Utilization and Optimization of Diesel Generation for Maximum Renewable Energy Integration

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Abstract Globally, the vast majority of generation within off-grid communities is supplied via diesel generation. The extent to which renewable energy source (RES) technologies can be effectively integrated into these systems depends, to a large degree, on the configuration and control of such existing infrastructure. Utilization and optimization of existing diesel generation is accordingly a key consideration for any successful RES proposal. This chapter explores both modern and legacy diesel technology and control, as available to maximize RES penetration within a hybrid diesel islanded network. Diesel generators are relatively inexpensive to purchase, offering a proven, reliable and stable generation source. Diesel generation is also supported via the ease and availability of both supplier engagement and technical expertise, services readily at hand to consumers. Their downside has proven to be the diesel fuel itself, given both volatile commodity pricing and damaging environmental emissions. These issues have created opportunity for alternative generation sources, and as we will seen throughout the proceeding chapters, the advent of both available and cost competitive RES technologies has given remote communities genuine generation alternatives. RES technologies will become increasingly important to island countries as they seek to reduce their emissions and operational costs. How readily RES technologies are adopted, will depend on how effectively these technologies can be integrated into

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existing networks, with this chapter advocating a hybrid diesel architecture as one solution to quickly and effectively deliver high RES penetrations. How do islanded countries embrace the challenges and opportunities of emerging RES technologies? Will diesel generators become obsolete within these future power systems structures? This chapter considers these queries, presenting existing generation as part of the recommended transition. In discussing the role of conventional generation, the audience is asked to recognize the residual value within legacy assets, identifying a cost optimized pathway for improved RES integration.

1 Introduction

Globally, diesel accounts for the majority of generation into off-grid and remote power systems [1, 2], with these communities exposed to some of the world's highest power prices [3–6]. Renewable energy source (RES) technologies are becoming increasingly relevant to these consumers, as they seek to not only lower their cost of energy, but also reduce the environmental emissions directly resultant from diesel fuel use [7, 8]. Power systems incorporating both conventional (thermal) and RES generation are termed hybrid power systems (HPS's). Unfortunately while RES technologies can offer cost competitive supply alternatives, their output is unpredictable, and at high levels of RES penetration a potential conflict arises. As RES penetration increases within a HPS, diesel generators constrain RES utilization, unable to lower their output below minimum load settings. These load set points are predetermined to ensure engine efficiency and preserve engine condition. Under high RES penetration, diesel load set points produce surplus generation, which must be absorbed via regulating devices such as dump loads or energy storages systems. Hence systems configured for high RES penetration currently involve increased complexity, expense and waste. Regardless of approach, it is not currently feasible to totally eliminate diesel generation within a HPS. Instead, minimal diesel usage is targeted.

Ancillary technologies available to increase RES penetration include battery, flywheel, dump load and demand management systems. All technologies require significant investment, increasing the possible RES penetration, but also increasing the HPS complexity. Improved access to RES technologies requires architectures offering minimal diesel and ancillary reliance. A key challenge in reducing the dependence on such technologies remains the performance of existing diesel generators, specifically their inability to run sustained at low loads [9, 10].

This chapter presents one approach to achieve a cost optimized level of RES penetration within a HPS. One which provides much of the benefit associated with prior ancillary approaches, yet at a fraction of the expense. Low load diesel is the ability to run diesel infrastructure below legacy load limits, for the acceptance of additional RES contribution. The chapter commences with discussion of the historical context and relevance of diesel generation, before introducing consideration for both the diesel fuel and emissions compliance aspects. The opportunities and challenges for diesel generation within islanded countries are then presented, ahead of recent developments within advanced diesel technology and control. Operational theory is briefly discussed, before model development and case study methodologies, both adopted to determine the impact of hybrid diesel power system performance under low load diesel application. Given consideration of the economies of low load diesel, the chapter concludes, finding low load diesel application to offer a viable, low cost, low complexity pathway to improved RES utilization.

2 Historical Diesel Perspectives

Rudolf Diesel invented the compression ignition engine in 1892, and since then our understanding, utilization and demand for the internal combustion engine has continued to grow and evolve within our environment. Diesel's first engine found little commercial application; it was not until he replaced the conventional fuel of the day, coal, with a by-product from the recent crude oil boom, that he developed a successful prototype engine. Today, both engine and fuel bear his name, having found application extensively across the transport (automotive, trucking, marine and rail), industrial and mining sectors. Stationary power generation remains only a small subset of this wider diesel engine market. This statement contrast dramatically with the prevalence of the diesel generator within islanded networks, by both installed capacity and total annual generation, diesel remains the largest energy supplier to islanded consumers globally [4, 11]. Diesel generation is accordingly critical for islanded communities, yet represents only a small percentage of any diesel suppliers' order book. It is primarily for this reason, that diesel technology research and development has failed to prioritise stationary power generation applications over the past decade. This is not to say that modern diesel technological and control advances have not been significant, it is simply to point out that they have not been progressed to address any perceived consumer need within islanded power systems. Modern technological and control advances have in reality, been driven by efficiency and compliance initiatives targeting the larger transport and industrial markets, with this technology filtering down into stationary power generation product lines via the economies of generic/commoditised engine platforms (shared engine platforms across markets). The distinction is subtle; however, the resultant technology pass-through presents significant opportunity for islanded networks, should they explore the full range of modern diesel generator capabilities.

How has the diesel generator risen to such prominence within islanded networks? For one very telling reason, the ease and availability of equipment, fuel and technical expertise. Diesel generator and fuel supply networks are well established to practically every corner of the globe [12]. Diesel generators power Antarctic expeditions as readily as they supply nomadic desert tribes, with little need to deviate from stock standard engine architectures. Diesel generation has been demonstrated in such remote applications for decades, representing a low risk supply approach. Indeed given both the geographic isolation and entrenched operational practices, diesel generators have, in many instances, been seen as the only generation options for islanded communities. Add the short lead times and small capital investment, and you can appreciate why diesel generation now represents the majority of existing and planned generation to islanded consumers [13]. Unfortunately, some significant downsides are associated with large-scale adoption of diesel generators for energy supply, principally diesel price volatility and diesel fuel emissions [14].

3 Diesel Fuel

Consideration of diesel fuel characteristics is always relevant in consideration of diesel generator performance, given the ability to bias performance comparisons via the introduction of non-standard fuel or atmospheric conditions (one reason for diesel test standards). Diesel fuel also represents the largest single contributor to the levelized cost of diesel electricity within islanded countries [15]. Thus, some familiarity of diesel fuel standards and test conventions is essential for the engineer in assessing the role of diesel generation within any power system. The term diesel fuel can refer to any fuel used within a compression ignition engine, however commonly refers to fuels refined for commercial vehicle use (ASTM International grade 2-D for the United States). Importantly such classification and standards set defined limits for the viscosity, volatility, cleanliness, density, acidity, low temperature performance, stability and heating value for various grades of diesel fuel. Such parameters are relevant to the operation of islanded diesel fired generation given their impact on the operability, reliability, cost and cleanliness of the resultant energy provision. Viscosity, the resistance to flow, is critical to successful lubrication where the fuel itself provides a barrier to opposing surfaces. For diesel fired generation this characteristic impacts fuel pump and injector performance, with both components at least partially dependent on the fuel for lubrication. Importantly, fuel cleanliness is also key to successful lubrication, with both inorganic components and organic acids responsible for abrasive and corrosive engine wear at certain levels.

Low temperature operability involves the solidification of wax components under certain temperatures, with the potential to gel the fuel. The quality of fuel available for islanded generation thus has an appreciable impact on engine performance, with any change to fuel quality likely to impact system performance [16]. Such considerations are most commonly encountered when biodiesel blending is contemplated. Biodiesel is the synthesis of vegetable or animal-based diesel fuel, as opposed to a fractional distillate of crude oil. Biodiesel blending, as the name suggests, involves the addition of biodiesel to crude based diesel products, and is considered further, separately in this chapter. Biodiesel blending represents a common approach to reduce diesel emissions, and while the potential to reduce the environmental impact of diesel generation exists, the quality of the fuel must be accessed to fully appreciate the engine and emission impacts.

Diesel fuel comprises of thousands of individual hydrocarbon components, most of which have a carbon number between 10 and 20, as shown in Fig. 1. Most commonly these compounds represent hydrocarbons from the paraffinic, iso-paraffinic, naphthenic or aromatic classes [17]. The impact of hydrocarbon class to fuel properties is summarized in Table 1.

The cetane number of a diesel fuel represents a measure of the combustion speed and ignition quality. It is an inverse of the octane rating, similarly used to define gasoline (petrol) fuel auto ignition tendency. The higher the cetane number, the superior the fuel quality.

Fuel density is conventionally represented as kg/m^3 or g/cm^3, representing the mass per unit volume of the fuel. Relatively density, sometimes referred to as specific gravity, is defined as the ratio of fuel density to the density of water at a reference temperature. Another common measure for fuel density used in the United States is API gravity, expressed as degrees API, Eq. 1 [18].

$$\mathrm{API}^0 = \left(\frac{141.5}{\text{relative density}}\right) - 131.5 \tag{1}$$

The heating value of fuel is the heat energy released upon ignition as represented adopting either a mass or volumetric basis. To convert between one to the other, the density of the fuel is used. Common values for both density and net heating value are shown in Table 2. The heating value of petroleum fuels can be estimated via Eq. 2 [18].

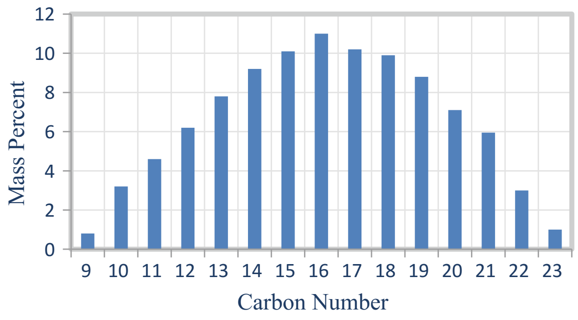

Fig. 1 Diesel fuel generic carbon distribution. *Source* Chevron 2007 [17]

Table 1 Hydrocarbon class fuel performance properties

Fuel property	n-Paraffin	Isoparaffin	Naphthene	Aromatic
Cetane number	++	+/0	+/0	0/−
Low temperature operability	−	+/0	+	+
Heating Value	−	−	0	+

+ positive or beneficial impact on fuel
0 neutral or minimal impact on fuel
− negative or detrimental impact on fuel
Source DieselNet 2013 [18]

Table 2 Density and net heating value of different fuels

Fuel	Density(15 °C) g/cm^3	Net heating value			
		MJ/kg	Btu/lb	MJ/m^3	Btu/gal
Gasoline	0.735	43.33	18,630	31,830	114,200
Premium gasoline	0.755	42.89	18,440	32,390	116,200
Jet fuel	0.795	42.85	18,420	34,060	122,200
Diesel fuel	0.850	42.64	18,330	36,240	130,000

Source DieselNet 2013 [18]

$$\text{Net Heating (MJ/kg)} = \left(46.423 - 8.972\rho^2 + 3.170\rho\right)(1 - (x + y + z)) + 9.420z - 2.499x \quad (2)$$

where

ρ represent the fuel density in g/cm^3 at 15 °C,
x represents the mass fraction of water,
y represents the mass fraction of ash,
z represents the mass fraction of sulfur.

4 Emissions Compliance

Intuitively, the engineer understands the link between engine load and temperature, a heavily loaded engine becoming hot in a very short time. From an emissions perspective, any change in engine and thus exhaust temperature, has a significant impact on exhaust emissions. In part such emissions performance is representative of combustion efficiency, however, thermal deactivation of the after treatment catalysts can also play a significant role. Hybrid diesel architectures place additional requirements on the way diesel engines are loaded and operate, and in doing so, detrimentally impact the emissions performance of the system.

Until recently, emissions compliance was approached via engine redesign, largely targeting combustion refinement. Engines have simply been made more efficient to meet prescribed targets. However, with increasingly stringent emissions limits, the rate of technology development is proving insufficient to deliver the required performance. Engine manufacturers are in addition to efficiency improvement, increasingly forced to adopt post combustion emissions treatment. As a result, most new diesel engines sold into regulated markets, now offer some form of advanced exhaust after treatment. Discussion on this topic is particularly relevant to systems targeting high RES penetration, given the temperature critical nature of many exhaust after treatment approaches (chemical treatments/catalytic reactions, for example), and the notable impact high RES penetration has on engine loading and thus exhaust temperatures.

Diesel engines, as with all combustion engines, produce an exhaust stream, expelling unwanted by products via the combustion process. Under ideal combustion conditions, these emissions would consist of carbon dioxide (CO_2), water vapour (H_2O) and unreacted air charge, Nitrogen (N_2) and Oxygen (O_2). Unfortunately, ideal combustion conditions are almost impossible to recreate, given the complexities of the process, and as such additional pollutants are also exhausted to atmosphere. These pollutants result from any combination of unburnt fuel, the presence of foreign substances (lubrication oil or particles of engine wear), catalytic reactions, or any combination of reactive components exposed to the high temperature and pressures resultant in the cylinder during combustion. Common pollutants include carbon monoxide (CO), various hydrocarbons (H_mC_n), nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM) [19]. It is even possible for exhaust after treatment system to contribute additional components to the exhaust profile, thus any change in engine duty cycle, fuel, control or environment needs to consider the possibility of emission variation and non-compliance.

Diesel emissions become a problem when the unwanted exhaust gases or pollutants exceed threshold quantities. One complexity of exhaust emissions compliance remains the different engine processes responsible for different pollution types. A risk to any engine modification program remains the possibility that measures successful in addressing one specific emission parameter, subsequently impact/increase the levels of other pollutants. A co-ordinated emissions compliance approach is thus a complex undertaking. In addition, increased attention is now being paid to particulate size, with various adverse health impacts linked to not only the type and volume of pollutant, but also the particle sizing. One common approach to classification of diesel exhaust particle matter defines particulates less the 10µm according aerodynamic diameter as follows (diameter of 1 g/cm^3 sphere) [20];

- *PM_{10}*—particles less than 10µm (typically material originating from engine wear)
- *Fine*—particles less than 2.5 µm
- *Ultrafine*—particles less than 0.1 µm (typically heavier hydrocarbons)
- *Nano*—particles less than 0.05 µm (typically lighter hydrocarbons).

