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Renewable Power and Energy Fractions Revisited: Insights from ARENA's RAR Portfolio

Bert Herteleer[1], George Dickeson[1], Bradley van Ree[1], Lachlan McLeod[1], Anthony Dobb[2] and Lyndon Frearson[1]

[1]Ekistica, Desert Knowledge Precinct, 0870 Alice Springs, Australia
[2]Australian Renewable Energy Agency, NewActon Nishi, 2 Phillip Law Street, 2061 Canberra, Australia
E-mail: bert.herteleer@ekistica.com.au

Abstract

This paper discusses new approaches and applications of the Renewable Power and Energy Fractions for ARENA-supported projects in the Regional Australia's Renewables program. Insights into how the final Renewable Energy Fraction is achieved for a selection of projects are obtained, given the interaction of the demand, generation and enabling technologies for those systems. Among the presentation methods show is the Renewable Energy Fraction duration curve which demonstrates the possible paths that can be taken to increased Renewable Energy Fractions and how this affects the distribution of Renewable Power Fractions seen on those systems over the course of a year. Similarly, the comparison of the daily REF achieved versus the peak RPF for that day provides further insights to the potential challenges when systems aim for increased amounts of renewables. The evaluation of systems as a black box and the use of the total efficiency are introduced, which elucidates the extent to which additional renewable generation is useful for fuel savings. The total efficiency then allows evaluating whether employing additional enabling technologies and different operational philosophies can result in larger absolute fuel savings and show the increased whole-of-system benefits from added renewables.

1. Introduction

We presented (Herteleer, Dobb and McLeod, et al. 2017) the terms Renewable Power Fraction (RPF) and Renewable Energy Fraction (REF), with the aim of clarifying the language as well as improving the understanding of renewable integration aspects. In this paper, we use measured data from a selection of ARENA's Regional Australia's Renewables (RAR) projects described in (Herteleer, Dobb and Boyd, et al. 2018) and (Herteleer, Dickeson, et al. 2018) to derive additional insights for the integration of renewable energy, and the ability to communicate these concepts with stakeholders.

As discussed in (Herteleer, Dobb and McLeod, et al. 2017), the RPF is defined in Eq. (1)

$$RPF = \frac{P_{ren}}{P_{load}} = \frac{P_{ren}}{P_{ren} + P_{fossil} + P_{store} + P_{dsm} + P_{transfer}} [\%] \quad (1)$$

where P_{ren}: actual renewable power delivered to the load, and P_{load} is the total demand in the system under consideration. By definition, the RPF is a value between 0% and 100%, where excess (renewable) power can be stored, transferred or spilled. The Renewable Energy Fraction (REF) over a period τ is defined below in Eq. (2)

$$REF_{\tau} = \frac{\sum_i E_{Ren,i}}{\sum_i E_{load,i}} = \frac{E_{ren,\tau}}{E_{ren,\tau} + E_{fossil,\tau} + E_{store,\tau} + E_{dsm,\tau} + P_{transfer,\tau}} [\%] \quad (2)$$

Note that many of the components in Eqs. (1) and (2) can be positive or negative, depending on the direction of power or energy flow, with the convention used of power and energy flowing from generator to the load being positive. Energy stored (e.g. in a battery) is seen by all generators as an increase in the load, whereas a release of stored (battery) energy comes from that temporary generator.

One of the largest sources of misunderstanding with renewable integration relates to the differences that are observed between the instantaneous ratio of renewable power to the load (the RPF), the daily REF (REF_{day}) and the headline or target annual fraction of renewable energy, the REF_{year}. While wind and solar power are inherently linked to the vagaries of weather, a more holistic view of the system also considers how the generation and load *shapes* and *timing* of these vary throughout the day and year.

This paper further provides new applications of the RPF and REF metrics which can improve the analysis and communication of the complex operational environment for renewable energy systems on electricity grids. The ARENA-funded RAR projects discussed are shown in Table 1.

Table 1: Overview of ARENA RAR-funded projects with performance data being used

Project	PV capacity [kW_{DC}]	Wind capacity [kW]	Target REF_{year}	Data used	Enabling technologies
Weipa[1]	1,700	-	~2%	Jan – Dec 2017	None
Docker River[2]	100	-	15%	Jan – Sep 2018	None
Lajamanu[2]	400	-	15%	Jan – Sep 2018	LLD
Maningrida[2]	800	-	15%	Jan – Sep 2018	LLD
Yuendumu[2]	500	-	15%	Jan – Sep 2018	None
Daly River[2]	1,000	-	≥50%	May – Sep 2018	BESS
Coober Pedy[1]	1,342	4,100	>70%	Mar – Aug 2018	BESS, dynamic resistor, diesel UPS (DUPS), dynamic control system

[1]: These projects are owned and operated by EDL (Energy Developments Limited).

