Energy xxx (2014) 1–26

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Fossil fuel depletion and socio-economic scenarios: An integrated approach

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ARTICLE INFO

Article history:
Received 14 January 2014
Received in revised form
12 September 2014
Accepted 14 September 2014
Available online xxx

Keywords:
Renewable limits
Fossil fuel depletion
Global warming
System dynamics
Peak oil
Global Environmental Assessment

ABSTRACT

The progressive reduction of high-quality-easy-to-extract energy is a widely recognized and already ongoing process. Although depletion studies for individual fuels are relatively abundant, few of them offer a global perspective of all energy sources and their potential future developments, and even fewer include the demand of the socio-economic system.

This paper presents an Economy-Energy-Environment model based on System Dynamics which integrates all those aspects: the physical restrictions (with peak estimations for oil, gas, coal and uranium), the techno-sustainable potential of renewable energy estimated by a novel top-down methodology, the socio-economic energy demands, the development of alternative technologies and the net CO_2 emissions.

We confront our model with the basic assumptions of previous Global Environmental Assessment (GEA) studies. The results show that demand-driven evolution, as performed in the past, might be unfeasible: strong energy-supply scarcity is found in the next two decades, especially in the transportation sector before 2020. Electricity generation is unable to fulfill its demand in 2025–2040, and a large expansion of electric renewable energies move us close to their limits. In order to find achievable scenarios, we are obliged to set hypotheses which are hardly used in GEA scenarios, such as zero or negative economic growth.

1. Introduction

In recent years, concerns about the depletion of energy and materials (e.g. peak oil), as well as limits to the ecosystem's assimilation capacity of residues (e.g. climatic change) have been raised in the social, political and business arena. All fossil fuels and minerals are finite and non-renewable on a human scale. These resources are thus limited physically and, more stringently, economically. However, different views about this phenomenon exist in the scientific discussion, opposing "geologists" (or pessimists) vs. "conventional economists" (or optimists). The first [67] argue that geological factors determine a peak in the extraction of each resource that technology can only slightly modify – see for example [22,81,128] and the activity of ASPO in http://www.peakoil.net and point out that these restrictions might have strong economic consequences [19,56,61,99,136]. However, the "conventional economists", applying the basis of neoclassical growth theory [127], claim that market mechanisms and human ingenuity will be able to both transform resources into reserves and find alternative energy sources to replace the scarce ones at a sufficient pace to avoid supply restrictions, and thus, not affect GDP growth [1,87,104,122,132]. This paper intends to shed light on this discussion by using a System Dynamics (SD) model that includes both the physical data of the energy resources and the economic data.

The fact that the peak of conventional oil has already occurred has been largely admitted in Academia (e.g. Ref. [100]) as well as by

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http://dx.doi.org/10.1016/j.energy.2014.09.063
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international institutional agencies -together with the acknowledgment of peak oil basic theory as an appropriate methodology – Refs. [13,147,148,150], representing government declarations (e.g. the European Energy Commissioner[1] in 2009) and even from some oil companies [97]. In 2012, the ratio of oil in the global energy consumption mix fell to its minimum value in the last 50 years [16]. Annual oil discoveries peaked in the 60s and no oil price rise since then could invert or stop the tendency of declining discoveries thereafter. Due to the close relation between natural gas and oil, the geological understanding of their deposits and depletion is very similar. Conventional wisdom has it that global coal and uranium reserves are ample and supply restrictions due to scarcity must not be expected within the next several decades or even this century, but this is disputed by several studies [35,40,60,96,115].

Consequently, renewable energy, and particularly solar and wind energy, are the two main sources of renewable energy which might substitute the decline in fossil fuel extraction [124]. However, recent studies of their limits show that their potentials might be even lower than the current final consumption of energy by means of fossil fuels [30–32]. Thus, if a long-term structural scarcity in energy supplies in the next few years and/or decades occurs, as suggested in the past (e.g. Reports from the *Club of Rome* [90,91], *Global 2000* [11]), and, more recently [29,85,102,142], this situation would be unprecedented in modern history. Moreover, the study of previous technological transitions shows that they are slow, in the order of decades [49].

On the other hand, energy consumption acts as a climatic change driver [70]. But few studies have focused on the effect of energy constraints in climate scenarios, e.g. Refs. [18,64,145].

While depletion estimation for individual fuels following different approaches are relatively abundant (see Refs. [85,93] for an overview), few studies have centered on the objective of giving a comprehensive study, including estimates for all fossil fuels: Refs. [2,42,81,85,95,142] and even fewer have analyzed the whole system and fuel interactions [29,102,151], as we propose with our model.