A typical PM size distribution is presented in Fig. 2 with two distributions, by number and by mass provided. Of relevance, the reader should note the high percentage of PM content within the nanoparticle range. PM exhaust emissions are thus characterized by a large number of very small, very light particles. These particles are so light that they have essentially no appreciable impact on the total mass of PM, with the tendency to beoverlooked. The distinction is important given increasing concern over the health impacts of small particle exposure (particles which penetrate deeper into organic tissue given their size), with modern engines performance standards evolving to address PM emission by both number and mass.

Carbon dioxide (CO_2) contributes the largest relative concentration of all such pollutant exhaust gases, principally given its role within the ideal combustion cycle; unfortunately, it is also a key contributor to human induced climate change, with

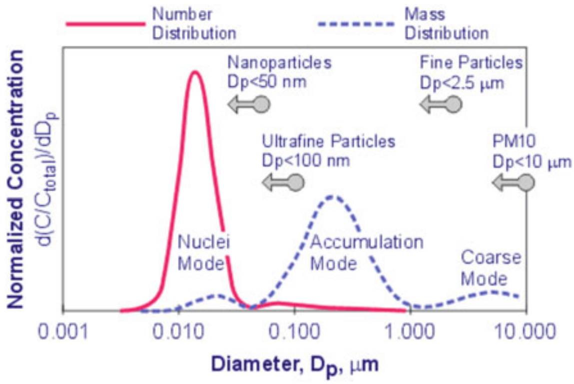

Fig. 2 Diesel particulate size distributions. *Source* DieselNet 2013 [20]

recent increases in the atmospheric levels of CO_2 known to play a role in the adverse warming of the earth's climate. CO_2 emissions are directly correlated to an engine's fuel consumption, and thus improvements in engine fuel efficiency directly result in reduced CO_2 emissions.

Carbon monoxide (CO) is a colourless, odourless gas, which becomes flammable at high concentrations. CO emissions from diesel engines typically range from 10 to 500 ppm [21], although exceedance of these limits can occur during engine transients. The oxidation of CO with O_2 over certain catalysts can release a significant amount of heat, resulting in possible thermal deterioration of various emissions after treatment technologies.

Hydrocarbons (H_nC_m) and particulate matter largely result from unburnt fuel and lubrication oil, with the latter effectively controlled with exhaust particulate filters. The generic formula for hydrocarbons represents n atoms of hydrogen with m atoms of carbon. Hydrocarbon gases may exhibit an irritating odour, and can be carcinogenic. Concentrations of hydrocarbons in diesel exhaust typically range from 20 to 300 ppm [21].

Nitrogen oxides (NO_x) principally consist of Nitric oxide (NO), and Nitrogen dioxide (NO_2), both poisonous and highly reactive gases. Concentrations of NO_x within diesel exhaust emissions are typically between 50 and 1000 ppm [21]. While NO is a colourless, odourless gas, NO_2 is a red/brown gas of unpleasant odour. NO_x have been identified as principal agent in the formation of ozone (smog) on hot summer days. As NO_x formation remains temperature dependent, one effective way to reduce NO_x formation is to lower the cylinder temperature. Selective catalytic reduction (SCR) of NO_x with urea has also proved highly effective at controlling NO_x emissions [22].

Sulphur oxides (SO_x), SO_2 and SO_3 generally originate from sulphur present in diesel fuel and lubricating oils, as a result efforts to limit sulphur oxides have involved the development of low sulphur and sulphur free fuels. For low sulphur fuels, lubrication oil consumption can start to present as a major source of SO_x emissions.

Measurement of diesel exhaust emissions are typically performed on a dynamometer test stand, with the dynamometer responsible for providing resistance to the engine torque via mechanical or electric resistance, Fig. 3. Pollution is typically recorded as grams of pollutant released per kWh of mechanical energy. It is important to note the destination between mechanical and electrical energy, for a diesel generator, engine mechanical output is always higher than the generator's electrical output (considering for losses in the generator). Engine manufacturers will typically use kWh mechanical (kWh_m) as a metric for fuel consumption and emissions reporting, with the reader required to confirm a similar measurement basis for any two test reports prior to comparison. The engine is run through a predetermined test cycle representative of real life operation. It is typical for high ramp rate events, common within a hybrid diesel system under high RES penetration, to represent a large share of any averaged emissions contribution, despite these events representing only a small percentage of total operating hours. Exhaust gas is typically collected by the sampling instrument, Fig. 4, prepared for analysis (including dilution and chilling) and analyzed using any one of electrochemical, infra-red or magnetic response.

Commercially available exhaust gas emissions sensors conveniently package multiple analysis technologies into a single unit, with the user able to operate the instrument without knowledge of the underlying principal. In this regard, emissions performance testing is simplified, however the operator should be aware of the specific instrument accuracy, sampling and response times as these are often insufficient to capture transient response. PM emissions are treated separately from gases exhaust emissions, with analysis typically using either opacity (optical) or

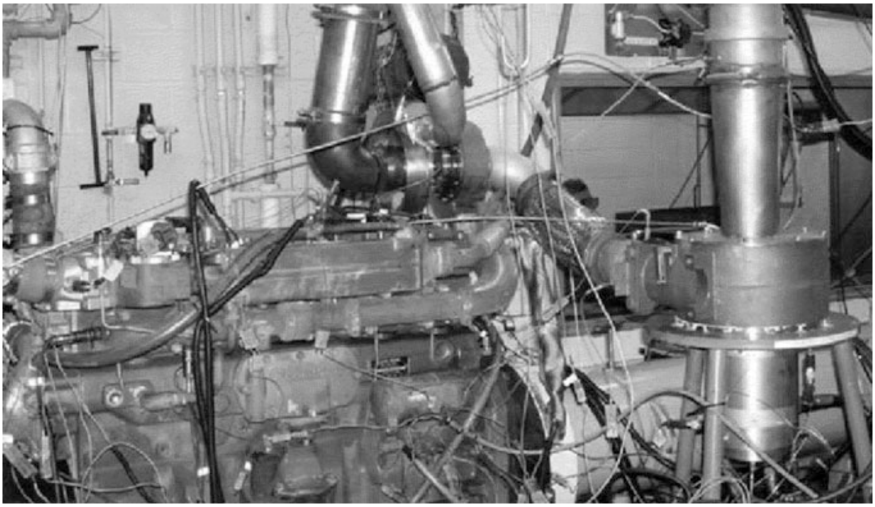

Fig. 3 Diesel engine test bed. *Source* John Deere 2005 [23]

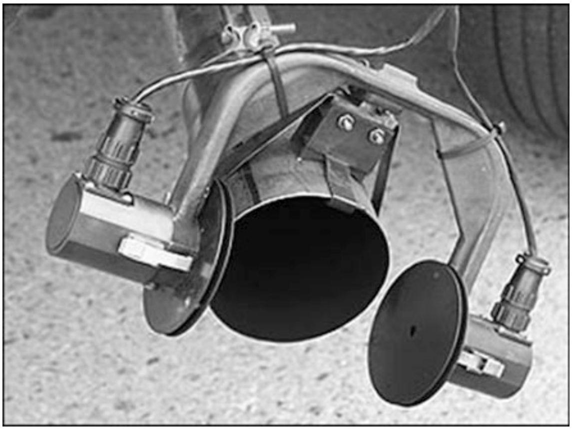

Fig. 4 Exhaust emissions measurement equipment. *Source* DieselNet [24]

gravimetric (weight) assessment of deposited particles to determine the PM mass. Under both of these approaches, comparison across tests can be poor unless the methodology is standardized, hence PM measurements are notoriously hard to correlate across dissimilar test and of most benefit in determining relative variations.

Diesel particulate filters are the most common and cost effective form of post exhaust solid phase emissions treatment, consisting simply of a particulate trap. The filter screens the exhaust flow utilizing a number of possible filtration mechanisms to remove particles from the exhaust stream. Such particles are primarily carbon soot, with the volume of soot sufficient to obstruct flow through the filter in as little as a few hours of operation. Diesel particulate filters subsequently use filter regeneration techniques to extend the service life of the filter indefinitely. In principal, these techniques allow for the supply of heat and air to the embodied carbon for the promotion of oxidation to gaseous CO_2.

Emissions control catalysts are the most common and cost effective form of post exhaust gas phase emissions treatment, consisting simply of passive catalyst system through which the exhaust gas is diverted. Catalytic converters typically adopt a noble metal as the active catalyst, such as platinum (Pt), palladium (Pd) or rhodium (Rh). Diesel oxidation catalysts have been used successfully to control CO, H_mC_n, and organic PM via oxidation of these exhaust gas compounds. Unfortunately, oxidation is also the mechanism for SO_x reaction to sulphuric acid H_2SO_4. Diesel oxidation catalysts are generally not effective at oxidation of NO_x emissions, with SCR catalysts generally adopted for this task. Another disadvantage of this approach is the temperature dependent performance of many catalysts, with reaction conversions increasing with temperature. Accordingly, function at light load and low temperature can present some problems for catalytic conversion systems, Fig. 5. A potential solution to light load applications has been the use of element absorbers to store emission contaminants (washcoat storage), until higher engine

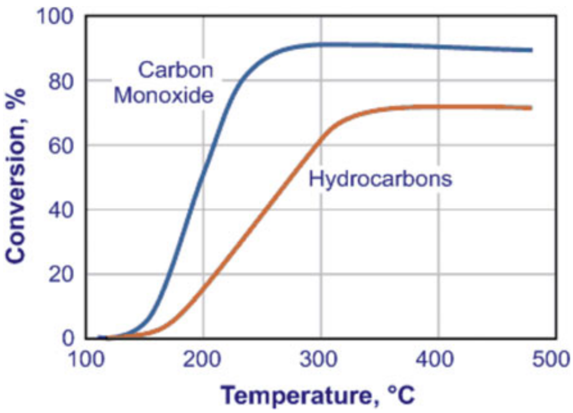

Fig. 5 CO and HC conversion in diesel oxidation catalyst. *Source* DieselNet [25]

loading provides more favourable catalytic temperatures, this approach however also adds further complexity to the emissions process.

The engineer charged with RES integration can start to appreciate the complexities of emissions compliance in addition to the integration and control requirements of any hybrid diesel architecture. In support of this goal, the significant reduction in total kWh generated via diesel supply can be used to demonstrate significant net environmental and health improvements, however should per kWh emissions performance exceed acceptable limits, modification to the after treatment system may be required.

5 Islanded Markets, Challenges and Opportunities

The preceding discussion could quickly lead the reader to form an overwhelming negative view towards existing diesel generation, however in moderation, existing diesel generation presents islanded communities with a supportive platform from which to advance RES integration. Admittedly, diesel fuel is expensive, both as a commodity and considering the environmental impact associated with its extraction, refinement, transportation, storage and eventual consumption [27]. Diesel fuel is however, in amble supply and can safely be stored, providing energy reserves for systems looking to stabilize a stochastic renewable energy supply. The challenge for many islanded countries is thus to, as far as possible, minimize diesel generation, via the introduction of alternative generation, and to limit diesel utilization to the provision of essential services, those unavailable from commercial RES's. The opportunity remains to transition diesel from a base load energy source to an energy storage source, and in doing so provide islanded communities with a pathway to reduced diesel reliance.

Estimates as to the global market capacity of installed diesel generators is in the order of 1000 GW, and growing, to meet the needs of emerging economies and communities hungry for electrification. This market serves among other communities the more than 10,000 inhabited islands around the world, home to an estimated 750 million islanders [28]. Within Asia, Indonesia itself claims over 1000 habited islands, with a national policy in place to achieve 70–90% electrification over the coming years. The state-owned electricity company, PNL, has an ambitious "1000 islands" program to deliver solar diesel hybrid systems across their portfolio. Within the Pacific Islands and Territories, a community exceeding some 3000 islands, major population centers rely almost exclusively on diesel generation, while at the same time facing the worlds' highest fuel costs [6]. Given a global push for increased electrification, growth in islanded consumption and reducing RES costs, these communities are increasingly turning to RES technologies to provide for their future energy needs. Acknowledgeing that 97% of these communities currently rely exclusively on diesel generation, there is both urgent and expansive opportunity to implement renewable energy systems into this market.

Case studies reviewing the cost of diesel fired generation across the pacific quantify the cost of diesel based electricity supply as between $300 and $400 US per MWh. A similar review of off-grid diesel fired generation costs for mining operations across Australia is presented in Fig. 6. It can be readily appreciated that for both wind and solar technologies returning a cost of generation under $200 US MWh, there exists amble scope for RES integration into these diesel systems. Modelling across the same pacific case studies referenced earlier concluding cost savings of between 12 and 16%, with PV generation contributing between 30 and 40% of the total island generation [5].