[2]: These projects are part of NT SETuP (Northern Territory Solar Energy Transformation Program), owned and operated by Power and Water Corporation.

LLD: Low-load diesel generator; BESS: Battery Energy Storage System

The concepts and applications introduced in this paper are the following:

- Evaluating the **daily peak RPF** versus **the daily REF:** the scatterplot (with each dot being one day) shows the worst (or best) peak RPF achieved on that day, and the corresponding REF obtained. This may be used to illustrate and understand how much balancing or stability issues may appear, or to communicate that grids can often handle high RPF values with current technology.

- **Renewable Energy Fraction duration curves:** By counting the number of hours where a system operates at a certain REF_{hour} and then displaying this as a cumulative portion of hours to REF_{hour} graph (similar to a load duration curve), further system comparisons can be made. This permits better understanding how various integration approaches and enabling technologies contribute to overall Renewable Energy Fraction achieved, and also suggests potential pathways to increase that system's REF.
- **Seasonality** in both the load and the generation as seen in the REF: because the REF and RPF integrate the demand and the generation in one metric, it is possible to identify and communicate which variations in the demand and/or the generation have the largest impacts on the system.
- **Total system efficiency η_{total}**: Considering the full power system as a black box model in which the inputs are fuel and renewable electricity and grid services, and the outputs are all power and grid services delivered to the grid, permits taking a holistic view on the benefits and (relative) disadvantages of renewable integration.
- **Uncertainties with higher RPF and REF values**: The change in the total system efficiency and synchronous generation efficiency for increasing REF (or RPF) values informs the financial investment case, yet the change itself is subject to increasing uncertainties. As such values are often (informed) best estimates in financial models, an improved appreciation of the uncertainty in the fuel savings is required to provide investors with sufficient clarity regarding the expected technical and financial performance of their investments.

2. Results and discussion

2.1. Peak daily RPF versus daily REF: technologies used and impact of enabling technologies

One way to evaluate how systems reach a certain REF_{day} is presented in Figure 1. This scatterplot shows how a selection of the projects in ARENA's RAR portfolio experience varying RPF_{peak} values to achieve similar daily Renewable Energy Fraction values. From a grid management perspective, maximising the REF_{day} while attempting to keep the RPF_{peak} during the day manageable is an important balance between grid management costs (high RPF_{peak} values) and renewable generation revenues (high REF_{day} and REF_{year} values). All of this however, needs to consider system security, the shape and timing of both the load and generation throughout the day and the year. A very high RPF_{peak} and very low REF_{day} indicates a poor match between generation and the load – for example, PV generation for a system where most of the demand is at night.

The peak RPF that is observed for the various systems shown on Figure 1 firstly reflects the relative size of the renewable generation capacity to the load, combined with the generator limits, operational strategy and presence (or absence) of enabling technologies such as low-load diesel (LLD) generators or Battery Energy Storage Systems (BESSs), for the period of time that there is data available. For example, Ramingining has an LLD and routinely achieves an RPF_{peak} of 90% and an average REF_{day} of approximately 20%, whereas Maningrida has diesel generators with higher minimum loading limits, and consequently its RPF_{peak} is around 60%, which then limits the average REF_{day} to around 17%.

