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Understanding Integration Aspects: Renewable Power and Energy Fractions

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Abstract

This paper introduces the Renewable Power Fraction and Renewable Energy Fraction as self-defining metrics to quantify and visualise the performance of renewable generators versus the total load, and show how corresponding Fossil or Demand Side Management Power and Energy Fractions can similarly be defined. Example use cases of the Renewable Power and Energy Fractions illustrate the applications of these metrics in both stand-alone grids, as well as portions of interconnected grids, for a variety of renewable generating technologies. The daytime Renewable Energy Fraction is also defined for use with solar technologies. The term renewable participation instead of penetration is suggested, to better discuss the role of renewables on the grid and to future-proof the terminology. By using the Renewable Power and Energy Fraction metrics, regulators, funding bodies or investors can form an intuitive view of how the renewable generation will interact with other generators and the load, and better understand the potentially large divergence between the annual Renewable Energy Fraction, and the day-to-day impacts such decisions entail. The improved clarity in lexicon will permit social license aspects of integration of renewable generation on the grid to be better addressed.

1. Introduction

Historically, the term (renewable) "penetration" has been used to describe and communicate the impact of non-dispatchable renewables on a (traditional) fossil-powered grid, and often but not always has the following meaning: the fraction of energy supplied by renewables, compared to the total energy delivered by all generators to the load for that grid. However, the same terminology of “penetration” is also used to describe the fraction of power delivered from renewables to the total load at that instant (Seguin, et al. 2016). Others, such as (Hancock 2011), (Lilienthal 2007) distinguish between power and energy penetration (Power and Water Corporation 2014), or call it power penetration / energy contribution, renewables portion or percentage, but as yet, there is no consensus regarding which terms to use to describe and understand the impact of renewables on the grid.

To reduce the ambiguity in communication and understanding regarding the impact of renewables on the grid, we propose new terms and definitions to discuss how much generators contribute to the power and energy needs of a grid’s load: the Renewable Power Fraction (RPF) and the Renewable Energy Fraction (REF). These metrics are, respectively, similar to the normalised efficiency (Herteleer, Huyck, et al. 2017) and Performance Ratio (International

Electrotechnical Commission 2017) for photovoltaic (PV) systems, although focused on the system integration aspects. The key point of the RPF and REF is that both the load (demand) and generation (supply) are considered together, and that a more holistic evaluation and communication is made possible. The RPF and REF can be used to analyse, visualise and monitor the performance of renewable generation compared to the total load, and form part of a larger toolkit to understand performance and integration of these resources.

The reader may ask why would we need new definitions which may be more cumbersome in daily parlance than “penetration”? The need for the Renewable Power and Energy Fractions stems from having to distinguish between the instantaneous and the long-term impact of renewables on the grid: “are we discussing the power or energy fraction of the total (and over which interval), and of which portion of the grid?”. Moreover, the REF and RPF are self-explanatory and remind the audience of their definition. As we show in the remainder of this article, the RPF and REF lend themselves well to visualisation and summary statistics, and enable better understanding and communication regarding the integration of renewables on the grid.

1.1. Definition of Power and Energy Fractions

For a renewable generator, the Renewable Power Fraction (RPF) is the power delivered by the renewable generator for use by the load, divided by the total power required by the load, within a defined area of the grid under consideration. In most cases, particularly for off-grid applications, this will be the whole grid, but it lends itself to use for portions of the grid, such as a feeder, an area served by a transmission line, or a state or province. The RPF is defined in Eq. (1)

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

where P_{ren}: renewable power, P_{fossil}: fossil-fuelled power, P_{store}: power delivered from a stored energy system (battery, flywheel, ...), P_{dsm}: demand-side management power, and $P_{transfer}$ the power that is imported or exported for larger grids, e.g. for states, or distributed generation over multiple feeders. Similarly, the Fossil Power Fraction (FPF), Stored Power Fraction (SPF) and Demand Side Management Power Fraction DSM-PF can be defined, if these are present in the grid, or part thereof considered.