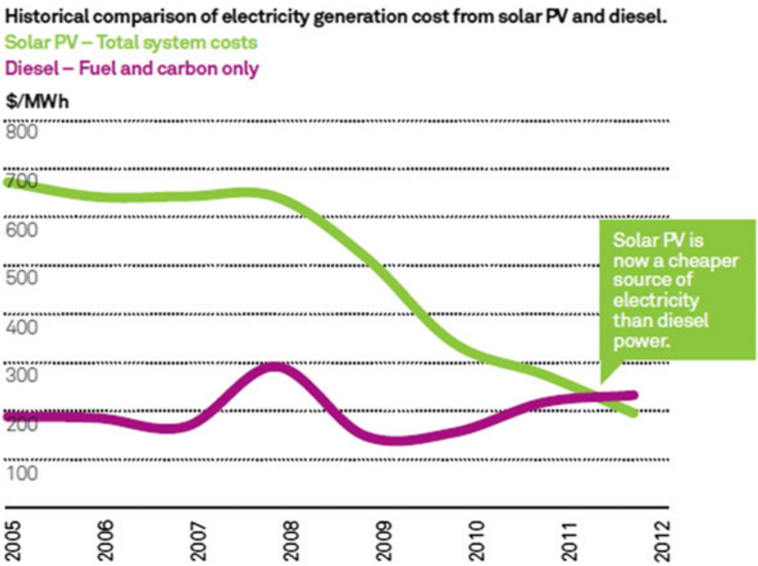

Fig. 6 Solar PV versus diesel generation cost comparison. *Source* AECOM 2012 [26]

While economic and environmental justification for RES integration appears straight forward, there are a number of issues to address. First the economic reality is never clear cut, with the true cost of diesel generation very rarely passed directly onto the consumer. Various government rebates, market subsidy's and tariff structures typically discount the cost of diesel fired generation to remote consumer [29]. The rational for such intervention is often well intentioned, to promote electrification to remote communities and to ensure affordable and accessible electrical supply, however, barriers to renewable integration are introduced, with no single entity able to appreciate the true pass-through cost of diesel generation. Second, diesel generation is most likely the established fuel source to the community, with diesel fuel well established within the commerce and customs of the community. Accordingly, those parties financially dependent on its continued prosperity stand to oppose RES integration. The RES developer is often wise to understand these existing commerce flows prior to finalizing the structure of any project, with one solution to share financial gains widely across the community to foster improved social license.

Unfortunately, the environmental argument is equally complex, with available land and land tenure often impacting RES deployment. A number of RES technologies can require a substantial footprint, as compared to a conventional diesel power station. Whether the proposed development impacts agricultural land, fisheries or possibly airspace, these resources are often limited and high prized within islanded countries, requiring the design and approvals process to carefully manage such considerations. Equally, the ownership model of these resources may involve multiple parties, or even entire villages, with lease and access agreements often difficult to secure in such instances. One solution to these concerns maybe to incorporate RES technologies into community assets, for which the community receives direct value, say in the case of elevating solar PV panels to provide accessible shade and vehicle parking at a community venue.

Technological barriers exist for RES integration given the added complexity additional generators impose into the network. In addition to scheduling and co-ordinating, these additional sources with legacy generation to meet demand, operators have to understand the safe levels of RES penetration given system stability requirements and the inability of common RES designs to allow for reactive power provision and islanded operation. Cultural barriers exist given the significant opposition many communities can have to new and unfamiliar power generation. The systems can be seen as complex, hard to operate and maintain, and unreliable, given human tendency to first blame new and unfamiliar change for any disruption, regardless of the actual fault condition. Many of these barriers are genuine issues for islanded communities. With little established RES expertise available, the operations and maintenance can appear overly complex. Historical development models, reliant on external aid funding and expertise to develop RES projects, do little to establish local ownership and expertise for the asset once the project is operational.

6 Hybrid Diesel Architectures

Off-grid hybrid systems are built to service communities unable to connect to conventional network electricity supply, offering these consumers a comparable level of service and reliability. As we have seen, the majority of these systems adopt diesel generation for their energy supply, however with an increasing justification for RES use, many islanded countries have transitioned to a hybrid diesel architecture. A hybrid diesel architecture is one using both diesel and renewable generation sources. The advantage of this approach is its ability to extract benefit from each generation source, mitigating the downsides inherent to either technology in isolation. Diesel generation is polluting and reliant on an available and affordable diesel supply. Renewable generation is highly variable, with the power system operator left with little control as to when and how much renewable generation will be available to consumers. Hybrid diesel systems use diesel generation to provide system stability and reliability, while integrating RES technologies to reduce emissions and reduce generation costs. As such the approach mitigates many of the risks inherent with RES reliance. The diesel generation system and infrastructure remain in place and available should the operator need to restore historical performance levels, with additional generation sources iteratively introduced to the system as familiarity and confidence regarding their performance is established. Hybrid diesel systems currently represent the default approach for any system upgrade or redevelopment.

Which RES to adopt within a hybrid diesel system is always a site specific consideration. Multiple RES technologies have been presented within this text, with the developer afforded an apparent wide array of possible technologies. In reality almost all systems currently use either wind, solar PV or both, as the mainstay of their renewable portfolio. The reason for the dominance of these two technologies is simply a matter of cost. Some considerations pertinent to either technology are presented below for completeness.

Wind is currently the most cost competitive renewable technology, subject to a suitable wind resource [30]. With the growth of the Chinese wind market, both as a consumer and supplier of technology, the industry has seen technology development move away from high wind speed platforms, to develop a range of moderate to low wind, large rotor solutions. This shift is reflective of the lower wind resource prevalent across much of mainland China, and indeed much of the rest of the world. Accordingly, there is now more choice in wind turbine technology than ever before. Key considerations for islanded countries contemplating RES suitability should not overlook transportation and erection issues. Wind turbine blades alone can span in excess of 70 m. Complex vehicle access can quickly rule out use of such a large rotor, while availability of lifting solutions to install tall tower wind turbines can equally become prohibitive if a crane with sufficient boom extension is not available regionally. Additionally with these large rotor platforms, rated to multi-MW output, the turbines may simply be too large for the local demand. Consideration of multiple smaller platforms may improve the purchasing position of the developer, with more prospective suppliers interested, however in response a larger number of suitable sites need to be available for development. Sites closer than 1000 m to occupied residences are typically avoided given the potential for audible noise pollution. Finally, wind development needs to consider the site extreme wind speed risk, with many cyclonic regions unsuitable for conventional wind technologies. Custom tilt-down, tilt-up solutions are available to mitigate this risk, but unfortunately limit the developer's technology choice, as few suppliers offer commercial products with this capability.

Solar is increasingly becoming the default option for hybrid diesel integration, while the systems return a higher cost of energy in comparison to wind developments, they have many attractive advantages. Of immediate note solar developments do not require an extensive site resource evaluation. Whereas for a wind project a minimum of 12 months of measured hub height wind data is required to select the appropriate technology and prepare a business case, solar PV projects can be commenced with little to no site monitoring. This ability allows solar projects to commence with substantially less delay and cost in comparison to a wind project. Solar also scales to practically any capacity the consumer may require, simply by adding or subtracting panels. This modular functionality allows solar to be distributed across a network, say on residential rooftops, or centrally located at a large solar farm, one downside to the latter being the large area required for solar projects, typically in the order of 6 acres per MW of installed capacity [31]. Solar is also incapable of providing network frequency and voltage support without inclusion of grid forming inverter technology. Regardless of the RES preference the possible renewable penetration, and thus the effectiveness of the hybrid architecture is significantly influence by the type, control and co-ordination of the generation sources, as discussed further in the next section.

Ancillary technologies commonly integrated within hybrid diesel systems include energy dissipation (dump load, co-generation, tri-generation) and energy storage (battery, flywheel) systems. Energy dissipation systems are essentially used to allow the generation to exceed demand, with the excess generation diverted to serve an artificial (dump load) or supplementary (co-gen, tri-gen) loads. Fast acting demand management of these loads can be used effectively to provide frequency response and control within an islanded power system. For example should the system encounter a dip in renewable output, instead of requiring a response from the online diesel generation, such ancillary loads can simply be curtailed to maintain the supply and demand balance. While dump loads are fairly cost effective, consisting essentially of paired dynamic resistors, the resultant energy throughput serves no useful function. For the higher complexity and higher cost co-gen and tri-gen applications, where waste heat is used to support a heating or cooling application respectively, much of this available heat (up to 70% of the fuels available thermal energy, of which almost half is recoverable) can serve a practical need within the community. Finally energy storage technologies are now available, facilitating storage of the energy for use within the system at a future time. The benefit of storage approaches is enormous, able to extend RES integration to meet

100% of an island countries demand. Unfortunately, such systems are currently cost prohibitive, with standard hybrid diesel architectures preferring to adopting a dump load capability to rationalize required system investment [13].

7 Advanced Diesel Technologies and Control

Advanced diesel technologies and control entail a range of approaches available within a hybrid diesel architecture to achieve cost optimized renewable penetrations. In other words, how to get the greatest value from any renewable capacity available within a hybrid diesel system. Correct selection and control of your generation sources is key to the effective operation of a hybrid diesel system, and to this extent configuration and control is the primary metric impacting on the success of any RES development.

7.1 Low Load Diesel (LLD)

Diesel generator sets are commonly adopted for a variety of reasons, including equipment affordability, availability of fuel supply and access to engineering support. Unfortunately, conventional diesel generators need to operate heavily loaded to ensure efficient and reliable operation, a scenario which leaves limited scope for meaningful renewable generation. Thus, consumers become stranded between the need to run their diesels heavily loaded, to ensure efficient operation, and their increasing awareness of the adverse impacts of climate change, of particular relevance to many islanded communities.

A range of innovative renewable energy technologies are increasingly becoming both available and cost competitive with diesel generation [10]. A hybrid approach coupling renewable generation with diesel generation is rapidly becoming a default solution to both reduce fossil fuel reliance and the cost of energy. As renewable penetration increases within a hybrid diesel system a potential conflict arises, with the diesel generators unable to lower their output below a minimum operating set point. Such load set points are predetermined to ensure engine efficiency and preserve engine condition. Under high renewable penetration, diesel load set points produce surplus generation, which must be absorbed via regulating devices such as dump loads or energy storages systems. Hence, systems configured for high renewable penetration currently involve increased complexity, expense and waste.

Low load diesel technology offers one solution to minimizing surplus generation under high renewable energy penetration, adjusting the way legacy generators are used within an islanded power system. Conventionally, diesel is used for the majority of power supply, with only a small component of renewable generation possible. Under low load application, diesel use is more about energy storage, with diesel called upon to back up renewable generation, covering periods when renewable generation is unavailable. How effectively communities' transition from diesel to emerging energy storage technologies relies on a systems ability to maximize their current renewable penetration. Low load diesel technologies significantly reduce the cost of high penetrations of renewable energy into remote and off-grid power systems. Removing the barriers to low load diesel operation promises to deliver the lowest cost pathway to reduce remote community reliance on diesel generation. LLD capability is available to both legacy and new diesel generators.

To understand the emergence of low load diesel application, the engineer must understand historical resistance to the practice, particularly as many communities reliant on diesel for their energy maintain these perspectives. Historically, a number of operational issues have been associated with low load operation including wet stacking, slobbering, turbocharger sooting and cylinder glazing or honing [33]:

- Wet Stacking
  Wet stacking is a condition diagnosed via the observation of unburnt fuel condensing within the diesel engines exhaust (otherwise known as the engines "stack"). Wet stacking is essentially a result of low cylinder temperatures, and given the correlation between load and temperature it is easy to understand the connection between low loads and wet stacking. At low loads, insufficient fuel is delivered to the cylinder to maintain the optimal thermal equilibrium. In many cases, constant rate engine cooling can contribute to this thermal imbalance, with the introduction of variable load engine cooling an effective investment. As the cylinder temperature drops, heat is removed from the hot combustion gases at an increasing rate. As a diesel engine relies on these hot combustion gases to provide an optimal combustion environment, a heat deficient leads to incomplete combustion. The fuel condenses in both the exhaust stack, turbocharger and within the lube oil, while soot accumulates on injectors, pistons, cylinder liners. Fuel seepage commonly presents an aesthetic and safety issue. By far the largest engine impact results from soot build-up or carbonization of the engine components, Fig. 7.
  Wet stacking is a positive feedback process, with incomplete combustion further reducing combustion efficiency across subsequent cycles. Sooting of the injectors reduces the accuracy, timing and spray formation of fuel delivery into the cylinder, and subsequently also impacts the combustion efficiency. Injector sooting represents an issue of increasing concern for modern engines, with modern technologies increasingly reliant on precise injector timing and burst performance to meet efficiency and emissions targets, Fig. 8. It is now common practice to adopt multiple injectors per cylinder, with each injector synchronized to a multiple burst pre and post combustion injection schedule, requiring micro second precision.
- Oil Dilution
  Oil dilution results as a symptom of low cylinder temperature and pressure. We have previously discussed the development of low cylinder temperatures, and

Fig. 7 Wet stacking of a diesel engine. *Source* Clifford Power [32]

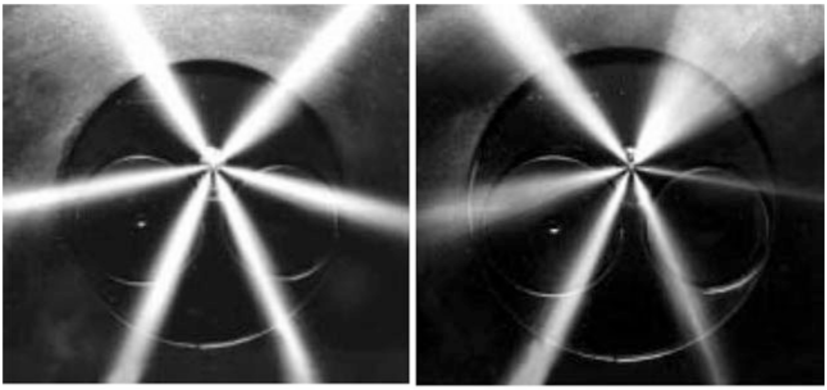

Fig. 8 Sooting of injectors and resultant spray disruption. *Source* Chevron 2007 [17]

equally, low pressures result from a combination of incomplete combustion and low air charge boost pressure. Air charge boost pressure being directly proportional to exhaust gas flow rates. Under these conditions the piston ring provides only a partial seal to the cylinder liner, with the resultant piston flutter leaving an excessive oil film against the cylinder walls. Oil which has subsequently mixed with fuel and returned to the engine sump exhibits modified properties as a result of additional contaminants, requiring more frequent oil replacement.

