the transient response within a 60 Hz system, to both load acceptance and load rejection, is presented in Figure 6. Both loading events are shown to occur one second into the presented plots. In all cases the diesel generator remains the systems primary means of frequency regulation. ESS technologies are shown to offer improved system dampening, via provision of additional kW supply (Figure 6). While all cases produce acceptable system security, integration of a battery provides for reduced transient overshoot and recovery time. In contrast, adoption of a LLD approach is shown to delay system response, owing to the reduced engine inertia. Despite such variations, the performance under all configurations remains within standards [36]. A similar result is observed for voltage variation. Accordingly, from a system security perspective, all configurations offer acceptable system security.
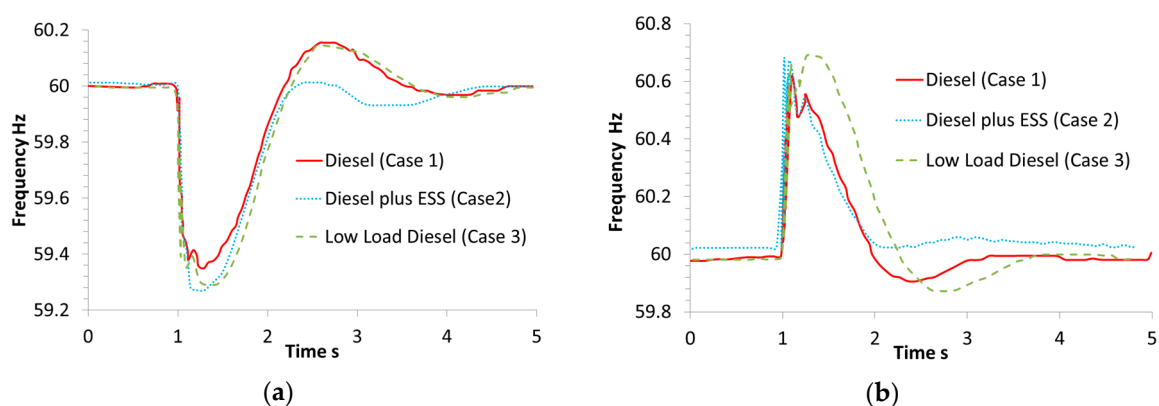

Figure 6. (**a**) System frequency response to 60% rated capacity step load increase; (**b**) system frequency response to 60% load decrease for diesel, diesel plus ESS and LLD case studies.

3. Discussion

One solution available for hybrid diesel systems looking to maximize RE penetration involves the integration of an ESS. While battery costs are broadly anticipated to reduce over time, they are currently cost prohibitive. Indeed costs would have to reduce by over 50%, to offer a comparable benefit to the proposed LLD approach. Importantly, lower ESS pricing, instead of excluding LLD application, alternatively shifts application in favor of a combined LLD plus ESS configuration. More probable is the role of LLD as a forerunner to ESS integration. LLD redefines the role given to diesel generation in support of system flexibility. LLD allows systems to progress past low RE penetrations, bridging the divide evident across low and high RE penetration systems. Conversion of an existing generator to LLD is presented as an affordable and accessible transitional technology able to provide an immediate pathway to medium RE penetrations without significant cost. Whilst conversion consists of little more than control refinement, plausible optimizations exist to delivering improved/extended low load operation. Such modification may include water jacket preheating, variable turbo geometries specific to low exhaust flow, pre-treatment (boost) of the engine air charge (supercharging), variable speed generation, and/or load variable cooling. All target increased cylinder temperatures and pressures under low load application. As the purpose of this paper is to demonstrate capabilities within existing diesel assets, no such subsystem refinement has been considered; however, consideration of such approaches represents a logical extension of the present research.