An Energy Fraction represents the portion of the total energy serviced by a technology, over a defined period. The Renewable Energy Fraction (REF) over a period τ is defined below in Eq. (2), and the Fossil Energy Fraction (FEF), Stored (SEF), and Demand Side Management (DSM-EF) can be used as needed.

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

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. Generally, the (implicit) REF that is most often used by regulators, governments and agencies is the $\mathrm{REF}_{\mathrm{year}}$ or $\mathrm{REF}_{\mathrm{annual}}$. In many cases, the area and the period for which the RPF and REF are calculated will be clear from the context, yet it is important to clarify this for certain cases, as the conclusions that can be drawn from these can vary significantly, as discussed further below.

The use of the metrics defined in this paper allow Ekistica and ARENA (and stakeholders in general) to better understand and quantify whether the projects are delivering on the promised levels of renewable power generation on the grid, while also permitting data to be anonymised if needed, and allowing communication about ARENA-supported projects to occur. More broadly, the RPF and REF as metrics allows clearer communication and understanding of the issues relating to the integration of renewables on the grid, for both isolated or stand-alone grids, and larger distributed grids.

Whereas a high value for the Renewable Energy Fraction does imply a correspondingly high value for the Renewable Power Fraction over the course of a day or a year, this assumption is not necessarily valid for lower Renewable Energy Fractions: it is possible to have a low amount of energy served by the renewable generator, yet have moments of the grid observing a high portion of power from renewables: a high Renewable Power Fraction. This may be due to a poor correspondence between the load’s and the renewable generator’s generation profile. For example, a site where the load drops during the daytime, and increases at night, while having PV as the main renewable generation source may *behave* or impact the grid as if it were larger than the annual or long-term REF value suggests.

When considering solar power without storage (PV, or solar thermal), it is also useful to focus on the special use case of Eq. (2): the daytime REF as defined in Eq. (3)

$$REF_{daytime,\tau} = \frac{E_{Ren,daytime,\tau}}{E_{load,daytime,\tau}} = \frac{E_{Ren,daytime,\tau}}{E_{total,daytime,\tau}}\ [\%] \qquad \mathbf{(3)}$$

The daytime REF indicates which portion of the energy during daylight hours is serviced by solar power (or more broadly, a source of renewable energy with a predictable or scheduled operational window), and conversely, how much energy needs to be obtained from different sources during the night. This is especially important for diesel- or gas-powered grids which are hybridised with PV, as the value of $\mathrm{REF}_{\mathrm{day}}$ is less than or equal to $\mathrm{REF}_{\mathrm{daytime}}$, reflecting the higher energy use over 24 hours versus the portion of the day where solar energy can be used directly. Focusing only on $\mathrm{REF}_{\mathrm{day}}$ (or $\mathrm{REF}_{\mathrm{year}}$) would under-estimate the potential and likely impact of PV on the grid, which then increases stakeholder engagement risks (Herteleer, Dobb, et al. 2017), and where the key stakeholders such as the grid operator, the regulator (if applicable) or end users have not had much experience with the technology.

One consequence of the above is that there are and have been wildly varying interpretations for what constitutes low, medium and high penetration (or *participation*[1]) of renewables on the

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[1] We suggest the use of the word participation over penetration, as the term is less emotionally loaded and future-proof: for systems dominated by renewables (i.e. $\mathrm{REF}_{\mathrm{y}}$ >50% & $\langle \mathrm{RPFmax} \rangle_{1h}$ ≥ 100% and especially for $\mathrm{REF}_{\mathrm{y}}$ >

grid, which reflect the knowledge, experience and risk awareness profile of the stakeholder using these terms, and how these evolve over time. Similarly, the technical and regulatory characteristics of grids or parts thereof may result in very different consequences. For example, given an identical load and renewable generation, but different types of fossil-powered generators on-site, one system may be classified as low renewable participation and needs few variability mitigation measures, whereas another system with less fossil-powered flexibility (e.g. older generators) would require mitigation measures commensurate with a medium participation classification.

