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Power systems without fuel

Josh A. Taylor [a,*], Sairaj V. Dhople [b,1], Duncan S. Callaway [c]

[a] Electrical and Computer Engineering, University of Toronto, Toronto, Canada ON M5S 3G4
[b] Electrical and Computer Engineering, University of Minnesota, Minneapolis, MN 55455, USA
[c] Energy and Resources Group, University of California, Berkeley, CA 94720, USA

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ABSTRACT

The finiteness of fossil fuels implies that future electric power systems may predominantly source energy from fuel-free renewable resources like wind and solar. Evidently, these *power systems without fuel* will be environmentally benign, sustainable, and subject to milder failure scenarios. Many of these advantages were projected decades ago with the definition of the *soft energy path*, which describes a future where all energy is provided by numerous small, simple, and diverse renewable sources. Here we provide a thorough investigation of power systems without any fuel-based generation from technical and economic standpoints. The paper is organized by timescale and covers issues like the irrelevance of unit commitment in networks without large, fuel-based generators, the dubiousness of nodal pricing without fuel costs, and the need for new system-level models and control methods for semiconductor-based energy-conversion interfaces.

Contents

* Corresponding author.
E-mail addresses: josh.taylor@utoronto.ca (J.A. Taylor), sdhople@umn.edu (S.V. Dhople), dcal@berkeley.edu (D.S. Callaway).
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1. Introduction

Eventually, whether from a deliberate shift to renewables or the depletion of planetary fossil fuel sources, major portions of power systems will run without fossil fuels. There is now extensive literature on this subject, see, e.g., [1,2], most of which focuses on the advantages and disadvantages of renewable energy sources. Here we also consider this scenario, but focus on the combined consequences of using renewables and eliminating fuel-based generators. We describe related perspectives and the status quo in Section 1.1 and fully define our scope in Section 1.2. We believe that it is important to discuss these issues both for the limiting case of exclusively renewable power production and also under mostly renewable power production, in which case planning and operational practices should reflect the large majority of renewables instead of a small minority of fuel-based generators.

Much of the salient physics of present-day power systems are attributable to fuel-based generators, which are most cost-effective at large unit sizes; for example, thermal limits constrain power production schedules, and synchronous machine rotor inertias dominate transient stability. While the addition of intermittent and distributed renewables will change the form of power systems, so will removing the fuel-based generators that account for much of its current character. Many of the consequences of removing fuel-based generators are well studied, for example the loss of system inertia and the need to replace generator reserves with storage and demand response. However, it is our perception that many important issues have not been thoroughly discussed, such as the need for new optimal power flow objectives to replace fuel costs and the attendant need for alternative economic mechanisms to marginal cost-based pricing. In some regards, removing fuel-based generators can result in significant benefits like the elimination of the unit commitment problem and the higher compatibility with DC technologies. We address such issues in a unified fashion by surveying existing discussions, identifying challenges, and suggesting new directions where appropriate.

Two key motifs of this paper are that (see Fig. 1)

- all timescales are shrinking, and
- a few large components will be replaced by numerous small components.

These changes have a number of salient consequences. For instance, renewables can be installed and maintained more quickly than fuel-based generators, bulk generation need not be scheduled days in advance to accommodate stringent startup and shutdown constraints, and the loss of mechanical inertia implies that transients will be dominated by the dynamic behaviors of many small, fast power-electronic energy-conversion interfaces.

We structure our discussions around the first motif, timescales, by first considering long-term planning in Section 2, then steady-state operation in Section 3, and then transient dynamics in Section 4. While so doing, we highlight the emergence and disappearance of new and old couplings. For example, renewable intermittency couples hourly steady-state dispatch decisions to regulation requirements. Similarly, wind and solar power sources consume negligible quantities of water compared to the cooling needs of fuel-based generators, drastically reducing the power system's dependency on the water infrastructure.

1.1. *The soft energy path and the status quo*

The rationale for a fully renewable energy infrastructure has long been well established; we now briefly summarize its beginnings and provide a few modern examples. In 1976, Lovins described the *soft energy path* as a future in which societal energy needs are met by simple, diverse technologies that rely on renewable energy sources [3,4]. The scale of these technologies could be small (e.g., customer sited) or large (e.g., utility scale), but for many devices that support the soft energy path the constituent parts are relatively small and modular (e.g., individual photovoltaic panels and wind turbines).

The soft energy path stands in contrast to the *hard energy path*, wherein energy is provided by a few large, resource intensive, complex technologies, which tend to induce caustic political dependencies and are prone to expensive physical failures. The case for the *soft energy path*—which we note does not include nuclear power—has been restated and reaffirmed in many ways over the past four decades. For instance, the capability of wind and solar to fulfill all of our energy needs is addressed in [5]. Distributed generation [6] and microgrids [7] are two related architectural paradigms where small, renewable technologies meet energy needs locally. Another compelling argument for the soft energy path is that *unused* wind and solar energy are lost while fossil fuels may be indefinitely "… [left] … in the ground for emergency use only" [3].

It may well be some time before continental-scale portions of power systems are fully on the soft energy path. However, there

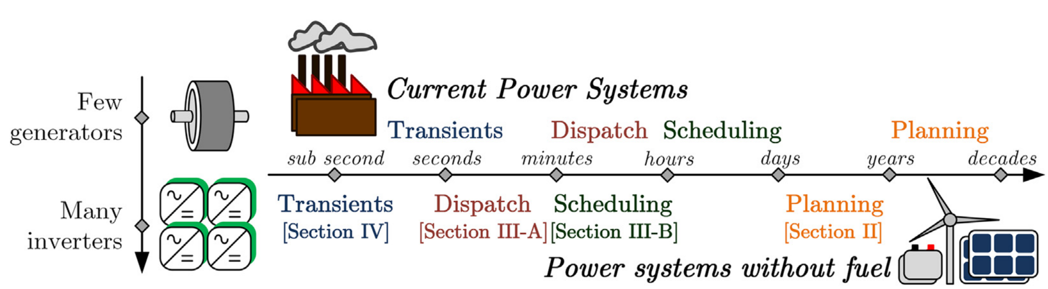

Fig. 1. No-fuel power systems will have fundamentally different spatio-temporal characteristics. Time scales governing operations and control will shrink, and energy-conversion interfaces will be distributed in form and function.