- Turbocharger Sooting
  At low loading exhaust volumes drop, to the extent that the turbocharger, Fig. 9, may idle. At idle the gaskets within the turbocharger are unable to maintain an effective seal, and oil passes through to the compressor. Oil ingress to the compressor, in addition to shooting of the turbo impeller blades, results in performance detrition, imbalance and possible turbo failure.
- White smoke
  White smoke is a direct symptom of low temperature combustion, with unburnt fuel leaving the exhaust stack as fuel vapour.
- Blow-by
  Blow-by refers to the phenomenon of exhaust gas blowing past the piston ring and into the crankcase. Some blow-by is unavoidable, however as blow-by increases so does the crank case pressure, placing additional strain on the crankcase seals and oil separator, leading to oil egress from the crankcase.

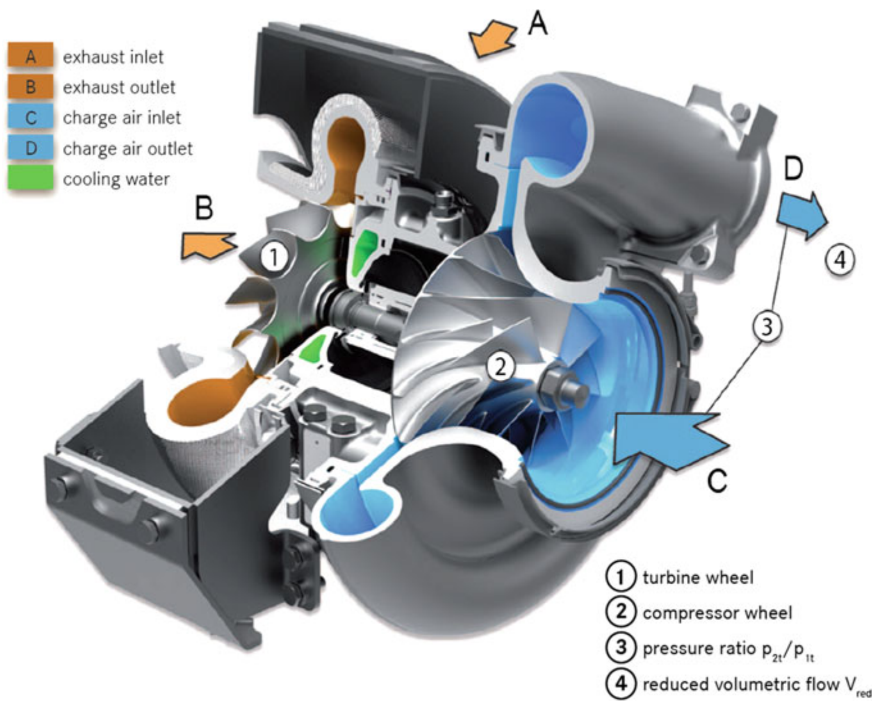

Fig. 9 Turbocharger geometry. *Source* MTU 2014 [34]

- Black smoke
  Black smoke is a direct symptom of low temperature combustion, with carbonized oil and fuel residue leaving the exhaust stack as black carbon particulate matter. Black smoke usually occurs following a period of low load operation, as the engine load is raised sufficiently to dislodge any carbon residue from the piston and cylinders. Most vehicle drivers are familiar with this phenomenon, having observation black exhaust smoke as a diesel truck accelerates. Upon application of the throttle, a thick cloud of black smoke is released to the annoyance of other motorists. While the black smoke presents health concerns, the emissions are beneficial to the engine, as they represents a purge of the engine's carbon accumulation. Black smoking is also only a short term phenomenon, lasting the period required to purge the carbon accumulation from the engine.
- Con rod bearing wear
  Varying cylinder pressures result in a non-uniform load profile across the con rod bearings. Excessive loading leads to increased bearing wear and reduced bearing life.
- Cylinder liner wear
  Cylinder wear can often be misunderstood, as a number of distinct wear mechanisms exist. Additionally, many engineers do not realize that modern engines require no run-in period. Running in an engine was historically required to remove slightly elevated ridges from the cylinder liners surface, effectively matching the piston ring and cylinder tolerances. As modern cylinder liners are produced with the required surface finish, they run efficiently off the shelf. The critical parameter under either scenario remains the surface finish of the liner. Too smooth, or too rough a surface and the liner has reduced capacity to hold the required oil film essential for lubrication. As mentioned, two distinct phenomena exist to reduce the surface roughness below optimal, bore glazing and bore polishing. Bore glazing occurs as fuel and oil derivatives coat the cylinder liner, flash burning to form a smooth glazed coating (similar in concept to glazing ceramics during kiln firing). If left too long without a purge cycle, cylinder glazing can require cylinder replacement or jeopardize the engine condition. Liner polishing is characterized by a mirror finish within the cylinder bore, indicative of local mechanical wear at that surface. The wear is often a result of oil contamination, leading to replacement of both the cylinder liner and oil, the later to restore the correct lubrication characteristics.
- Piston ring carbonization
  Accumulation of carbon on the piston ring can result in polishing. Carbonization results from the same low load mechanism described above, however in this instance a high risk of piston seizure exists.

Thankfully a number of technologies and approaches exist to mitigate the issues historically preventing low load application of diesel generator sets. Essentially, they all seek to improve the thermal characterisation of the engine, with a number of technologies discussed further below.

7.2 Load Variable Cooling

Stationary power diesel generator sets commonly adopt a geared fixed speed cooling fan. If the engine is running the fan is on. Not only is this inefficient, it restricts low load capability given unnecessary air movement and some degree of convective cooling of the engine. Load variable cooling is one easy approach to improve both efficiency and low load diesel capability.

Heat transfer to the coolant system represents between one quarter and one third of the total combustion energy for a conventional diesel engine [35]. This number may surprise some readers, with a substantial amount of heat flowing from the engine. Under normal operation this is actually the purpose of the cooling system, to extract excess heat from the engine to ensure the function and condition of the engine components. With increasing adoption of low load operation (that of increased RES utilization), the thermal proposition is somewhat reversed, requiring the retention of thermal inertia within the engine block (while a similar requirement exists during startup, startup remains a short duration application, whereas low load operation is not). Thermostatic valves are commonly employed to bypass the flow of cooling fluid during startup and low load operation, however as stated, the coolant fans typically remain on. Parasitic loss for cooling fan operation is typically within the order to 2–3% of the engines rated mechanical output. Load variable cooling introduces opportunity to reduce much of this parasitic loss, by as much as 80% [35], typically via the introduction of a hydrostatic or variable speed fan drive. In addition to load variable cooling, redesign of the cooling system for low load application introduces opportunity to incorporate heat recovery mechanisms into the cooling circuit. Such heat recovery systems are common for combined heat and power applications, where the waste thermal energy is used to supply a heat load in parallel (co-generation). Under a load variable cooling application, this same heat energy is efficiently stored within the system to serve as a thermal source when benefit exists in elevated water jacket temperatures. The concept has found limited commercial application, principally via the integration of a dump load element into the engines water jacket, allowing for additional heat to be made available to the diesel engine during periods of high renewable penetration (and consequently low diesel loading). The benefit of which being higher permitted RES utilization via reduced low load level operation and improved diesel engine ramp rate (transient) response characteristics. Cold engine performance is known to delay transient response by 50–100% subject to ramp rate requirements. While variable load cooling has been observed to increase fuel efficiencies by up to 16%.

7.3 Multi-burst Common Rail Injection

While modern diesel engines are essentially all direct injected, injector capability varies significantly across platforms and suppliers. Common rail injection, supported by electronic governor control is essential to ensure the required injector capability, that of accurate metering combined with fast response. Injector research and development has also seen a move to higher and higher injection pressures, primarily to improve fuel delivery and spray formation, a key driver of combustion efficiency. Significant injector development and refinement is ongoing, with advanced materials being incorporated to further improve response times and flow control (for example direct acting piezoelectric injectors are able to provide flow rate shaping via control of the charge stored in the piezoelectric stack). To this extent injection systems now commonly represent over 30% of the entire engines production costs.

Fortunately or not, refinement of inject performance is outside of the control permitted for most diesel operators. However it is imperative in selecting a diesel generating set that the engineer be aware of the injector options given the tuned combustion staging available across a range of load profiles with improved injector control and response.

7.4 Variable Injection Nozzle Geometry

Injector nozzle geometry is typically optimized for conventional loading applications, with variable injector nozzle geometry one recent development, providing the ability to customize nozzle geometry for low load applications. The ability to reduce nozzle geometry at low loads extends to superior fuel delivery pressures, better spray penetration and formation and improved combustion efficiency. Variable injector nozzle geometries are typically achieved via multiple injection holes, with the injector able to select across ports to suit the loading condition.

7.5 Cylinder Switching/Deactivation

Cylinder deactivation, also known as variable displacement, is used effectively to reduce fuel consumption and emissions under low load operation. The principal involves turning off an even number of cylinders during low load operation to allow for a higher fuel and air loading across the remaining cylinders. Cylinder deactivation is achieved by keeping the inlet valves, and in some cases also the exhaust valves closed, while deactivating the injectors to those same cylinders. Deactivated cylinders reduce the air consumption across the air charge system, reducing pumping loses and allowing for higher cylinder pressures across all remaining active cylinders. The resultant deactive cylinders act as an "air spring" further improving the mechanical efficiency of the engine. As the engines mechanical output remains fixed, simply with fewer cylinders to supply the required torque, fuel loading increases to simulate proportionally higher loaded operation. A number of deactivation combinations are possible to any engine, with the ratio of deactive cylinders proportional to the de-rated capacity of the engine.

For example, an eight cylinder engine rated at 400 kW, deactivated to four cylinders, would be capable of delivering an adjusted 200 kW. The benefit being this load state now represents a higher cylinder loading and therefore efficiency, than that available when the entire engine was active. It is vital that the engine manufacturer select the configuration of cylinders to ensure balanced engine operation under any available state, however this is easily achieved for large displacement multi-cylinder engines. The benefits of cylinder deactivation also extend to exhaust emissions given the temperature dependent nature of much of the pollutant formation.

7.6 Turbocharging

Turbocharging has proven to be so successful in extracting additional energy from the diesel engines exhaust stream that there exists a myriad of different turbocharger designs and applications. One reason for this range of application is that turbochargers have proven to be very effective at achieving peak boost pressures, or operating effectively over a range of speeds, but not both. To recapture some of the engines exhausted energy, as much as 25% of the engines total output, turbochargers exist.

In principal, a turbocharger consists of an exhaust gas turbine rigidly coupled to a compressor turbine. As the exhaust turbine spins in the high velocity exhaust gas stream, it drives the compressor turbine, which in turn provides compressed air to boost air charge density available to the engines cylinders, Fig. 10. Some issues exist with turbocharger performance, principally turbo lag and low load/low exhaust flow performance. Turbo lag represents a time delay post engine governor response, as the exhaust side turbo waits for increased exhaust flow to become available downstream of the cylinders. Of note these conditions have historically been a deterrent to the use of highly turbo reliant [high brake mean effective pressure (BMEP)] diesel engines, however thankfully a number of approaches exist to improve these characteristics. Principally approaches to improve low load turbo performance entail addition of multiple turbocharger elements to limit reliance on a single stage turbocharger, including those discussed below;

- *Superchargers* are any application used to boost air charge pressure, in much the same way as a turbocharger, only without the reliance on exhaust flow. Typically superchargers are engine driven pumps or compressors, although

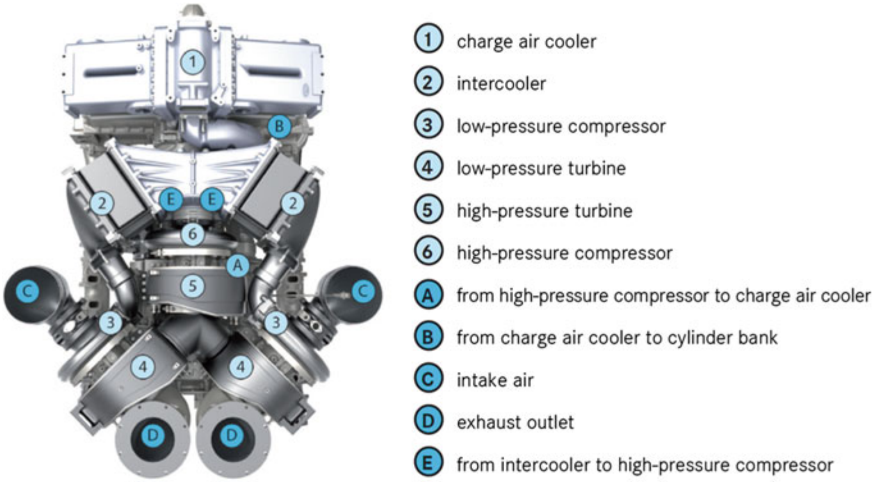

Fig. 10 Air charge passage via sequential turbocharging. *Source* MTU 2014 [34]

dynamic or pulse supercharging is also possible. Dynamic or pulse supercharging uses pressure wave formation as the principal to boost air charge pressure available to the cylinder. Combined supercharger and turbocharger systems offer improved low load engine performance with superchargers experiencing no turbo lag. While superchargers offer many benefits over a turbocharger they often (in the case of engine driven systems) impose an additional fuel penalty on the system, limiting their application to services unavailable to a turbocharger solution.