While it is beyond the scope of this work to quantify the limits, we do note that classification of the (potential) impact of renewables on the grid is generally better served by the RPF than the REF, as mitigation strategies for grid stability are much more focused on the short-term power contribution, rather than the longer-term energy involvement. Best classification and communication results will likely be achieved with RPF-REF pairs, and further work will explore such limits. In what follows, we present a few use cases of the Renewable Power and Energy Fractions, and how this lexicon can be used for analyses and communication with stakeholders.

2. Example use cases and applications of the Renewable Power and Energy Fractions

2.1. *PV only: seasonality of load and generation*

The seasonal and daily variation of PV is well-known, yet its interaction with the load is occasionally forgotten. The value of using the REF and the RPF to better visualise, understand and communicate on the interaction of the load and the renewable generation is illustrated in Figure 1, where much higher values (and day-to-day variations) are shown in the RPF zoom on

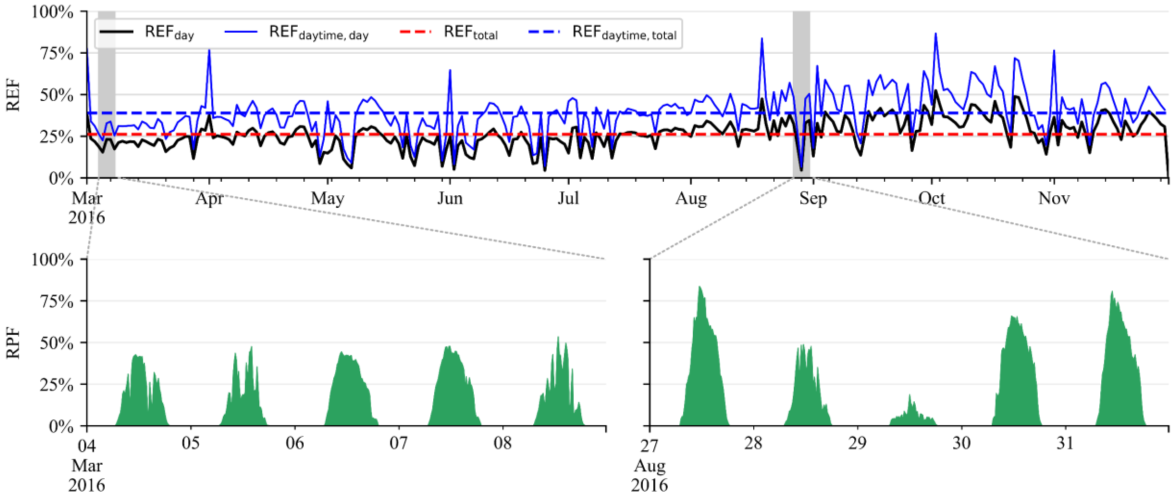

Figure 1: REF_{day}, $\text{REF}_{\text{daytime}}$ and the respective $\text{REF}_{\text{total}}$ for a solar-diesel project. The seasonality of both load and generation is visible in the REF_{day}, $\text{REF}_{\text{daytime}}$ and maximum RPF values.

75% & $\langle \text{RPFmax} \rangle_{1h} \geq 100\%$), it can be argued that the term *fossil*-powered “penetration” is needed, and that for both cases, the term “participation” over “penetration” treats both generation types equitably.

the end of August, versus the RPF zoom for March. Figure 1 is a PV-diesel isolated grid project funded by ARENA, with the feeder on which this PV system is installed operating without curtailment.

Figure 1 also shows how the long-term REF hides the variability of the daily REF, and points to the potential risks of focusing on one single summary value ("REF$_{\text{total}}$ = 24%"), over understanding that over the months considered, the REF$_{\text{day}}$ varies from lows of 5% to highs of more than 40%, and that the RPF can exceed 75% in this example: the peak RPF observed is thus more than 3 times the total or year-to-date REF. When looking at the daytime REF (REF$_{\text{daytime}}$), the shorter period (roughly 12 hours, versus 24 hours in one day) over which the ratio of generation to load is computed further shows the higher relative impact of the PV generation during the daytime hours: the total daytime REF is 39%, or almost 1.5 times the REF$_{\text{total}}$.

