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Linking energy policy, electricity generation and transmission using strong sustainability and co-optimization

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ABSTRACT

The design of a sustainable electricity generation and transmission system is based on the established science of anthropogenic climate change and the realization that depending on imported fossil-fuels is becoming a measure of energy insecurity of supply. A model is proposed which integrates generation fuel mix composition, assignment of plants and optimized power flow, using Portugal as a case study. The result of this co-optimized approach is an overall set of generator types/fuels which increases the diversity of Portuguese electricity supply, lowers its dependency on imported fuels by 21.30% and moves the country towards meeting its regional and international obligations of 31% energy from renewables by 2020 and a 27% reduction in greenhouse gas emissions by 2012, respectively. The quantity and composition of power generation at each bus is specified, with particular focus on quantifying the amount of distributed generation. Based on other works, the resultant, overall distributed capacity penetration of 11.88% of total installed generation is expected to yield positive network benefits. Thus, the model demonstrates that national energy policy and technical deployment can be linked through sustainability and, moreover, that the respective goals may be mutually achieved via holistic, integrated design.

1. Introduction

A sustainable electricity system is one in which all stages of the energy path are addressed, including the composition of the generation mix, the allocation of centralized and distributed generation, and their subsequent deployment. This work aims to create a link between a national, sustainable electricity policy and the performance of its transmission grid, recognizing that the latter may better fit within the former if they are co-designed and optimized.

The goal of sustainable energy systems is to deliver affordable energy services while raising the living standard for the global population, chiefly through increased energy efficiency and deployment of renewables [1]. In particular, the latter can contribute to mitigating the emissions of greenhouse gases (GHG), namely carbon dioxide (CO_2), and enhancing energy security of supply and independence.

From the beginning of the Industrial Revolution, carbon emissions have increased non-linearly per year to 38 Gt CO_2 in 2004. Three quarters of these emissions were due to human activities, of which fossil-fuel combustion accounted for 56.60% [2]. The consequence of these emissions has been an increase in the concentration of atmospheric CO_2 to the current value of 383.72 parts per million (ppm) [3], which is the highest recorded in the 650,000 years preceding industrialization [4]. Among other effects, the mean surface temperature of the earth has been rising, with average 2007 temperatures being 0.91° higher than in 1907, making the former the eighth warmest year recorded [5]. Various international agreements have been ratified to address this anthropogenic-induced climate change. The most wide-reaching of them is the Kyoto Protocol to the United Nations Framework Convention on Climate Change which requires Annex I countries to achieve an overall target of at least a 5% decrease in emissions below 1990 levels in the period 2008–2012 [6]. A number of regions and countries have implemented national emissions policies, with examples of the European Commission (EC) successor to Directive 2001/77/EC which will require 20% energy from renewables by 2020 [7] and the United States Government 2008 announcement of a halt to GHG emissions by 2025, with sustained reduction from then.

Combining rising oil and gas prices with a recognized dependence of the developed world on foreign resources, the issue of security of supply and energy independence is being raised more commonly. For many countries, achieving the latter may require a switch from imported fossil-fuels to domestic supplies of coal or the stimulation of natural, indigenous wind, solar, geothermal, hydro and biomass resource use. The research conducted in the field of energy security of supply includes: deriving an underestimated cost of 3×10^{-7} €/MWh for each barrel of oil not supplied to the market

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in the event of a supply disruption [8]; a cost of 4×10^{-9} €/MWh due to a rise in energy prices [9]; the use of the Shannon–Weiner Index (SWI)[1] to assess the degree of dependence on a specific fuel or technology type and the total system exposure to price perturbation, with a target value of at least two [10]; and metrics of net energy import dependence and percentage of indigenous fuels used as indicators of the energy independence [11].

Concurrent with emissions limits are the continued changes in the domestic electricity markets in the form of deregulation. As a result, independent power producing is becoming more widespread and there is increased deployment of distributed generation (DG). Current drivers of DG are environmental, commercial, and regulatory, however there are widely agreed negative network effects of voltage rise, harmonic distortion and issues with islanded operations [12].

A wealth of research is devoted to locating DG in order to maximize its benefits and minimize its negative grid impacts. Assigning DG to buses with the highest locational marginal pricing has been suggested as a method of increasing social welfare [13]. Conversely, an analytical, weighted, multi-objective optimization proposed the assignment of DG based on network performance impacts [14]. Additional specialized approaches have investigated deployment of DG on feeders with particular load profiles [15]. The consensus is that the type and location of DG, and its subsequent degree of penetration, are critical to its benefits not being overshadowed by decreased network performance.

Types of DG include conventional, dispatchable generators and variable-output plants such as solar photovoltaics (PV) and wind. While both types can provide grid support, only the renewables can realize the environmental advantages of DG deployment. However, to mitigate the network effects due to their fluctuating outputs, it has been suggested to pair them with the dispatchable generation [16].