4. Materials and Methods

Economic evaluation for LLD application was undertaken in Matlab using Homer. Transient response was simulated in Matlab using Simulink. For the presented analysis, load and resource data for King Island, Tasmania was adopted [34]. King Island was selected for the ability to validate simulation results to observed system performance, specifically the system's ability to utilize high RE penetrations. The economic model develops an annual, hourly time series simulation of all generation sources, determining the lowest cost generation mix able to satisfy consumer load. Possible system configurations are ranked according to cost of energy (CoE), [37]. Power system simulation develops a 20 s time series of key system parameters, inclusive of step load acceptance ($t = 6$ s) and step load rejection ($t = 16$ s).

4.1. Diesel Generation Modeling

The model adopts a standardized approach to diesel fired generation [38,39], with frequency controlled by the governor and voltage controlled by the automatic voltage regulator. In this regard, conventional diesel and LLD platforms share a similar mechanical architecture. Diesel generation is dispatched based on the needs of the system and the status of any available RE generation sources.

Low load diesel application differs from conventional diesel operation given modified engine parameters, principally lower cylinder temperature and pressure. Low temperature and pressure result from a complex interaction of reduced combustion efficiency, reduced cylinder to piston ring alignment, reduced turbocharger velocity and proportionally reduced air charge pressures, all culminating in reduced engine efficiency at low loading. Low load engine response is simulated via manipulation of the engine specific delay (τ_1), as defined within the governor, actuator and engine model (Figure 7). The model describes the conversion of fuel, to torque, and finally rotational shaft velocity. The role of the governor is to regulate the output shaft speed (ω) via control of the fueling rate ($\dot{m}_f$). Governor response is represented by the transfer function $Gr(s)$, as determined by the angular speed error $\Delta\omega$ (rad/s) between ω and its set point ω_{ref}. As the engine speed varies, the governor identifies the variation, instructing the actuator to regulate fuel supply accordingly. The actuator system is represented by a first order network, characterized by the actuator constant K_2 and current driver constant K_3. Inherent to the actuator operation is the delay constant (τ_2), representing the response time of the actuator. Representative values for these parameters are provided in [40].
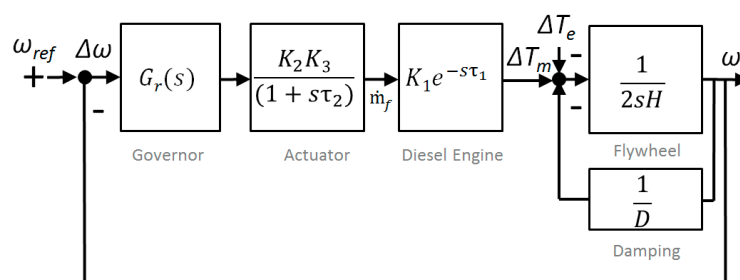

Figure 7. Diesel engine—Governor model [40].

Diesel generator control is overseen by the engine control unit (ECU), which integrates control of all engine subsystems. The excitation system of the generator assumes a modified IEEE2 model.

4.2. Wind Generation Modeling

A wind turbine consists of a horizontal axis rotor, coupled to a geared drive chain, which itself couples to a generator. The mechanical drivetrain, yaw and pitch mechanisms are located atop a sectionalized steel tower, within the nacelle. Wind generator output is represented by the measured hub height mean wind speed, the turbine electrical efficiency and turbine power curve. Wind generation

extracts kinetic energy from the wind, harnessing this resource to develop torque. Many differing electrical systems exist for the conversion of mechanical to electrical energy for wind turbines, although by far the most common system adopts a double-fed induction generator (DFIG) (Figure 8).
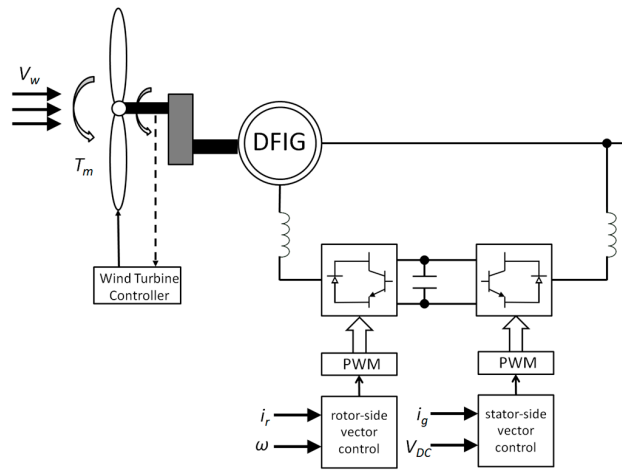

Figure 8. Doubly fed induction generator schematic.

