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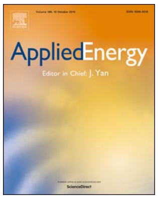

Security of supply in a carbon-free electric power system: The case of Iceland

Pablo Duenas[a,*], Andres Ramos[b], Karen Tapia-Ahumada[a], Luis Olmos[b], Michel Rivier[b], Jose-Ignacio Pérez-Arriaga[a,b]

[a] *MIT Energy Initiative, Massachusetts Institute of Technology, 77 Massachusetts Avenue, 02139 Cambridge, MA, United States*
[b] *Instituto de Investigación Tecnológica, Escuela Técnica Superior de Ingeniería, Universidad Pontificia Comillas, C/ Santa Cruz de Marcenado 26, 28015 Madrid, Spain*

HIGHLIGHTS

- Medium- and long-term security of decarbonized power supply in Iceland is analyzed.
- Illustrative example of decarbonized power system in the face of zero marginal cost.
- Bilateral contracts with curtailment clause are included into a hydrothermal model.
- Transmission upgrades improve security of supply and defer generation investments.
- Renewable technologies alone can provide outstanding levels of security of supply.

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ABSTRACT

Security of supply and progressively climate change are guiding countries' energy policy worldwide. Iceland is a paradigmatic example of gaining energy independence and decarbonizing the power sector while meeting its growing demand. In this paper, we focus on some of the main generation and transmission expansion alternatives that the country is considering for the next decade in an environment dominated by an increasing demand and a generation mix with virtually zero variable cost. We assess the medium- to long-term dimensions of security of supply as determinants of the system configuration and resources utilization. Based on a stochastic hydrothermal scheduling model that includes DC power flows and generation expansion decisions, our analysis indicates that hydro, geothermal and wind renewable resources are more competitive than fossil fuels, while demand flexibility can also contribute to gain security of supply at comparable costs. In addition, our methodology incorporates a detailed bilateral contracting structure typically used by Icelandic generators and consumers to agree on power prices and negotiated curtailments. The modeling and security evaluation could be of interest in other countries and regions where inflexible thermal generation and hydro resources create a market characterized by prices that are close to zero during long periods, but spike when resources are scarce.

1. Introduction

Iceland is a sparsely populated country—about 327,000 inhabitants in 2014—whose electricity demand, 17.6 TWh in 2014, places Iceland on the top of the global ranking of electricity consumption per capita, according to the World Bank database [1]. The Icelandic 54 MWh electricity consumption per capita more than doubles that of Norway, which is second in the ranking. Cheap and reliable electricity have attracted energy-intensive consumers, such as aluminum, silicon and ferrosilicon industries, and data centers. In addition, Iceland offers 100% renewable electricity and high quality of supply, and its power system is not connected to any other system due to its geographical position (1000 km to Scotland and 2500 km to Labrador Peninsula by sea). Iceland is undoubtedly an example for (mostly isolated) countries or areas that pursue a reliable and decarbonized energy system.

Access to a secure energy supply is essential for a good standard of living in modern societies. Energy scarcity and outages can have a severe adverse impact on businesses, schools, homes, finances, and telecommunications, and can lead to public safety incidents. According to the International Energy Agency [2], energy security is "the uninterrupted availability of energy sources at an affordable price". Gracceva and Zeniewski [3] define a secure energy system as one which evolves over time with an adequate capacity to satisfy the energy service needs of its users under any circumstance.

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[*] Corresponding author.
E-mail addresses: pduenas@mit.edu (P. Duenas), andres.ramos@iit.comillas.edu (A. Ramos), katapia@mit.edu (K. Tapia-Ahumada), luis.olmos@iit.comillas.edu (L. Olmos), michel.rivier@iit.comillas.edu (M. Rivier), ipa@mit.edu (J.-I. Pérez-Arriaga).

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Nomenclature

Indexes

P,p	period
N,n	load level
G,g	power plant
$X(g)$	candidate expansion for power plant g
E,e	reservoir
$H(e)$	hydro plants of reservoir e
$U(e)$	upstream hydro plants of reservoir e
$R(e)$	upstream reservoir of reservoir e
S,s	hydro scenario
$A(s,p)$	scenario ancestor of hydro scenario s in period p
i,j	node
$L(i,j)$	transmission line connecting nodes i and j
$Y(g,i)$	location of power plant g at power bus i
$K(L)$	transmission corridor containing line l
T,t	consumer
B,b	level of curtailment