- *Sequential Turbocharging* (*STC*) involves the use of multiple turbochargers, typically connected in series configuration (multiple stage STC), to provide for precompression of the intake air, followed by further high pressure compression within a subsequent high pressure turbo charger, Fig. 10. Sequential turbocharging can also adopt parallel architectures (single stage STC), operating on much the same principal, with deactivation of turbochargers under either structure possible to tune the engine response. Sequential turbocharging in this manner provides improved dynamic response, a wider operating range and higher boost pressures than that available to single turbo architectures.
- *Variable geometry turbocharging* (VGT) involves either pivoting vanes (Fig. 11), or moving walls to provide flexibility over the pressure ratio/flow relationship, and by extension the torque characteristics of the turbocharger, Fig. 12. The benefit for this additional complexity is improved low load and transient response. VGT can also be used to enhance the function of engine compression braking, via closing of the VGT vanes.
- *Turbo compounding* (*TC*) allows for improved turbocharger recovery, offering improved fuel economy of up to 10% coupled with improved transient response [23]. In principal, the system adds a power turbine to a conventional

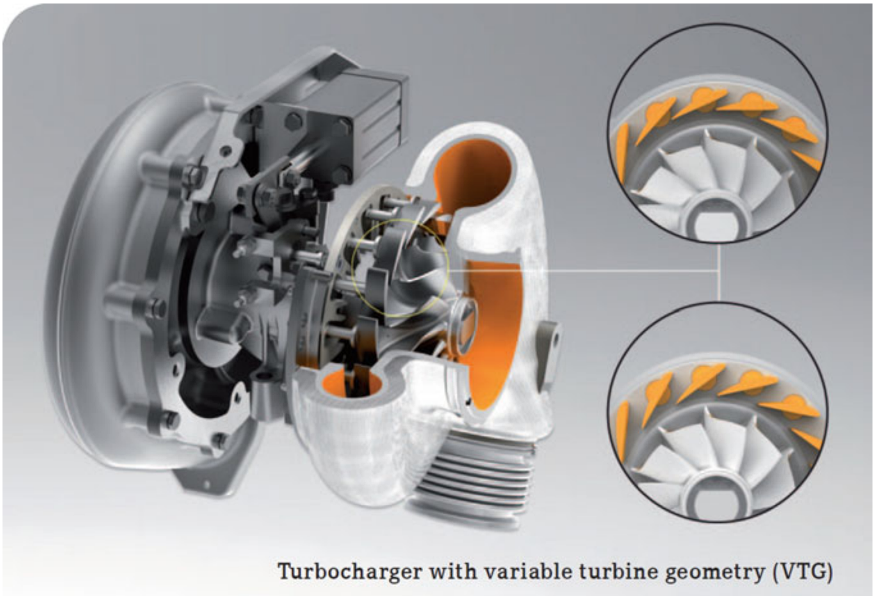

Fig. 11 Variable gate turbo geometry. *Source* MTU: 2014 [34]

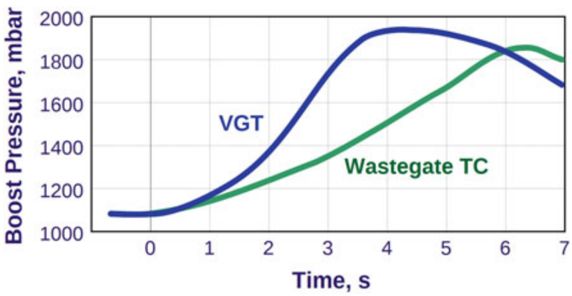

Fig. 12 Air charge boost pressure response under VGT. *Source* DieselNet 2013 [36]

turbocharged system, where the power turbine is connected to either a gear train or a generator (as opposed to the conventional compressor) to provide for an additional source of energy to the diesel engine. In the case of mechanical coupling the power turbo could be connected directly to the engines crankshaft via a gear train, potentially boosting peak engine power output by up to 10%. In the case of electrical coupling, the power turbo provides a source of electrical energy which can be consumed by the engine or stored for future use. Unfortunately TC offers little benefit under low load operation, and may actually be detrimental to low load efficiency, unless the generator can be configure to run as a motor, in which case, the process becomes assisted turbocharging.

- *Assisted turbocharging* is much the same as turbo compounding, only the energy flow is reversed and now flows from the engine to the turbocharger, for the purpose of assisting turbocharger output. Assisted turbocharging can thus provide significant advantage to low load application.

7.7 Reverse Power Acceptance

For vehicle applications, engine braking is essentially reverse power acceptance, using the diesel generator's mechanical friction to offer a dump load capability, aiding to slow down the vehicle without excessive use of brakes. For stationary power applications, the same functionality can be used to allow the diesel generator to provide a load for the system. For example, under high renewable penetration it is advantageous to run you diesel generators as lightly loaded as possible (refer to the earlier discussion of low load diesel application). In such a scenario, should you be able to maintain your diesel engines at no load (zero mechanical output, varies from idle operation, as for the later, shaft speed is allowed to vary) a unique problem arises, that of peaking RES output. As the RES generation varies, you will inevitable overshoot the notional set point, say as the wind gusts around its average value. In this instance where does the additional energy go. Your diesel engines are not actively contributing kW's to the system, as they are at no load, they therefor have no ability to further throttle back to allow for additional RES contribution. One possible solution is to use the engine braking (motoring) capability of the diesel generator to absorb some of this short term transient. This approach has not found practical application with islanded power systems, primarily given operational concerns over motoring generator sets and the risk of mechanical failure quickly leading to engine destruction. Never the less, some permissible motoring of the generator set could assist in elevating engine temperature and providing improved engine response. An approach which has found some commercial applications is that of engine integrating dump load, which allows a separate resistive element to act as a resistive load, the resultant heat being used to increase the engines thermal inertia. In support, it is also possible to maintain mechanical inertia of the alternator via inclusion of a clutch, able to separate the engine and alternator. In doing so the alternator can act as a synchronous condenser, allowing for the diesel engine to be turned off whilst maintaining a fast start capability should the diesel need to be brought online quickly. While the later approach involves significant additional complexity, particularly within the engine control unit, its ability to extend reverse power acceptance beyond the rated capacity of the engine, and eliminate the no load fuel consumption has found favour with niche suppliers.

7.8 Exhaust Gas Recovery (EGR)

EGR is a key technology in emissions compliance for modern diesel generators, involving the recirculation of some exhaust gases back into the air charge volume. This practice reduces NO_x emissions, principally via the reduction in combustion flame temperature. This result is achieved through a combination of reduced oxygen, as exhaust gases displace some O_2, reduced combustion efficiency, given the additional moisture and CO_2 introduced, and modified cylinder gas enthalpy. EGR is not directly related to low load application, however as the practice involves reduced cylinder temperatures it has an adverse effect on low load capability. As such low load application should seek to eliminate EGR use and seek alternative NO_x reduction approaches.

7.9 Under Frequency Voltage Roll-Off (UFRO)

Temporary voltage relief, to aid improved engine response under large load acceptance scenarios, is one easy mechanism to improve power security within islanded power systems under high RES penetration. The application allows the system voltage to dip temporarily, in proportion to the frequency dip, reducing the load on the engine. UFRO is a common application within many automatic voltage regulators and assists in the application of low load response.

7.10 Variable Speed Diesel (VSD)

Engine mechanical losses are proportional to engine speed, independent of load. Hence as the load decreases within a constant speed application, the losses remain, becoming an ever increasing percentage of the supplied energy. This is one reason why it is typically undesirable to run an engine lightly loaded. At the same time, diesel generator sets are sized for maximum demand, regardless of how infrequent this demand might present. By definition, these units spend much of their life partially loaded. Variable speed diesel concepts allow the diesel engine to move away from fixed speed operation, typically lowering shaft speed at low loads, to capture fuel efficiency and improved responsiveness associated with variable speed operation. VSD concepts also add significantly benefit to any LLD application, with low load VSD able to maintain combustion temperatures comparable to conventional operation.

VSD application can adopt one of two approaches, with mechanical or electrical solutions possible. The mechanical solution involves the integration of a variable speed coupling, typically a gearbox as commercialized by CVT corp [37], Fig. 13. Regardless of the coupling mechanism, mechanical solutions add significant complexity to the drivetrain, typically requiring an increased maintenance obligation. For this reason, electrical solutions appear to offer increased reliability and suitability within islanded applications.

Electrical solutions essentially entail replacement of the synchronous alternator with either a DFIG or permanent magnet generator (common technologies for wind turbine application) [38, 39]. Electrical VSD concepts require a frequency converter to meet the constant frequency requirement of the grid, and while the increased cost and complexity of power converters have been a barrier, a number of electrical VSD concepts are now commercialized, particularly in the small generator set market [40]. Of relevance for hybrid diesel architectures it is possible for multiple generators, say wind, energy storage and diesel to share a common power converter, further reducing cost [41].

Theoretical fuel savings resultant from VSD application have been suggested up to 50% [42], Fig. 14, although some deterioration in full load fuel efficiency is observed given the losses inherent to the power converter. In addition, a VSD application is able to extract a higher resultant torque than a conventional fixed speed engine [43]. While power converter costs remain prohibitively high for VSD adoption, as we see the cost of power converter technology reduce the benefits of low load VSD technology are anticipated to be realized across a range of market applications and generator set sizes.

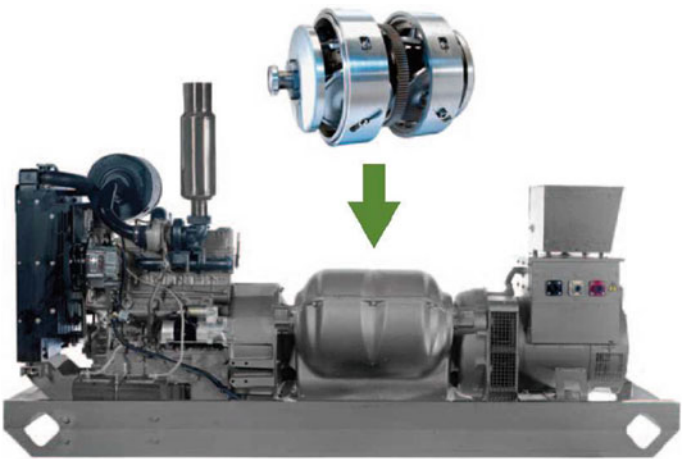

Fig. 13 CVT corp variable speed transmission concept for variable speed generation. *Source* CVT Corp 2016 [37]

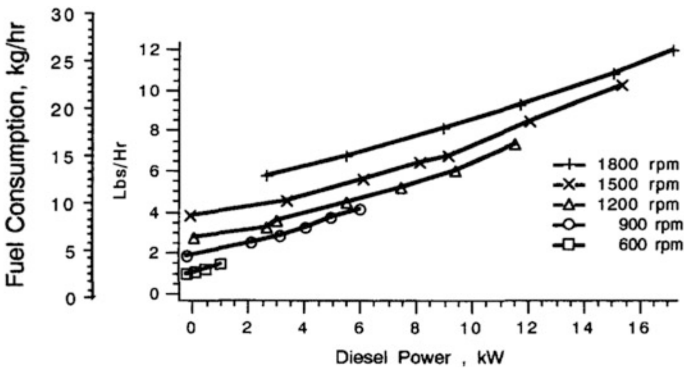

Fig. 14 Fuel consumption for VSD application [38]

7.11 DC Diesel (DCD) Hybrids

As RES technologies reduce in price, emerging energy storage and battery technologies are commercialized, and wind turbines move towards full power conversion platforms, increased justification presents for islanded applications to implement direct current networks. Upon historical review, AC networks have largely evolved from a requirement for efficient transmission of power, generated within large central power stations, to consumers located across the vast geography of the network. For islanded applications these requirements commonly do not apply, with small community loads located in close proximity to available renewable resources. In addition renewable and ancillary technologies such as solar PV and battery storage work on direct current and are commonly distributed across a network at both domestic and industrial levels. Further, with discussion of variable speed wind and diesel generation, direct current output of these generation sources also becomes viable. DCD acknowledges this technology shift in identifying the optimal location and sizing for AC/DC power conversion, allowing for a dedicated central DC bus or transmission system. AC conversion is only undertaken, if at all, prior to consumption of AC within a residence or facility.

7.12 Biodiesel Blending

A brief discussion of biodiesel blending is presented given its increasing relevance to hybrid diesel power systems and its direct impact on the engine thermal profile. In principle, biodiesel presents an opportunity to utilize available on-island waste products as a blended diesel derivative, thus reducing reliance on costly imported fuels. However a number of issues require careful consideration, including technical, economic and social impacts. Common queries include, what blending ration is optimal, and what impact will the blended fuel have on engine performance and emissions compliance? Is the available biodiesel feedstock reliably available in sufficient quantities to support ongoing viability? Will biodiesel use modify conventional agricultural practice and productivity (introducing competing demand with food production)? Such concerns complicate the technical viability of producing a biologically derived fuel from vegetable oils or animal fats. Suitable sources of which include soybean, palm, coconut, used frying oil or algae. Even when these feed stocks can be obtained at subsidized, or no cost, their refinement typically adds a price premium to that of pure diesel, especially when considering the small scale of operation typical of an islanded economy.

As such, biodiesel blends typically use any waste oil derivatives in small quantities, far below the 7% blending limit currently imposed by equipment suppliers [45]. Such limits are typically driven by engine warranty provisions and the potential of biodiesels to foul piston rings and injectors above certain levels. Of note standard provisions assume ever increasing biodiesel capability (*Bxx* limits) from engine technologies.

Biodiesels blends can be characterized by the follow generic traits, although some variation specific to feed stock does exists:

- Lower heating value;
- Higher cetane value;
- Higher viscosity (restricting use in cold climates);
- Higher freezing temperature (restricting use in cold climates);
- Lower toxicity;
- Increased combustion odour;
- Biodegradable (impacts storage life and water absorption);
- Modified corrosive properties.

In regards to emissions compliance, the general trends presented in Table 3 can be expected, although these are subject to a number of parameters including the biodiesel source and quality, engine configuration, test cycle and environmental conditions. The general trend is for reduced resultant pollutant emissions linked to biodiesel combustion.

Biodiesel blending is considerably more complex an undertaking than initially apparent, it impacts on almost every aspect of the engine performance from injector timing, combustion rate, compression ratio, flame propagation, oxygenation and exhaust temperature. Some of these benefits are positive, while others are negative, for both engine performance and longevity. In addition, biodiesel blending has implications for LLD, VSD and DCD application, with careful consideration of these impacts recommended prior to any widespread adoption. As a minimum practice, biodiesel introduction should work iteratively up to targeted blend ratios with the exercise more suited to a lab research environment than that of an operating islanded power system.