This also shows how projects with PV as the primary (or only) renewable generating technology can impact the grid much more than the long-term summary metric suggests. Compared to the daily Performance Ratio (PR$_{\text{day}}$) of a well-working system, the variation of the REF$_{\text{day}}$ and REF$_{\text{daytime}}$ is potentially much larger, as both the numerator (the PV generator in this example) *and* the load (denominator) vary. Hence, it is possible to use graphs such as these to communicate with, and educate, stakeholders that there is much more to be considered than the single annual Renewable Energy Fraction target value.

For reporting on projects where anonymity is not required, graphing absolute values for the component technologies, as well as using graphs of REF and RPF then permits identifying whether the load or the generation has the largest variation, and which corrective measures (Frearson, et al. 2015) need to be taken, if required. One such example of the use of corrective measures is Figure 2, where the PV system is able to provide approximately 15% of the energy over the interval shown, yet with moments where the RPF exceeds 75%, while the battery system ensures that the diesel generators function within their operational boundary limits.

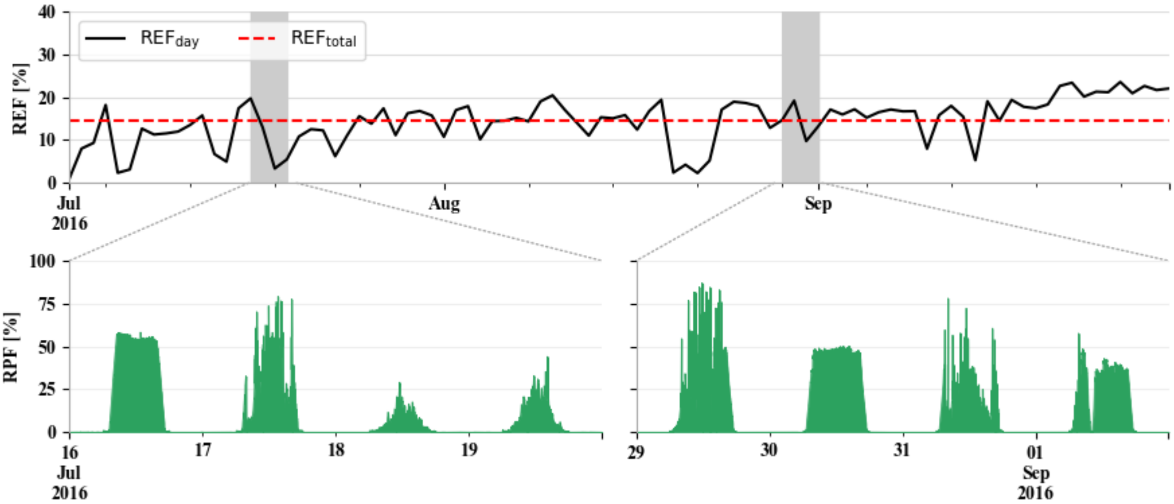

Figure 2: The Renewable Energy Fraction and Power Fractions over a few months for a PV-diesel system with battery storage and comparatively high night-time loads.

The large difference between the REF$_d$ and RPF points to both variations in the solar resource, as well as the load, as the typical peak RPF during the day is around 55% for the period shown. Further, this system has a comparatively high night-time load, which thus also indicates that, to achieve higher REF values, a variety of measures may be employed, from a much larger PV system, using wind power, or significant load shifting towards the daylight hours to better coincide with the solar generation profile.

2.2. Multiple renewable sources

The RPF and REF lend themselves well to communicate how much renewable generators and technology types contribute to the total load, as shown in Figure 3, which was created from data obtained from AEMO for the state of South Australia (AEMO 2017). From this and similar figures, it is possible to read the highest and lowest contributions of renewables to the state's total power demand, which helps in communicating with the wider public about the current state and potential for further investment in renewable generation to the total load. Importantly, the RPF and REF may also point to actions that can be undertaken on the load instead of generation, such as ARENA's demand side response funding (ARENA 2017), and is thus a further illustration of these concepts stimulating the audience to take a holistic view of the entire system under consideration, whether that is the National Electricity Market (NEM) in Australia, or a state's contribution to the whole.

