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# Towards 100% renewable energy systems: Uncapping power system flexibility

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## HIGHLIGHTS

- **100% VRES systems:** combined analysis of all related technical and policy challenges.
- **Transition elements:** classification of the complete range of challenges in 9 elements.
- **Development regimes:** policy actions in 3 VRES penetration regimes (low-medium-high).
- **Policies:** comprehensive guideline and detailed presentation of policies per regime.
- **Roadmap:** lists of actions per regime act as transition roadmap to 100% VRES systems.

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## ABSTRACT

Relying almost entirely on energy from variable renewable resources such as wind and solar energy will require a transformation in the way power systems are planned and operated. This paper outlines the necessary steps in creating power systems with the flexibility needed to maintain stability and reliability while relying primarily on variable energy resources. These steps are provided in the form of a comprehensive overview of policies, technical changes, and institutional systems, organized in three development phases: an initial phase (penetration up to about 10%) characterized by relatively mild changes to conventional power system operations and structures; a dynamic middle phase (up to about 50% penetration) characterized by phasing out conventional generation and a concerted effort to wring flexibility from existing infrastructure; and the high penetration phase that inevitably addresses how power systems operate over longer periods of weeks or months when variable generation will be in either short supply, or in over-abundance. Although this transition is likely a decades-long and incremental process and depends on the specifics of each system, the needed policies, research, demonstration projects and institutional changes need to start now precisely because of the complexity of the transformation. The list of policy actions presented in this paper can serve as a guideline to policy makers on effectuating the transition and on tracking the preparedness of systems.



## 1. Introduction

Carbon dioxide emissions from burning fossil fuels are responsible for more than half of carbon emissions contributing to global warming (US Environmental Protection Agency, 2015). Blunting the worst effects of climate change requires shifting power generation to low carbon energy sources such as wind and solar energy. Transitioning to such variable renewable energy sources (VRES) has become an economic and technological possibility, as the cost of wind and solar energy begins to match traditional technologies (Fraunhofer I.S.E., 2013; Ecofys, 2014), as shown in Fig. 1.

Electric power production and consumption occur simultaneously, underscoring the importance of balancing supply and demand—an increasing challenge as levels of variable generation rise. System balancing has historically been performed by controllable power plants. This practice largely continues today, except that the variable output of wind and solar plants increases the

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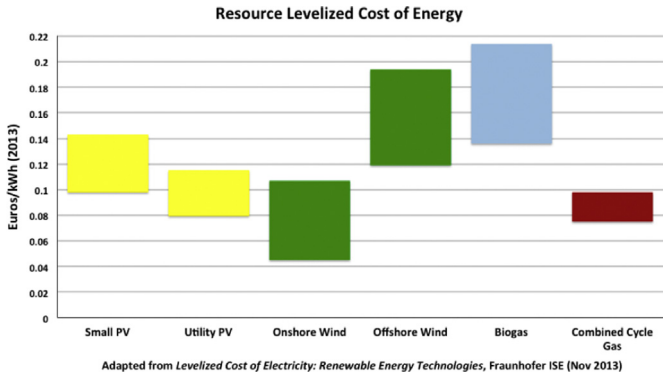


**Fig. 1.** Comparison of levelized cost of Electricity for renewable energy technologies to conventional generation technologies (adapted from Fraunhofer I.S.E. (2013)).

need for flexibility[1] in the power system to respond. A set of options are available to provide the needed flexibility including energy storage, demand, networks, greater controls on VRES, and adjustment of system operation rules (Ecofys, 2014b). To enable these options, radical changes in the way power systems are organized and operated are needed. In our analysis, we link the transition to higher VRES penetration rates to power system flexibility, and adopt a broader view, where flexibility expands to all actions (long-term planning and real-time operation) needed to ensure system security, reliability and economic operation.

