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Sustainable energy systems in an imaginary island

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ABSTRACT

The study of sustainable energy systems is an interdisciplinary endeavour which entails the analysis of a large amount of diverse data and complex interactions that are better understood if developed from first principles. This paper reviews the approaches to this analysis and presents as a general case study, a fossil free imaginary island whose electricity, heat and mobility demand are fulfilled with sustainable and renewable energies only. The detailed hourly balance between supply and demand highlights the importance of energy storage, which is achieved by reversible hydropower and storage in electric vehicles.

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1. Introduction

The analysis of a sustainable energy system is a complex interdisciplinary exercise that involves a thorough understanding of technology, physics, electrical engineering, modelling, economics and sociology. Teaching energy systems, in particular to a heterogeneous audience, thus becomes a challenge which can be facilitated by the development of particular case studies that illustrate the most relevant issues that can emerge in this area.

Sustainable energy systems are usually approached with the support of software packages designed for that purpose [1]. However, from the educational point of view, it is more interesting to tackle the problem from scratch. The results will certainly be less realistic as assumptions will be made to make the problem more tractable in the available time frame. This methodology may also be useful at the early stages of a feasibility analysis for a particular project. It provides a comprehensive view of the problem, of its variables and constraints, which is a crucial requirement for choosing the most suitable software package for further in-depth studies. Additionally, hidden parameters and variables are exposed to those outside the renewable energy circle, such as policy makers and investors.

Our study departs from a fictional case study, which has served as the backbone of a course on sustainable energy systems for engineering students at the University of Lisbon. Its overall purpose is to design a fossil free energy system for an isolated region, an imaginary remote island whose main characteristics were arbitrarily set and are presented in Table 1. Besides this, the only data used are the solar radiation, wind speed, temperature and precipitation time series, and typical load diagrams for the corresponding climate data.

This paper presents an overview of the state of the art Sustainable Energy System (SES) methodologies for isolated systems and describes the complete analysis of the energy system of the fictional case study, including electricity supply and demand, heating and mobility, thus detailing the methodology used to build a 100% renewable energy system from scratch. This methodology requires reviewing the different renewable energy technologies, energy demand conditioning tools and energy storage alternatives, which are extensively discussed.

2. Overview of SES analysis

Sustainable energy systems with 100% renewable energy share require an understanding of the renewable energy resource characteristics and availability and how can the different available technologies be integrated and managed in order to meet the energy demand. A well cemented understanding of the problem should be built upon a gradual approach, starting from basics and preferably without the use of a dedicated computer tool for the purpose that, more often than not, acts as a black box to the user. This approximation allows gaining sensibility to the subject, which enables the proper choice of the appropriate tool for a particular application, helping in the preparation of the input data and the critical analysis of the outputs.

Table 1
Island general assumptions.

Population	50,000
Population density	100 person/km^2
Average family size	2.5 person
Number of cars	0.5 car/person

An approach of this type is presented by Mackay in 'Without the hot air' [2], a well-known and fruitful discussion of sustainable energy systems from first principles. Here, the potential of different renewable sources for the UK are individually analysed and are then articulated to match energy demand. The potential of energy storage is briefly reviewed, but it is only considered on an annual scale and not on a more detailed level, such as on an hourly scale. It concludes that in UK around 92% of the energy demand can be fulfilled by renewables. However, an integrated sustainable energy plan requires temporal simultaneity of energy consumption and production, an analysis not performed in 'Without the hot air'.

Jebaraj and Iniyan [3] present a broad review of energy models. They identify various emerging issues related to the energy modelling, covering models of energy planning, energy supply and demand, forecasting, renewable energy, emission reduction and optimization. Also, models based on neural network and fuzzy theory are reviewed and discussed. On the other hand, Connolly et al. [1] review computer tools for analysing the integration of renewable energy into energy systems. In order to aid the selection of a suitable energy tool for a particular application, 37 different software tools are comprehensively analysed. The paper contains individual descriptions of each of the energy tools reviewed, outlining the context of the information provided, and provides a sample of the existing studies completed by each of the energy tools in consideration. The authors conclude that there is no energy tool that addresses all issues related to integrating renewable energy.

Wide analyses of particular 100% renewable energy systems have been conducted in many studies and a review of them is presented by Lund et al. in [4]. The range of applicability goes from the town level to global scenario level, including countries of different sizes although none is focused on small isolated regions. Østergaard and Lund [5] outline the energy situation of the Danish city of Frederikshavn, including all electricity, heating and transportation demands, developing a technical scenario for the transition to an energy system based on locally available RES such as geothermal, wind off-shore, biogas and waste. Special focus is given to the impacts of geothermal energy on the energy system dynamics. Also in Denmark, Lund and Mathiesen [6] and Mathiesen et al. [7] present a methodology including hourly computer simulations and propose a series of required changes to the "business as usual" reference scenario to achieve 50% of RES in 2030 and 100% of RES in 2050. It includes a socio-economic feasibility study of the 2030 system, the marginal feasibility of each individual proposal, socio-economics costs, health costs, commercial potential and job creation, and the energy balances