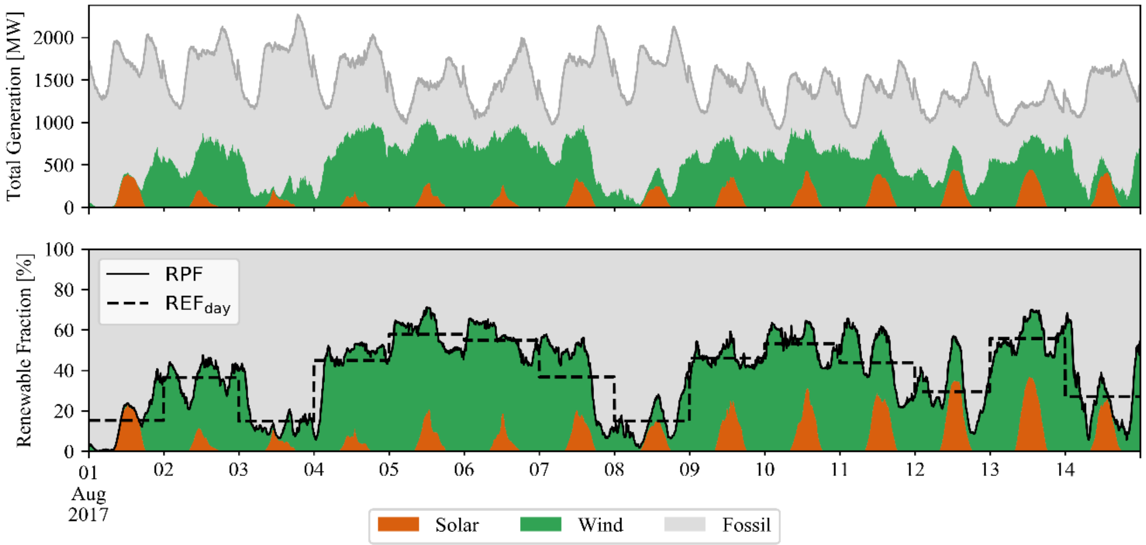

Figure 3: The RPF and REF$_{day}$ and the renewable technologies that contribute to it for the state of South Australia over the first two weeks of August 2017, contrasted with the absolute values.

Figure 3 shows how the RPF and REF combine the demand with the generation into one metric, and that a high(er) RPF does not necessarily imply higher renewable generation. This is clearly visible around midnight of 6 August 2017, where the decrease in the load with an almost constant participation of wind results in an increase of the RPF. From this graph, it is also possible to appreciate the relative contribution of solar PV versus wind, which is the dominant source of renewable power and energy in South Australia. The daily REF also illustrates how these numbers may have very different RPF values behind these. For example, 1, 3 and 8 August have almost identical values for the REF_d, with 1 August's REF_d being primarily due to PV's contribution and thus has a much larger spread in minimum and maximum RPF values than the much more constant RPF value on 3 August, and a clear RPF peak visible on 8 August.

Overall, Figure 3 shows the value and benefits of diversification and physical separation versus the cases shown in Figure 1 and Figure 2, where the renewable generator is much more concentrated and currently of one type only. Such risks are known for (smaller) isolated grids, yet often poorly formulated, resulting in the potential for delays or the need for continued stakeholder education (Herteleer, Dobb, et al. 2017).

Figures such as these permit communication on the different generation technologies used, allowing the audience to appreciate the potential impacts of having PV and wind power coinciding (as visible on 12 August, for example) or complementary, such as on 3 August, and can show how high or low the instantaneous participation of renewables can be on the grid, and how this likely differs from the Renewable Energy Fraction over the period considered.

2.3. Challenges not fully addressed by the RPF or REF

Even though the RPF, $REF_{daytime}$ and REF enable many types of analysis and can improve communication by either improved visualisation or the use of agreed-on metrics, these cannot address all needs of stakeholders and end users. Similarly for PV systems, depending on the situation, the absolute yield, relative yield, Performance Ratio or normalised efficiency may be analysed, and users of these tools have to be mindful of their respective strengths and weaknesses. The following examples discuss some of the challenges not fully addressed by the RPF or the REF.