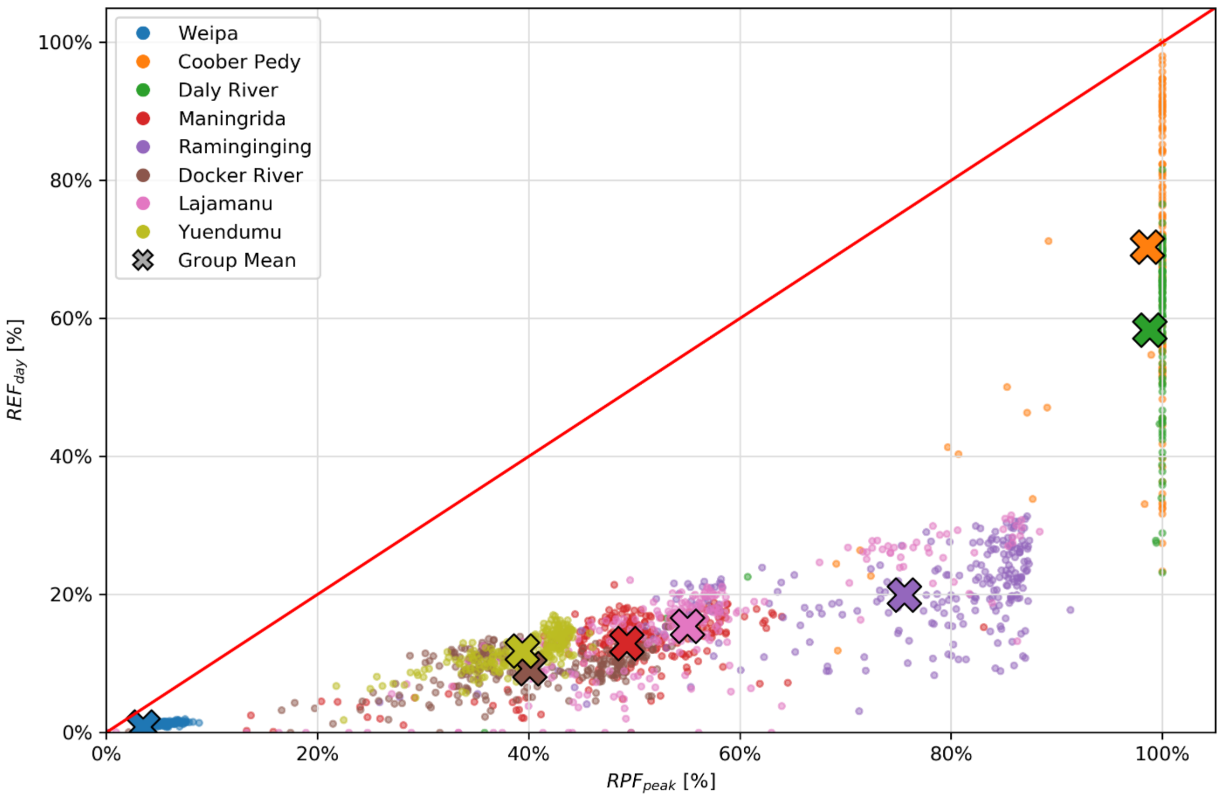

Figure 1: Daily peak RPF observed versus daily REF achieved for ARENA RAR-funded projects. The red line indicates the theoretical condition where a system operates at that peak RPF for 100% of the time. The period of data for each system varies (see Table 1), and the seasonality in both load and generation must be kept in mind.

The impact of the relative size of renewable generation to the synchronous generation is also clearly evident for Weipa: the PV system at 1.7 MW_{DC}, 1.2 MW_{AC} is much larger than any of the individual NT SETuP projects, yet in relative terms on its grid it is smaller. For Daly River, the use of the BESS and the large PV system relative to the system demand result in the peak RPF reaching 100% (i.e., the diesel generators can be turned off during several hours during the day), and thus a much higher REF is achieved, at close to 60% for the measured period. Coober Pedy is the example of the next step in the average REF achieved (average REF_{day} greater than 70% for the measured period), with moments where it operates at 100% RPF for the full day, due to the combination of wind and PV as generation sources, and multiple enabling technologies to ensure reliable operation of that grid.

2.2. Renewable Energy Fraction duration curves

For PV-only systems without storage, the theoretical number of hours in the year where the REF_{hour} > 0% is approximately 50%. In practice, as the inverters need a minimum amount of irradiance to operate, the cumulative portion of hours in the year where PV can effectively contribute to the electricity generation is limited to about 45%.

From Figure 2, it is possible to observe differences among the shown systems. For example, the impact of the relative size of the renewable generation to the demand: in relative terms, Weipa is smaller than Docker River, which is smaller than Ramingining which has the most PV installed relative to the demand, without any storage, yet Weipa's PV system at 1.2 MW_{AC} is much larger than Docker River (100 kW_{AC}) and Ramingining (500 kW_{AC}). Ramingining further benefits from the low load diesel generator in place, which increases the final REF achieved.

The jump to an REF_{hour} of 100% for Daly River is possible due to its larger PV system and large BESS, which permits operation at that level for close to 50% of the time, as it is suited for smoothing, is grid-forming (i.e. permits diesel-off operation) and has a storage capacity for load shifting of PV-stored energy over multiple hours. In the case of Coober Pedy, the presence of the wind generation being complementary to the PV (Energy Developments Limited 2018) and the enabling technologies present increases the number of hours per day (and thus per year) where there is renewable generation, resulting in 80% of the time with an REF_{hour} at or greater than 40%. (Note that a complete year of data is not yet available for most of the systems discussed and these values will change with more data and seasons covered – refer Table 1).