This is also the system considered within this paper. The active power capabilities of a DFIG are limited by a number of factors, including rotor and stator voltage, stator current, rotor speed and stability limits [41]. For this paper the DFIG is considered only at unity power factor [14]. The DFIG is controlled by a back-to-back pulse width modulated converter, which consists of a rotor side converter (RSC) and a grid side converter (GSC). A vector control strategy is used for the active power and voltage control via the RSC, with both DC link voltage and the reactive power control undertaken via the GSC [27].

4.3. Energy Storage System (ESS) Modeling

High RE penetration systems require both energy storage and an associated dispatch strategy. The dispatch strategy determines the interaction of system components and the energy exchange between them. The model assumes a load following methodology, permitting only RE generation to charge the batteries. Simulation uses a kinetic battery model, treating the ESS as a two tank system (Equation (1)). One tank represents available energy and the other bound energy [42]. The rate of energy transfer between the tanks is dependent on the charge difference between them. In representing ESS performance the kinetic battery model prohibits either full charge or discharge of the battery, while limiting the rate of energy exchange to the previous state of charge. The maximum amount of power that the battery can discharge is given by Equation (2), while the maximum amount of power the battery can accept is defined in Equation (3) [43]. An ESS is defined by its capacity curve, lifetime curve, efficiency, and minimum state of charge.

$$Q = Q_1 + Q_2 \tag{1}$$

$$P_{discharge} = \frac{-kcQ_{\max} + kQ_1 e^{-k\Delta t} + Qkc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + 1 - e^{-k\Delta t})} \tag{2}$$

$$P_{charge} = \frac{-kQ_1 e^{-k\Delta t} + Qkc\left(1 - e^{-k\Delta t}\right)}{1 - e^{-k\Delta t} + c\left(k\Delta t - 1 + e^{-k\Delta t}\right)}, \tag{3}$$

where Q_1 is available and Q_2 is bound energy, k is the rate constant, a measure of how quickly energy can convert between bound and available energy, and c is the capacity ratio, the size ratio of the available energy tank compared to the combined available and bound tank size. The kinetic battery

model also accounts for rate-dependent losses and temperature effects on capacity. A battery reaches its end of life when it deteriorates to the specified degradation limit (30% modeled). To determine optimal ESS sizing multiple simulations were undertaken across a range of possible battery sizes (inclusive of a no battery model). This process determined the cost-optimized battery size, with this approach used for subsequent analysis.

The control methodology for the battery adopts a power management approach, with reference to system frequency via PI control (Figure 9).
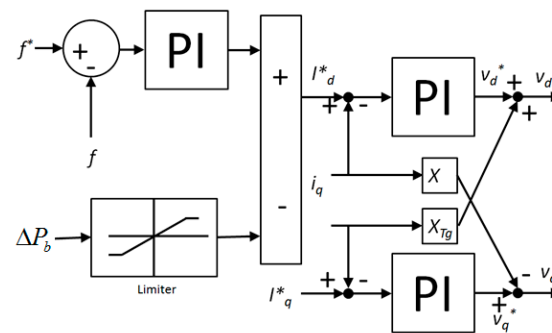

Figure 9. Battery control strategy.

5. Conclusions

Low load diesel application offers isolated and remote communities significant commercial and environmental benefit. In extending system capability to medium RE penetrations, LLD is able to return fuel savings of between 8% and 18%, in comparison to conventional operation. Resultant savings reduce the cost of energy by up to 8%. Across medium RE penetrations LLD is shown to increase investment IRR by 50%, effectively bridging both the commercial and technical divide evident across low to high RE penetration systems (those with and without storage). Improvement to system flexibility is delivered without significant capital investment, and without the complexity of energy storage integration. The results successfully identify a novel pathway for consumers to transition from low to medium levels of RE penetration, without additional cost, system complexity, or risk to system security.