In the case of isolated or stand-alone grids where an investment in solar power is aimed at diesel fuel consumption displacement, the REF does not give a correct quantification of the amount of fuel saved. To an extent, this is a logical result, as fuel savings (or lack thereof) depend on a multitude of factors, many of which are due to the nature of the generators in question, as well as other factors such as the weather (for the fuel savings baseline) and the load patterns. However, the REF_{month} and REF_{year} could be used to illustrate the variation in the generation and load throughout the year, and to reach a better understanding of when the fuel savings can be expected.

The RPF and REF graphs require the audience to interpret the images with care, as the interpretation of percentage[2] values, and subsequent relative or absolute differences may result in the wrong conclusion(s) being drawn. In the context of interpreting RPF and REF values, variations in these values can be caused by *both* the generation and the load. As many attempt to address such analyses from a generation-dominant or load-dominant perspective, the wrong

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[2] For example, a change in the RPF from 20% to 25% is a 5 percentage-point increase, but results in this example in a relative increase in the RPF of 12.5%. Is this change due to the renewable resource increasing, due to the load decreasing, or a combination? This is not answered by an RPF graph on its own.

conclusion could be derived. It is therefore important to verify assumptions and conclusions by also looking at absolute values or other known performance metrics such as the Performance Ratio or the normalised efficiency. While the REF and RPF scale with the load over the day, and then over the year, the renewable generator may be producing significantly different amounts of energy in summer versus winter, but if the load has changed in the same manner, these changes are not observable from RPF or REF graphs in isolation.

The consequences for the grid or portion considered, of achieving a certain REF or RPF value can also vary significantly. This contrast is especially important between isolated or off-grid situations, and grid-connected systems: for example, both may achieve an identical $\mathrm{REF}_{\mathrm{year}}$ value, but the grid stability and mitigation strategies that need to be employed are strongly context-dependent and thus will very likely not be identical: in one case, it may suffice to have battery storage on standby or the spinning reserve of diesel generators, in the other, other generators will need to be involved, and demand management or other additional strategies may be required.

3. Conclusions

This article has introduced new definitions to characterise the behaviour of renewables on the grid: the Renewable Power Fraction, the Renewable Energy Fraction, and the daytime Renewable Energy Fraction for solar technologies. These terms and metrics can form part of the lexicon to evaluate, monitor and communicate on the integration of renewables on a grid or portion thereof. The RPF and REF lend themselves for analyses for entire, fully isolated (“off-grid”) systems, as well as portions of larger grids in the grid-connected case. The RPF and REF also have a key benefit in being self-explanatory to the audience, more so than terms such as penetration or contribution, and permit an impartial discussion among investors, generators, regulators and end users of (renewable) energy.

The use of the RPF and REF encourages a more holistic view of the electricity system, as variations in the supply-side (generation) and the demand (load) are considered together. Where results are not anticipated or appear counter-intuitive, these metrics can then form the starting point for more in-depth analyses, where a judicious use of the analysis and visualisation tools at our disposal is necessary. To improve on the social license for all types of renewable generation, we recommend utilising long-term daily Renewable Energy Fraction and Power Fraction images, similar to those shown in this paper over the course of various months to one year, to communicate in an analogous manner to long-term images for the daily Performance Ratio.

As has been shown in this paper, summary metrics such as the daily or annual Renewable Energy Fraction encompass a wide range of shorter-term values that may exhibit much more variation. Visualising such changes, from either modelled or measured data, then allows an informed discussion, and where needed, education of stakeholders. While no single metric will solve all communication and stakeholder engagement issues, a shared lexicon to discuss and understand to which extent renewables contribute positively or negatively to the (local) grid is of importance if RPF and REF values for grids worldwide grow as current trends indicate. The improved avenues of communication using the terminology of this paper can be a further step in addressing some of the structural barriers for increased uptake of renewable energy.

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