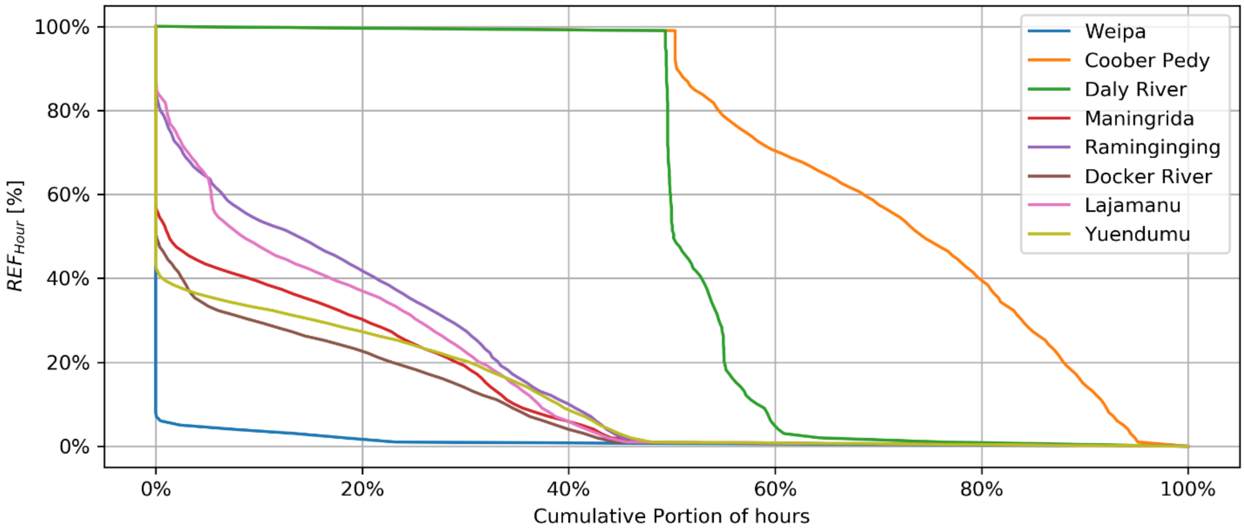

Figure 2: REF_{hour} duration curves for ARENA RAR-funded projects.

For systems with similar load and generation profiles, increasing the PV capacity without storage may follow a similar transition as shown from Weipa (REF_{year} ~2%) to Maningrida (REF_{year} ~15%). Adding more PV *and* using an enabling technology such as an LLD further increases the number of hours at higher REF_{hour} values (this is clearly visible for Lajamanu, where the LLD mode was not used all of the time, whereas Ramingining uses its LLD more often). The path to then reach a similar result to Daly River, will very likely require a grid-forming BESS with sufficient power capacity to permit operation at 100% REF_{hour}, as well as an increase in the PV generator capacity. By increasing the energy storage capacity of that BESS, the amount of time that the system can operate at 100% REF_{hour} is increased, which while expensive, may be easier to implement compared to large-scale changes in demand. For systems that have the benefit of a complementary renewable generation source to PV such as Coober Pedy, where the wind turbines also generate power at night, the number of hours in the year with renewable generation is further increased. This also shows that there are different paths to an REF_{year} value, with the availability of renewable generation sources (solar, wind, hydro, biomass) determining what additional technologies are required to reach such levels.

A further point of interest is that both Daly River and Coober Pedy see a step change from 100% REF_{hour} to a lower value (about 50% for Daly River, around 90% for Coober Pedy), which marks the transition from asynchronous to synchronous-supported operation. Conversely, this illustrates that these two systems aim to avoid operating in conditions where there may be ambiguity regarding the state and responsibility of the generation and protection systems for stability of the system.

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2.3. Seasonality

While the seasonality of the load and PV generation are generally well understood, the combined interaction of both as seen in the Renewable Energy Fraction for different seasons is also an important consideration. Figure 3 shows how the load, PV generation and REF_{hour} vary in summer (December) and winter (July) for Maningrida, which is located in the North-East of the Northern Territory.