Author Contributions: J.H. conceived and undertook the simulations; J.H., M.N. and X.W. analyzed the data; J.H. and M.N. wrote the paper.

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References

1. Micangeli, A.; del Citto, R.; Kiva, I.N.; Santori, S.G.; Gambino, V.; Kiplagat, J.; Viganò, D.; Fioriti, D.; Poli, D. Energy Production Analysis and Optimization of Mini-Grid in Remote Areas: The Case Study of Habaswein, Kenya. *Energies* **2017**, *10*, 2041. [CrossRef]
2. Akinyele, D.; Belikov, J.; Levron, Y. Challenges of Microgrids in Remote Communities: A STEEP Model Application. *Energies* **2018**, *11*, 432. [CrossRef]
3. Hamilton, J.; Negnevitsky, M.; Wang, X. Low load diesel perceptions and practices within remote area power systems. In Proceedings of the International Symposium on Smart Electric Distribution Systems and Technologies (EDST), Vienna, Austria, 8–11 September 2015; pp. 121–126.

4.   Arriaga, M.; Cañizares, C.A.; Kazerani, M. Renewable Energy Alternatives for Remote Communities in Northern Ontario, Canada. *IEEE Tran. Sustain. Energy* **2013**, *4*, 661–670. [CrossRef]

5.   Al-Hammad, H.; Becjer, T.; Bode, A.; Gupta, S.; Kreibiehl, S. *Renewable Energy in Hybrid Mini-Grids and Isolated Grids: Economic Benefits and Business Cases*; FS-UNEP Collaborating Centre for Climate & Sustainable Energy Finance: Frankfurt, Germany, 2015. Available online: http://fs-unep-centre.org/sites/default/files/publications/hybridgrids-economicbenefits.pdf (accessed on 11 February 2018).

6.   Elmitwally, A.; Rashed, M. Flexible Operation Strategy for an Isolated PV-Diesel Microgrid without Energy Storage. *IEEE Trans. Energy Convers.* **2011**, *26*, 235–244. [CrossRef]

7.   Nayar, C. Innovative Remote Micro-Grid Systems. *Int. J. Environ. Sustain.* **2012**, *1*, 53–65. [CrossRef]

8.   Nikolic, D.; Negnevitsky, M.; de Groot, M.; Gamble, S.; Forbes, J.; Ross, M. Fast demand response as an enabling technology for high renewable energy penetration in isolated power systems. In Proceedings of the IEEE PES General Meeting, National Harbor, MD, USA, 27–31 July 2014; pp. 1–5.

9.   Hamilton, J.; Negnevitsky, M.; Wang, X. Economic Rationalization of Energy Storage under Low Load Diesel Application. *Energy Procedia* **2017**, *110*, 65–70. [CrossRef]

10.   Li, W.Y.; Bagen, B. Reliability evaluation of integrated wind/diesel/storage systems for remote locations. In Proceedings of the IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Singapore, 14–17 June 2010; pp. 791–795.

11.   Xu, L.; Islam, S.; Chowdhury, A.A.; Koval, D.O. Reliability evaluation of a wind-diesel-battery hybrid power system. In Proceedings of the Industrial and Commercial Power Systems Technical Conference, Clearwater Beach, FL, USA, 4–8 May 2008; pp. 1–8.

