MODELLING AND SIMULATION OF RENEWABLE ENERGY SYSTEMS

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Keywords: Energy systems analysis, renewable energy systems, energy tools, energy planning, energy policy, implementation, EnergyPLAN.

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Summary

At a global level, it is essential that the world transfers from fossil fuels to renewable energy resources to minimise the implications of climate change, which has been clearly demonstrated by the Intergovernmental Panel on Climate Change [1]. At a national
level, for most countries the transition to renewable energy will improve energy security of supply, create new jobs, enhance trade, and consequently grow the national economy. However, even with such promising consequences, renewable energy only provided approximately 13% of the world’s energy in 2007 [2]. Therefore, identifying how to utilise more renewable energy is one of the most pressing challenges facing many countries at present.

Due to the ever-growing complexity of modern energy systems, energy-system-analysis tools are often used to analyse the potential of renewable energy in future energy systems. As renewable energy becomes more prominent, more energy-system-analysis tools are being created. The key element in this transfer is often to show coherent technical analyses of how renewable energy can be implemented, and what effects renewable energy has on other parts of the energy system. However, when beginning an investigation into the potential of renewable energy, it is difficult to identify which energy-system-analysis tool is the most suitable for the investigation. As a result, a selection of energy tools will be presented here to illustrate the type modelling that is possible for renewable energy systems and also, to illustrate the variety of energy tools that exist. For example, some tools focus on local community energy projects, while others consider national energy systems and some tools consider the annual amount of energy being consumed, while others focus on the hourly operation of the system. The variety of tools available has led to the conclusion that the optimum tool for a study is very dependent on the initial objectives which have been set.

This paper will 1) give an overview of a number of different energy tools and models and 2) provide a deeper description of one of these tools (EnergyPLAN) along with the methodology followed with it. EnergyPLAN has been used to establish how intermittent renewable energy, primarily in the form of wind power, can be accommodated in Denmark while reliably operating the electric grid. In addition, various case studies are presented on individual technologies and complete energy system strategies, which outline how it is possible to reach a 100% renewable energy system in the coming decades.

1. Introduction

Overall, the push towards renewable energy in any nation is typically driven by three main concerns: climate change, security of supply, and job creation. Although the significance of these issues changes from one country to the next depending on their natural resources, political stability, and demand for energy, the world as a whole will need to overcome two of these if it will ever achieve a sustainable future: climate change and energy security.

Climate change is caused by a change in the balance between the short-wave solar radiation coming into the earth’s atmosphere and the long-wave solar radiation leaving the earth’s atmosphere. At present, there is more solar radiation entering the earth’s atmosphere than there is leaving it, which is called radiative forcing. The recorded consequences of radiative forcing over the past two centuries include an increase in global average surface temperatures, an increase in global average sea level, and a decrease in northern hemisphere snow cover [3]. If these trends continue, predictions
indicate that it will lead to dramatic changes in the world’s climate which will alter water supplies, ecosystems, food supplies, coastlines, and even health. The potential implications are so devastating that the Intergovernmental Panel on Climate Change (IPCC) believes that “unmitigated climate change would, in the long term, be likely to exceed the capacity of natural, managed and human systems to adapt” [1]. However, the severity of these changes will depend on the level of greenhouse gases (GHG) which are emitted into the atmosphere in the future. Since CO₂ emission from energy production creates 64% of the world’s GHG emissions alone, the IPCC have concluded that “all assessed stabilisation scenarios concur that 60 to 80% of the reductions over the course of the century would come from energy supply and use and industrial processes” [1]. Consequently, to avoid devastating and irreversible changes to the world’s climate over the next century, energy production will need to be decarbonised by replacing fossil fuel production with renewable energy.

At present the world’s energy supply is dominated by fossil fuels. This is primarily due to the design of energy systems over the past century. In most developed systems that exist today, fossil fuels are the primary source of all energy, be it electricity, heat, or transport. As a result, in 2007 81.4% of the world’s energy was produced from fossil fuels. Even more concerning however, is the fact that by 2030 the International Energy Agency (IEA) expects the world’s energy demand to grow from 12,029 Mtoe in 2007 to 17,014 Mtoe (142%), with fossil fuels then accounting for 80.5% of the world’s energy. Mirroring this increase in energy production towards 2030 will be an increase in world CO₂ emissions. As discussed previously, further increases in CO₂ emissions will have detrimental implications for the world and hence, future energy production is clearly not sustainable. Furthermore, this increase in energy production and increase in fossil fuel consumption will lead to another major global issue, which is energy security of supply.

The most recent assessment of fossil fuel reserves carried out by British Petroleum (BP) estimated that there is only 46 years of oil, 63 years of gas, and 119 years of coal remaining which is economically accessible based on 2009 consumption levels [4]. Although it could be argued that technological developments will increase production in the future, as they have done in the past, any increase will most likely be offset by the aforementioned increase in future demand and the expected reduction in new reserves. This was quantified by Shafiee and Topal [5] who created a model that included the projected consumption and depletion of fossil fuels into the future. The results indicated that reserve depletion times for oil, gas, and coal could be as soon as 35, 37, and 107 years respectively [5]. Therefore, although there is ambiguity surrounding the exact date of fossil fuel depletion, it is evident both within [4] and outside [5] of the petroleum industry, that reserves are depleting within decades not centuries.