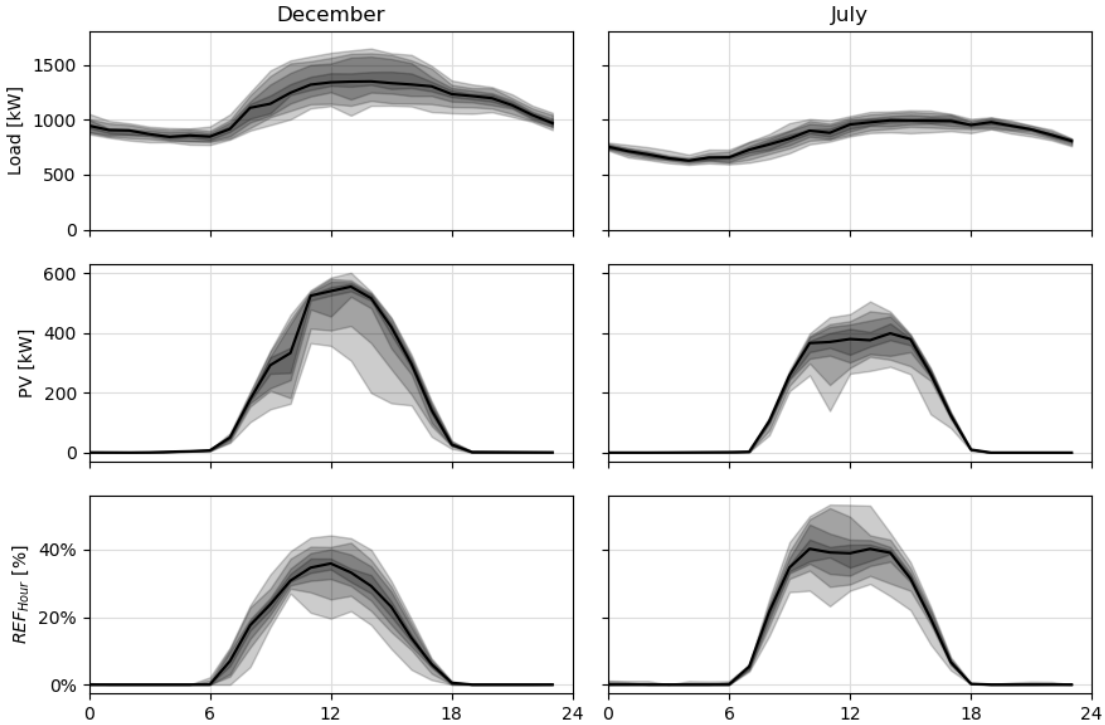

Figure 3: Daily load, generation and resulting REF_{hour} for 1 month in summer (December) and winter (July), with the darkest colour indicating most occurrences during the month.

Figure 3 shows how the variations in the load and generation profiles for Maningrida in summer and winter result in varying amounts of curtailment: the winter month with a lower load sees the PV system curtailed to ensure stable operation of the grid, given the spinning reserve and generator limit settings, whereas the higher demand in summer permits more PV power to be delivered to the load. In winter, a higher REF is achieved than in summer, yet in absolute terms, more PV energy is delivered to the grid in summer than in winter. Results such as these reinforce the need for careful consideration of metrics employed when discussing the integration of renewables on the grid.

2.4. Total system efficiency

While the Renewable Energy and Power Fraction metrics are powerful tools for understanding performance of renewable generators versus the total load, such analysis can run the risk of equating increased renewables with proportionate decreases in fossil fuel consumption and carbon emissions. In reality, an increased REF can result in changes to plant efficiency due to the reduced loads imposed upon diesel generators. In the face of such complexity, the energy inputs to outputs of a hybrid power station can be treated as a black box system, as shown in

Figure 4. This black box model description, while broad[1], does elucidate the operation of the hybrid power systems discussed here, and also serves as a reminder that the RPF and REF metrics do not cover or summarise all services required for a grid's safe and reliable operation. Some of these aspects are discussed in more detail in (Herteleer, Dickeson, et al. 2018).