This paper provides an overview of the policies, technical changes, and institutional systems necessary to enable this transition, envisioned as a transformative process with three key phases. The work is largely a synthesis of the many reports and studies on this subject, such as (International Energy Agency, 2014; Western Governors' Association, 2012; IEA-RETD Executive Commitee Meeting, 2014; International Energy Agency, 2011; The Regulatory Assistance Project (RAP), 2014; European Climate Foundation, (ECF), 2012; Van Hulle et al., 2014; Electric Power Research Institute (EPRI), 2015; National Renewable Energy Laboratory (NREL), 2012; Dragoon, 2010; International Renewable Energy Agency (IRENA), 2014). The extensive body of work is summarized for a less technical audience that will need to put in place the needed policies, technical changes, and institutional systems. The unique contribution of this work is that it provides a holistic view of this complex transformation process and a broader analysis of the various issues and their interactions rather than focusing on single fragments of the process. We therefore adopt a broader analysis of the variety of topics and present a large number of references to sources for further reading on each topic.

The paper is organized as follows. Section 2 presents the key elements and challenges of the transition to power systems relying almost entirely to variable renewables. Section 3 presents a comprehensive overview of the needed changes in policy and institutional frameworks to enable this transition, classified on three development regimes. Section 4 concludes.

## 2. Method: analysis of the key elements and challenges for the transition to ultra-high VRES shares

The work represented in this paper is the result of an extensive survey of existing literature, personal communication with a range of experts in the field, and employing an international panel of experts[2] (Ecofys, 2015). Nine elements emerged as the key drivers for the transformation that are likely common to all power systems, as shown in Fig. 2. The relative importance of these features will vary from system to system depending on local conditions, but each of them represents an important contribution to developing systems capable of functioning efficiently and reliably on variable renewable resources. These key elements are discussed in detail below.

### 2.1. Exploiting demand side flexibility

Conventional power systems primarily rely on controlling supply for balancing purposes. Controlling demand takes a more central role at higher VRES penetration levels by acting as a relatively low cost source of power system flexibility (Klobasa and Ragwitz, 2006; Milligan and Kirby, 2010).[3] As discussed in (López-Peñaet al., 2012), demand side management clearly provides the lowest cost source of renewable energy support. Future demand management will mobilize a broad array of end uses enabling both increases and decreases in demand on a regular basis, expand demand flexibility (by adding storage capability where warranted) and coordinate active demand management with energy efficiency opportunities. (Navigant Consulting, 2012)

Additionally, implementing new demand technologies may represent another significant source of power system flexibility, specifically through the increased electrification of the transport and heating sectors. For example, vehicles powered directly or indirectly by electricity or heat pumps (especially when combined with thermal storage) could add a distributed energy storage capacity close to demand (Kiviluaoma and Meibom, 2010; Papaefthymiou et al., 2012),

### 2.2. The role of expanded and liberalized markets

Market structure plays an important role in the cost and capability of systems relying on larger contributions from VRES. The driving forces behind market transactions look significantly different in power systems relying primarily on zero variable cost resources. The value of energy at the wholesale level becomes very low due to the abundance of zero variable cost energy (National Renewable Energy Laboratory (NREL), 2012). Grid support services likely come to dominate market trading, reflecting the increased value of flexibility and optionality necessary to ensure reliable power from variable resources. This development will bring additional risk exposure for the VRES producers which translates into requiring greater financial support or introducing different mechanisms to stimulate development than in a low risk environment. In this respect, capacity markets may be necessary to ensure reliability by supporting needed flexible resources that might not be competitive on energy basis (Klessmann et al., 2008).

Ensuring low cost service will require markets open to as many participants as possible, including traditional generating resources, variable resources, distribution system-level generation, demand resources, and energy storage. Further, the markets will transact in near real time (in order to increase forecast accuracy) and in short time increments (to allow constant adaptation to fluctuations). Further, markets should cross regional and national borders to the extent possible, both to allow participation from a broader range

[1] Broadly speaking, flexibility is the ability of controllable power system components to produce or absorb power at different rates, over various timescales, and under various power system conditions.

[2] The extensive list of experts is contained in the Acknowledgments in Ecofys (2015). The expert panel met several times throughout the course of preparing the document and provided extensive comments and suggestions.

[3] Already at the moment significant economic benefits are being experienced in some systems, e.g. the US PJM market claims more than 11,000 MW of participating demand response, with yearly payments on the order of several million dollars for 2015 (PJM, 2015).