



Original research article

# Flexibility, dynamism and diversity in energy supply and demand: A critical review

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## ARTICLE INFO

### Keywords:

Flexibility  
Demand response  
Efficiency  
Whole-systems

## ABSTRACT

Flexibility is vital to the operation of electricity systems. It ensures that the system can keep supply and demand in balance in real time. Until recently the provision of flexibility was a fortunate by-product of thermal power generation using fossil fuels as a convenient storage medium. The rapid emergence of renewables poses a major challenge to this model. As thermal power stations are increasingly displaced with more variable renewable sources of electricity, new forms of flexibility are urgently needed. Two promising candidates for this role are energy storage and demand side response.

This paper argues that in low carbon systems flexibility may at times and in certain places supersede the need for component efficiency, in order to improve overall system efficiency. We reach this conclusion after reviewing the origins of flexibility on the supply and the demand side. In both domains the concepts of material redundancy, tolerances and skills are pertinent and help our understanding of the potential for and limitations to flexibility.

On the demand side new capacities may need to be developed, including skills and societal norms, if the gap between technical and realised potential is to be closed.

## 1. Introduction

Modern society has achieved a remarkable and near complete decoupling in the temporality of consumption from locally available resources. Food, water, energy and even information are now available ‘on demand’. This achievement was made possible through a combination of extensive networks and storage embedded throughout the supply systems.

Where these infrastructures exist, foods can be consumed at any time of year, regardless of seasonality or origin; water is available irrespective of recent local rainfall; and information is reaching similar levels of ubiquitous availability via data centres (stores) and the internet (network). Energy, too, has become available as and when needed. The expectation level of this provision has become such that even brief supply disruptions can be perceived as crisis-like events.

Consumption patterns in all these domains are demand-driven. Infrastructures are specified and sized to meet whatever the demand side ‘demands’, a paradigm known as ‘predict and provide’. The relative ease with which fossil fuels can be extracted, transported and stored has allowed for these structures to develop at acceptable (economic) costs. Renewable low carbon generation, which is more dependent on temporally changing resources, would be more costly to integrate at scale

under this paradigm. It has been shown that the overall cost of energy systems would become highly sensitive to the ability of demand to respond to the availability of low cost/low carbon sources. By 2030, the UK’s National Infrastructure Commission estimates that up to £8.1bn could be saved annually if ‘smart solutions’ are taken full advantage of [1].

A return to more sustainable societies may therefore necessitate among other things a re-appreciation of the rhythms, seasonality and availability of local resources. To what extent electricity demand can be flexible and contribute towards this effort remains subject of much conjecture [2–4].

This paper reviews the origins of flexibility in systems of energy provision and use. It explains how the emergence of low carbon sources challenges conventional models of planning, operation and markets. This is followed by an attempt to unpack the concept of flexibility on the demand side, with the aim to improve the often vague discourse in relation to Demand Side Response (DSR) measures. We conclude with recommendations to address this gap with new sources of data.

### 1.1. Different capacities: energy, power and flexibility

A clear understanding of the relationship between energy, power

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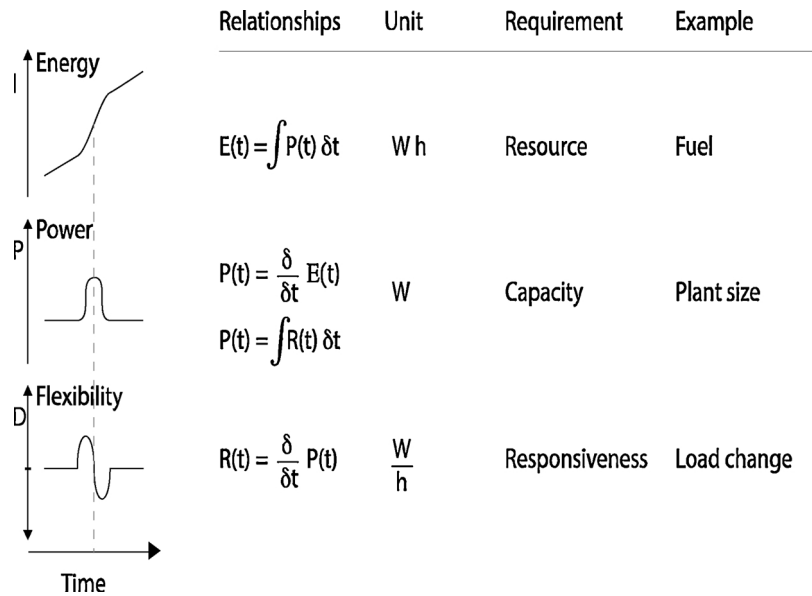