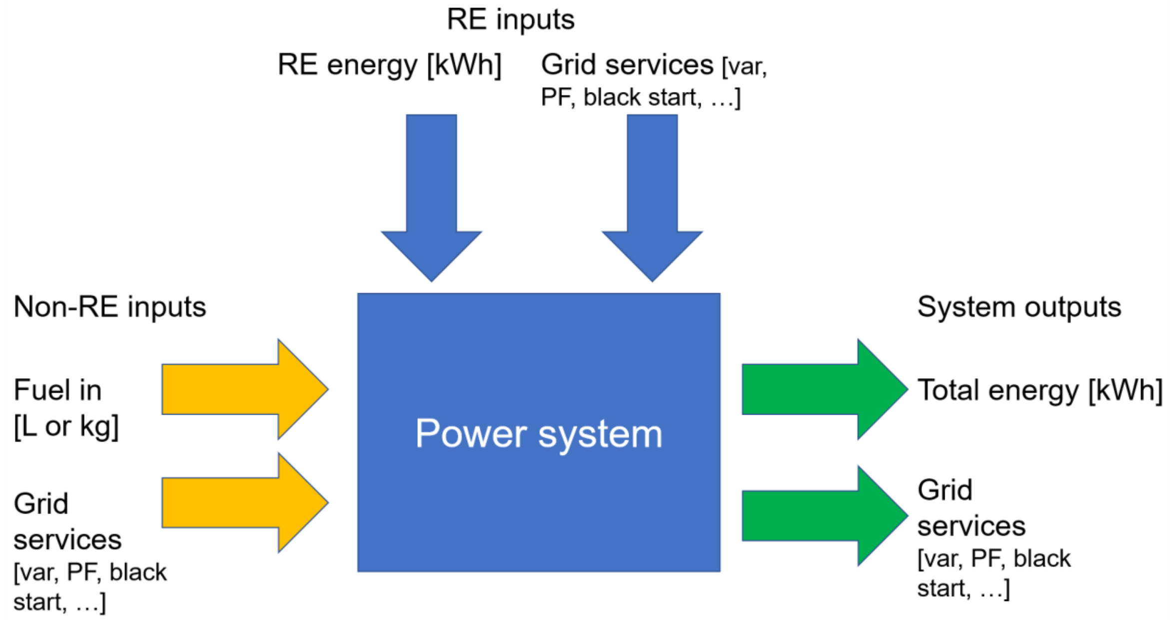

Figure 4: Black box model for a power system: at 0% REF this is a traditional system, at 100% REF this is fully renewable and it operates as a hybrid system in the stages in between.

On the energy side, the total fuel efficiency (η_{total}), defined as the total energy generated per litre of fuel consumed, can be used to better understand the true impact of renewable integration. This considers how the addition of renewables to a traditional diesel[2]-powered grid with a diesel efficiency[3] (η_{diesel}) can make each litre of fuel "generate" more electrical energy, as shown in Eq (3).

$$\eta_{total} = \frac{E_{total}}{Fuel_{total}} = \frac{E_{non-RE} + E_{RE}}{Fuel_{total}} = \underbrace{\eta_{diesel}}_{kWh/L} * \left(1 + \frac{REF}{1 - REF}\right) = \frac{\eta_{diesel}}{1 - REF}\left[\frac{kWh}{L}\right] \quad (3)$$

The simplified (theoretical) approach takes the η_{diesel} to be fixed, whereas in reality the change in the generator's efficiency as its net load decreases also needs to be considered. This is discussed in more detail below.

An example of the application of η_{total} is shown in Figure 5, which depicts the operation of the Ramingining hybrid power station over five days in July 2018. The low-load genset used can enable significantly increased renewable power fractions, but simultaneously results in decreased genset fuel efficiency. By examining the overall efficiency shown in the bottom subplot of Figure 5, the overall benefit can be clearly interpreted. This energy benefit must then be balanced against the potential of higher maintenance costs and potentially even early replacement of LLDs, which may negate some of the fuel saving gains.

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[1] For example, how do grid services "flow" through the system; how much should/can each component contribute to the grid services required to deliver the electrical energy to the end users?
[2] Diesel is used as an example here, yet the concept is more broadly applicable, for both off-grid and on-grid systems.
[3] The diesel efficiency is the inverse of the *diesel heat rate* (L/kWh or kg/kWh), which is an often-used term within the diesel-powered industry.