12.   Mendis, N.; Muttaqi, K.M.; Perera, S.; Kamalasadan, S. An Effective Power Management Strategy for a Wind–Diesel–Hydrogen-Based Remote Area Power Supply System to Meet Fluctuating Demands under Generation Uncertainty. *IEEE Trans. Ind. Appl.* **2015**, *51*, 1228–1238. [CrossRef]

13.   Kayikci, M.; Milanovic, J.V. Dynamic Contribution of DFIG-Based Wind Plants to System Frequency Disturbances. *IEEE Trans. Power Syst.* **2009**, *24*, 859–867. [CrossRef]

14.   Mendis, N.; Muttaqi, K.M.; Perera, S.; Uddin, M.N. A novel control strategy for stand-alone operation of a wind dominated RAPS system. In Proceedings of the 2011 46th IEEE Industry Applications Society Annual Meeting, Orlando, FL, USA, 9–13 October 2011.

15.   Haruni, M.O.; Gargoom, A.; Haque, M.E.; Negnevitsky, M. Dynamic operation and control of a hybrid wind-diesel stand alone power systems. In Proceedings of the Applied Power Electronics Conference and Exposition (APEC), Palm Springs, CA, USA, 21–25 February 2010; pp. 162–169.

16.   Zhu, B.; Tazvinga, H.; Xia, X. Switched Model Predictive Control for Energy Dispatching of a Photovoltaic-Diesel-Battery Hybrid Power System. *IEEE Trans. Control Syst. Technol.* **2015**, *23*, 1229–1236.

17.   Changjie, Y.; Sechilariu, M.; Locment, F. Diesel generator slow start-up compensation by supercapacitor for DC microgrid power balancing. In Proceedings of the IEEE International Energy Conference (ENERGYCON), Leuven, Belgium, 4–8 April 2016; pp. 1–6.

18.   Mishra, S.; Ramasubramanian, D.; Sekhar, P.C. A Seamless Control Methodology for a Grid Connected and Isolated PV-Diesel Microgrid. *IEEE Trans. Power Syst.* **2013**, *28*, 4393–4404. [CrossRef]

19.   Tribioli, L.; Cozzolino, R.; Evangelisti, L.; Bella, G. Energy Management of an Off-Grid Hybrid Power Plant with Multiple Energy Storage Systems. *Energies* **2016**, *9*, 661. [CrossRef]

20.   Mendis, N.; Muttaqi, K.M.; Sayeef, S.; Perera, S. Application of a hybrid energy storage in a remote area power supply system. In Proceedings of the IEEE International Energy Conference and Exhibition (EnergyCon), Manama, Bahrain, 18–22 December 2010; pp. 576–581.

21.   Hamilton, J.; Negnevitsky, M.; Wang, X.; Tavakoli, A.; Mueller-Stoffels, M. Utilization and Optimization of Diesel Generation for Maximum Renewable Energy Integration. In *Smart Energy Grid Design for Island Countries*, 1st ed.; Springer: Cham, Switzerland, 2017; pp. 21–70.

22.   Bernal-Agustín, J.L.; Dufo-López, R. Multi-objective design and control of hybrid systems minimizing costs and unmet load. *Electr. Power Syst. Res.* **2006**, *79*, 170–180. [CrossRef]

23.   Vrettos, E.I.; Papathanassiou, S.A. Operating Policy and Optimal Sizing of a High Penetration RES-BESS System for Small Isolated Grids. *IEEE Trans. Energy Convers.* **2011**, *26*, 744–756. [CrossRef]

24.   Miranda, I.; Silva, N.; Leite, H. A Holistic Approach to the Integration of Battery Energy Storage Systems in Island Electric Grids with High Wind Penetration. *IEEE Trans. Sustain. Energy* **2016**, *7*, 775–785. [CrossRef]

25. Toliyat, A.; Kwasinski, A. Energy storage sizing for effective primary and secondary control of low-inertia microgrids. In Proceedings of the 6th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Aachen, Germany, 22–25 June 2015; pp. 1–7.

26. Bahramirad, S.; Reder, W.; Khodaei, A. Reliability-Constrained Optimal Sizing of Energy Storage System in a Microgrid. *IEEE Trans. Smart Grid* **2012**, *3*, 2056–2062. [CrossRef]

27. Hamilton, J.; Tavakoli, A.; Negnevitsky, M.; Wang, X. Investigation of no load diesel technology in isolated power systems. In Proceedings of the IEEE Power and Energy Society General Meeting (PESGM), Boston, MA, USA, 17–21 July 2016; pp. 1–5.