DG is well-sited in high load areas [14], where branch congestion [12] and power losses [17] may be reduced, particularly towards the end of feeders or near to branch points [15,18]. However, multiple voltage-support DGs in close proximity may work in opposition with each other [19] requiring consideration of the spatial intensity of DG deployment. Since the presence of DG transforms the traditional passive distribution network into, effectively, an active transmission system [20], optimal power flow (OPF) analyses can be used to assess the subsequent network performance once the generator assignment has occurred [21].

In summary, the current level of carbon emissions is at odds with binding national and international targets. Moreover, the continued dependence on the fuels, from which the carbon emissions proceed, prolongs the risks of perturbing the energy supply. Switching to indigenous fuels can mitigate the latter, while restructuring the fuel mix composition to include more renewables can address both challenges. Therefore, electricity system planners must determine how much of each type of technology or fuel to include in their power generation mix in order to achieve these goals. However, given the benefits and potential drawbacks of DG, planners must also consider where to locate their generation capacity and how much should be centralized or distributed. This work proposes a link between the emissions policy, fuel mix and generator assignment questions posed, using 2006 data for mainland Portugal as a case study to illustrate the results.

[1] The SWI is normally used in competition analysis, accounting for relative size and distribution of market players. Analogously, a highly concentrated marketplace (SWI < 1) represents a system which is dependent on one or two sources and could be susceptible to sustained interruption. Alternatively, in a fully competitive case (SWI > 2), there are multiple sources and consumers can be confident in continued supply in the event of an disruption.

2. Model

The aims of the work were accomplished using a recursive optimization model, comprising the generation fuel mix, constrained assignment of generators to buses, and OPF of subsequent network.

2.1. Portuguese transmission network

The network was modelled using the 2005 Union for the Co-ordination of Transmission of Electricity (UCTE) map of the 400 kV and 220 kV transmission lines [22]. The model consisted of 57 buses, with bus 1 being the slack bus, connected across 107 branches. Additionally:

- generator power and fuel-type were derived from the transmission grid map of the network operator, *Rede Eléctrica Nacional* (REN) [23];
- bus loads were determined using a variation of the method in [24], where a weighted distribution of the population of each of the five mainland administrative regions – *Alentejo, Algarve, Centro, Lisboa e Vale do Tejo*, and *Norte*– was used to assess regional peak demand.[2] For *Norte* and *Lisboa e Vale do Tejo*, the city buses comprising *Porto* and *Lisboa* were assigned demand by population, with the remaining load in the respective regions divided equally across the other buses;
- line characteristics were, in r/x/b format: 0.0417/0.1396/ 0.0319 Ω/km for 400 kV and 0.0457/0.1417/0.0324 Ω/km for 220 kV, all at a base power of 100 MVA;
- a power factor of 0.95 was used, representing the demand seen at each load bus by the transmission system; and
- a negative load of −1200 MW employed, representing maximum demand from the single bus representing Spain at 1100 h on all third Wednesdays per month in 2005 [25].

The total modelled transmission line length of 4311.43 km was within 1% of the UCTE published value of 4355 km [25].

2.2. Power generation fuel mix optimization

A power generation fuel mix model was proposed which optimizes penetration of generator types using strong sustainability principles as its core [26]. The objective is to achieve a high fuel mix diversity, as a proxy for security of supply, subject to delivering the electricity at no more than the current retail price of 504.60 €/kW[3]; meeting current energy demand; reducing carbon emissions by the quotient of the carbon footprint and forest sequestration capacity, yielding an emissions factor of 898.41 kg CO_2/kW; and stabilizing material input per unit service (MIPS) at the current rate of 39.99 kg/kW (Table 2). The generation technologies used in the model were wind, large hydro, geothermal, biomass, PV, combined cycle natural gas (CCGT), coal, nuclear, and oil (Table 1).[4]

[2] Although peak demand is used to illustrate the co-optimized concept in this work, it is acknowledged that a study focusing only on the peak demand can only be simplistic by not representing the full suite of demand possibilities. However, a peak demand analysis gives a reasonable worst case planning scenario under normal operating conditions (that is, in the absence of perturbations). Consequently, the offpeak demand will not require any more installed generation at a particular location, although the system may operate sub-optimally during those periods.

[3] This retail price for the electricity constraint corresponds to an average residential price of electricity of 0.14 €/kWh for households consuming 3500 kWh annually, of which 1300 kWh are at night. See Eurostat table NRG_PC_ 204_ H for details.

[4] The selected nine generator fuels/types represent 93.71% of installed capacity, with the remaining 6.29% comprising pumped hydro storage. See Eurostat table NRG_113A for details.