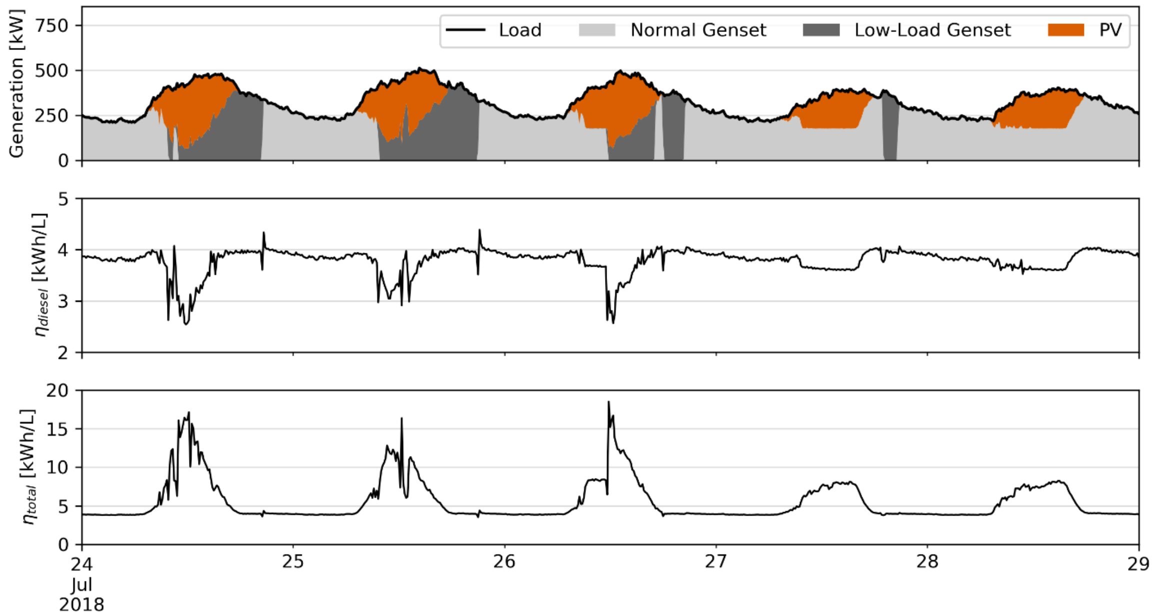

Figure 5: Time series of load and generation, diesel generator efficiency and total system efficiency for Ramingining

Given an assumption of a fixed fuel efficiency of diesel generators (an average value of 3.7 kWh/L), the expected overall efficiency of a hybrid power station can be expressed in terms of the overall renewable energy fraction, as shown in Eq (3). In practice, however, η_{total} will typically deviate from this idealisation due to the inefficiencies sustained at high renewable fractions (as demonstrated in Figure 5), as the diesel generators operate more time at inefficient loading levels, as shown in **Figure 6**.

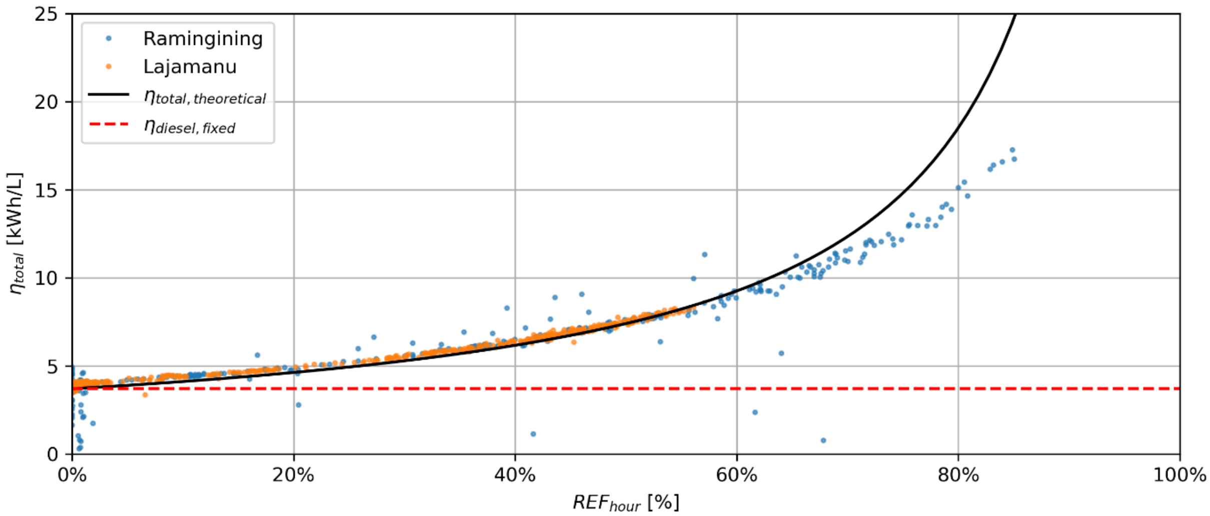

Figure 6: Total system efficiency as a function of the REF_{hour}, comparing the theoretical estimate to observed points, for Ramingining and Lajamanu.