28. Hamilton, J. Low Load Diesel: A Low Cost, Low Complexity Approach to High Renewable Energy Penetration within Remote and Isolated Power Systems. Ph.D. Thesis, Centre for Renewable Energy and Power Systems, University of Tasmania, Hobart, Australia, 2017.

29. Dettmer, R. Revolutionary energy-a wind/diesel generator with flywheel storage. *IEE Rev.* **1990**, *36*, 149–151. [CrossRef]

30. Welz, R. Low Load Operation for s1600 Gendrive Engines OE Development Newsletter Power Generation 15-005, MTU Friedrichshafen. April 2015. Available online: https://www.scribd.com/document/375864097/15-005-Low-Load-Operation-for-S1600-Gendrive-Engines (accessed on 19 March 2018).

31. Brooks, P. Limitations on Low Load Operation for Fixed Speed Engines, Marine Application Bulletin 2.05.00, Cummins. February 2015. Available online: https://gce.cummins.com/ace_aebs/aeb01017.pdf (accessed on 26 February 2018).

32. Konstandopoulos, A.G.; Kostoglou, M.; Skaperdas, E.; Papaioannou, E.; Zarvalis, D.; Kladopoulou, E. Fundamental Studies of Diesel Particulate Filters: Transient Loading, Regeneration and Aging. *SAE Pap.* **2000**. [CrossRef]

33. Jabeck, B. The Impact of Generator Set Underloading Caterpillar. 2014. Available online: https://forums.cat.com/t5/BLOG-Power-Perspectives/The-Impact-of-Generator-Set-Underloading/ba-p/69719 (accessed on 11 August 2017).

34. Gamble, S. Approaches and lessons from King Island and Flinders Island hybrid projects. In Proceedings of the Informa Remote Area Supply Conference, Sydney, Australia, 22–23 March 2016.

35. Meyer, S. Round the Clock Milestone for Renewable Energy. 2015. Available online: http://www.kingislandrenewableenergy.com.au/news/2015/round-clock-milestone-renewable-energy (accessed on 13 November 2015).

36. Tasmanian Economic Regulator, Tasmanian Electricity Code in Chapter (4A) Bass Strait Island Chapter (Systems Operations and Network Services Provision). 2013. Available online: http://www.economicregulator.tas.gov.au/electricity/regulatory-framework/codes/tasmanian-electricity-code-downloads (accessed on 4 January 2017).

37. Lambert, T.; Gilman, P.; Lilienthal, P. Micropower System Modeling with HOMER. In *Integration of Alternative Sources of Energy*; Sons, J.W., Ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2006.

38. International Organization for Standardization. *Reciprocating Internal Combustion Engine Driven Alternating Current Generating Sets*; ISO 8528:2005; International Organization for Standardization (ISO): Geneva, Switzerland, 2005.

39. International Organization for Standardization. *Reciprocating Internal Combustion Engines—Performance*; ISO 3046:2002; International Organization for Standardization: Geneva, Switzerland, 2002.

40. Roy, S.; Malik, O.P.; Hope, G.S. An adaptive control scheme for speed control of diesel driven power-plants. *IEEE Trans. Energy Convers.* **1991**, *6*, 605–611. [CrossRef]

41. Hau, E. *Wind Turbines Fundamentals, Technologies, Application, Economics*, 3rd ed.; Springer: Berlin/Heidelberg, Germany, 2000; pp. 96–105.

42. Manwell, F.; McGowan, J.G. Lead acid battery storage model for hybrid energy systems. *Sol. Energy* **1993**, *50*, 399–405. [CrossRef]

43. Bako, Z.N.; Tankari, M.A.; Lefebvre, G.; Maiga, A.S. Lead-acid battery behavior study and modelling based on the Kinetic Battery Model approach. In Proceedings of the 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), Birmingham, UK, 20–23 November 2016; pp. 673–677.