Parameters

D_{tipn}	load demand by consumer at node, period and load level [MW]
CQ_{tb}	cost of load curtailment by consumer and curtailment level [\$/MWh]
CP_{tb}	maximum instantaneous curtailment (power) by consumer and level [%]
QE_{tb}	maximum annual curtailment (energy) by consumer and level[%]
QA_{tb}	maximum expected curtailment (energy) by consumer and level [%]
Dur_{pn}	duration of period and load level [h]
W_s	probability of hydro scenario [p.u.]
Q_g^{max}	maximum power production of power plant [MW]
Q_g^{min}	minimum power production of power plant [MW]
QX_g	capacity expansion of power plant [MW]
CV_g	variable production cost of power plant [\$/MWh]
CS_g	startup cost of power plant [\$]
CX_g	annualized cost of expansion of power plant [\$/MW-yr]
$F_{H(e)}$	production function of hydro plant [MWh/hm^3]
$HO_{H(e)}$	head effect (intercept) in hydro plant [MW]
$HS_{H(e)}$	head effect (slope) in hydro plant [MW/hm^3]
Q_e	maximum water reserve in reservoir [hm^3]
Q_{ef}	final reservoir level [hm^3]
I_{esp}	natural water inflows to reservoir for hydro scenario in period [hm^3]
S^B	base power [MW]
$R_{L(i,j)}$	resistance of line [p.u.]
$X_{L(i,j)}$	reactance of line [p.u.]
$K_{L(i,j)spn}$	losses coefficient of line in scenario at period and load level [p.u.]
$Q_{L(i,j)}$	maximum capacity of line [MW]
$Q_{K(L)}$	maximum capacity of corridor [MW]

Variables

u_{gspn}	commitment of power plant in hydro scenario at period and load level {0,1}
y_{gspn}	startup of power plant in hydro scenario at period and load level {0,1}
z_{gspn}	shutdown of power plant in hydro scenario at period and load level {0,1}
x_g	expansion of power plant {0,1}
q_{gspn}	production of power plant in hydro scenario at period and load level [MW]
θ_{ispn}	voltage angle
$f_{L(i,j)spn}$	power flow of line in hydro scenario at period and load level [MW]
$fp_{L(i,j)spn}$	positive flow from i to j in hydro scenario at period and load level [MW]
$fn_{L(i,j)spn}$	positive flow from j to i in hydro scenario at period and load level [MW]
l_{ispn}	power losses allocated to node in hydro scenario at period and load level [MW]
nsp_{tbispn}	curtailment by consumer and level at node in hydro scenario at period and load level [MW]
r_{esp}	water reserve of reservoir in hydro scenario at end of period [hm^3]
s_{esp}	water spillage of reservoir in hydro scenario at period [hm^3]

Cases

RC	Reference Case
HO	Highlands Option – Network expansion
IO	Interregional Option – Network expansion
DO	Diesel Option – Network expansion, sensitivity analysis
WO	Wind Option – Generation expansion
NWO	Non-Wind Option – Generation expansion
GO	Gas Option – Generation expansion, sensitivity analysis
CO	Curtailment Option – Generation expansion, sensitivity analysis

Security of supply has been a major guiding factor for energy policy worldwide. In addition, climate change is increasingly conditioning energy policies. Most countries have pledged to limit CO_2 emissions by increasing renewable generation, energy efficiency, and other measures. How to maintain or even gain security of supply while decarbonizing the energy sector has also motivated our analysis. As mentioned above, Iceland is an example of a country that is gaining energy security and progressively decarbonizing its energy sector. Yet the future path is not clear and Iceland continues to face an increasing energy demand that may compromise its security of supply. The electricity demand is expected to continue increasing during the next decade—more than 2% annually for household and commercial segments and up to 5.4 TWh for energy-intensive ones.[1] Therefore, Iceland faces the challenge of accommodating roughly 6.9 TWh of new demand, about 40% of the current demand, by 2030.

In this paper, we analyze and assess the options, at the power generation and transmission levels, that are currently under discussion in Iceland to achieve high levels of security of energy supply during the next decade. Nevertheless, this contribution should not only be restricted to Iceland, but put into the broader context of the many countries and areas that will find themselves in similar circumstances in the near future; that is, pursuing security of supply while decarbonizing their energy system. In particular, the described model is of interest to systems with relevant hydro resources and inflexible thermal (e.g., nuclear or geothermal) power plants, which creates the conditions for zero-price periods and price spikes.

This price volatility has led Icelandic producers and consumers to negotiate bilateral contracts with which both parties value zero-cost producing resources. Although our approach focuses on the

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[1] Projections provided by Orkustofnun and Landsvikjun, the Icelandic energy regulator and main power company, respectively.