The combined effect is still positive in energy terms for the full system, yet it illustrates how the addition of renewable energy on the grid may also lead to increased relative fuel costs for non-renewable generators. This will likely affect the profitability of non-renewable generators, as not only the total volume sold decreases, the reduced loading of generators see the cost of non-renewable generation per kWh also increasing due to the reduction in the fuel efficiency.

2.5. Uncertainties with higher REF values

While increasing the REF of a system may be desirable for economic (lower Levelised Cost of Energy – LCOE) or other considerations (climate change mitigation, noise, …), the addition of renewable generation to power systems must be financed, for which, among the standard business case considerations, the magnitude and nature of uncertainties in financial models must be considered, see (Richter, et al. 2017). For example, the estimated or modelled η_{total} value in a financial model may be input as a fixed number, which can then be subjected to a sensitivity analysis.

As **Figure 6** illustrates, the theoretical η_{total} for increasing REF resembles a hyperbolic growth curve, which reaches infinity when the REF approaches 100%, whereas the average of the observed η_{total} deviate downwards from this theoretical line: there is a limit to the efficiency gain that can be achieved *while the (diesel) generator runs*: Diesel generator fuel consumption can be split into a fixed and variable portion, with the variable portion of fuel usage declining for increasing REF and RPF. The combined uncertainty of the likely decrease in η_{diesel} (in more general terms, $\eta_{non\text{-}RE}$) and the change in the η_{total} can be significant, especially for REF_{year} values above 70-80%. This is an area where much more work will be required to provide sufficient clarity and certainty for financing institutions.

Looking back to Figure 2, it also shows that in the region of 80-99% REF_{hour}, it may be better to switch to a diesel-off mode sooner (i.e. have a step-change from a predetermined REF value to 100% REF), as the marginal gains in fuel savings are likely not worth the increased operational risks, without the use of other enabling technologies to ensure safe operation – a BESS for Daly River and a combination of enabling technologies at Coober Pedy. These issues have also been identified and discussed by (IRENA 2017), (International Energy Agency 2017), (Herteleer, Dickeson, et al. 2018) and (Energy Developments Limited 2018).

As such, increasing the REF without considering the potential ramifications (e.g. on the basis of **Figure 6**) is not necessarily the best or even intended outcome for power systems, but rather the combination of reduced lifetime costs as captured by the LCOE, which reflect capital and operational expenditures (CAPEX and OPEX) – the latter metric including fuel costs or savings, combined with reduced emissions.

A further point here is that there are a multitude of possible paths to reach a certain REF value: for example, to reach an REF of 50%, well-sized PV with a large BESS and frequent moments of 100% RPF can be used, or operation with synchronous generators (LLDs, for example) with PV and wind can also result in an REF of 50%, yet the fuel savings for both systems will be different. This path *independency* between different projects to reach similar REFs makes the evaluation and comparison between these subject to careful considerations, as each project has its specific local context, reliability requirements, and load and generation profiles.

3. Summary

This paper expands the application of the Renewable Power and Energy Fraction metrics and presents new use cases for analysis and communication. Looking at the daily peak RPF versus daily REF, it is possible to observe the likely balancing and ramping impacts for each system, versus the renewable generation. By then also taking the concept of load duration curves and applying this to the hourly REF over the year, different projects can be compared, which permit a deeper insight as to the relative sizes of PV systems versus the total demand, and the impacts that enabling and other renewable generation technologies have on the performance over the period considered.

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Taking a whole-of-system view, the total system efficiency η_{total} can be related to the Renewable Energy Fraction and, at short timescales, the Renewable Power Fraction. This then can be used to obtain new insights into how the complete system (renewable and non-renewable generation) results in fuel savings which cease to grow, or may even decline, for high REF values. Consequently, step changes from synchronous-supported operation to renewable-only operation with grid-forming capabilities and (essential) ancillary services will be likely, unless synchronous generators are operated for grid stability and reliability purposes. The uncertainties around the effective total efficiency as a function of the REF are an area where much more work will be required to provide sufficient certainty to finance high-REF systems.

Lastly, the use of the RPF and REF for analyses must be performed while considering the full context of the system(s) under study, as these metrics cannot capture all non-energy related aspects. Equating similar REF_{year} results with similar fuel savings for different systems and technologies employed is an approximation that rarely will hold true, and it is important to understand and communicate that reliable, low-emissions and cost-effective generation of electrical energy depends on the provision of energy *and* multiple ancillary services to consumers.

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