Table 3 Effects of biodiesel fuel on exhaust emissions

Emission	**Effect of biodiesel**
Regulated emissions	
Carbon monoxide	↓
Hydrocarbons	↓
Nitrogen oxides	↑
Total particulate matter (TPM)	↑ OR ↓
Unregulated emissions	
Carbon particulates	↓
Organic particulates (SOF)	↑
Sulfate particulates	↓
Visible smoke	↓
PAH, nitro-PAH	↓
Aldehydes	↑ OR ↓
Legend: ↑ biodiesel increases emissions (relative to standard diesel)	
↓ biodiesel decreases emissions (relative to standard diesel)	

Source Diesel Net 2009 [44]

8 Operational Theory

Diesel generators remain the backbone for the majority of deployed island country networks. To understand how a diesel generator works, a basic understanding of the diesel engine and generator component architectures and interaction is required. A diesel generator consists of a diesel engine, controlled by the engine governor and a synchronous alternator controlled by the automatic voltage regulator (AVR). Both of these systems are co-ordinated by the Engine Control Unit (ECU). Operation of the engine and alternator is considered separately in this text to reduce system complexity for the reader, with the coordination of the two required to define a conventional diesel generator. We start our discussion with consideration for the diesel engine, often referred to as the prime mover, given its role in the conversion of chemical energy to mechanical rotation. At its simplest level, the diesel engine comprises of an engine block, cylinder head, cylinders, running gear, pistons, fuel system, valve and injection systems, air charge system, cooling and exhaust systems. These component groupings in turn consist of a number of common components and subsystems, the function of which is briefly presented below.

The structural foundation of the engine is provided by the engine block, to which the cylinder head is mechanically fastened. In this manner, the block can be considered the body of the engine. The function of the head is to provide a pressurized seal for each cylinder environment, with the head commonly consisting of either a single casting or multiple heads to cover respective cylinder groupings, subject to the size of the engine. The cylinder head houses the injectors, intake and exhaust values, in addition to the valve guides and seats. Within the cylinder head, porting allows for the flow of coolant around the engine for dissipation of heat from the cylinder walls. Gaskets, seal rings and grommets are commonly used to provide a seal between the block and head given any irregularity which may exist between the two surfaces.

The bore, defining the engine cylinder may be machined directly within the engine block, however, it is preferable and common practice to insert a pressed cylinder liner, given both exacting piston to cylinder tolerances and the ability to replace liners should they exhibit excessive wear. Liners must be able to withstand the extreme heat and pressure developed during combustion while maintaining alignment of the piston and piston rings. To assist in lubricating, honing grooves within the liner assist to retain a film of lubrication oil.

The running gear, responsible for torque transfer from the cylinders, consists of any number of, con rods, bearings and crankshaft. The fuel system comprises of fuel pump and injectors. The valve system in turn comprises of inlet and exhaust valves, with a number of auxiliary components to support sequencing under correct operation, Fig. 15. The air charge system commonly comprises a turbo, Fig. 10, and intercooler. The function of the air charge system is to supply clean air to the cylinders at an appropriate density to ensure efficient combustion. The air charge manifold and ducting should be kept as short as possible with minimal obstructions to ensure acceptable pressure losses. A turbocharger is used to boost the air pressure, while an intercooler is used to reduce the temperature of this high pressure

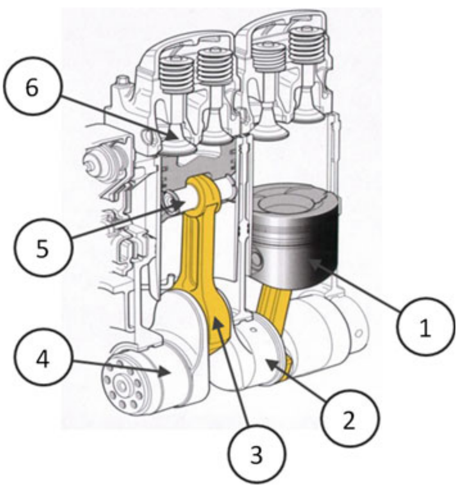

Fig. 15 Running gear cross section incorporating the piston (*1*), crankshaft (*2*), con rod (*3*), bearing (*4*), cross head (*5*), and valve (*6*). Image reproduced with permission from MTU Friedrichshafen

charge. Air filters are essential to any air charge system given the impact of dust and debris on accelerating engine wear, although again pressure drop over such a filter should be kept to a minimum.

The cooling system is essentially a heat exchanger working on either an air-cooled or water-cooled principal. The basis for adopting either system is commonly engine size, with smaller engines adopting air-cooled systems and larger engines reliant on water-cooled systems. For water-cooled systems the quality of the water is vital to ensure reliable operation, with untreated river or sea water unsuitable for use given the presence of minerals and salts, and the potential for solidification of these elements (scaling). For this reason closed cooling systems are common practice, eliminating any exposure of the treated coolant to the environment.

Diesel engines are conventional classified by fuel type, speed, application or rated capacity. Speed is by far the most common grouping with speed indicative of both the weight, cost and by inference the life of the engine. For stationary power applications, both high speed (>1000 rpm) and medium speed (400–1000 rpm) solutions are common. For AC diesel generator sets, the speed of the engine is set to the network frequency according to Eq. 3, [46].

$$n = f\frac{60}{p} \tag{3}$$

where

n is the speed of the machine in rpm;
f is the required network frequency; and
p is the number of pole pares in the alternator.

Both two stroke and four stroke working cycles are common diesel engine configurations. Two stroke engines having twice the power strokes of a four stroke engine given a common rpm reference. It is however incorrect to assume that a two stroke engine develops twice the power of a four stroke engine, in part because of inefficiencies in combining the intake and exhaust functions with the compression and combustion process respectively. The four stroke engine has many advantages over its two stroke counterpart, including improved ramp rate and transient performance and increased low load capability, both key selection criteria for any islanded application.

The power output of a diesel engine is often referred to as brake power, simply referring to the act of measuring this output against some form of mechanical resistance or brake. Brake power is always lower than the theoretical power (indicated power) of an engine given the presence of internal engine friction. The mechanical efficiency of the engine can be defined as the ratio of brake to indicated power. The brake power of an engine is calculated according to Eq. 4 [47], defining the relationship between cylinder pressure and shaft torque.

$$P = \frac{p.l.A.w.N}{k} = 2\pi\omega T \quad (4)$$

where

- p is the brake mean effective pressure (average pressure acting on the piston as applied throughout the entire stroke),
- l is the stroke of the engine piston,
- A is the piston area,
- w is the number of working strokes per unit of time,
- N is the number of active cylinders in the engine,
- k is a constant dependent on units selected (typically k = 1000 for SI units), and,
- ω is the shaft rotational speed, and,
- T is the shaft torque.

The role of the engine is to accept fuel and air, providing an optimal ignition environment for the conversion of cylinder pressure to mechanical torque. Torque is delivered through the engine via the running gear. It is the resultant output shaft speed which provides the feedback loop to the governor, facilitating speed control. The diesel engine and governor model, Fig. 16, describes the conversion of fuel, supplied to the engine in response to actuator control, to cylinder pressure then crank torque, and finally rotational shaft velocity. The role of the governor is to regulate the output shaft speed (ω) via control of the fuelling rate. Inherent to the governor operation are governor and actuator delay ($\tau 2$ and $\tau 3$) [49]. Governor delay representing the response time of the governor within the ECU. Actuator delay is inclusive of any mechanical response delay, prior to injector response (shaft speed change prior to fuel injection, thus introducing additional set point error).

In Fig. 16, p_i and p_f represent the indicated cylinder pressure and the engines mechanical losses represented as an equivalent pressure drop. Diesel engine delay

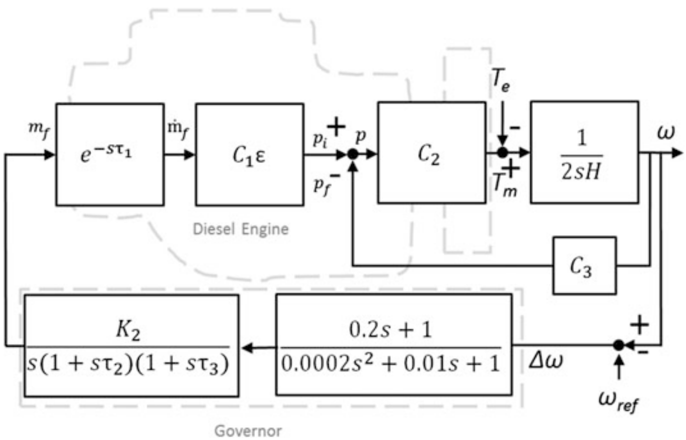

Fig. 16 Diesel engine governor and engine model [48]

($\tau 1$) results from both crank angle delay, the engines inability to accept a predetermined fuel load due to the crank angle position, and an ignition delay, determined by the cylinder environment. Crank angle delay is a function of cycle timing, with a four stroke engine having to complete combustion and exhaust stokes prior to any subsequent intake. Ignition delay represents a function of cylinder temperature, pressure, fuel stoichiometry and environmental factors. Cylinder effective pressure is developed according to Eq. 5, [48].

$$p = C_1 \dot{m}_f \varepsilon_t \tag{5}$$

where C_1 is the proportionality constant, $\dot{m}_f$ is the fuel consumption rate (m_f representing the fuel delivery rate) and ε_t is the thermal efficiency (the thermal efficiency, defined as the brake power divided by the thermal energy of the consumed fuel, is not to be confused with the mechanical efficiency). Mechanical torque is developed according to Eq. 6 [48].

$$T_m = \frac{P}{2\pi\omega} = C_2 p \tag{6}$$

where

C_2	is a proportionality constant
$p = p_i - p_f$	as defined earlier, and
$T = T_m - T_e$, with T_e	representing electromechanical torque.

Shaft speed is defined considering H, the generator sets combined mechanical inertia.

The alternator essentially consists of two parts, the stator, which carries the armature winding, in which emf is induced, and the rotor, which carries the field winding, and is supplied via dc current. From an engine perspective, any change in load must be met by a response from the governor, adjusting the fuel load to the engine for constant speed output. Equally any change in load must be met by a response in alternator excitation, which regulates the field current to maintain stable terminal voltage. In this manner, the governor controls the system frequency and the AVR controls the system voltage. The efficiency of the alternator is defined as the ratio of realized power to that of supplied power. Typically, alternator efficiency will increases with unit size, with an efficiency range of 0.92–0.95 characteristic for commonly sized stationary diesel generators sets (100 kW to 1 MW in size).

The dynamic model of the synchronous generator is represented by a sixth-order state-space model used in Simulink [49]. The internal impedance of the machine is implemented via phase specific voltage sources in series with RL impedance. The equivalence circuit is represented in q-axis and d-axis rotor reference frames, as shown in Figs. 17 and 18. The subscripts used are defined as follows:

d/*q* represent the *d*- and *q*-axis quantity, respectively;
R/*s* represent the rotor and stator quantity, respectively;
l/*m* represent leakage and magnetizing inductance, respectively;
f/*k* represent field and damper winding quantity, respectively;

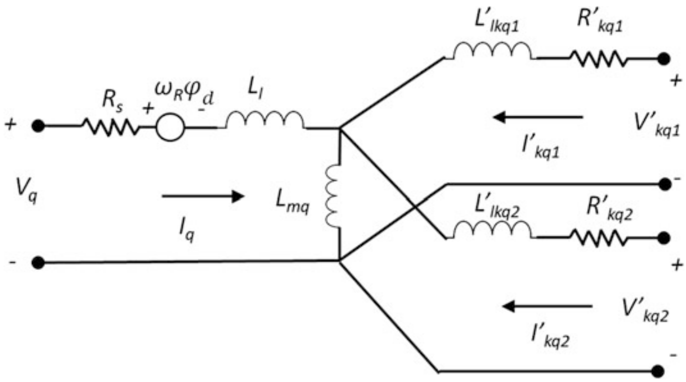

Fig. 17 Equivalent circuit model of electrical system of synchronous machine in *q*-axis frame of Ref. [49]

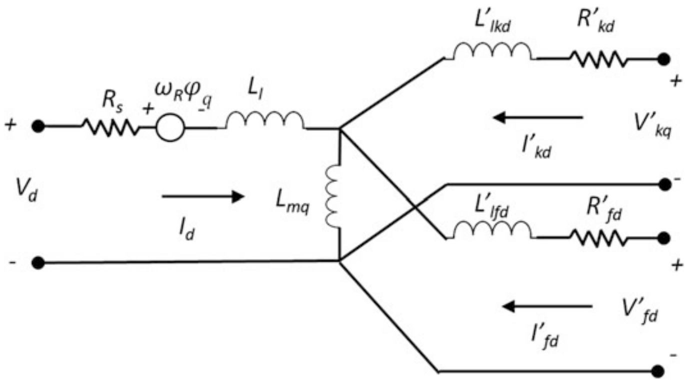

Fig. 18 Equivalent circuit model of electrical system of synchronous machine in *d*-axis frame of Ref. [49]

Electrical system response is defined by Eqs. 7–12, [50]

$$V_d = R_s i_d + \frac{\mathrm{d}}{\mathrm{d}t}(\varphi_d) - \omega_R \varphi_q \tag{7}$$

$$V_q = R_s i_q + \frac{\mathrm{d}}{\mathrm{d}t}(\varphi_q) - \omega_R \varphi_d \tag{8}$$

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{\mathrm{d}}{\mathrm{d}t}\left(\varphi'_{fd}\right) \tag{9}$$

$$V'_d = R'_{kd} i'_{kd} + \frac{\mathrm{d}}{\mathrm{d}t}\left(\varphi'_{kd}\right) \tag{10}$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{\mathrm{d}}{\mathrm{d}t}\left(\varphi'_{kq1}\right) \tag{11}$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{\mathrm{d}}{\mathrm{d}t}\left(\varphi'_{kq2}\right) \tag{12}$$

where

$$\begin{aligned}
\varphi_d &= L_d i_d + L_{md}\left(i'_{fd} + i'_{kd}\right) \\
\varphi_q &= L_q i_q + L_{mq} i'_{kq} \\
\varphi'_{fd} &= L'_{fd} i'_{fd} + L_{md}\left(i_d + i'_{kd}\right) \\
\varphi'_{kd} &= L'_{kd} i'_{fd} + L_{md}\left(i_d + i'_{fd}\right) \\
\varphi'_{kq1} &= L'_{kq1} i'_{kq1} + L_{mq} i_q \\
\varphi'_{kq2} &= L'_{kq2} i'_{kq2} + L_{mq} i_q
\end{aligned}$$

The equations for the mechanical system are below, Eqs. 13 and 14, [49];

$$\omega(t) = \Delta\omega(t) + \omega_o \tag{13}$$

$$\Delta\omega(t) = \frac{1}{2H}\int_0^1 (T_m - T_e)\mathrm{d}t - D\Delta\omega(t) \tag{14}$$

where

D is the damping factor representing the effect of damper windings,
$\omega(t)$ is the rotor speed,
$\omega(o)$ is the operational speed,

The standard parameters of a synchronous generator are found either by test, as in IEEE Std115-1983 (R1991) or IEEE Std 115A-1987, or supplied directly via the manufacturer. Model specific detail data, specific direct and quadrature axis model structures, with their associated element values, to transient and sub-transient reactances and time constants is presented in Table 4.