This paper intends to shed light on these issues by describing and showing the results of the model we have developed, *WoLiM* (World Limit Model), which is a continuation of previous System Dynamic models developed [29,93]. WoLiM is a structurally-simple and transparent model that compares data from many different sources and helps to view global panoramas. The SD approach allows the combination of different kinds of variables from different knowledge sources, such as socio-economic, geological and technological, so they can be managed and integrated. The model includes the exhaustion patterns of non-renewable resources and their replacement by alternative energies, the estimations of the development and market penetration of alternative technologies, the energy demand of the World's economy under different socio-economic scenarios, the sustainable potential of renewable energies, and the estimations of CO_2 emissions related to fossil fuel consumption, all of them viewed in a dynamic framework.

On the other hand, scenario methodology offers an approach to deal with the complexity and uncertainty inherent to these interrelated issues and has become very popular in recent Global Environmental Assessments (GEAs), e.g. IPCC's Assessment reports [69,70,75], UNEP's Global Environmental Outlook [137,138,140] or the Millennium Ecosystem Assessment (MEA) [89]. Each storyline entails the representation of a plausible and relevant story about how the future might unfold. We judge that this methodology is an adequate one for the design of the socio economic scenarios that are needed as inputs to our model. The paper, therefore, quantifies and implements five representative storylines identified in GEA studies (as described in Ref. [144] and use them as input policies of the WoLiM model. *By using this methodology, we replicate the usual visions of the future explored by these international agencies, allowing them to be confronted with the case of the energy development constraints. In fact, to date, these international scientific bodies have largely ignored these constraints* [3,26,64].[2]

The paper is organized as follows: Section 2 overviews the model and its main hypothesis and limitations. Section 3 describes the modeling of non renewable and renewable resources. Section 4 explains the estimation of energy demand and Section 5 describes the calculation of CO_2 emissions. Scenarios and results are described in Sections 6 and 7. Finally, conclusions are drawn in Section 8.

2. Overview of the WoLiM model

In recent decades, many global energy-economy-environment models, most focusing on climate change analysis, have been developed (e.g. MESSAGE [101], IMAGE [15], MERGE [86], etc.), some based on system dynamics [12,28,46]. However, most of these models tend to use (very) large resource estimates [88] that are subject to high uncertainties and are strongly biased towards overestimation due to the preeminence of optimistic economic assumptions [26,64,115]. Thus, few models explicitly recognize resource limits such as peak oil and relate them to the economic growth [29,51,90,91,93]. The WoLiM model does recognize such limits and adopts the approach of URR (Ultimately Recoverable Resources), which is an expert-estimate of the total amount of resource that will ever be recovered and produced.

The WoLiM model,[3] which continues previous works [29,33,93], includes the following trends in a dynamic framework:

- The exhaustion patterns of non-renewable resources (URR approach and maximum extraction curves).
- The replacement of non renewable by alternative energies.
- The energy demand of the World's economy under different socio-economic scenarios.
- The sustainable potential of renewable energies.
- The net CO_2 concentrations.

WoLiM is based on a lineal structure (see Fig. 1) which starts by choosing a scenario framework that consists of a set of socioeconomic and technological assumptions and policies that are integrated in a coherent and sensible way (this scenario methodology is described in Section 6). The projection of the socio-economic drivers establishes the world energy demand. This demand is then disaggregated by sectors according to the different end-use sectors (electricity, industry, transport, etc.), and the energy demand of each sector is disaggregated into the demand by resources (liquid fuels, gas, electricity, etc.). These demands are compared to the production of each particular resource, which is limited by the geology-based peaks and the rates of technological substitution. Finally, the net CO_2 emission and concentration levels are computed.

[1] Original post deleted. A transcription can be found in <http://europe.theoildrum.com/node/5397>.

[2] For example, some international economic organizations such the OECD [105] project that global GDP will grow at around 3% per year over the next half century. It will almost triple in the years 2010–2060, although world GDP distribution among countries will be very different from now: China and India will together account for 46 % of global GDP in 2050, up from less than 13 % today. No mention, however, about how scientific knowledge on resources constraints, likely future scarcities and some other economic uncertainties may affect these forecasts.

[3] For a full description of the WoLiM model see Ref. [24].

Please cite this article in press as: Capellán-Pérez I, et al., Fossil fuel depletion and socio-economic scenarios: An integrated approach, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.09.063