In summary, climate change is already being witnessed around the globe through increasing surface temperatures, rising sea levels, and decreasing snow cover. However, these changes are expected to intensify as more GHG emissions are emitted into the atmosphere. It is evident that 64% of total GHG emissions are related to CO₂ from energy production alone, primarily through the burning of fossil fuels and hence the energy sector needs to be decarbonised. However, based on current and projected trends in global energy production, it is clear that the world’s dependence on fossil fuels is set to increase and correspondingly GHG emissions will also increase. In addition, due to
the scale of the world’s fossil fuel dependence it is currently predicted that oil and gas resources will have depleted within the next century. Therefore, from an environmental, sustainability, and even security perspective, it is essential that the world eradicates its addiction to fossil fuels and moves towards a renewable based energy supply.

1.1. Renewable Energy

Renewable resources can produce energy without catastrophic climate issues and in a sustainable manner. However, it exists in many forms, with each type offering some unique advantages and drawbacks. In total, there are five primary sources of renewable energy: biomass, wind, water, solar, and geothermal. During the early 20th century, only biomass and water (in the form of hydroelectricity) remained competitive with fossil fuels. However, after significant RD&D over the last 30 years, a number of renewable technologies have now become economically competitive with conventional fossil fuels, which is evident from Figure 1. As a result, renewable energy has started to play an increasing role in energy production. Furthermore, with continued RD&D, the projections in Figure 1 indicate that the cost of renewable energy is expected to fall even further, while conventional fossil fuel generation is expected to rise. Consequently, from a costs perspective, renewable energy has already and will continue to be a realistic alternative for large-scale energy production. However, there is one key difference between conventional fossil fuels and a number of evolving renewable energy technologies: control.

![Figure 1: Historical costs of renewable and fossil fuel based electricity generation along with projected costs for 2015 and 2030 (adopted from references [6-8]).](image)

These new renewable energy devices harness resources such as wind, wave, tidal, and solar, with the most suitable device usually dependent on the natural resources within the region being considered. Naturally, these resources cannot be controlled to suit the...
demands of humans and hence the electricity generated from these renewable devices can vary significantly, which is portrayed in Figure 2. Therefore, renewable energy is providing a new form of intermittent power onto a system which has been designed to operate using dispatchable and predictable fossil fuel technologies. This intermittency can lead to many problems, especially within the electricity sector [9-16]. Therefore, to transfer from a fossil fuel to a renewable energy system, greater flexibility will be necessary within future energy systems, which will also introduce greater complexity in existing energy systems. This is not only in terms of intermittency, but also in terms of the balance necessary between electricity and heat supply units such as CHP, power plants, and boilers. This becomes even more complex with the addition of mobility, fuels, and heat pumps, which are often necessary to create even more flexibility between the various sectors of the energy system.

A crucial element in this complex transfer to renewable energy is to show coherent technical analyses of how renewable energy can be implemented, and what effects renewable energy has on other parts of the energy system. Such analysis requires computer tools (Energy tools are used to create energy models: Therefore, the computer programs discussed in this paper are referred to as ‘tools’, which can be used to create various types of models.) that can create answers for these issues by modelling defined energy systems. It is time-consuming to create new tools for each and every analysis, hence if feasible and accessible tools exist, these should be used. In this paper, a review of the various energy tools available for modelling renewable energy systems is presented to outline the various approaches to this issue. Subsequently, the approach adopted by the EnergyPLAN tool is explored in detail and finally, a range of case studies are presented for assessing individual technologies as well as developing complete energy strategies.

![Figure 2: Predicted hourly output from a 1 MW wind, wave, tidal, and solar electricity generator in Ireland during week 1 of January 2007.](image)

2. Renewable Energy System Analysis Tools

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The results presented in this section culminated from a review of the various energy tools available in 2009 for modelling renewable energy systems [17]. Only tools which could assess the feasibility of integrating more renewable energy were included in this review. Otherwise, there were no significant limitations so the results could demonstrate the range of options currently available. Initially, 68 energy tools were considered for this review while 37 of these were included in the final analysis.

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David Connolly (david@plan.aau.dk) is an Assistant Professor at Aalborg University who focuses on energy system analysis, large-scale energy storage, and electricity markets. He graduated with a first-class honours degree in Mechanical Engineering and received the University Gold Medal from the University of Limerick in 2007. Subsequently, he joined the Charles Parsons Initiative (www.cpi.ul.ie) also at the University of Limerick to undertake a Ph.D. in energy systems analysis. This focused on the integration of fluctuating renewable energy onto the Irish energy using large-scale energy storage. In line with this, he has developed a computer tool to locate potential locations for constructing large-scale energy storage and he has also developed a model of the Irish energy system using EnergyPLAN (www.EnergyPLAN.eu). This was used to quantify the energy storage capacities required for increasing penetrations of wind energy in Ireland and also, to create a 100% renewable scenario for Ireland. To date
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