The excitation system consists of an exciter, autonomic voltage regulator (AVR), measuring elements, power system stabilizer and limiters and protective circuits as shown in Fig. 19. The exciter provides dc power to the synchronous machine field winding. The exciter is controlled by the AVR in steady state operation, although during disturbances, due to field current changes in the generator, it also impacts on the damping of power transients. The power system stabilizer provides an input signal (based on rotor speed variation, accelerating power, and frequency deviation) to the regulator, to dampen power system oscillation. Measuring elements obtain excitation system input values such as generator armature voltage, armature current, and the excitation current and voltage. A limitation and protection unit provides

Table 4 Standard parameters of a synchronous generator

Parameter	Description	Manufacturer's value	Units
Ra	Stator resistance	0.033	pu
Xd	D-axis synchronous reactance	3.13	pu
Xq	Q-axis synchronous reactance	1.6	pu
Xl	Leakage reactance	0.074	pu
X'd	D-axis transient reactance	0.184	pu
X'q	Q-axis transient reactance	1.6	pu
X"d	D-axis sub-transient reactance	0.148	pu
X"q	Q-axis sub-transient reactance	0.161	pu
T'do	D-axis O.C. transient time constant	2.11	s
T'qo	Q-axis O.C. transient time constant	0.012	s
T"do	D-axis O.C. sub-transient time constant	0.012	s
T"qo	Q-axis O.C. sub-transient time constant	0.089	s
Sbase	MVA upon which above data is provided	830	kVA

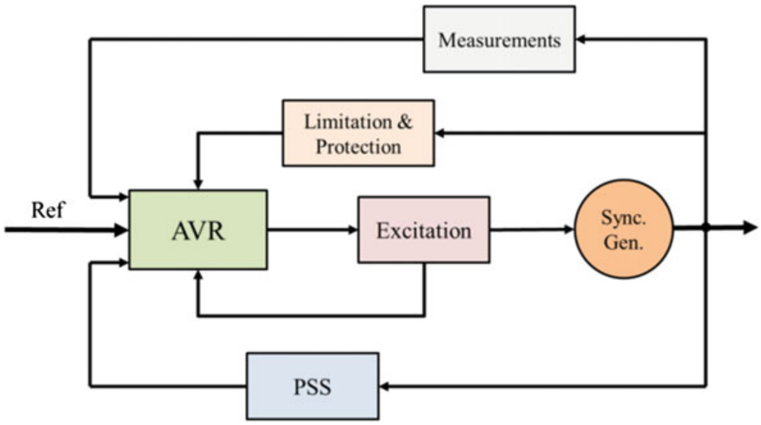

Fig. 19 Excitation system of synchronous generators

proper control and protective functions to ensure that capability limits of the exciter and synchronous generator are not exceeded.

Excitation systems can be divided into three main categories [50]: DC excitation system (type DC), AC excitation system (type AC) and static excitation system (type ST). Type DC utilizes direct current generation with a commutator as the system's source. Type AC uses an alternator and either a stationary or rotating rectifier to produce a direct current to the field winding of a synchronous generator. Type ST utilizes a transformer or auxiliary generator windings and rectifiers as a power source. A model for the AVR and exciter can be sourced either from [51, 52] or may be supplied directly by the manufacturer. A typical model for the AVR and exciter has been provided by Stamford, and is presented in Fig. 20 (Table 5).

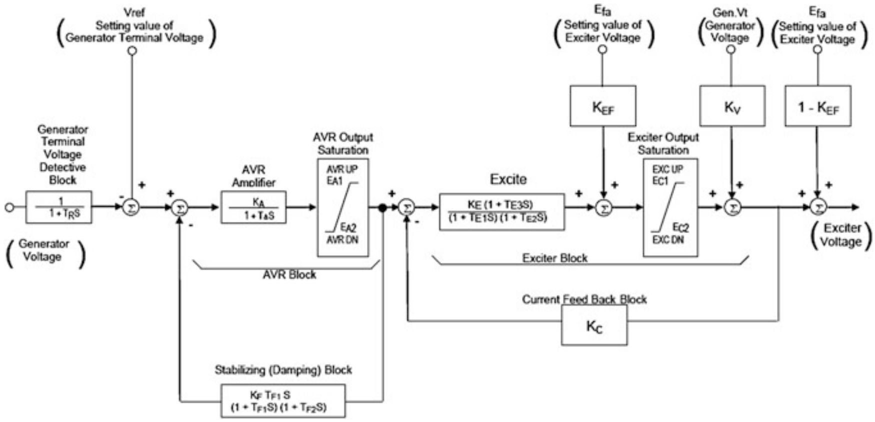

Fig. 20 Modified to IEEE2 Exciter (Stamford AVR's), courtesy of Stamford AvK

Table 5 Generator and AVR data for modelling, courtesy of Stamford AvK

Parameter	Model reference	Value
Regulator forward gain	(KA)	500
Feedback gain	(KF)	0.04 > 0.01
Input filter constant	(TR)	0.01 s
Amplifier time constant	(TA)	0.1 s
Feedback time constant	(TF1)	0.7 s
Feedback time constant	(TF2)	0.05 s
Minimum AVR output	(EA2)	0
Maximum AVR output	(EA1)	8
Maximum rate of change	(DM)	2500
Exciter gain	(KE)	1
Exciter voltage offsets	(KEF)	0
Exciter voltage offsets	(KV)	0
Exciter current F/B gain	(KC)	0
Exciter time constant	(TE1)	See below
Exciter time constant	(TE2)	0
Exciter time constant	(TE3)	0
Maximum exciter output	(EC1)	3
Minimum exciter output	(EC2)	0
Exciter saturation @ 75%	(SE1)	110%
Exciter saturation @ 100%	(SE2)	190%
Exciter time constant	(TE1)	0.22–0.91

9 Diesel Modelling Simulation (Conventional/D-UPS and LLD)

System and technology simulation allows for rapid system prototyping and evaluation. Under such a methodology we examine three common diesel engine configurations, as evaluated via simulation to determine the merits of the each specific topology, case studies 1–3:

- Case 1: Two conventional diesel generators (CDG's) paired.
- Case 2: One CDG and one Diesel UPS with large inertia flywheel.
- Case 3: One CDG and one low load diesel (LLD).

All modelled diesel generator units have identical capacities (1 p.u.) with a constant 0.6 p.u. system load assumed. As, a CDG operating at 60% rated capacity is close to its optimal efficiency loading, it would seem practical to run CDG one at 0.6 p.u. with CDG two turned off. In considering this mode of operation, we need to examine the systems reserve requirements. Power systems are required to demonstrate sufficient reserve to maintain consumer supply under a variety of contingencies. One such contingency is loss of any single generator, should the generator trip off-line for any reasons. This is exactly the scenario modelled for discussion below, Fig. 21.

In Case 1, the second CDG unit is off to limit fuel consumption and preserve engine condition. If both CDG's were on, they would both be required to operate at a conventional low load limit (30% of rated capacity). In Case 2 and 3, the secondary unit is replaced by either a Diesel UPS (UPS-D) with large inertia, or low load diesel (LLD), which are considered On, but in idle mode. For the Diesel UPS this entails decoupling of the engine and alternator/flywheel via a mechanical clutch. For the LLD this entails operating the diesel generator set at no load.

In all case studies a simulated fault, leading to loss of the primary CDG, results in the primary CDG being disconnected and at $t = 4$ s, Fig. 21. At this time the system needs to respond to maintain supply to a constant consumer load. The system behaves as follows:

The results of the simulation are presented in Fig. 22, demonstrating the frequency response for different system configurations. In Case 1, CDG two is unable to start in sufficient time to prevent an excessive drop in frequency, with the cold reserve CDG engine unable to ramp sufficiently to avoid an under frequency power system blackout. In Case 2, the inertia available in the grid is large (thanks to the addition of the flywheel spinning reserve), the drop in frequency is subsequently moderated (2% dip) when the 0.6 p.u. load is picked up by the Diesel UPS. The system is critically damped, and the frequency is eventually returned to stable operation after 10 s (a representative time for the reserve engine to be brought online via closure of the mechanical clutch). In Case 3, the system frequency again drops at a similar rate to that observed under conventional diesel operation, Case 1,

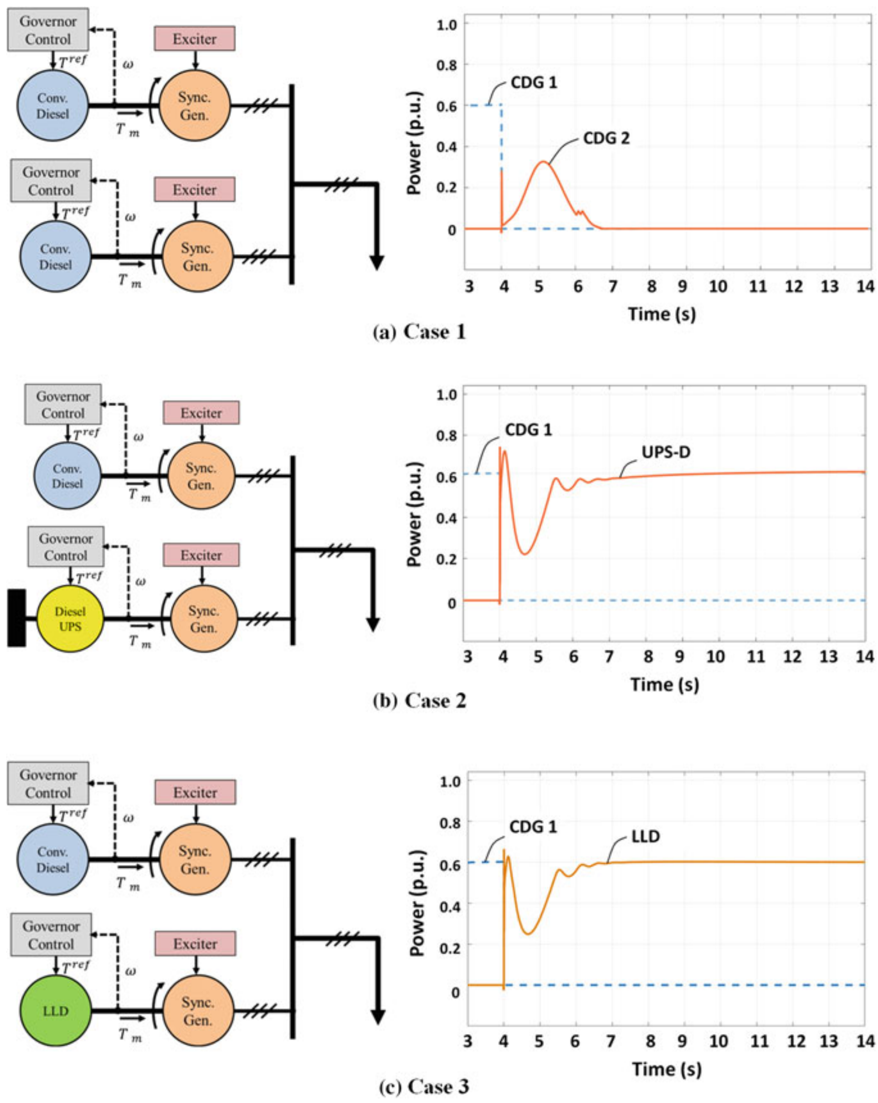

Fig. 21 Different case configurations and loading represented under $N - 1$ simulation

(6% dip), although in this instance the LLD remains online, with the low load diesel offering improved ramp rate response, to that of a cold start diesel. Figure 22 also shows larger frequency transient under Case 3, although the settling time is short, and supply is maintained.