Fig. 1. Energy, Power, Flexibility – a relationship of derivatives.

and flexibility is important for this discourse. Fig. 1 provides a framework with places flexibility as a derivatives of energy and power. The rate at which energy is consumed over time is power. When the rate of energy consumption increases, as shown by the steeper slope in the middle section of Fig. 1, more power is required to serve this need. The relationship between power and flexibility can be seen as analogous. When more power is required, generators have to ‘ramp up’, which calls on their flexibility to deliver a change in power output.

Confusingly, the term ‘capacity’ is applied in the context of all three – energy, power and flexibility – but with very different meanings. In power generation and networks ‘capacity’ refers to the maximum power that can be delivered, measured in Watt. From a systems perspective the rated power of an individual component is less relevant than its ability to deliver power when needed. For this the concept of ‘capacity credit’ has been introduced, which is a probabilistic measure of the ability to contribute towards peak demand requirements. For a stand-alone wind turbine this can be as little as 10% of the rated capacity, for PV in the UK it is closer to zero, due to the fact that the sun doesn’t shine during the typical winter evening peak demand.

In the context of storage, capacity usually refers to the maximum amount of energy that can be held in storage (Watt × hours).

The capacity to be flexible is a different concept altogether. We will use it here to signify a potential to change power at a certain rate (Watt/hour).

From a demand side perspective energy, power and flexibility also provide meaningful distinctions. Much attention on the demand side has focussed on efficiency, demand reduction and sufficiency, which are means by which to reduce the amount of energy required [5,6]. More recently interest has turned to addressing issues around peak demand, which is a measure of power [7]. Flexibility of demand is beginning to be explored in the form of demand response as part of load shifting initiatives [8–10].

### 1.2. The role of efficiency

The relationship between efficiency and flexibility is nuanced and interesting. Energy efficiency (minimum energy input for maximum energy output) is a meaningful concept for fossil fuel based generators, where fuel is the constrained and valuable input. For renewables the input is a zero cost sustained resource and the same measure of efficiency is not as meaningful. Here energy output is better measured against constrained inputs such as investment cost, space requirements

or environmental impact.

On the demand side efficiency often refers to units of energy service per unit energy on the assumption that energy is a constrained and valued input. In practice some people feel more time than energy constrained and thus argue that filling the kettle to the top is more efficient, because it reduces the number of times one has to fill it, thus saving valuable time.

Framing therefore matters in efficiency and for system efficiency in particular. Energy system efficiency is a complex combination of component efficiencies and by no means the sum of them. For fossil based systems, efficiency results in fuel savings, which coincide with cost and emission savings. However, with the emergence of renewable resources the value of efficiency becomes highly dynamic and time dependent. At times of surplus generation, when the energy input is not constrained, reduction of demand has no benefit for the system. Conversely, at times of supply shortage, such as during peak demand with low renewable generation, load reductions can have significant cost (operational and investment), emission and security benefits.

This new dynamic requirement for load changes puts flexibility in a similar relation to low carbon system-efficiency as component-efficiency has for high carbon systems. Whereas load reduction makes high carbon systems run more efficiently (more energy service with less fuel), it is flexibility that could do the same for low carbon systems, by potentially delivering more energy services with less constrained resources.

In the following Section we will explore the origins of flexibility on the supply side, before doing the same for the demand side. This process is intended to highlight some fundamental requirements for flexibility to be present and means by which to engage them.

### 1.3. The need for flexibility in low carbon systems

The dramatic fall in the costs of renewable energy and their rapid deployment is challenging existing systems and market structures [11]. This has two reasons: 1) many renewable sources of electricity have negligible running costs and 2) their output is less controllable than the sources they displace. Much is made of the second point in public debate, but it could be the less important of the two [12]. Variable supply is no different from variable demand in a system context and systems always had to cope with variable demand. Grunewald and Torriti [13] found that load profiles have become less variable over the past 30 years and the ratio of peak to mean demand has fallen. An increase in

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