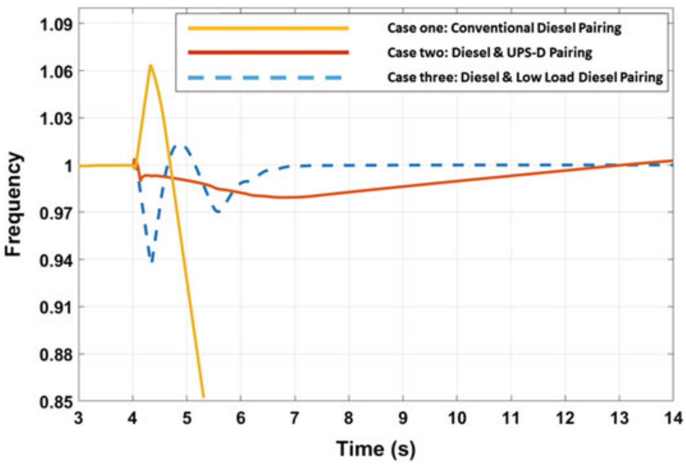

Fig. 22 Frequency response for different types of configurations

Review of the provided simulation provides useful insight into the real world operation of diesel engines, their capabilities and constraints. We can appreciate that power system security may often require more than one diesel engine to be in operation, despite the ability of one diesel to readily meet the apparent load. The need to have two diesel engines running pushes both into a load share arrangement, where they are run inefficiently and lightly loaded. Accordingly system reserve requirements often results in increased system fuel usage and engine wear. One acceptable solution to this issue is to introduce spinning reserve into the system, typically via the introduction of a flywheel (although a battery may alternatively be used to provide synthetic inertia). System inertia provides a dampening effect, affording the reserve diesel unit time to start, thus eliminating the need to have the reserve unit in operation. While this approach ensures engine condition and saves fuel, it unfortunately adds significant cost and complexity to the system design. In Case 3, LLD application achieves functionally adequate spinning reserve via operation of a low load diesel. For Case 3, LLD application achieves much of the fuel reductions afforded under Diesel UPS application, with both approaches permitting the primary diesel to run optimally loaded. (It is important to appreciate the parasitic losses required to motor the flywheel when operational as a synchronous condenser. These losses are approximately equivalent to no load LLD operation). LLD application in principal permits a diesel engine to be run at low load for the provision of security reserve. While LLD application consumes fuel to maintain a no load state, it saves fuel in comparison to a twin CDG architecture, Case 1 (typically 2–3%). Both UPS-D and LLD approaches are thus able to offer the required system security while both returning moderate fuel savings and improving system flexibility. Within hybrid diesel systems, those utilizing RES generation, such improved flexibility can deliver dramatically greater benefit. It is thus within hybrid diesel architectures where LLD finds commercial application.

Accordingly, discussion of the prior case studies can be extended to hybrid diesel systems, inclusive of RES technologies. Within hybrid diesel networks, spinning reserve is increasingly in demand to address RES variability. LLD offers hybrid diesel architectures maximum RES utilization, while providing the additional spinning reserve requirements of such systems. LLD applications accordingly offer optimal savings when paired with high penetration RES generation. In Fig. 23, hybrid system performance is assessed, adopting both a conventional (30%) and LLD (10%) low load constraint. The figure presents the average January daily load profile, with RES generation and demand identical across simulations. Of note, the system energy spillage is significantly reduced under LLD application. Over the course of a year, LLD is modelled to return diesel fuel savings of 10%, with a 16% reduction in fuel consumption possible under a no load limit (0%) [8]. LLD achieves this additional efficiency in partnership with RES generation, given its ability to accept maximum renewable energy content (with the engines able to run lightly loaded at high RES penetration). Within HPS LLD improves renewable penetration, reducing fuel consumption, while maintaining system security without the need for additional energy storage [9]. Accordingly under both diesel and diesel hybrid architectures, LLD has a valuable role to play in maintain system security, reducing fuel consumption, reducing system complexity and minimizing system cost.

10 Economics of Diesel Generation

Diesel generation has historically been presented as the ideal solution to remote and islanded consumers seeking improved electrification. Diesel generators remains a low risk, readily available, well supported and demonstrated technology. However, in recent years we have observed a reliance on diesel generation to expose such communities to volatile commodity and thus energy pricing (terminal gate diesel fuel price). Pricing which is many times higher than in established markets given the premium paid for remote area transport and storage. Diesel prices paid by many

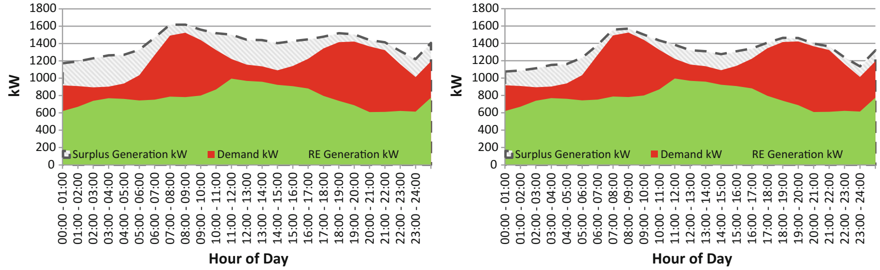

Fig. 23 Load, RES generation and energy spillage under conventional (*left*) and LLD application (*right*)

islanded nations are among the highest paid globally, often 3 or 4 times the price paid for conventional supply [6]. Society has also increasingly come to understand the negative health and environmental impacts linked to diesel emissions.

A number of alternative technologies exist to reduce diesel reliance, with these technologies capable of achieving cost parody with diesel generation [5]. While it is difficult for any reference text to make comment on the cost competitiveness of various RES technologies, given the pace of developments across this sector, it is anticipated these technologies will decrease in cost as they achieve improved economies of scale. The following case studies are provided to demonstrate the current cost competitiveness of RES architectures, with an anticipation that future RES costs will fall below the cost of diesel generation for many islanded countries. As the following cases studies illustrate RES integration can achieve both economic and environmental benefits for islanded communities, with the scale of such benefit dependent on the geography, natural resource, population density, location and seasonality of the application. As the case studies below will illustrate RES integration can be used to reduce energy costs, restructure an underperforming and unreliable power system, or to remove diesel generation entirely from a network, with both the costs and benefits scaling proportional to the intended application.

10.1 Viti Levu Island, Fiji, Pacific

Fiji is a Melanesian island nation in the South Pacific, consisting of 110 permanently inhabited islands, home to over 880,000 islanders. Fiji has developed a diverse mix of renewable technologies including hydro, wind and biomass, the installed capacity of which exceeds 62% of total generation capacity [53]. Over 60% of generation is supplied via renewable technologies, delivering Fiji both the lowest oil dependency and the lowest cost of energy among all the islands of the Pacific [29]. Fiji is home to emerging economic activity, inclusive of mining, manufacturing and construction industries, which expansion of RES integration, including geothermal and solar, envisaged to meet 99% of demand across all sectors by 2030.

Viti Levu, the main island within Fiji, Fig. 24, represents the majority of RES capacity within Fiji, as serviced by a central 132 kV transmission backbone. As such, RES penetration on Viti Levu is significantly higher than the national average, Table 6.

10.2 Cabo Verde, Atlantic Ocean

Cabo Verde is a volcanic archipelago of 10 islands sitting of the western coast of Africa. Given its climate and resources, it imports most of its food and relies on desalination for most of its drinking water. The economy is heavily reliant on

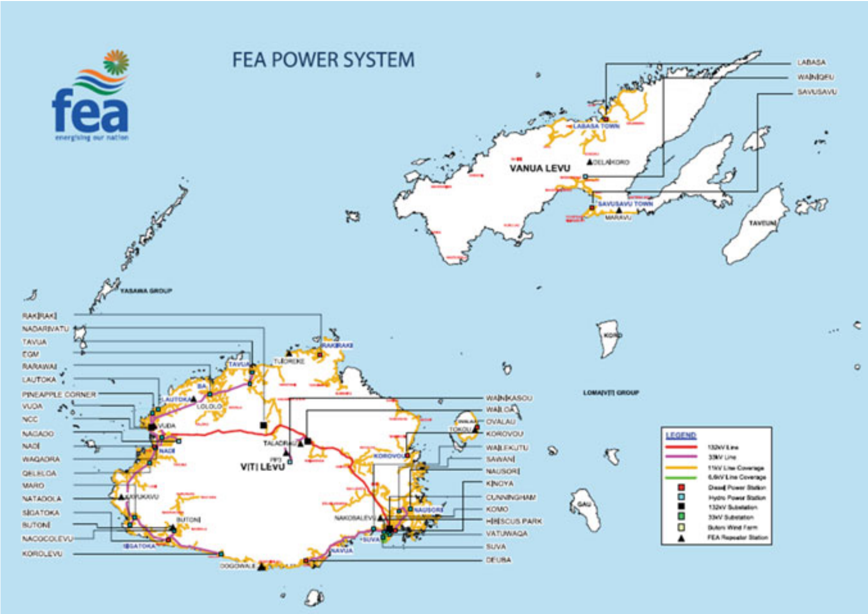

Fig. 24 FEA service supply network, Fiji. *Source* FEA

Table 6 Fiji Energy market metrics

Electricity access (2012)		92%
Installed capacity (2012)	263 MW	
Renewable capacity combined (2012)	164 MW	62%
Renewable capacity hydro (2012)	129 MW	49%
Renewable capacity wind (2012)	10 MW	4%
Renewable capacity solar (2012)	Unknown	n.a.
Renewable capacity biomass (2012)	25 MW	9%
Total generation (2012)	823 GWh	
Renewable generation combined (2012)	493	60%
Renewable capacity hydro (2012)	452	55%
Renewable capacity wind (2012)	33	4%
Renewable generation solar (2012)	Unknown	n.a.
Renewable generation biomass (2012)	8	1%
Electricity tariff (subsidized)	8 c/kWh	
Electricity tariff (unsubsidized)	17 c/kWh	

Source IRENA 2014 [29, 53]

tourism and fishing. With a high dependence on diesel generation and unaffordable electricity tariffs, the Cabo Verde's utility became insolvent, requiring administration by the government. As a result of subsequent modernisation, a quarter of the countries energy supply is now met via renewable generation, Table 7, with the

Table 7 Cabo Verde energy market metrics

Electricity access (2012)		99%
Installed capacity (2012)	140.5 MW	
Renewable capacity combined (2012)	33.9 MW	24%
Renewable capacity hydro (2012)	n.a.	n.a.
Renewable capacity wind (2012)	26.4 MW	19%
Renewable capacity solar (2012)	7.5 MW	5%
Renewable capacity biomass (2012)	n.a.	n.a.
Total generation (2012)	330 GWh	
Renewable generation combined (2012)	68.7	21%
Renewable capacity hydro (2012)	n.a.	n.a.
Renewable capacity wind (2012)	61.3 MW	19%
Renewable generation solar (2012)	7.4 MW	2%
Renewable generation biomass (2012)	n.a.	n.a.
Electricity tariff (subsidized)	38 c/kWh	

Source IRENA 2014 [29]

government setting a target to reach 50% over the next few years. Cabo Verde endures one of the highest electricity tariffs in the world, creating a market attractive to Independent Power Producers (IPPs), with the government keen to reprivatize the utility and reach its RES targets purely via private investment, unsupported by any feed in tariff or alternative subsidy.

11 100% Renewable Energy System Design

We have talked of increasing diesel fuel prices and falling RES prices. As these price trajectories extend past the commercialisation of battery storage systems, many market participants anticipate a rapid transition to 100% RES architectures. While this end point appears to be the logical progression of higher and higher RES penetration, indeed King Island in Tasmania is already able to run 100% diesel off, both the timing and the costs associated with this transition are unknown. While the commercialisation of energy storage will no doubt be advanced via the adoption of partner technologies, such as electric vehicles (electric vehicle uptake creates an ideal supply stream of repurposed batteries for the stationary power storage market) Unfortunately cost parody for these systems is expected to be at least a decade away. With this in mind, the prospects for any imminent energy storage revolution should not be used as an excuse for delay or inaction by islanded countries. Many cost effective steps are available to transition existing power systems in preparation for an eventual 100% RES capacity. These include configuring a power system to be modular and expandable, maximising the costs effective level of RES integration, and updating or reconfiguring diesel generation to allow for maximum RES utilization. It is also important for all stakeholders to acknowledge diesel generation as an essential component to the operability of islanded country power systems, irrespective of energy storage. 100% RES configurations remain reliant on some form of scheduled generation reserve for occasions when renewable supply and storage is unable to meet demand. Diesel generation is ideally placed to meet this requirement given the infrastructure is already in place. Thus, the end game appears to be one of reduced reliance on diesel, acknowledging the residual value these technologies can plan in transitioning communities to the power systems of the future. This chapter has presented a few such opportunities, with the audience reminded that for many islanded countries, electrification is an essential pathway to improve the living standards and opportunities for their communities. How effectively we meet this need remains reliant on our ability to communicate the embodied challenges and opportunities available to existing generation infrastructure.

12 Conclusion

It can be easy to identify opportunity for RES integration within islanded countries solely reliant on diesel fuel for electricity generation. In response, the default approach to system design and development is increasingly to adopt hybrid diesel architectures. Less apparent are the societal challenges inherent in moving these communities away from an established and reliable technology. As the level of RES integration increases additional technical challenges also present around maintaining robust and secure power systems.

This chapter presents possible solutions, advocating a step-by-step transitional approach to the promotion of increased RES utilization. The main advantage of this approach has been to extract maximum value from the existing generation footprint. We have seen how diesel generator operability, often considered as a simple but inflexible supply solution, is in fact a complex and adaptable technology, able, if configured correctly, to run in cooperation with various RES technologies. Indeed multiple approaches exist to configure and control legacy diesel generator as a means to integrate greater levels of renewable penetration. As systems transition from diesel dependence to greater RES utilization, the degree to which value is returned depends heavily on an understanding of the opportunities and challenges presented in this chapter. Principally opportunity to move away from legacy load limit constraints, to capture significantly improved RES value under LLD application.

Preliminary modelling has demonstrated how LLD approaches offer improved system flexibility, given either a diesel, or diesel hybrid architecture. Under a hybrid scenario, diesel assets are required to perform in parallel to a variable RES, and hence the requirement for flexibility is greatest. While spinning reserve or energy storage can be integrated into a system to improve RES integration, a simpler and more cost effective approach is to run your diesel generator sets at low load. As the technical barriers to low load operation are addressed, LLD presents as both an improved system security and improved RES penetration enabler, accessible to all diesel power systems.

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